Evaluating the performance of AquaCrop model for potato production under deficit irrigation

Aemro Wale[1], Mekete Dessie[2], Hailu Kendie[3]

[1] Sekota Dry-Land Agricultural Research Center, P.O. Box: 62; Sekota, Ethiopia

[2] Bahir Dar Institute of Technology, Bahir Dar University, P.O. Box: 26; Bahir Dar, Ethiopia

[3] Amhara Agricultural Research Institute, P.O. Box: 527; Bahir Dar, Ethiopia

Corresponding author e-mail: aemrowale@gmail.com

Abstract

Crop modeling is a powerful tool for estimating yield and water use efficiency in this regard, and it plays an important role in determining water management strategies. This study was performed in Lasta district, for two successive years. The aim was to evaluate the performance of Aquacrop model for potato producing area and study the effects of water shortage on potato production and water use efficiency. The irrigation water levels for potatoes were 100% ETC, 75% ETC, and 50% ETc. A randomized complete block design was used to arrange six treatments. Observed weather parameters for specific site together with measured crop parameters from optimum experiment conducted during 2018/19 were used to develop climate, soil and crop files in Aquacrop and to calibrate the model. Observations from the 2019/20 growing season and independent data were used to validate the model. Model calibration showed a good fit Coefficient of determination (R^2) = 0.98, Root mean square error (RMSE) = 9.6%, Nash-Sutcliffe efficiency (E) = 0.92, index of agreement (d) = 0.98 and coefficient of residual moss (CRM) = -0.07 for canopy cover (CC) as well as good prediction for biomass (R^2 = 0.98, RMSE = 1.8t/ha, E = 0.96, d = 0.99, CRM = -0.13). Model validation showed good simulation for CC by 100% water application at development and mid growth season and the other stages applied 75% (T3) (R^2 = 0.98, RMSE = 9.4%, E = 0.94, d = 0.98, CRM = -0.12) conditions. The model prediction biomass (R^2 = 0.98, RMSE = 2.2t/ha, E = 0.94, d = 0.98, CRM = -0.2) reasonably well for field with pooled data (T3). The highest yield (33.27t/ha) and water use efficiency (8.23kg/m^3) were obtained when 100% irrigation water was applied during the development and mid-growth seasons, and 75% irrigation water was applied during the other stages, while the lowest yield (22.21t/ha) and water use efficiency (6.67kg/m^3) 75% irrigation water applied through out the growth stages was recorded. As a result, we conclude that the irrigation water used (75, 100, 100, and 75% ETc) is better adapted to the agro-ecological conditions in Lalibela and other similar areas. The AquaCrop model is therefore easy to use, requires fewer input data, and its sufficient degree of simulation precision makes it a valuable instrument for estimating crop production under deficit irrigation and for water management to improve the efficiency of agricultural water use.

Keywords: Biomass, Calibration, Canopy cover, Validation, Water use efficiency

Introduction

Potatoes (Solanum sp.) are the fifth most common crops globally, after sugar cane, maize, rice, and wheat (Montoya *et al.,* 2016). It is one of the tuber crops full-grown in Ethiopia by more than one million farmers (CSA, 2018/2019). Potato is gazed as a high-potential sustenance security crop since of its bent to convey a high yield of high-quality product per unit input with a little crop cycle usually less than 120 days than main cereal crops (Hirpa *et al.*, 2010). Ethiopia is blessed with suitable climatic, soil, and topographic conditions for potato production. The national average yield is about 7-8 tons/ha, which is currently low as opposed to the world's average output of 15t ha^{-1} (FAO, 2011). Some of the teething troubles for the small yield of potato production are drought and flood, pests and diseases, soil erosion, the shift in rainfall pattern, and deterioration in available water (Deressa *et al.*, 2009).

As a result, better water utilization efficiency for potato production is needed in order to produce more crops per drop while reducing irrigation resources. The limited availability of water resources needs the development of new approaches to save water and energy, the utmost of which should emphasize on improving water use efficiency (Shahnazari *et al.,* 2007, Soomro *et al.,* 2020). To ensure food security, it is essential to use the water wisely in order to increase food production while saving water as much as possible or to increase field crops water use productivity. The world's population is growing by the day, posing a serious threat to future agricultural production, particularly in areas where water is the scarcest resource. Deficit irrigation is a technique, which enhances the economic use of water (Fereres and Soriano, 2006, Domínguez *et al.,* 2012); moreover, this approach can have a resilient effect on potato crops, by means of declines in crop yield and tuber quality (Shock *et al.,* 1998, Fabeiro *et al.,* 2001, Kashyap and Panda, 2003, Onder *et al.,* 2005, Vos and Haverkort, 2007, Ierna and Mauromicale, 2012, Gebremedhin *et al.*, 2015).

AquaCrop, a water-driven model for use as a decision-making support mechanism in planning and scenario analysis in various seasons and locations (Foster *et al.*, 2017, Mibulo and Kiggundu, 2018, Corbari *et al.,* 2021). Even if the model is comparatively simple, it elaborates on the fundamental process involved in crop productivity and the response to water deficits, both from a physiological and agronomic perspective (Tefera and Mitiku, 2021). It is intended to combine simplicity, precision, and robustness, and is suited to resolve situations where water is a primary limiting factor in crop production (Banchu, 2020). It necessitates fewer input data than other models (Hsiao *et al.,* 2009; Steduto *et al.,* 2009). Once validated, the model is easy and needs fewer resources and it could be a useful tool in irrigation scheduling to reduce crop risk (Tsubo *et al.,* 2005, Soltani and Hoogenboom, 2007). As well, AquaCrop may be used to investigate and evaluate another management that increases water productivity and achieves more sustainable water use (Bessembinder *et al.,* 2005, Amirouche *et al.,* 2021). It simulates crop yield and biomass variation under various irrigation water scenarios. Observing the regular water balance is needed to understand the inward and outgoing water. A critical issue is the development of the most favorable strategies for using and managing available water resources in agricultural production (Smith, 2000, Boudhina *et al.,* 2017).

The model related to water input as the primary constraint to crop development, particularly in arid and semiarid areas(Bradford and Hsiao, 1982, Boudhina *et al.,* 2019). Deficit irrigation is a good potential irrigation approach, according to several reports, (Ali and Talukder, 2008, Behera and Panda, 2009, Blum, 2009), in which less water is used than expected during in the planting season.

Zand-Parsa *et al.* (2006), created a maize simulation model, whereas (Farahani *et al.,* 2009, García-Vila *et al.,* 2009) used the AquaCrop model besides cotton both full and deficit irrigation agriculture. They stated that in order to evaluate the effect of changes in irrigation water quantity for quinoa, sunflower, and maize in the AquaCrop model, the critical parameters for calibration, including such normalized water productivity, canopy cover, and total biomass, should be tested under a variety of environment, soil, cultivar, irrigation technique, and field management conditions (Geerts and Raes, 2009, Heng *et al.,* 2009). The model, according to both scientists, can be used for scenario analysis and provides a good balance of robustness and performance precision.

Drought is the main climate-linked risk in the northeastern Amhara especially north wollo and wag-himra and generally in some parts of northern Ethiopia. The rainfall is, however, short, inconsistent, and inadequate, and also the landscape of the area is rising and falling, which impacts the crop productivity in the area. So, deficit irrigation could be a promising irrigation water management technique for these areas, allowing farmers to apply restricted amounts of water to their crops in the time and amount necessary for optimum crop water productivity. Crop type and cropping pattern, soil, depth and fertility, climate, water quality, and irrigation system type all contribute to this degree of water deficit. Most of the farmers were using the furrow irrigation system, but the irrigation is not properly managed on top of the prevailing water scarcity in the area calling for more interventions such that water has to be managed properly and efficiently. The goal of this research was to use the AquaCrop model to better understand deficit irrigation and develop optimal deficit irrigation water management strategies for potato production.

Material and methods

Study area description

The research was conducted two years in 2018/19 and 2019/20 at Kechne Abeba irrigation schemes at Lasta woreda, North Wollo (Figure1). The geographical location of the area is between 11°57’38.44” north of latitude and 39°4’4.91” east of longitude with an altitude of 2103 m.a.s.l. The rainfall is seasonal varying in-depth, space, and time. The mean long-term annual rainfall (January 2000-March 2020) in the area is about 799.3mm and it is erratic and uneven in distribution. The average minimum and maximum temperatures in the area are11.8 ^{o}C and 27.4 ^{o}c respectively (Figure 2 a & b). The study site was chosen to be representative of the woreda's diverse soil and climate conditions. The area is intensively cultivated and the production is subsistence farming. Rain-fed agriculture is the main practice in the study area.

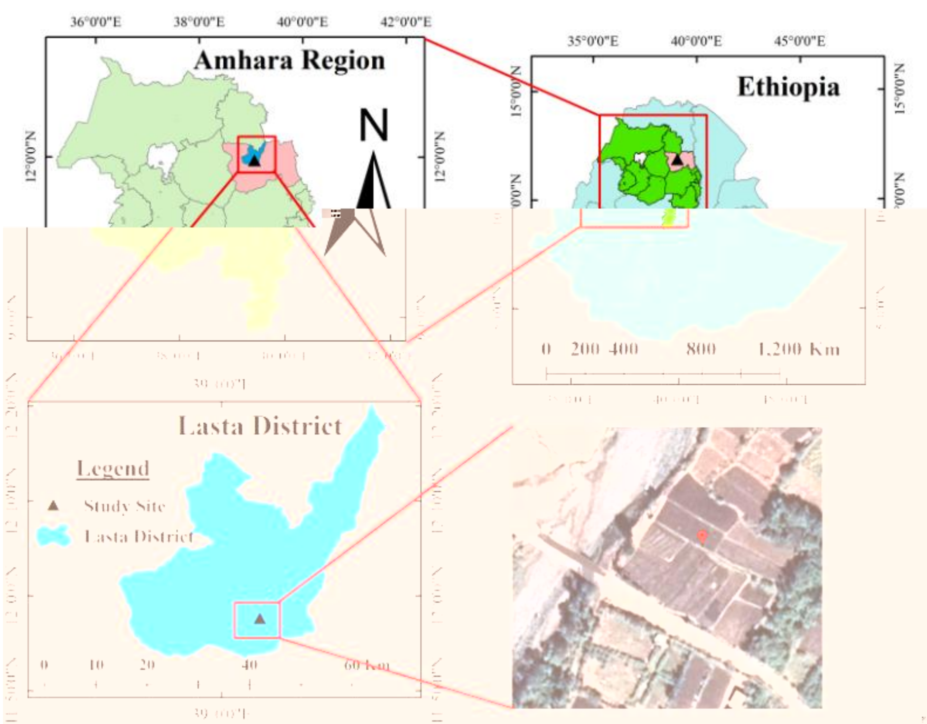
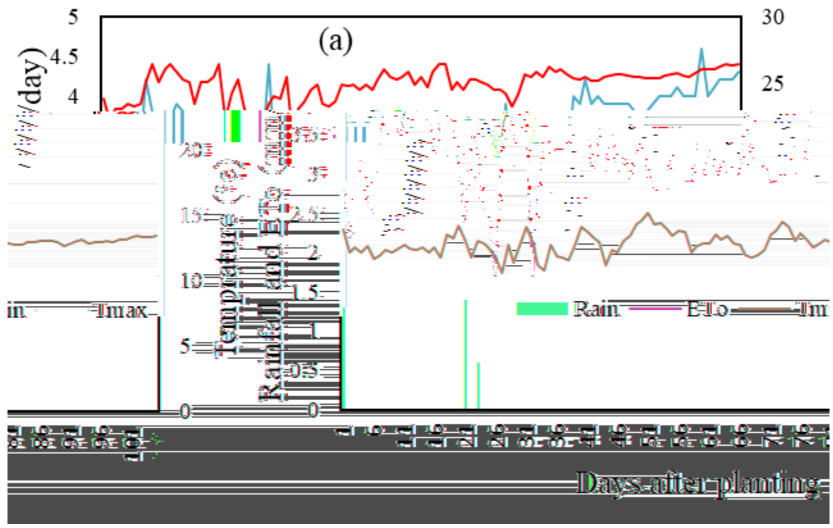


Figure1.1 Location map of the study area



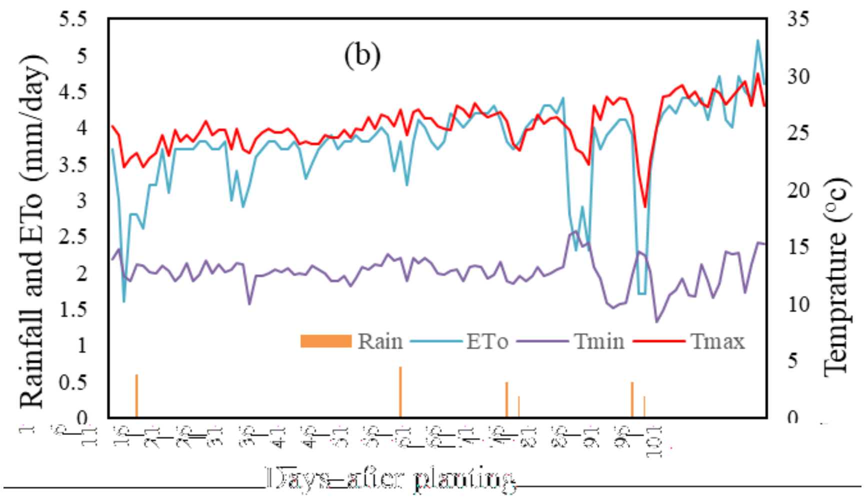


Figure 2. (a) and (b) weather conditions for the 2018/19 and 2019/20 crop growing season respectively.

Experimental design and treatments

The design of the experiment was based on a randomized complete block design with three replications. Three irrigation treatments (100, 75, and 50%) with the fourth growth stages of potato of water application methods were tested in the field experiment. The plot size of the experiment was 3m * 3.75m and the spacing among plots and each block was 1m and the total experimental area was 23m *13.25m. The test crop potato (Belete variety) was selected since it is widely used in the area and also recommended for the area. The tubers were directly sown on October 16, 2018, and November 20, 2019. Well, sprouted potato tubers were planted on prepared ridges with the spacing of 75 and 30cm between row and plants, respectively (Abdalhi and Jia, 2018, Beshir *et al.,* 2018, Gebremedhin *et al*, 2015). In the 2018/19 and 2019/20 growing seasons, harvesting occurred when tubers reached maturity, which occurred 105 days after planting.

Fertilizer was applied at the rate of 300kg/ha urea half at planting and a half at 45 days after sowing and 50kg/ha triple super phosphate (TSP) at planting. The frequency of irrigation water was used at five days interval (Gebreslassie, 2009). Prior to planting all plots were irrigated with an equivalent volume of water up to the field capacity limits. Weeding, furrow maintenance, fertilizer application, water application, diseases, and pest management techniques were all completed on time and in the same order for each treatment.

Table 1.1 Total number of treatment combinations

	Potato crop growth stages			
Treatment	Initial stage	Development stage	Mid-season stage	Late season stage
T1	100%	100%	100%	100%
T2	75%	75%	75%	75%
T3	75%	100%	100%	75%
T4	50%	100%	100%	50%
T5	75%	100%	100%	50%
T6	100%	75%	75%	50%

Water requirement of potato

The fixed schedule and crop water demand for irrigation were determined using the CROPWAT computer model version 8.0, according to FAO 56 methodology (Allen *et al.*, 1998). The crop coefficients (Kc) used in the reference irrigation treatment (100%) depending on FAO 56 which would have been the different as per the vegetative growth stage of the potato crops 0.5 at the onset of growth, 1.15 at tuber formation, and 0.75 before ripening. Crop factor (Kc) for each growth stage was obtained from (Allen *et al.*, 1998) and ETc was determined using equation 1.

$$ET_C = ET_O * K_C \quad (1)$$

Where; ETc is crop evapotranspiration in mm and ETo is reference crop evapotranspiration in mm. Since it would be based on evapotranspiration, it is able to quantify net irrigation water demand (NIR) by subtracting effective rainfall(Pe) during the experimental season, which can be described using equation 2.

$$NIR = ET_C - Pe \quad (2)$$

Furrow irrigation application efficiencies, in general, vary from 45-60% (Allen *et al.*, 1998). Using equation 3, the requirement of gross irrigation (GIR) was calculated with an application efficiency (Ea) of 60%.

$$GIR = NIR/Ea \tag{3}$$

Statistical analysis

The effects of different treatments were statistically evaluated using the analysis of variance methodology, and mean separation was calculated using Least Significance Difference (LSD) at 5% significance levels using XLSTAT 2018 to identify optimal deficit irrigation management practices based on yield-related parameters and water use efficiencies.

AquaCrop model input data

It's a crop water productivity model that simulates herbaceous crop yield to water (Steduto *et al.*, 2012). The setup of the model needs input data containing climatic parameters, crop, soil and field, and irrigation management data.

Climate data

The weather parameter was collected from Lalibela meteorological station located closer to the experimental farm. Meteorological data required by the model are daily values of minimum and maximum temperature, rainfall, reference crop evapotranspiration, and mean annual atmospheric carbon dioxide concentration. ETo was estimated using the ETo calculator using the daily maximum and minimum temperature, wind speed at two-meter above the ground surface, solar radiation and mean relative humidity. The model uses 369.41ppm as a reference standard for atmospheric carbon dioxide concentrations, which would be the average of CO_2 concentrations in the atmosphere from 1902 to today at Mauna Loa Observatory in Hawaii, according to IPCC projections for the A1B scenario (Abedinpour *et al.,* 2012, Gebremedhin *et al.,* 2015, Montoya *et al.*, 2016).

Crop parameters

Canopy cover, above-ground biomass, tuber yield, and plant height data samples were taken out every 20 days for each irrigation treatment and replicate based on the recommendation stated in (Bitri *et al.,* 2014, Karunaratne *et al.*, 2011). The overhead mobile camera was used to capture the canopy cover. Then the captured picture was analyzed using GreenCrop Tracker image analyzer software (Kale, 2016). At each sample, two plants were removed from each experimental plot, and the dry biomass of leaves, stems, and tubers was collected (Montoya *et al.*, 2016). The above-ground dry biomass of each sample was determined by weighing it after it had been held in an oven for 48 hours at 65°$_C$ (Abedinpour *et al.*, 2012) and the tuber dry matter for 72 hours at 65°$_C$ (Gebremedhin *et al.*, 2015). The date of emergence, initial and maximum canopy cover, period of flowering, the start of senescence, and maturity were recorded. In addition, the coefficient of the crop for transpiration at full canopy cover, canopy decline coefficient, soil water depletion beginnings for prevention of leaf growth and transpiration, and canopy senescence acceleration are used (Hsiao *et al.*, 2009). These criteria should apply to a wide range of conditions and should not be limited to a single crop cultivar (Heng *et al.*, 2009).

Soil characteristics

The physical and chemical properties such as soil texture, EC, PH, organic matter, bulk density, field capacity, permanent wilting point, and saturation of soil were analyzed and characterized in samples taken from the study area at different depths of 0-20cm, 20-40cm, and 40-60cm (Demelash, 2013) (Table 2). The saturated hydraulic conductivity was determined using the empirical equations' pedo transfer function (Saxton and Rawls, 2006). Because the soils were all the same texture, the soil water retention curves did not show any variation for most superficial horizons.

The hydrometer process was used in the laboratory to estimate the soil texture of the field. The bulk density was calculated from an undisturbed soil sample taken with a core sampler and considered as the proportion of the oven-dry weight of soil to a known core sampler volume. It differs considerably and the measurements were taken at three different soil depths of the soil profile (0-20, 20-40, 40-60) and three samples across the experimental field. The gravimetric approach was used to assess the soil moisture content and measured as a dry weighted fraction (Demelash and Alamirew, 2011). In the laboratory, the water content at field capacity and permanent wilting point were determined by applying 0.33 and 15 bars to a saturated soil sample, respectively, using a pressure plate. Soil PH was determined from saturation pest extract using a PH meter (Demlash, 2013, Gebreslassie *et al.*, 2015).

Irrigation and field management

Irrigation management consists of data applying to both the conditions of full irrigation and deficit irrigation with four growth stages. In the deficit, irrigation water was applied on the same day as the entirely irrigated plot, but the irrigation depths were decreased to 75 and 50% of the full irrigation. Water was applied in a known volume of watering-can which could be converted and the handheld watering-can was used to control the quantity of water entering each furrow of the experimental plot (Yihun, 2015). The volume of applied water can be calculated as follows equation 4.

$$V = A*D \qquad (4)$$

Where V = volume of applied water (lit)

A = area of irrigated plot (m^2)

D = depth of application (mm)

The field management components were recorded like the soil fertility levels, weed infestation, irrigation method, application depth and time of irrigation event, and furrow end bunds to remove surface runoff. Equation 5 was used to calculate water use efficiency (WUE), which indicates the amount of yield (Y, kg ha^{-1}) given per unit of water used (ETc, m^3 ha^{-1})and evaluates the most efficient use of water.

$$WUE = \frac{Y}{ETc} \qquad (5)$$

Model Calibration

The model was performed via an iterative method that provided the data values which better simulated the primary crop growth variables canopy cover, biomass, crop yield, and water use efficiencies. These parameters are calibrated for the optimal goodness of match between both the measured and the simulated values (Afsharmanesh *et al.*, 2014, Afshar and Neshat, 2013, Gebreselassie *et al.*, 2015). The values were used to form the findings of the study data from the 2018/19 irrigation season. The crop cultivar-dependent conservative and non-conservative parameters were regarded as constants. The non-conservative parameters were adjusted according to the field measurements. The crop growth coefficient (CGC) and crop senescence coefficient (CDC), as well as normalized water productivity (WP*), are conservative parameters that are calibrated using field sample results. The CGC and CDC were calculated using the estimates suggested by Raes *et al.* (2012b) and data such as maximum canopy cover (CCx) and initial canopy cover (CC_0). Thus, the CGC and CDC are determined using a nonlinear resolve to achieve the best possible match between the measured and simulated canopy cover.

Model Validation

The model was run out with the experimental data for the year 2019/20 growing season (Afsharmanesh *et al.*, 2014, Afshar and Neshat, 2013, Gebreselassie *et al.*, 2015). The calibrated model was used to simulate with the data input of the experimental during the year 2018/19 to predict the yield, water use efficiency, biomass, and canopy cover. Furthermore, such predicted values were compared to the experiment's actual results, and the model validation output statistics were assessed.

Model Evaluation Criteria

During the calibration and validation processes, the AquaCrop model simulation findings of water use efficiency, biomass, yield, and canopy cover were evaluated. The prediction error statistics were used to verify the internal consistency between the simulated and observed values. To evaluate the model's efficiency (performance), the following statistical approaches were used. The total values or average deviation of measured values from determined values is indicated by the normalized root mean square error (NRMSE or CV). Equation 6 was used to calculate the NRMSE formula.

$$\mathrm{NRMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{Si}-\mathrm{Mi})^2} \times {}^{100}/_{\overline{\mathrm{M}}} \qquad (6)$$

Where Si and Mi are the simulated and measured values, separately, and n is a number of observations. The NRMSE unit is the same for all variables, and the average of the n measured results was used.

The root mean square error (RMSE) represents a measurement of the total, or it is the mean values of Mi mean deviation between the observed and simulated values which is a synthetic predictor of the absolute model uncertainty. Values of mean residual and mean relative error close to 0 indicate minor deviations between simulated and observed mean thus suggesting slightly systematic deviation and bias in the entire data collection.

The RMSE (Heng *et al.*, 2009) was calculated in equation 7.

$$\mathrm{RMSE} = \sqrt{1/n\sum_{i=1}^{n}(\mathrm{Si}-\mathrm{Mi})^2} \qquad (7)$$

The coefficient of determination (R^2) estimates the combined distribution against the independent dispersion of the measured and simulated series. The values of 0 mean there is no correlation at all, while a value of 1 means that perhaps the dispersion of the simulated is equal to that of the observed, in equation 8.

$$R^2 = \frac{(\sum_{i=1}^{n}(Mi - \overline{M})(Si - \overline{S})}{\sqrt{\sum_{i=1}^{n}(Mi - \overline{M})^2}\sqrt{\sum_{i=1}^{n}(Si - \overline{S})^2}} \qquad (8)$$

The coefficient of efficiency (E) varies from −∞ to one (perfect fit), and an efficiency of less than zero indicates that the calculated mean values might have been a better simulator than the model.

The E (Nash and Sutcliffe, 1970) was determined using equation 9.

$$E = 1 - \frac{\sum_{i=1}^{n}(Mi - Si)^2}{\sum_{i=1}^{n}(Mi - \overline{M})^2} \qquad (9)$$

The Willmott index of agreement, d (Willmott and Matsuura, 2005) was also used and determined through equation 10.

$$d = 1 - \frac{\sum_{i=1}^{n}(Si - Oi)^2}{\sum_{i=1}^{n}(|Si - MO| + |Oi - MO|)^2} \qquad (10)$$

Where; Oi is the measured value; MO is the mean value of n measured values, and n is the number of measurements.

Using equation 11, the Coefficient of Residual Moss (CRM) was measured, which shows the model's tendency for exaggeration or underestimation of value relative to observed values (Eitzinger *et al.*, 2004)

$$CRM = \frac{\sum_{i=1}^{n} Mi - \sum_{i=1}^{n} Si}{\sum_{i=1}^{n} Mi} \qquad (11)$$

Results and discussion

Soil properties

Water at field capacity and permanent wilting point of the soil is determined to be 33.50 and 21.13%, respectively (Table 2). On a volumetric basis, the water content at field capacity varied between 35.3 and 33.5%. The top 0 to 20cm had a larger average water content of field capacity value of 35.3%, while the subsurface 40 to 60cm had a lower value of field capacity that was 33.5%. The moisture content at the permanent wilting point varied with depth, with values as high as 21.9% at the top (0 to 20cm) and as low as 20.2% at the subsurface (40 to 60cm). The difference in field capacity and the permanent wilting point is directly related to total available moisture (TAW), which is the depth of water that a crop can absorb from its root system. The total average available soil moisture was 133.67mm m^{-1} of soil depth and the maximum infiltration rate of the soil was 40mm h^{-1}. As a result, the optimum degree of TAW is present in topsoil; while lower concentrations are located in the subsurface soil (Table 2).

Table 2. Physical and chemical characteristics of the soil at the research site.

Soil parameters	Soil depth (cm)			
Particle size distribution (%)	0 – 20	20 - 40	40 - 60	Average
Clay	35.15	32.39	36.50	34.68
Silt	31.72	32.56	30.83	31.70
Sand	33.13	35.05	32.67	33.62
Texture	Clay loam	Clay loam	Clay loam	Clay loam
Bulk density (g/cm3)	1.441	1.522	1.535	1.499
OM (%)	1.12	1.01	1.01	1.05
PH	6.5	6.6	6.8	6.63
TN (%)	0.06	0.05	0.03	0.05
Ava.P (ppm)	13.72	18.28	9.57	13.86
ECe (ds/m)	0.11	0.23	0.17	0.17
Water content				
FC (vol. %)	35.3	34.7	33.5	34.50
PWP (vol. %)	21.9	21.3	20.2	21.13
Sat (vol. %)	45.3	44.9	44.4	44.87
TAW (mm/m)	134	134	133	133.67
Ksat (mm/day)	61.2	66.96	80.4	69.52
Irrigation water				
PH			6.9	
ECw (ds/m)				0.21

Yield of potato

The result indicates that the yield was substantially ($p<0.05$) affected by the deficit irrigation for certain treatments and showed no significance for other treatments when evaluated with T1 and among treatments (Table 3). The highest tuber yield was obtained in T1 (33.94t/ha) which corresponds to the whole growth stage at full irrigation application 100% of ETc. This was similar to the findings of Patel and Rajput, (2013) which were reported that water application with no deficit of 100% of ETc at any stage of plant growth gave the highest yield. T3 produced comparable yield (33.27t/ha) with T1 despite a water deficit at the beginning and end of the season (75% of ETc), while the other stages were irrigated at full demand (100% of ETc).

Stressing the potato crop by 25% deficit irrigation at the early and late growth stages with roughly the same irrigation period resulted in a tuber yield compared to a 0% deficit with the entire growing season of potato. This result was consistent with both the finding of Yihun (2015), Bekele and Tilahun (2007) that shows' stressing the crops during initial and late-season stage does not impact the crop yield significantly. The lowest tuber yield was found under T6 (21.80t/ha) which would have been a 25% deficit at the development and mid-season stage, 50% deficit at late-season stages as compared to T1, T3, and T5 (Table 3). This result shows that the potato crop is sensitive at the development and mid-season that are affected by deficit irrigation on tuber yield. The result agrees with the finding of Pereira and Shock (2006) that states the potato is a relatively sensitive crop in terms of both yield and quality under conditions of restricted water supply at development and flowering/tuber bulking. Other findings have also reported that potato is known to be very prone to water stress during the initiation of tuber and bulking stages (Ierna and Mauromicale, 2012, Ierna and Mauromicale, 2006, Pavlista, 2015). The result was also similar to those found in other studies (Fabeiro *et al.*, 2001, Ferreira and Carr, 2002) the optimum irrigation applications at a sensitive stage of potato would increase tuber yield and water consumption efficiency. Total potato tuber yield was proportional to the availability of water but as stress intensity increased total tuber yield decreased (Demelash, 2013).

Water use efficiency (WUE)

The outcput of this analysis showed that water consumption efficiency was variable based on the treatments of irrigation applications (Table 3). The optimum WUE was obtained from T3 and T1 which were 8.23kg/m^3 and 7.65kg/m^3, respectively. Water consumption efficiency was found to be lowest in T2 and T4. During the early and late stages of the growing season, applying 75% of the maximum irrigation water depth instead of 100% with a five-day irrigation interval improved water use efficiency.

These results are similar to those reported by Demelash (2013) and Onder *et al.* (2005). Implementing deficit irrigation techniques would result in major cost savings in irrigated agriculture without sacrificing yield. The result is now in line with Fabeiro *et al.* (2001), Shock and Feibert (2002) which described that water deficit is effective in improving water consumption and water productivity without causing significant yield reductions for the different crops, including potato. Similarly, Kirnak *et al.* (2005), Sarkar *et al.* (2008), and Woldetsadik (2003) reported that the efficiency of water use was higher at lower levels of available soil moisture. The difference in total tuber yield between T1 and T3 was only 0.67t/ha, which was statistically insignificant in terms of yield change.

However, a significant depth of water was saved 9% in T3 (Table 3). The result showed that a significant depth of water (387m^3/ha) was saved without significant yield reduction in T3 as compared to T1. Hence diverting this saved water to another irrigable land to improve the field irrigated can account for decreases in agricultural productivity. This will be used to irrigate an additional land of 0.1ha with a yield benefit of 3.33t/ha of potato crop production.

The results from field trials confirmed that with deficit irrigation strategies it is possible to increase WUE and save water for irrigation. This could be especially important for areas facing drought and limited water resources for the agricultural production of potatoes. Mansouri-Far *et al.* (2010) stated that irrigation water could be preserved and yield maintained (as a responsive crop to drought stress) in water-limited conditions. The deficit irrigation treatments saved a significant depth of water to irrigation, leading to an increase in WUE. Similar data were obtained by other authors (Liu *et al.*, 2005, Shahnazari *et al.*, 2007). Water productivity and water use efficiencies increase under deficit irrigation, relative to its value under full irrigation, as shown experimentally for many crops (Fan *et al.*, 2005, Zwart and Bastiaanssen, 2004).

This result described that adding 75% of ETc during the beginning and late-season stages of the crop growth stages have improved water efficiency than applying other deficit treatments in potato tuber yield. The highest amount of water was saved in T6 (28.6%) and 9% water was saved in T3 taking into account T1 as control 100% of ETc. When the treatments are compared in terms of yield reduction T3 had 1.9% which shows there is the lowest yield reduction than other treatments and T6 (35.7%) the highest yield reduction (Table 3).

Plant height of potato

The irrigation treatments on the mean plant height of potatoes were statistically significant ($P<0.05$) (Table 3). During the sensitive stages of potato, variation in the level of the water application had a major impact on plant height. When full irrigation was used during the growing season, the plants reached a maximum height of 45.53cm. The shortest plant height (37.43cm) was obtained with a 0% deficit at the development and mid-season stages, and a 50% deficit at the early and late-season growth stages of the potato. There were no statistically significant variations in plant height between the irrigation treatments T1, T3, and T5 ($P<0.05$).

The beneficial effect of water in maintaining the turgidity of the cell, which is a major prerequisite for growth, is demonstrated by the growing plant height with sufficient application depth of irrigation in the development and mid-season stages (Vaux Jr and Pruitt, 1983). On the contrary, shortening of plant height underwater moisture stress may be due to stomatal closure and reduced CO_2 and reduce nutrient uptake by the plants, hence, photosynthesis and other biochemical process are hampered, affecting plant growth (El-Shawadfy *et al.*, 2014). The plant's height is a good indicator of water stress. Deficit irrigation, according to some authors, causes plant height to be reduced (Pandey *et al.*, 2000). This result is consistent with Gadissa and Chemeda (2009), who reported that pepper plant height decreased with reduced irrigation levels and increased with increased irrigation levels. The availability of water in the sensitive stage of the plant was proportional to its height.

The findings of this study were also in line with those of Al-Moshileh (2007), who noticed that increasing soil water supply increased plant growth parameters significantly. Irrigation, according to Kumar et al. (2007), had a major impact on plant height, which in turn affected crop yield.

Table 3. Effects of various parameters on irrigation techniques.

Treatments	Marketable yield (t/ha)	Unmarketable yield (t/ha)	Total yield (t/ha)	Water use efficiency (kg/m^3)	Plant height (cm)	Irrigation water (m^3/ha)	Water saved (%)	Yield reduction (%)
T1	32.66a	1.27a	33.94a	7.65ab	45.53a	4437	0	0
T2	21.14c	1.06a	22.21c	6.67d	38.46b	3329.5	25	34.6
T3	31.84a	1.43a	33.27a	8.23a	41.56ab	4050	9	1.9
T4	22.48c	1.23a	23.71c	6.50d	37.43b	3662.3	17.5	30.1
T5	26.51b	1.29a	27.80b	7.38bc	41.50ab	3775.3	14.9	18
T6	20.67c	1.13a	21.80c	6.89cd	38.65b	3166.7	28.6	35.7
LSD(0.05)	2.06	0.42	2.06	0.58	4.58			
CV (%)	6.21	26.83	5.91	6.29	8.79			

Model sensitivity, calibration, and validation

Sensitive parameters

The most important variable in AquaCrop was obtained by sensitivity analysis testing (Geerts *et al.* 2009 and Salemi *et al.*2011). The result of the sensitivity of the model (Table 4) shows that the crop transpiration coefficient when canopy cover is complete, canopy growth coefficient, canopy decline coefficient, reference harvest index, maximum canopy cover, and normalized water productivity had the highest sensitivity. The finding of Afshar and Neshat (2013), who conducted a potato experiment and found that the model is sensitive to the normalized water productivity and reference harvest index. Incomparable research by Casa *et al.* (2013) conducted a field experiment to simulate potato crop yield, maximum canopy cover, canopy growth coefficient, canopy decline coefficient, and water productivity are sensitive parameters. In another study, Montoya *et al.* (2016) performed a field experiment, where the effects of various potato irrigation treatments, the canopy growth coefficient, the coefficient canopy decline, and the normalized water productivity are sensitive parameters.

Table 4.1 Sensitive parameters from calibrated during 2018/19

Parameters	Calibrated values	Original values
Crop transpiration coefficient(K_{cTr})	1.45	1.1
Canopy growth coefficient(CGC)	20%/day	17.3%/day
Canopy decline coefficient(CDC)	17%/day	8.0%/day
Reference harvest index(HIo)	85%	70.0%
Normalized water productivity(WP*)	20.0g/m2	17.0g/m2
Maximum canopy cover(CCx)	95%	85%

Model calibration

The conservative and non-conservative crop input parameters were calibrated through the AquaCrop water productivity model. The calibrated model was validated with the independently measured experimental dataset to verify the model for a series of data under different deficit irrigation scenarios. For all levels of water application scenarios, the AquaCrop model simulates the observed canopy cover, biomass, water use efficiency, irrigation water, and yield. The full 100% irrigation water application scenario was used to describe crop development under the non-limiting condition in the model. Based on the computed data of full and deficit irrigation water application treatments, the model has been adjusted.

The main calibrated parameters for canopy cover are the CGC, CDC, water stress (P_{upper}, $P_{lower,}$ and the shape factor) which affect the leaf expansion and early senescence. Canopy cover per seedling was determined according to the knowledge of the crop characteristics by specifying row spacing and plant spacing. Then, the simulation was done for the above crop phenology and the effects were correlated with the observed values. In the model initial canopy cover (CCo) was estimated based on the data from agronomic practices from row planting, row spacing 0.75m, and plant spacing 0.30m. Hence, the estimated initial canopy cover for the given potato crop has been found 0.22% (4.4 plants/m^2 or 44,444 plants/ha). To estimate the canopy expansion rate, the phenological data of the crop criteria described in Table 5 such as dates of emergency, maximum canopy cover, senescence, and maturity were used. The model results in the fast canopy expansion and moderate canopy decline coefficient. The canopy decline coefficient and canopy growth coefficient were used 17%/day and 20%/day, respectively. The stress parameters such as canopy expansion and canopy senescence coefficient were modified and readjusted to approximate the measured canopy cover. The reference harvest index was calibrated as 85%, which was well within the range recommended by Raes *et al.* (2012b) for potato crops (70-85%).

Table 5.2 Crop parameters and their calibrated model values during 2018/19

Parameters	Unit	Value
Crop phenology		
Planting to emergence	DAS	7
Planting to maximum canopy	DAS	50
Planting to start tuber formation	DAS	54
Planting to maximum rooting depth	DAS	60
Planting to start of canopy senescence	DAS	85
Planting to maturity	DAS	105
Crop growth and development		
Base temperature	^oc	10
Upper temperature	^oc	30
Planting density	Plants/m^2	4.4
Initial canopy cover (CCo)	%	0.22
Canopy growth coefficient (CGC)	%/day	20.0
Canopy decline coefficient (CDC)	%/day	17.0

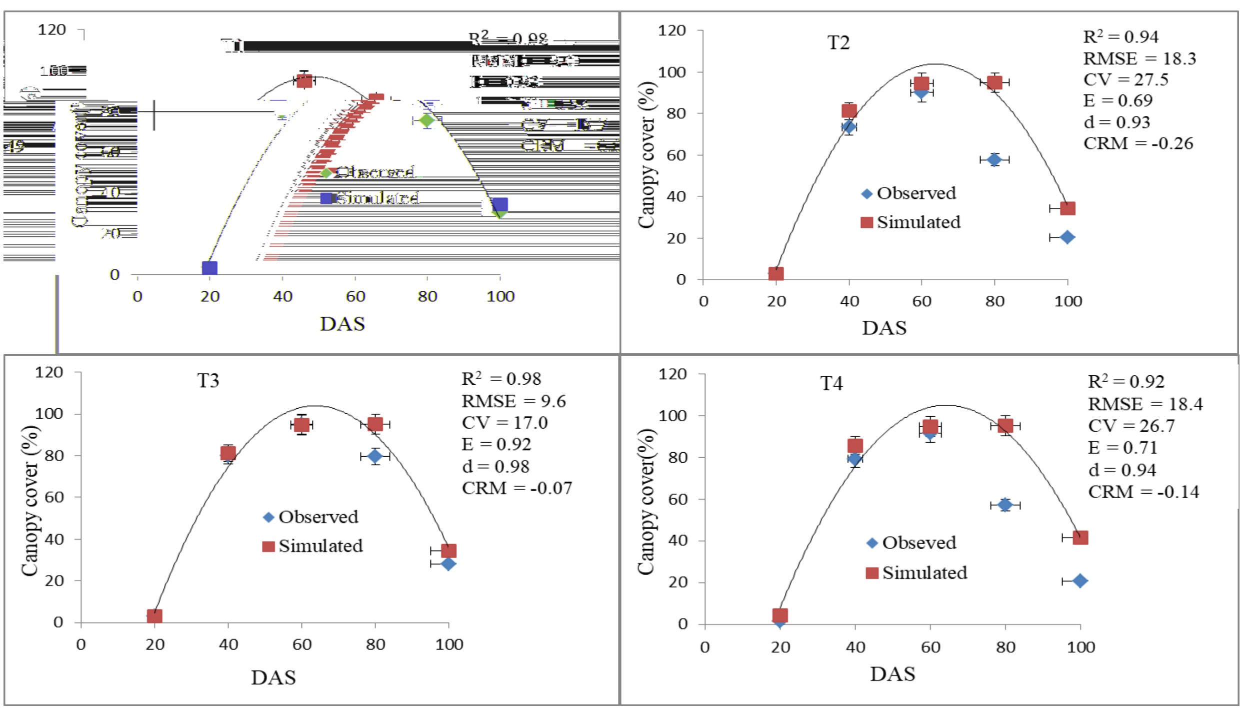
Maximum canopy cover (CCx)	%	95
Length to build up of HI	DAS	46
Normalize water productivity (WP*)	g/m^2	20
Water extraction pattern throughout the effective root zone	%	40,30,20,10
Maximum root extraction over the effective root zone	mm/day	18.0
Crop transpiration coefficient	-	1.45
Canopy shelter in late season	%	60
Maximum rooting depth (m)	Meters	0.6
Shape factor for effective rooting deepening	%	1.5
Yield formation		
Reference harvest index (HIo)	%	85
Water stress before the start of yield formation positive impact on HI as a consequence of restricted growth in the vegetative cycle	-	Strong
Water stress during yield formation positive effect on HI result of affecting leaf expansion	-	Strong
Water stress during yield formation negative effect on HI as just a result of water stress-inducing stomatal closure	-	small
Water stress		
The upper threshold for water stress for canopy expansion(P_{upper})	-	0.1
The lower threshold for water stress for canopy expansion(P_{lower})	-	0.45
The upper threshold for soil water stress effect on stomatal closure(P_{upper})	-	0.45
Water stress on early canopy senescence (P_{upper})	-	0.55
Aeration stress sensitivity for waterlogging	Vol%	8.0
Shape factor for canopy expansion	-	3
Shape factor for stomatal closure		3
Shape factor for early canopy senescence		3

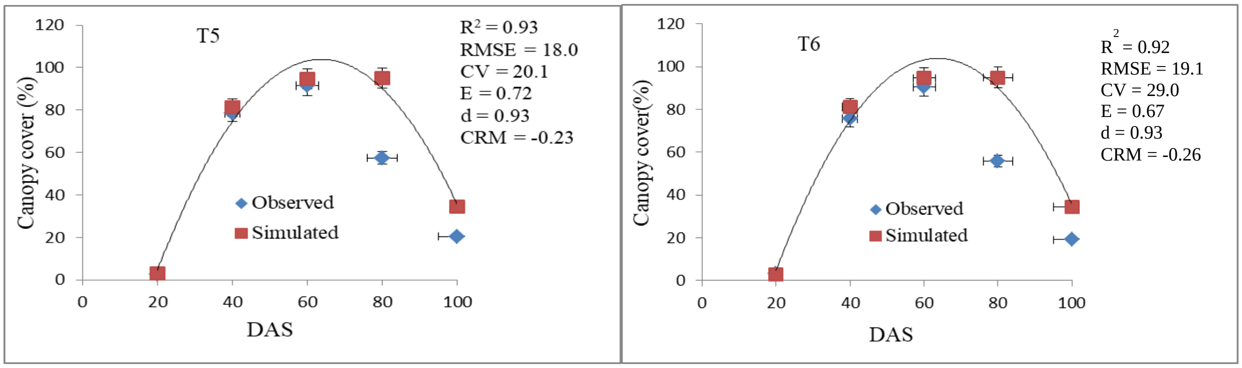
Canopy Cover (CC)

Crop parameters were used to model the CC to obtain a good agreement between both the simulated as well as the values of the observed potato crop (Table 5). Just after the method of calibration, the normalized water productivity was calculated as 20.0 gm^{-2}, and so this value was within the range suggested by Raes *et al.* (2012b) for C_3 crops (15-20 gm^{-2}) and the confidence level defined within the field results. The result of the calibration indicating that the model was capable of simulating CC under different water conditions (Figure 3). In general, the model predicted the seasonal trend in CC as well. However, the model tended to overestimate CC during 80 days after sowing in all treatments (Greaves and Wang, 2016).

The observed and the simulated CC developments were fitted well for treatment receiving full irrigation throughout the growth stage was confirmed by the statistical values in Figure 3. The result of this study revealed which model was able to simulate correctly the CC development, but it was seen that the value of CC was overestimated from the senescence to the end of a cropping season in the calibration period 2018/19.

Montoya *et al.* (2016) showed that a strong ability of AquaCrop in simulating CC of potato in the calibration of various water application scenarios. This research is in accordance with other authors (Ngetich *et al*, 2012) who describe a remarkable match between both the measured and simulated CC on different irrigation treatments. The statistical parameter, coefficient of residual moss having values of negative meant that the model exaggerates the CC. From Figure 3 it is clear that the CC was overstated by the model especially 80 and 100 days after sowing, during crop senescence of potato. Pawar *et al.* (2017), Amirouche *et al.* (2021) who confirmed that the model overestimates CC during the mid-season stage of the crop supported with the CRM value was negative. The calibration was satisfactory as the measured and expected CC values of E ranged from 0.67 to 0.93 at different water application scenarios.





Figugre 3. Model calibration of simulated and observed canopy cover during 2018/19

Biomass

The model simulated and measured biomass within full and deficit irrigation conditions (Figure 4). Most of the treatment receiving both irrigation applications shows overestimated biomass at 40, 60, and 80 days after sowing. This was maintained by the mathematical values of the CRM was negative values. The finding of Ndambuki (2013) which indicated that the model overestimated the biomass on flowing and maturity of the correctly simulated, the values of a CRM is negative. The treatment delivery of deficit irrigation (T3) described a good fit with the simulated biomass. As seen from Figure 4 the calibrated of deficit irrigation (T3) there was a close association between the observed and predicted biomass. The model was calibrated with model efficiency E of 0.96. This study is in agreement with Greaves and Wang (2016) who identified that the AquaCrop model is a good fit with the measured and simulated biomass of the statistical values of $R^2 = 0.99$, RMSE = 1.16, E = 0.97, and d = 0.99 getting deficit irrigation.

In general, the observed and estimated values are in good condition, as shown by the low RMSE, high D, and E values. The value of the statistics mentioned in the current study is similar to those found in other crops. Abedinpour *et al.* (2012) confirmed that the coefficient of efficiency found that various irrigation treatments were applied between 0.65 and 0.99. The AquaCrop model can be adjusted to simulate potato biomass, yield, and efficiency of water in the study site and becomes a valuable method to help the decision for irrigation purposes.

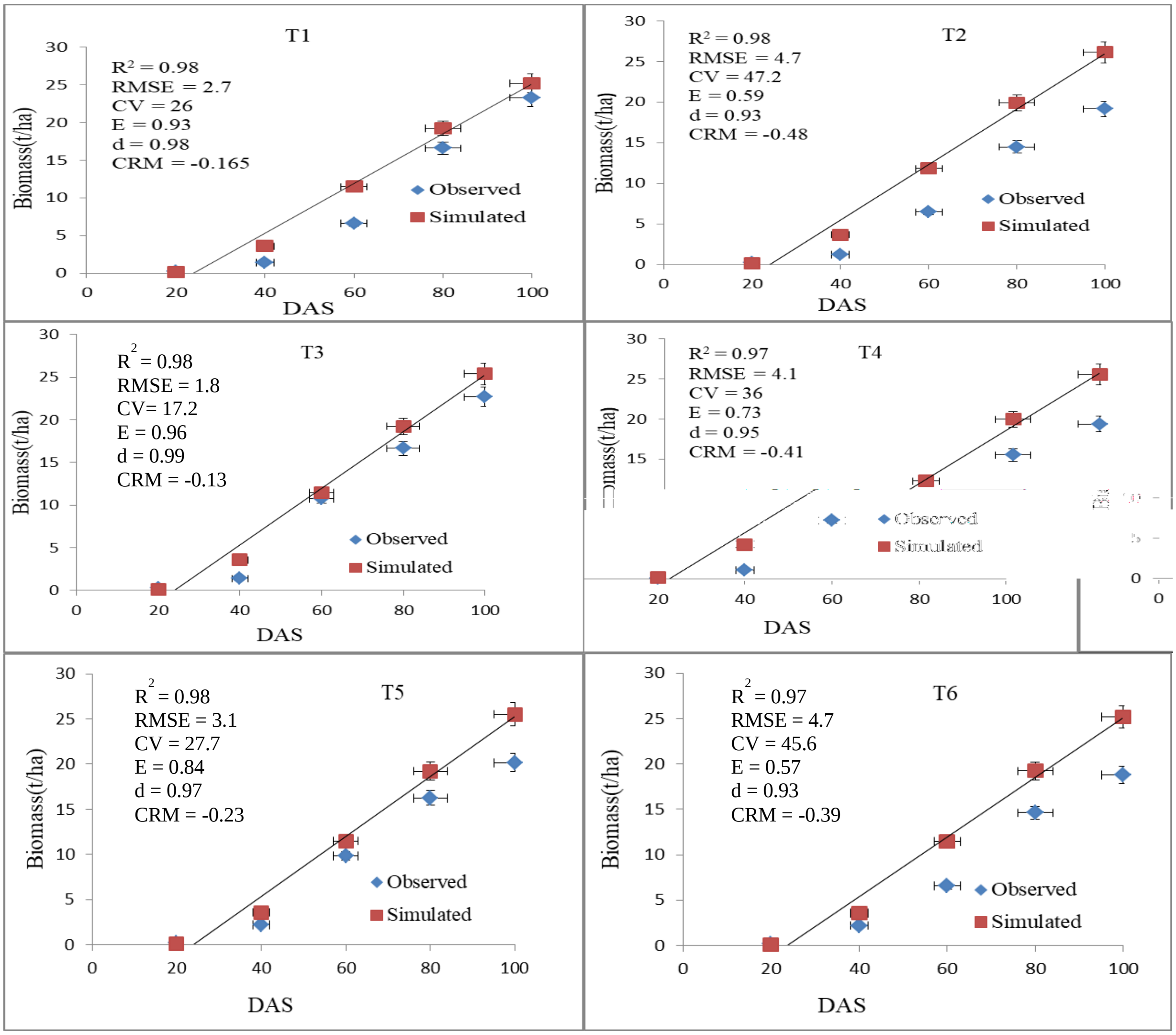


Figure 4. Model calibration of simulated and observed during 2018/19

Harvest index

The value of the harvest index for the different irrigation water application scenarios is derived from the field experiment. For the treatment receiving full irrigation, the harvest indexes obtained was 0.82. The harvest index value displays a decreasing trend under water stress condition that is 0.81, 0.69, and 0.68 for T3, T2, and T6, respectively. A similar trend was reported by Demelash (2013), Farré and Faci (2009), and Yihun (2015) for potato, maize, sorghum, and teff for water stress conditions. Karunaratne *et al.* (2011) also reported on Bambara groundnuts in critical growth stages to show a decreasing trend in the harvest index for water stress conditions.

Since soil water stress has a strong impact on the potato harvest index, the effect of soil water stress on different growth stages was recorded and modified in the model. According to the study, water stress prior to flowering has a strong positive impact on the harvest index due to reduced vegetative growth. Water stress during yield formation had a strong positive and small negative impact on harvest index (Table 5) as both a result of water stress affecting leaf expansion and inducing stomatal closure respectively. The result indicates that irrigation application stress at the development and mid-season periods affect potato yield.

Yield, WUE, and Irrigation water

The measured potato tuber yields in the field experiment range between 22.89 and 35.15t/ha, while the simulated values range between 18.99 and 34.08t/ha (Table 6). The experiment in 2018/19, deviations of -3.02 and -20.53% values of both the simulated and measured were found. The yield reduction mainly occurs when stress is experienced during the potato-sensitive growth stages like development and mid-season. This result

Table 6.3 Selected parameters of simulated and measured values for calibration period

Treatment	Yield			WUE			IW		
	Simulated	Measured	Dev	Simulated	Measured	Dev	Simulated	Measured	Dev
T1	34.08	35.15	-3.14	7.35	8.06	-9.65	483.1	435.80	9.79
T2	19.95	23.29	-16.74	6.12	7.43	-21.40	386.8	326.85	15.49
T3	33.5	34.51	-3.02	8.31	8.78	-5.66	433.1	393.12	9.22
T4	22.01	24.81	-12.72	6.21	7.08	-14.01	404.2	350.45	13.29
T5	26.01	28.88	-11.03	7.15	7.91	-10.62	412.3	364.97	11.47
T6	18.99	22.89	-20.53	6.03	7.31	-21.22	376.7	313.22	16.85

Model validation

The crop parameters that were calibrated were used to validate the model. The validation simulation of the seasonal growth of canopy cover and the accumulation of biomass was carried out during the 2019/20 irrigation season.

Canopy cover (CC)

The data obtained for the 2019/20 irrigation season were used for validation of the model (Figure 5) and show the result of the statistical parameters. The AquaCrop model overestimated the canopy cover during the crop senescence 80 &100 days after sowing, in all treatments because of high evapotranspiration during these periods (Figure 5). The model, overestimated comparatively high canopy cover from flowing to the harvesting of deficit irrigation, was obviously insufficient in deficit irrigation at critical growth stages (flowing and tuber bulking) due to water stress. Similarly, Casa *et al.* (2013), Greaves and Wang (2016) announced which model overestimated the estimated canopy cover under the water deficit condition of sensitive stages of potato and maize. The validation of critical stages of potato at development and mid-season phases indicates the application of 100% and 75% irrigation water offers good match between the predicted and observed canopy cover of the T3 (Figure 5).

The high values of E and d for the T1 and T3 indicate the overall good agreement between the projected and measured CC. The T6 recorded a high d value of 0.93 but a moderate efficiency value of 0.68. T3 compared to other deficit treatments, showing high model accuracy simulating canopy cover. The test statistics reflect the fitness of the model seen between observed and estimated canopy cover, as shown in (Figure 5). The stress in the development and mid-season phases of the potatoes, as measured and simulated by the coefficient of efficiency, was poor, indicating that the model's output was acceptable in this level's stressed condition. During the validation period, the model's overall performance was overestimated canopy cover, and the coefficient of residual moss value was negative.

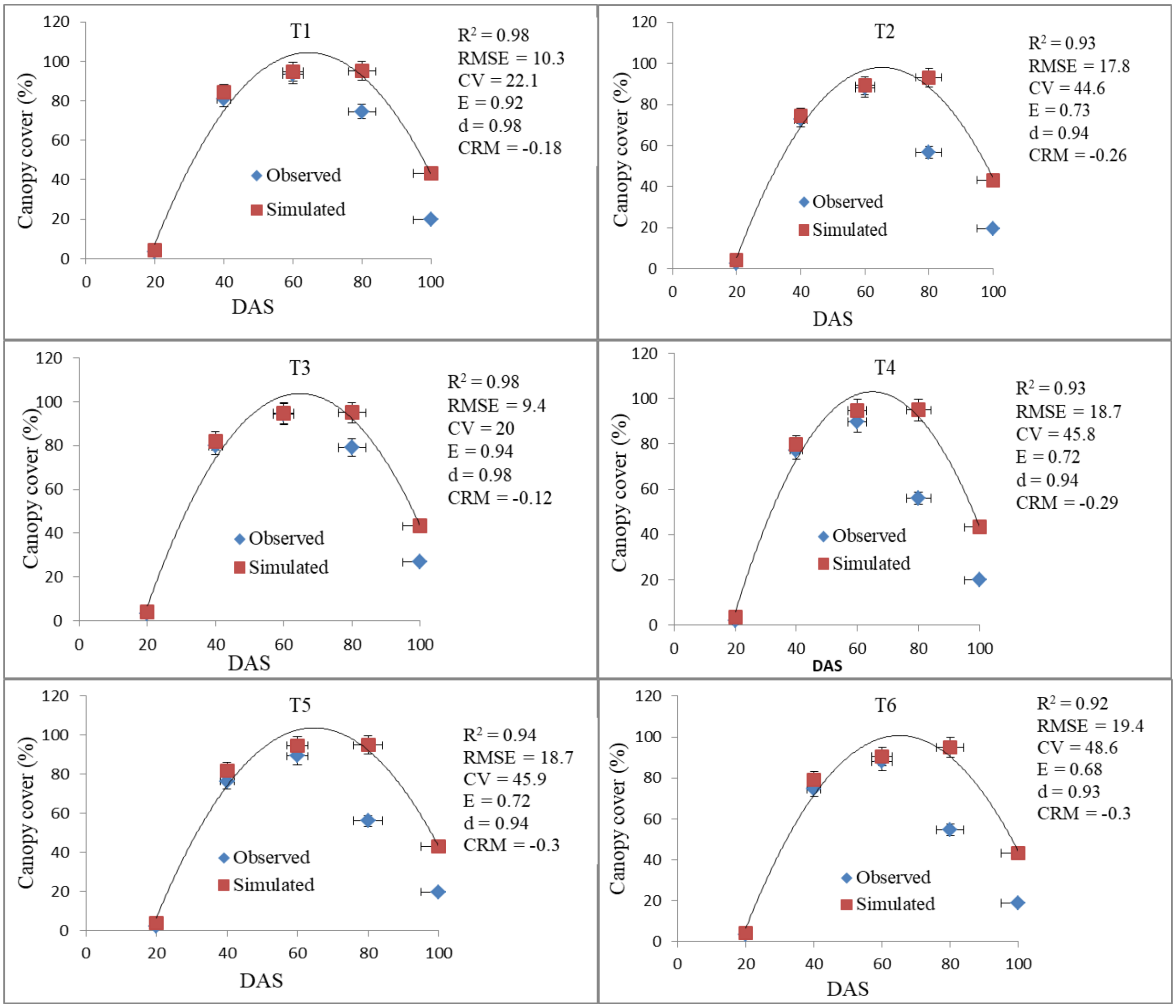


Figure 5. Model validation of simulated and observed canopy cover during 2019/20

Biomass

To validate and calibrate crop parameters for field-grown potato, the biomass obtained at 20-day intervals during the field experiment was compared to the AquaCrop model prediction (Figure 6). There is generally a fair match between the data sets measured and simulation, with the exception of the crop deficit sensitive stages and the 50% deficit in the early and late seasons. Except for the initial stage at 20 days after sowing in all treatments, the model tends to indicate an overestimation of biomass. The model's efficiency in potato biomass was overestimated, and the value of the residual moss coefficient was negative.

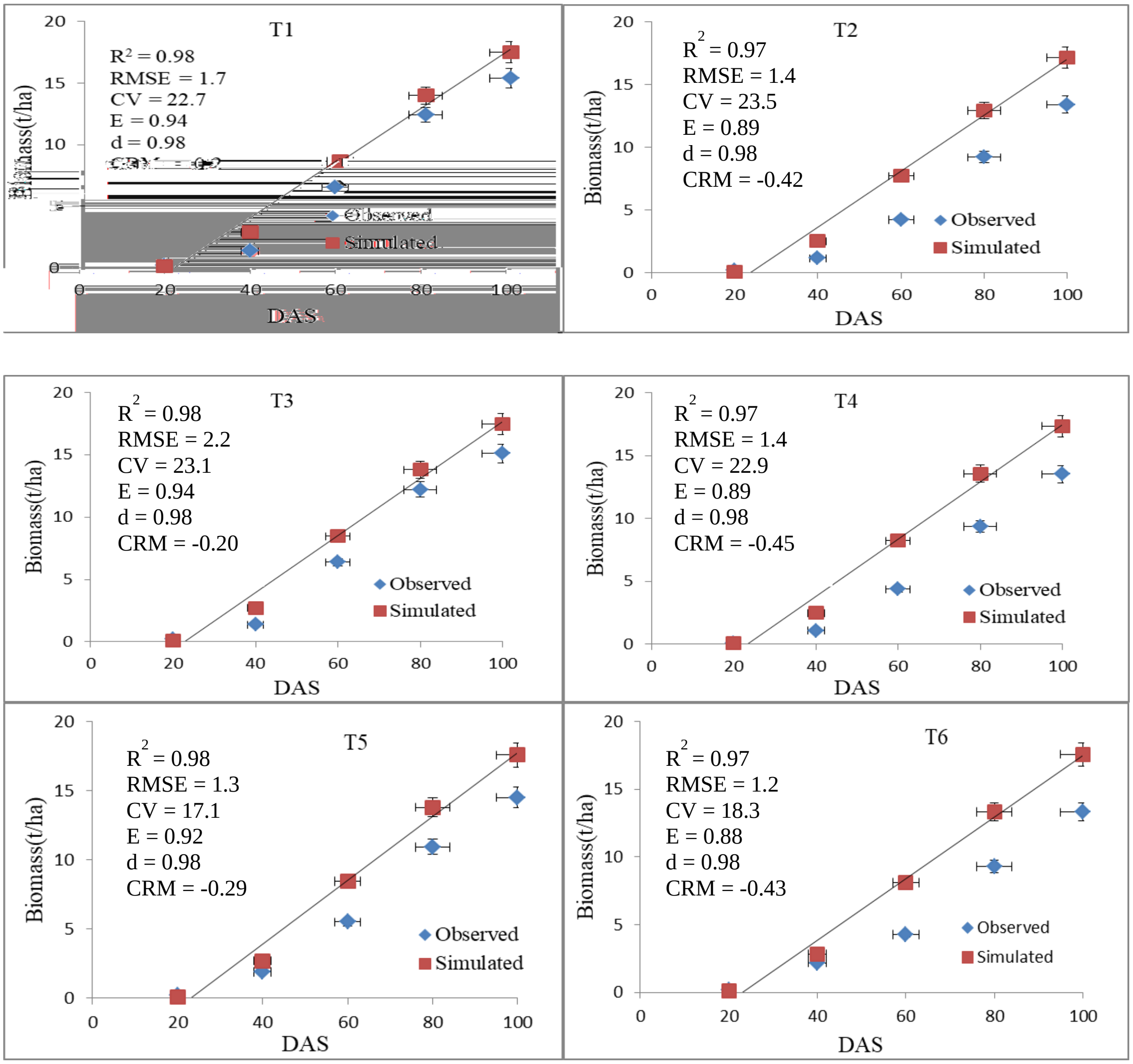


Figure 6. Model validation of simulated and observed biomass during 2019/20

Yield, efficiency of water use, and irrigation water

Potato yields measured in field experiments ranged from 20.72 to 32.74 t/ha, while simulated values varied from 16.82 to 31.67 t/ha (Table 7). During 2019/20, a difference of between -3.3 and -23.2% was found between the simulated and measured values. The reduction in potato yield usually occurs when stress occurs during the sensitive growth stages, such as development and mid-season. The above result is in agreement with the finding of Casa et al. (2013) and Montoya et al. (2016). For the deficit at critical points, the simulated yield deviation from the observed yield was greater than 12%, signifying that the model accuracy decreases under conditions of extremely stressed water environments. Similar observations were discussed by (Evett &Tolk, 2009).

For the various irrigation treatments, the disparity in seasonal crop water between simulation results and measurements identified in the field experiment. The seasonal crop water requirements were consistently overestimated by AquaCrop, and the deviations grew as the water deficit increased. For the experimental treatments, the variations range from 4.6 to 12% (Table 7). The findings are consistent with those of Katerji *et al.* (2013), who found that AquaCrop overestimated the seasonal ETc and that the deviations increased as stress levels increased. The gap between measured and simulated water use efficiency of potato yield is high for T2 and T6 as compared to other deficit treatments, due to a significant mismatch between simulated and observed crop water requirement values. However, calculated water use efficiency appeared to be better in the T3, implying the potential for water savings, provided that the yield was comparable to that obtained in the full irrigation during the growing season of potato and other deficit treatments.

Table 7. Validation parameter of measured and simulated results.

Treatment	Yield			WUE			IW		
	Simulated	Measured	Dev	Simulated	Measured	Dev	Simulated	Measured	Dev (%)
T1	31.67	32.74	-3.4	6.54	7.25	-10.9	4789	4516	5.7
T2	17.78	21.12	-18.8	4.92	6.23	-26.6	3789	3390	10.5
T3	31.03	32.04	-3.3	7.22	7.69	-6.5	4369	4169	4.6
T4	19.82	22.62	-14.1	5.05	5.92	-17.2	4156.5	3819.5	8.1
T5	23.85	26.72	-12.0	6.09	6.85	-12.5	4173.5	3900.5	6.5
T6	16.82	20.72	-23.2	5.19	6.47	-24.7	3636.5	3201.5	12.0

Conclusion and recommendation

One of the irrigation management strategies that could save water is deficit irrigation. By keeping the moisture content of the soil below the optimum level during particular growth stages of the season or during the growing season, it is possible to define the periods during which the water deficit will have a limited impact on crop production. Deficit irrigation saves water and improves water productivity while maintaining an optimal yield close to maximum irrigation. According to field experiments, 75 and 50% late-season (T6) of the total requirement of crop water showed higher yield reductions than other deficits irrigation. Deficit irrigation, on the other hand, had a yield reduction of 75% at the beginning, late season, and 100% at all other stages of irrigation water application on potato production.

It proposed that the water deficit could have a major effect on yield at the development and mid-season stages of the potato. With deficit irrigation strategies, it's indeed possible to increase yield, water use efficiency, and save significant water depth for irrigation, according to the findings of this report. T1 and T3 produced the highest yields of potato tubers, with yields of 33.94t/ha and 33.27t/ha, respectively. T6 had the lowest yield of potato tubers (21.8 t/ha). Meanwhile, the yield difference between T1 and T3 was $P<0.05$, which was not important. Taking the above findings into account, it can be concluded that the potato crop has responded positively to mild water stress conditions at our study site. Identifying the sensitive growth stages of a specific cultivar under local weather and soil fertility conditions allows for irrigation scheduling that maximizes crop yield while conserving scarce water. As a result, we discovered that the most vulnerable times for potatoes to be irrigated at 100% ETc were during the second and third periods.

The AquaCrop model must be calibrated and validated for each crop, soil, and environment. Data from 2018/19 was used to calibrate the system, and data from 2019/20 was used to validate it. The sensitivity analysis on canopy cover and biomass of calibration treatments showed that Kc_{Tr}, CGC, CDC, HIo, WP*, and CCx had the highest sensitivity. The findings of this study revealed that such a model can simulate biomass, canopy cover, yield, and water productivity/use efficiency for full supplied irrigation and treatment with some stages of water deficit; however, the model was less satisfactory under water deficit (75 and 50%) at the most important physiological stage of potato compared to the full irrigation at sensitive stages. The highest and lowest accuracy for predicting canopy cover, biomass, yield, and water use efficiencies were obtained at T3 and T6, respectively. According to field experiments and modeling, the AquaCrop model can predict potato biomass, canopy cover, water efficiency, and yield with reasonable accuracy under various irrigation and growth conditions.

The highest yield of potatoes and water efficiency was found from T3 (33.27t/ha) and (8.23kg/m^3) by providing 75% ETc during the early and late seasons, while 100% receiving the development and mid-season stages, which is still better than 100% ETc all through the growing period. As a result, we believe that irrigation water applied (75, 100, 100, and 75% ETc) is better suited to Lalibela and other similar agro-ecological conditions. This finding could help to improve food security by increasing crop yields, particularly in areas where water is scarce.

Acknowledgements

My great thanks go to the Amhara Agricultural Research Institute (ARARI) and Sekota Dry Land Agricultural Research Center (SDARC) for granting the graduate study and also the financial support for the research. I appreciate all the Soil and Water Research Directorate staff members of the SDARC who offered me memorable support.

References

Abedinpour, M., Sarangi, A., Rajput, T., Singh, M., Pathak, H. & Ahmad, T. 2012. Performance evaluation of AquaCrop model for maize crop in a semi-arid environment. *Agricultural Water Management,* 110**,** 55-66.

Afshar, A. & Neshat, A. 2013. Evaluation of Aqua Crop computer model in the potato under irrigation management of continuity plan of Jiroft region, Kerman, Iran. *Int. J. Adv. Biol. Biom. Res,* 1**,** 1669-1678.

Afsharmanesh, A. A. G. R., Adeli, M. & Malekian, A. 2014. Assessment of aquacrop model in the simulation of potato yield and water use efficiency under different water regimes. *Journal of Biological and Environmental Sciences,* 8.

Al-Moshileh, A. 2007. Effects of planting date and irrigation water level on onion (Allium cepa L.) production under central Saudi Arabian conditions. *Scie. J. King Faisal University (Basic and Applied Sciences),* 8**,** 75-85.

Ali, M. & Talukder, M. 2008. Increasing water productivity in crop production a synthesis. *Agricultural water management*, 95**,** 1201-1213.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998. FAO Irrigation and drainage paper No. 56. *Rome: Food and Agriculture Organization of the United Nations,* 56**,** e156.

Amirouche, M., Smadhi, D. & Zella, L. 2021. Calibration and validation of the Aquacrop model for the culture lettuce (lactuca sativa l.) under fertilization levels in pluvial condition. *Agricultural Engineering International: CIGR Journal*, 23**,** 36-46.

Banchu, B. 2020. *Evaluation of the applicability of Aquacrop Model to simulate crop response to deficit irrigation.* ASTU.

Behera, S. & Panda, R. 2009. Integrated management of irrigation water and fertilizers for wheat crop using field experiments and simulation modeling. *Agricultural water management,* 96**,** 1532-1540.

Bekele, S. & Tilahun, K. 2007. Regulated deficit irrigation scheduling of onion in a semiarid region of Ethiopia. *Agricultural Water Management,* 89**,** 148-152.

Bessembinder, J., Leffelaar, P., Dhindwal, A. & Ponsioen, T. 2005. Which crop and which drop, and the scope for improvement of water productivity. *Agricultural water management,* 73**,** 113-130.

Bitri, M., Grazhdani, S. & Ahmeti, A. 2014. Validation of the AquaCrop model for full and deficit irrigated potato production in environmental condition of Korça Zone, south-eastern Albania. *International Journal of Innovative Research in Science, Engineering and Technology,* 3**,** 12013-12020.

Blum, A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field crops research,* 112**,** 119-123.

Boudhina, N., Masmoudi, M., Alaya, I., Jacob, F. & Mechlia, N. B. 2019. Use of AquaCrop model for estimating crop evapotranspiration and biomass production in hilly topography. *Arabian Journal of Geosciences,* 12**,** 259.

Boudhina, N., Masmoudi, M. M., Mechlia, N. B., Zitouna, R., Mekki, I., Prévot, L. & Jacob, F. 2017. Evapotranspiration of Wheat in a Hilly Topography: Results from Measurements Using a Set of Eddy Covariance Stations. *Water and Land Security in Drylands.* Springer.

Bradford, K. & Hsiao, T. 1982. Physiological responses to moderate water stress. *Physiological plant ecology II.* Springer.

Casa, A. D. L., Ovando, G., Bressanini, L. & Martínez, J. 2013. Aquacrop Model Calibration in Potato and Its Use to Estimate Yield Variability under Field Conditions. *Atmospheric and Climate Sciences,* 03**,** 397-407.

Chimdi, A., Gebrekidan, H., Kibret, K. & Tadesse, A. 2012. Status of selected physicochemical properties of soils under different land use systems of Western Oromia, Ethiopia. *Journal of Biodiversity and Environmental Sciences,* 2**,** 57-71.

Corbari, C., Ben Charfi, I. & Mancini, M. 2021. Optimizing irrigation water use efficiency for tomato and maize fields across italy combining remote sensing data and the AquaCrop Model. *Hydrology,* 8**,** 39.

Demelash, N. 2013. Deficit irrigation scheduling for potato production in North Gondar, Ethiopia. *African J. Agric. Res,* 8**,** 1144-1154.

Demelash, N. & Alamirew, T. 2011. *Deficit Irrigation Scheduling for Potato Production in North Gondar Zone, Ethiopia.* Haramaya University.

Deressa, T. T., Hassan, R. M., Ringler, C., Alemu, T. & Yesuf, M. 2009. Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Global environmental change,* 19**,** 248-255.

Domínguez, A., De Juan, J., Tarjuelo, J., Martínez, R. & Martínez-Romero, A. 2012. Determination of optimal regulated deficit irrigation strategies for maize in a semi-arid environment. *Agricultural Water Management,* 110**,** 67-77.

Eitzinger J, Trnka M, Hosch J, Zalud Z, Dubrovsky M (2004). Comparison of CERES, WOFOST and SWAP models in simulating soil water content during growing season under different soil conditions. Ecol, Model. 171:223–246.

El-Shawadfy, M. A., El-Ansary, M. Y., El-Bahnasawy, A. H., Awad, M. A. & El-Noemani, A.-S. A. 2014. Sunflower yield, water use efficiency and soil moisture content as affected by irrigation systems and regimes in old land of Egypt. *American-Eurasian Journal of Sustainable Agriculture***,** 1-12.

Evett, S. R. & Tolk, J. A. 2009. Introduction: Can water use efficiency be modeled well enough to impact crop management? Agronomy Journal, 101, 423-425.

Fabeiro, C., De Santa Olalla, F. M. N. & De Juan, J. 2001. Yield and size of deficit irrigated potatoes. *Agricultural Water Management,* 48**,** 255-266.

Fan, T., Stewart, B., Payne, W. A., Wang, Y., Song, S., Luo, J. & Robinson, C. A. 2005. Supplemental irrigation and water–yield relationships for plasticulture crops in the Loess Plateau of China. *Agronomy Journal,* 97**,** 177-188.

Fao, F. 2011. Available online at: http://faostat. FAO. org/site/291/default. aspx. *Food and Agriculture Organization*.

Farahani, H. J., Izzi, G. & Oweis, T. Y. 2009. Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton. *Agronomy journal,* 101**,** 469-476.

Farré, I. & Faci, J. M. 2009. Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. *Agricultural Water Management,* 96**,** 383-394.

Fereres, E. & Soriano, M. A. 2006. Deficit irrigation for reducing agricultural water use. *Journal of experimental botany,* 58**,** 147-159.

Ferreira, T. & Carr, M. 2002. Responses of potatoes (Solanum tuberosum L.) to irrigation and nitrogen in a hot, dry climate: I. Water use. *Field Crops Research,* 78**,** 51-64.

Foster, T., Brozovic, N., Butler, A. P., Neale, C. M., Raes, D., Steduto, P., Fereres, E. & Hsiao, T. C. 2017.AquaCrop-OS: A tool for resilient management of land and water resources in agriculture. EGU General Assembly Conference Abstracts, 2842.

Gadissa, T. & Chemeda, D. 2009. Effects of drip irrigation levels and planting methods on yield and yield components of green pepper (Capsicum annuum, L.) in Bako, Ethiopia. *Agricultural Water Management,* 96**,** 1673-1678.

García-Vila, M., Fereres, E., Mateos, L., Orgaz, F. & Steduto, P. 2009. Deficit irrigation optimization of cotton with AquaCrop. *Agronomy journal,* 101**,** 477-487.

Gebremedhin, Y., Berhe, A. & Nebiyu, A. 2015. Performance of AquaCrop model in simulating tuber yield of Potato (Solanum tuberosum L.) under various water availability conditions in Mekelle area, northern Ethiopia. *JNSR,* 5**,** 123-30.

Gebreselassie, Y., Ayana, M. & Tadele, K. 2015. Field experimentation based simulation of yield response of maize crop to deficit irrigation using AquaCrop model, Arba Minch, Ethiopia. *African Journal of Agricultural Research,* 10**,** 269-280.

Geerts, S. & Raes, D. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural water management,* 96**,** 1275-1284.

Geerts, S., Raes, D., Garcia, M., Miranda, R., Cusicanqui, J.A., Taboada, C., Mendoza, J., Huanca, R., Mamani, A., Condori, O. 2009. Simulating yield response of quinoa to water availability with AquaCrop. Agron. J.101, 499–508.

Greaves, G. & Wang, Y.-M. 2016. Assessment of FAO AquaCrop Model for Simulating Maize Growth and Productivity under Deficit Irrigation in a Tropical Environment. *Water,* 8**,** 557.

Heng, L. K., Hsiao, T., Evett, S., Howell, T. & Steduto, P. 2009. Validating the FAO AquaCrop model for irrigated and water deficient field maize. *Agronomy Journal,* 101**,** 488-498.

Hirpa, A., Meuwissen, M. P., Tesfaye, A., Lommen, W. J., Lansink, A. O., Tsegaye, A. & Struik, P. C. 2010. Analysis of seed potato systems in Ethiopia. *American journal of potato research,* 87**,** 537-552.

Ierna, A. & Mauromicale, G. 2006. Physiological and growth response to moderate water deficit of off-season potatoes in a Mediterranean environment. *Agricultural Water Management,* 82**,** 193-209.

Ierna, A. & Mauromicale, G. 2012. Tuber yield and irrigation water productivity in early potatoes as affected by irrigation regime. *Agricultural Water Management,* 115**,** 276-284.

Kale, S. 2016. Assessment of AQUACROP model in the simulation of wheat growth under different water regimes. *Scientific Papers-Series A, Agronomy,* 59**,** 308-314.

Karunaratne, A., Azam-Ali, S., Izzi, G. & Steduto, P. 2011. Calibration and validation of FAO-AquaCrop model for irrigated and water deficient bambara groundnut. *Experimental Agriculture,* 47**,** 509-527.

Kashyap, P. & Panda, R. 2003. Effect of irrigation scheduling on potato crop parameters under water stressed conditions. *Agricultural water management,* 59**,** 49-66.

Katerji, N., Campi, P. & Mastrorilli, M. 2013. Productivity, evapotranspiration, and water use efficiency of corn and tomato crops simulated by AquaCrop under contrasting water stress conditions in the Mediterranean region. *Agricultural Water Management,* 130**,** 14-26.

Kirnak, H., Higgs, D., Kaya, C. & Tas, I. 2005. Effects of irrigation and nitrogen rates on growth, yield, and quality of muskmelon in semiarid regions. *Journal of plant nutrition,* 28**,** 621-638.

Kumar, S., Imtiyaz, M., Kumar, A. & Singh, R. 2007. Response of onion (Allium cepa L.) to different levels of irrigation water. *Agricultural Water Management,* 89**,** 161-166.

Liu, F., Jensen, C. R., Shahanzari, A., Andersen, M. N. & Jacobsen, S.-E. 2005. ABA regulated stomatal control and photosynthetic water use efficiency of potato (Solanum tuberosum L.) during progressive soil drying. *Plant Science,* 168**,** 831-836.

Mansouri-Far, C., Sanavy, S. A. M. M. & Saberali, S. F. 2010. Maize yield response to deficit irrigation during low-sensitive growth stages and nitrogen rate under semi-arid climatic conditions. *Agricultural Water Management,* 97**,** 12-22.

Mibulo, T. & Kiggundu, N. 2018. Evaluation of FAO AquaCrop model for simulating rainfed maize growth and yields in Uganda. *Agronomy,* 8**,** 238.

Montoya, F., Camargo, D., Ortega, J., Córcoles, J. & Domínguez, A. 2016. Evaluation of Aquacrop model for a potato crop under different irrigation conditions. *Agricultural Water Management,* 164**,** 267-280.

Nash, J. E. & Sutcliffe, J. V. 1970. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of hydrology,* 10**,** 282-290.

Ndambuki, J. 2013. Application of AquaCrop model in deficit irrigation management of cabbages in Keiyo Highlands. *International Journal of Water Resources and Environmental Engineering,* 5**,** 360-369.

Ngetich, K., Raes, D., Shisanya, C., Mugwe, J., Mucheru-Muna, M., Mugendi, D., Diels, J., Books, R., Sheets, F. & Oer, R. 2012.Calibration and validation of AquaCrop model for maize in sub-humid and semi-arid regions of central highlands of Kenya. Proceedings of the Conference of RUFORUM Third Biennial Conference, Entebbe, Uganda, 24-28.

Onder, S., Caliskan, M. E., Onder, D. & Caliskan, S. 2005. Different irrigation methods and water stress effects on potato yield and yield components. *Agricultural water management*, 73**,** 73-86.

Pandey, R., Maranville, J. & Admou, A. 2000. Deficit irrigation and nitrogen effects on maize in a Sahelian environment: I. Grain yield and yield components. *Agricultural water management*, 46**,** 1-13.

Patel, N. & Rajput, T. 2013. Effect of deficit irrigation on crop growth, yield and quality of onion in subsurface drip irrigation. *International Journal of Plant Production*, 7**,** 417-435.

Pavlista, A. D. 2015. Scheduling reduced irrigation on ‘Atlantic’potato for minimal effect. *American journal of potato research*, 92**,** 673-683.

Pawar, G., Kale, M. & Lokhande, J. 2017. Response of AquaCrop model to different irrigation schedules for irrigated cabbage. *Agricultural Research*, 6**,** 73-81.

Pereira, A. & Shock, C. 2006. Development of irrigation best management practices for potato from a research perspective in the United States. *Sakia. org e-publish*, 1**,** 1-20.

Raes, D., Steduto, P., Hsiao, T. & Fereres, E. 2012a. Aquacrop reference manual p. Rome, Ithaly FAO. *Land and Water Division*.

Raes, D., Steduto, P., Hsiao, T. & Fereres, E. 2012b. Reference Manual AquaCrop (Version 4.0). *AquaCrop Website http://www. fao. org/nr/water/aquacrop. html*.

Rhoades, J. & Chanduvi, F. 1999. *Soil salinity assessment: Methods and interpretation of electrical conductivity measurements*, Food & Agriculture Org.

Salemi, H., Soom, M.A.M., Lee, T.S., Mousavi, S.F., Ganji, A., KamilYusoff, M. 2011. Application of AquaCrop model in deficit irrigation management of Winter wheat in arid region. Afr. J. Agric. Res. 6, 2204–2215.

Sarkar, S., Goswami, S., Mallick, S. & Nanda, M. 2008. Different indices to characterize water use pattern of micro-sprinkler irrigated onion (Allium cepa L.). *Agricultural Water Management*, 95**,** 625-632.

Saxton, K. E. & Rawls, W. J. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil science society of America Journal*, 70**,** 1569-1578.

Shahnazari, A., Liu, F., Andersen, M. N., Jacobsen, S.-E. & Jensen, C. R. 2007. Effects of partial root-zone drying on yield, tuber size and water use efficiency in potato under field conditions. *Field Crops Research,* 100**,** 117-124.

Shock, C. & Feibert, E. 2002. Deficit irrigation of potato. *Deficit irrigation practices.*

Shock, C., Feibert, E. & Saunders, L. 1998. Potato yield and quality response to deficit irrigation. *HortScience,* 33**,** 655-659.

Smith, M. 2000. The application of climatic data for planning and management of sustainable rainfed and irrigated crop production. *Agricultural and Forest Meteorology,* 103**,** 99-108.

Soltani, A. & Hoogenboom, G. 2007. Assessing crop management options with crop simulation models based on generated weather data. *Field Crops Research,* 103**,** 198-207.

Soomro, K. B., Alaghmand, S., Shahid, M. R., Andriyas, S. & Talei, A. 2020. Evaluation of AquaCrop model in simulating bitter gourd water productivity under saline irrigation. *Irrigation and Drainage,* 69**,** 63-73.

Steduto, P., Hsiao, T., Fereres, E. & Raes, D. 2012. Crop yield response to water. FAO Irrigation and Drainage Paper No. 66, Food and Agriculture Organization of the United Nations, Rome, Italy. ISBN 978-92-5-107274-5.

Tadesse, A., Ayalew, A., Getu, E. & Tefera, T. 2006. Review of research on post-harvest pests. *Increasing crop production through improved plant protection,* 2**,** 475-563.

Tadesse, T., Haque, I. & Aduayi, E. 1991. Soil, plant, water, fertilizer, animal manure and compost analysis manual.

Tefera, T., Kanampiu, F., De Groote, H., Hellin, J., Mugo, S., Kimenju, S., Beyene, Y., Boddupalli, P. M., Shiferaw, B. & Banziger, M. 2011. The metal silo: An effective grain storage technology for reducing post-harvest insect and pathogen losses in maize while improving smallholder farmers' food security in developing countries. *Crop protection,* 30**,** 240-245.

Tefera, A. H. & Mitiku, D. T., 2021. Models comparative study for estimating crop water requirement and irrigation scheduling of maize in Metekel Zone, Benishangul Gumuz Regional State, Ethiopia. *International Journal of Agricultural Economics,* 6**,** 59.

Tsubo, M., Walker, S. & Ogindo, H. 2005. A simulation model of cereal–legume intercropping systems for semi-arid regions: I. Model development. *Field crops research,* 93**,** 10-22.

Vaux Jr, H. J. & Pruitt, W. O. 1983. Crop-water production functions. *Advances in irrigation.* Elsevier.

Vos, J. & Haverkort, A. 2007. Water availability and potato crop performance. *Potato Biology and Biotechnology.* Elsevier.

Willmott, C. J. & Matsuura, K. 2005. Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Climate research,* 30**,** 79-82.

Woldetsadik, K. 2003. *Shallot (Allium cepa var. ascolonicum) responses to plant nutrients and soil moisture in a sub-humit tropical climate*.

Yihun, Y. M. 2015. *Agricultural water productivity optimization for irrigated Teff (Eragrostic Tef) in water scarce semi-arid region of EthiopiaAgricultural water productivity optimization for irrigated Teff (Eragrostic Tef) in water scarce semi-arid region of Ethiopia*, CRC Press/Balkema.

Zand-Parsa, S., Sepaskhah, A. & Ronaghi, A. 2006. Development and evaluation of integrated water and nitrogen model for maize. *Agricultural Water Management,* 81**,** 227-256.

Zwart, S. J. & Bastiaanssen, W. G. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural water management,* 69**,** 115-133.