Employment of the SSEB and CROPWAT models to estimate the water footprint of potato grown in hyper-arid regions of Saudi Arabia

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Abstract.

Quantifying crops' water footprint (WF) is essential for sustainable agriculture especially in arid regions, which suffers from harsh environmental conditions and severe shortage of freshwater resources such as Saudi Arabia. In this study, WF of irrigated potato crop was estimated for the implementation of precision agriculture techniques. The CROPWAT and the Simplified Surface Energy Balance (SSEB) approaches were adopted. Soil, plant, and yield samples were randomly collected from six potato fields belongs to the Saudi Agricultural Development Company, Wadi-Ad-Dawasir region, Saudi Arabia. Subsequently analyzed for potato tuber yield (t ha^{-1}). The consumptive crop water use (CWU) was computed, as the actual evapotranspiration (ET_a), using the SSEB algorithm. The vegetation indices (NDVI, normalized difference RedEdge-NDRE, MSAVI, RedEdge chlorophyll index-RECI and NDMI) were computed from the obtained sentinel-2 and Landsat-8 data and used as inputs to predict the crop productivity (CP), the CWU, and subsequently the WF. The results indicated that the NDRE showed the best prediction accuracy for potato CP (R^2 = 0.72, P>F = 0.021) followed by the MSAVI (R^2 = 0.64, P>F = 0.018). The CWU, however, was successfully estimated (as ET_a) using the SSEB algorism with an overall accuracy of 89.2%, where the differences between the actual amounts of irrigation water and the estimated ET_a ranged between 12.6% (autumn) and 10.6% (winter) during the season. Based on the CROPWAT-SSEB estimates, the average total WF of potato was found to be 6846 m^3 ton^{-1}. Out of this, the green and blue WF contribution was estimated at averages of 8% and 92%, respectively. Comparison between the blue WF from the SSEB-CROPWAT and the field-data based estimates showed a good agreement (nRMSE = 8.4%, nMBE = 12.9% and relative error – RE ranging from 1.1 to 14%. The effect of planting date on the WF estimation also studied in this research and slight variation of 1.5% (prior) to 7.5% (after) about two months to the baseline planting dates was noticed. It can be concluded that the WF assessment could be satisfactorily

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estimated using the CROPWAT/SSEB models for irrigation management.

Keywords.
SSEB, CROPWAT, vegetation indices, water footprint, satellite data

Introduction

The pressure on water use is increasing dramatically worldwide, with special reference to irrigation water in agriculture and related sectors. According to reports from the Food and Agriculture Organization (FAO) of the United Nations, the current consumption of freshwater for agriculture in hyper-arid climates such as Saudi Arabia is unsustainable. The Kingdom of Saudi Arabia (KSA) is making concerted efforts to develop a sustainable agricultural sector amidst the acute shortage of freshwater resources and harsh environmental conditions. Despite freshwater scarcity in the Kingdom, about 70-80% of the available freshwater resources are used in the agricultural sector. Hence, agricultural monitoring and quantification of crop water footprint (WF) ensure timely information on areas under different crops, crop conditions, production forecasts, and quantities of water used for crop production. Such valuable data would be quite useful in decision-making practices, particularly concerning agriculture and food security issues (Xinchun et al., 2018).

The water footprint analysis (WFA) is a general tool, introduced by Hoekstra and Hung (2002) to assess the consumption of freshwater by different products during their preparation stages. Nowadays, the WFA tool has gained increasing applicability in determining the consumption of freshwater by crops (rain-fed or irrigated). In general, the crop WF refers to the volume of freshwater used, during the period of its production, to produce a unit of the product (Chapagain et al., 2006; Hoekstra et al., 2011; Xinchun et al., 2018), and is determined as $m^3\ kg^{-1}$, $m^3\ t^{-1}$, etc. The three components of the crop WF are the green, blue, and grey WF. The green and blue footprints refer to the consumptive use (evapotranspiration, ET_a) of water by plants, while the grey WF represents the amount of water used to assimilate the pollutants from fertilization or water quality standards. Whereas, the WF approach focuses primarily on the consumptive use (ET_a) of water by plants rather than the amount of water withdrawn from the source (Hoekstra, 2003). Due to its increased merits, the application of the WFA tool to assess the use of freshwater by crops has become very popular and essential for the efficient management of irrigation water (Rodriguez et al., 2015; Madugundu et al., 2018; Geng et al., 2019; Gebremariam et al., 2021).

Advances in satellite remote sensing and GIS techniques have contributed significantly to the development of agricultural information management systems by integrating soil, crop, and weather parameters (Lambin et al., 1993; Aldaya & Llamas, 2008; Tuninetti, 2015). Satellite remote sensing allows obtaining water consumptive use (i.e. ET_a) by plants by using various algorithms derived from the surface energy balance (SEB) equation, such as the Surface Energy Balance Algorithm over Land (SEBAL). The SSEB algorithm, which is characterized by its simplicity, minimal data requirements, and ease of implementation without significant loss of accuracy, has been widely used for estimating ET_a of agricultural fields through several models including the Mapping Evapotranspiration with Internalized Calibration (METRIC) model, the Surface Energy Balance System (SEBS), the Simple Algorithm For Evapotranspiration Retrieving (SAFER), the Simplified Surface Energy Balance (SSEB), the Simplified Surface Energy Balance Index (S-SEBI), the Two-Source Model (TSM), and the Two-Source Time-Integrated Model (TSTIM) (Senay et al., 2007; McShane et al., 2017).

Many of the previous studies on the WF in crop production focused on either global scale (Aldaya et al., 2010; Chapagain et al., 2006) or local scales (Ahmed & Ribbe, 2011; Tsakmakis et al., 2018; Karandish & Simunek, 2019). On the other hand, WF assessments made at regional, local or global scales mostly use climate, soil, and crop datasets and often result in WF estimates of varying accuracy (Aldaya et al., 2010; Lovarelli et al., 2016; Zhuo et al., 2014). This study was attempted to address the water management issues, i.e. the WF irrigated potato, for adaptation of precision agriculture techniques especially for variable irrigation water application. The major objectives are to: (1) quantify the WF of potato production according to local climates, (2) comparison between the blue WF determined based on the satellite-derived SSEB and that obtained from field data combined with the CROPWAT model.

Materials and Methods

Study area and experimenal fields

The experimental work was conducted on six agricultural fields in the Saudi Agricultural Development Company - INMA, Wadi-Ad-Dawasir region, Saudi Arabia, and lies within the latitudes of 19º 53' 11.32" and 20º 02' 10.32" N and the longitudes of 44º 49' 30.17" and 44º 57' 26.14" E, covering an area of about 5400 ha. The climate in the study area is hyper-arid with temperatures ranging between 7 °C during winter and 49 °C in summer months, with sparse rainfall (~128 mm) mainly distributed between November and April. The soil in the study farm is characterized as sandy loam and the major cultivated crops were potato, wheat, melon and other vegetable crops.

Table 1. Details of experimental fields and crop details.

Season	Irrigation type	Field ID	Area (ha)	Variety	Sowing date	Harvest Date
Autumn	C.P	72N	29	Caruso	5-Sep	29-Dec
Autumn	DRIP	82F	56	Hermes	17-Sep	10-Jan
Winter	DRIP	49F	25	Hermes	19-Dec	13-Apr
Winter	Dragon line	60F	40	FONTANE	16-Nov	18-Mar
Winter	C.P	49N	25	F.F +Hermes	23-Dec	24-Apr
Winter	DRIP	30N	21	Caruso+ Hermes	20-Dec	21-Apr

Sampling method and field data

A total of 120 sampling locations were randomly selected in six experimental fields, and georeferenced using a handheld GNSS receiver (GeoXH6000, Trimble, USA). Growth/phenology stages and biophysical parameters (LAI, canopy surface temperature) were recorded from emergence to harvest. Yield samples were randomly collected from the potato fields by harvesting an area of 2.5 m^2 at each sampled location. The collected yield samples were weighed and converted to a common unit, t ha^{-1} after the removal of damaged/irregular-shaped potatoes.

CROPWAT input data

CROPWAT model requires three major inputs which could be categorized under climatic, crop, and soil datasets. The crop-related information, including planting dates, cropping pattern, and yield were obtained from the records of the experimental farm. Other inputs for the CROPWAT model such as length of the growth period, crop coefficients, maximum rooting depth for each crop were obtained from Allen et al. (1998).

Satellite data and image analysis

Sentinel-2 A and B (S2) data were downloaded (September 2020 – April 2021) from the Copernicus website (https://scihub.copernicus.eu/dhus/#/home) and analyzed using the Sentinel-2 toolbox of SentiNel Application Platform (SNAP) software program (ver. 3.4), developed by the European Space Agency. All datasets were maintained with the map projection of the Universal Transverse Mercator (UTM), WGS84 datum, North zone-38. Area related to the experimental fields (region of interest - ROI), was extracted and selected vegetation indices (VIs) were computed and subsequently used as inputs for developing crop productivity (CP) and consumptive use of water by a crop (CWU). The studied VIs includes the NDVI, normalized difference RedEdge-NDRE, MSAVI, RedEdge chlorophyll index-RECI and NDMI. Subsequently, crop productivity (CP) was estimated with the help of developed prediction models with the use of crop yield (t ha^{-1}) and vegetation indices (VIs) derived from S2 data. The developed regression models were cross-validated, and best-fit models were used for the generation of yield maps.

Assessment of Water Footprint (WF)

The total consumptive water footprint (WF, m^3/t) of a crop is the sum of the blue and green components of WF, as shown in Eq. (1) (Hoekstra et al., 2011).

$$WF = WF_G + WF_B \quad (1)$$

where WF_B is the blue WF, WF_G is the green WF.

Estimation of crop water use (ET_a)

Crop water use (CWU), determined as actual evapotranspiration (ET_a), was estimated by adopting the SSEB algorithm as described in Senay et al. (2007). The SSEB approach involves two basic steps. ET_a is computed as a product of the reference ET fraction (ET_f) and the reference ET (ET_o) as given in Eq. 2.

$$CWU = ET_a = \mathrm{ET}_f \times \alpha \, ET_o \qquad (2)$$

where α is a multiplying factor that is generally set to 1.2. The reference evapotranspiration (ET_o) was calculated based on the F.A.O. Penman-Monteith method integrated within the CROPWAT model, as per Allen et al. (1998).

Evapotranspiration fraction (ET_f)

The ET_f variable is the key to the SSEB approach since it captures the impact of soil moisture on ET_a, while ET_o determines the potential ET under nonlimiting water supply conditions. The ET_f was calculated from the land surface temperature (LST) and air temperature data sets based on the assumptions, that a hot pixel (T_h) experiences little or no ET (Bastiaanssen et al., 1998; Allen et al., 2005), and a cold pixel (T_c) represents maximum ET. Both the Sentinel-2 (S2) and Landsat-8 (L8) images were used for mapping ET_f. Where the vegetation fraction was computed using S2 data and land surface temperature (LST) was computed using TIRS bands of L8 data. The hot pixels are selected using an NDVI image as a guide to identify the locations of dry and non-vegetated (or sparsely vegetated) areas that exhibit very low NDVI values. Similarly, the cold pixels are selected from well-watered, healthy, and fully vegetated areas that have very high NDVI values. The ET fraction ($ET_{f,x}$) is calculated for each pixel "x" as per Eq. 3.

$$ET_{f,x} = \frac{dT_h - dT_s}{dT_h - dT_c} \qquad (3)$$

where dT_h is the difference between surface temperature (T_s) obtained from L8 data and air temperature (T_a) at the hot pixel dT_c is the difference between T_s and T_a at the cold pixel dT_x is the difference between T_s and T_a at a given pixel "x". Moreover, as the selection of hot and cold pixels are critical in the SSEB approach, extensive care has been taken in the selection of reference points. Well-watered dense vegetation, preferably with an NDVI value greater than or equal to 0.7 was considered a cold pixel. Whereas, the hot pixel was selected from non-irrigated bare areas, with an NDVI value <0.2. Land surface temperature values for each of the six pixels (3 hot, 3 cold) were extracted using ArcGIS 9.0 software. The resulting database files were imported into an Excel spreadsheet where average hot and cold pixel values were calculated. Subsequently, the images containing ET_f for each pixel were used to estimate actual ET (i.e. ET_a) throughout the growing season.

$$CWU_G = 10 \times \sum_{d=1}^{lgp} ET_G \qquad (4)$$

$$CWU_B = 10 \times \sum_{d=1}^{lgp} ET_B \qquad (5)$$

The CWU (m3/ha) for each water-use type was calculated using Eqs. (4) and (5) (Aldaya et al., 2012). Where ET_G is the green water evapotranspiration and ET_B is the blue water evapotranspiration from day one (d=1) until the specified length of the growth period (lgp). The factor, 10, is meant to convert water depths in millimeters into water volumes per land surface (m^3/ha).

Finally, the green and the blue WF for each crop were determined using the method presented in Hoekstra et al. (2011) as shown in Eqs. (6) and (7). Both the blue and green WFs of a given crop was computed by dividing the crop water use (CWU) (m3/ha) of the crop by the yield (CP) (t/ha).

$$WF_G = \frac{CWU_G}{CP} \qquad (6)$$

$$WF_B = \frac{CWU_B}{CP} \qquad (7)$$

where CWU_G and CWU_B are the green (rainfall) and blue (surface and groundwater) water uses by the crop. CP is the yield based on crop water requirements and actual evapotranspiration outputs from CROPWAT/SSEB model.

WF_B based on field data

In computing the blue WF, the volume of irrigation water used to fulfill the deficit was considered as the blue water (Scarpare et al., 2016). The blue WF was calculated using Eq. (8).

$$WF_{MB} = \frac{10 \times \left(Ir - (DP + RO)\right)}{Y_f} \qquad (8)$$

where WF_{MB} (m^3/ton) is the blue WF estimated from measured irrigation data, Y_f is the potato tuber yield as obtained from field records, *Ir* is the irrigation water applied during the irrigation season (mm), DP is the deep percolation water leaving the root zone (mm), RO is surface runoff water. Since it is difficult to measure the losses from such large fields, an average irrigation efficiency of 70% was considered in the CP irrigation systems (Borsato et al., 2019) to account for the lumped losses due to surface runoff and deep percolation.

Statistical analysis

The blue WF estimates based on CROPWAT/SSEB model and field data were compared using selected indices such as the normalized root mean square error (nRMSE), the normalized mean bias error (nMBE), and relative error (RE). The use of normalized indices helps to better evaluate the performance of a model (Karandish and Simůnek, 2019). Statistical Package for Social Sciences (SPSS) version 20 was used to evaluate the statistical significance of the difference between the blue WF estimates based on the CROPWAT model and field data.

Results and Discussion

Climatic data

The main climatic datasets required by CROPWAT are average monthly values of rainfall, minimum and maximum temperatures, wind speed, relative humidity, and sunshine hours.

Climatic data were obtained from the weather station installed in the experimental farm. The trends of average monthly minimum and maximum temperature, relative humidity, wind speed, and duration of sunshine hours. The mean daily maximum air temperature ranged from 37 °C (May) to 47 °C (August), whereas the mean daily minimum temperature ranged from 14.2 °C in January to 38°C in August with a mean temperature of 34 °C. The average relative humidity was 22.6 %, with the peak values occurring from November to February and minimum values from May to September. The wind speed in the area was lowest in October and highest in July. The duration of sunshine hours ranged from 9.5 to 13.5, with an average value of 11. The effective rainfall was computed using the CROPWAT model. Similarly, reference evapotranspiration was calculated using the Penman-Monteith method (Eq. (2)) (Allen et al., 1998). The monthly values of rainfall and reference evapotranspiration are presented in Table 3. The annual rainfall was 68 mm occurred during February and April. The reference evapotranspiration (ET_o) was maximum during May-August, amounting to 20 mm/day, with a minimum of 8 mm/day in August. The average ET_o was found to be 13.2 mm/day. The monthly ET_o ranged from 138 mm (January) to 588 mm in August, with an average of 375 mm/month.

Table 2. Predicted potato crop water use (i.e. ET, mm) using SSEM model

DAS	Winter					Autumn				
	Min	Max	Mean	STD (±)	SE (±)	Min	Max	Mean	STD (±)	SE (±)
> 30						3.83	5.32	4.52	0.16	0.02
31 – 40						7.36	9.87	8.42	0.26	0.04
41 - 50						7.62	11.09	9.30	0.28	0.04
51 - 60	10.34	12.57	11.35	0.41	0.06	9.39	13.36	10.67	0.51	0.07
61 - 70	8.93	13.52	10.75	1.00	0.16	9.24	15.13	11.55	0.78	0.11
71 - 80	9.38	16.10	13.65	1.86	0.29	9.30	18.07	13.55	1.96	0.28
80 - 90	7.36	15.09	9.98	1.73	0.27	7.01	18.06	9.48	1.61	0.23
91 - 100	5.95	11.93	7.59	1.39	0.21	5.63	14.22	8.51	0.97	0.14
101 - 120						11.69	18.25	15.79	0.90	0.13
121 - 130	3.94	10.28	7.16	1.34	0.21	2.85	10.79	5.33	1.35	0.19
131 - 140	4.57	8.00	5.86	0.65	0.10	4.73	8.06	5.99	0.58	0.08
Overall	**7.21**	**12.50**	**9.48**	**1.20**	**0.19**	**7.15**	**12.93**	**9.37**	**0.85**	**0.12**

Crop Yields

The harvested yield (t ha^{-1}) of potato tuber ranged from 72.2 t ha^{-1} to 91.7 t ha^{-1} with an average commercial harvest (CH) of 56 t ha^{-1}. The results indicated that the NDRE showed the best prediction accuracy for potato CP (R^2 = 0.72, P>F = 0.021) followed by the MSAVI (R^2 = 0.64, P>F = 0.018). Based on ground truth data and NDVI, the collected data was categorized into three classes (Table 3).

Table 3. NDVI class wise potato tuber yields (CH is the commercial harvest and AGB is the above-ground biomass).

NDVI Class	Autumn (t ha^{-1})				Winter (t ha^{-1})			
	Tuber	Tuber (CH)	AGB	Total	Tuber	Tuber (CH)	AGB	Total
> 0.36	74.1	68.2	17.6	91.7^{a}	51.4	45.6	5.9	57.3^{a}
0.28 to 0.35	61.8	52.4	15.7	77.5^{b}	43.4	34.9	5.3	48.6^{ab}
0.18 to 0.27	58.7	47.2	13.5	72.2^{c}	37.1	31.4	3.9	40.9^{b}

Quantification of the WF_{Field} was carried out based on the collected field data (crop yield, Y_f) and the amount of irrigated water (i.e. estimated as per CROPWAT), as described by Scarpare et al. (2016). The average green WF (WF_G), blue WF (WF_B), and total WF (WF_T) of for potato crop were 8.6 (± 4.2), 227 (± 10.6), and 230 (± 16.4) $m^3 t^{-1}$, respectively.

Conclusion or Summary

A field study was conducted to predict crop yield and CWU for potato crop using Landsat-8 and Sentinel-2A satellite images. Empirical yield prediction models were developed using the commercial harvested (CH) yields and VIs extracted from S2 satellite datasets. The SSEB model, used for the estimation of crop ET, was executed using Landsat-8 data.

Table 4. Extract of potato yields (CH is the commercial harvest and AGB is the above-ground biomass).

Season	Irrigation type	Field ID	Yield (t/ha)	AW (m^3/ha)	WFP (m^3/ton)
Autumn	C.P	72N	43	913.6	612.0
Autumn	DRIP	82F	47	570.0	620.3
Winter	DRIP	49F	39	199.9	551.3
Winter	Dragon line	60F	37	684.9	886.1
Winter	C.P	49N	41	199.9	748.5
Winter	DRIP	30N	35	263.9	661.3

The CWU, however, was successfully estimated (as ET_a) using the SSEB algorism with an overall accuracy of 89.2%, where the differences between the actual amounts of irrigation water and the estimated ET_a ranged between 12.6% (November) and 10.6% (December) during the season. Based on the CROPWAT-SSEB estimates, the average total WF of potato was found to be 684.6 m^3 ton^{-1}. Out of this, the green and blue WF contribution was estimated at averages of 8% and 92%, respectively. Comparison between the blue WF from the SSEB-CROPWAT and the field-data based estimates showed a good agreement (nRMSE = 8.4%, nMBE = 12.9% and relative error –RE ranging from 1.1 to 14%. The effect of planting date on the WF estimation also studied in this research and slight variation of 1.5% (prior) to 7.5% (after) about two months to the baseline planting dates was noticed. It can be concluded that the WF assessment could be satisfactorily estimated using the CROPWAT/SSEB models for irrigation management.

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