Utilization of Landsat-8 data for the estimation of carrot and maize crop water footprint under the arid climate of Saudi Arabia

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Abstract

Understanding the spatial variability of Water Footprint (WF) of crops is essential for the efficient use of the available water resources. Therefore, this study was designed to bridge the gap in knowledge existed in the area of WF in the arid climate of Saudi Arabia by quantifying the remote sensing based blue-WF (WFblue) of maize and carrot crops cultivated during the period from December 2015 to December 2016. Agrometeorological (empirical) estimated WF components, namely, the WFblue, the green-WF (WFgreen) and the grey-WF (WFgrey), were determined at a farm scale in conjunction with the climatic conditions and cropping patterns. On the other hand, the WFBlue was estimated from Landsat-8 data using energy balance and yield models. The empirical approach based WFBlue was used as a reference for the accuracy assessment of the Landsat-8 estimated WFBlue. The empirically estimated WF of silage maize ranged from 3540 m3 t-1 to 4960 m3 t-1. Out of which the WFgreen, the WFblue and the WFgrey composed 0.74%, 83.28% and 15.98%, respectively. For the carrot crop; however, the WF ranged between 2970 m3 t-1 and 5020 m3 t-1. Where, the WFgreen, the WFblue and the WFgrey represented 0.50%, 77.31% and 22.19%, respectively. Using Landsat-8 data, the WFblue was found to vary across the crops from 2552 m3 t-1 (silage maize) to 3010 m3 t-1 (carrot). Results also revealed a highly significant linear relationship between the empirical and the Landsat-8 derived WFBlue (R2 = 0.77, P>F = 0.001). The utility of Landsat-8 data in mapping WF showed reliable seasonal estimates, which can greatly enhance precision management practices of irrigation water.

Background

Water scarcity is considered as one of the most critical problems facing many societies worldwide, and is directly interlinked to the food sector as over 80% of the world water withdrawal is to meet the requirements of the increasing population and the continuing development (Jury and Vaux, 2005). Water Footprint (WF), originated from the conception of Virtual Water (VW), can be defined as being the total volume of freshwater used to produce the goods, and is measured as volume of water consumed (evaporated) and polluted per unit of time (Hoekstra and Hung, 2005). Therefore, WF is an effective means used to quantify stress on water resources to address global, regional, national and local water scarcities.

The three components of the WF that provide an overview of the use of water through the demarcation of the consumed water are the green, the blue and the grey WF (Hoekstra et al., 2011). The green WF (WFGreen) is characterized by the consumption of green water resources (rainwater as far as it is not considered as run-off). The blue WF (WFBlue) refers to the consumption of blue water resources (surface and groundwater). The grey WF (WFGrey); however, refers to the pollution and is defined as being the volume of freshwater required to absorb the load of pollutant concentrations in a given natural environment.

Many studies have highlighted WF as a tool for global, regional and national water savings. For example, studies of Cao et al. (2014) in China, Verma et al. (2009) in India, Van Oel (2009) in the Netherlands, Chapagain and Orr (2008) in the UK and Bulsink et al. (2010) in Indonesia. However, such studies are very limited in Saudi Arabia (Multsch et al., 2011, 2013, 2017) and are not available at the level of either fields or farms, which both suffer from climate change, scarce water reserves and limited rainfall.

Most of the existing methods calculate the WF using data from national statistics, reports and climatic databases (Hoekstra et al., 2011; Multsch et al., 2017). Remote sensing techniques; however, provide the possibility of mapping the WF of a specific crop using models, such as crop growth, productivity, and crop water use patterns (Tampouratizi et al., 2015). Therefore, this study was designed to bridge the gap in knowledge existed in the area of WF in the arid climate of the Kingdom of Saudi Arabia. This was conducted by quantifying and analyzing the spatial variation of WF of maize and carrot crops cultivated during the period from December 2015 to December 2016 in the Eastern region of the Kingdom. For the study, remote sensing methods were applied to estimate WFBlue by utilizing images from the Landsat-8 satellite. Moreover, the three elements of the WF (blue, green and grey) at the field level were empirically estimated and used as a reference for the accuracy assessment of Landsat-8 derived products.

Methods

Study Area: The study was carried out in six agricultural fields (50 ha each) that belonged to the Tawdeehia Arable Farm located about 250 km Southeast of Riyadh, the capital city of Saudi Arabia, at coordinates of 24° 11' 00'' E and 48° 56' 14.6'' N. The farm under an arid climate with hot summers (40 ± 2 °C) and cold to moderate winters (15 ± 3 °C), with a mean air temperature of 35°C. The annual rainfall was about 90 mm, most of which occurred in the period from November to February. Due to the high crop water demand, along with the highly erratic rainfall, irrigation depended entirely on groundwater delivered by center pivot irrigation systems. The major crops cultivated in the study area were forages (alfalfa, Rhodes grass and corn) and vegetable crops (carrot, cabbage, cauliflower, broccoli and lettuce).

Field Data: For the determination of WF of carrot and maize crops, a field survey was conducted to understand the cropping pattern of the experimental farm and to develop the sampling strategy. Carrot crop was cultivated throughout the year; while, maize crop was cultivated twice a year (March – June and July - November). In the experimental farm, maize was grown in 23 fields and carrot was cultivated in only seven fields during the period from December 2015 to December 2016. For this study, six center pivot irrigated fields were considered as sample fields, namely, four silage maize fields (TE-2, TE-9, TE-11 and PAL) and two carrot fields (3-5 and 5-5). Data sets pertaining agricultural practices, such as sowing and harvesting dates, crop growth stages, the amount of applied irrigation water, agroclimatic data and crop yields (Ya), were obtained for the whole crop growth period. Except for the agroclimatic data, which was extracted from an Eddy Covariance system installed in the farm, the data sets were taken from the records of the experimental farm.

WF of agricultural crops: The methodology used for the determination of the WF of experimental crops is provided in Figure 1. Agrometeorological (empirical) and remote sensing methods were both applied to estimate the WF of silage maize and carrot crops. The empirical estimates, derived from in-situ data sets, such as evapotranspiration, rainfall and crop yield, were used for the accuracy assessment of remote sensing output.

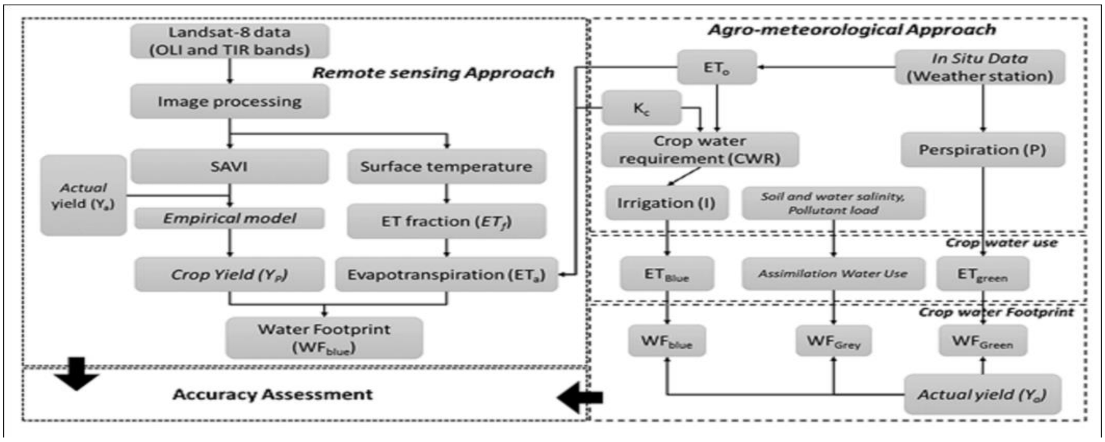

Figure 1. Methodology used for the quantification of crop WF.

For the empirical approach, the crop water requirement (CWR) was calculated by multiplying the reference ET (ETo) by the crop coefficient (Kc), as described by Savva and Frenken (2002). The Kc values used in this study were taken from the list provided by Allen et al. (1998), and the ETo (mm d-1) values were estimated as per ASCE-EWRI (2005). The effective rainfall (Peff) was also considered in the assessment of CWR (Kuo et al., 2006) using a CROPWAT software program (Ver. 8.0). Based on the amounts of CWR and Peff, the agricultural water requirement for each experimental field was estimated, as described by Chowdhury et al. (2013). The green and blue components of the crop water use (CWU, m3 ha-1) were calculated from the accumulation of the daily evapotranspiration (ET, mm d-1) over the entire growing period, as described by Multsch et al. (2017). Subsequently, the WF of both maize and carrot crops was calculated, based on the framework explained by Chapagain and Hoekstra (2011), as a ratio of the CWU (m3 ha-1) and the crop yield (t ha-1). Hence, the obtained WF of silage maize and carrot crops was expressed in m3 t-1.

Remote sensing approach: A total of thirty two cloud-free Landsat-8 satellite images (Path 164 and 165; Row 45) were acquired, during the study period, from the USGS Earth Explorer portal (http://earthexplorer.usgs.gov). Initially, Landsat-8 datasets were converted to spectral radiance and, subsequently, transformed to a Top-Of-Atmosphere (TOA) reflectance (USGS, 2013). The spectral reflectance and land surface temperature products were generated using the “ACTOR” module of Geomatica software program (ver. 2015). Subsequently, Landsat-8 data was analyzed for soil-adjusted vegetation index (SAVI), land surface temperature, a fraction of ET (ETf) and actual ET (ETa).

Simplified surface energy balance (SSEB) model was used for estimating ETa of carrot and silage maize crops. Pre-defined hot and cold conditions of each pixel were used to compute the ETf as described by Senay et al. (2013). Each Landsat-8 scene was processed separately for computing ETa on the day of satellite overpass. All the available daily ETa images were used to compute ETa for the entire growth period (ETgp) of each crop. The ETgp, derived from Landsat-8 products, was used for the estimation of the WF of carrot and silage maize crops. After computing the ETgp of each crop, based on the precipitation days and irrigation, the ETgp was segregated into blue and green components of ETa. Subsequently, the WF (blue and green) was computed as the ratio between the crop water use (CWU) and the predicted yield (YP). The accuracy of Landsat-8 derived blue component of WF (WFBlue) was compared to the WFBlue obtained from the empirical approach. The performance indicators used for the accuracy assessment included Pearson correlation coefficient (R2), root mean square error (RMSE), mean bias error (MBE) and Nash-Sutcliff Efficiency (NSE).

Results

The recorded minimum, maximum and mean annual air temperatures were 19.3, 34.04 and 26.48 °C, respectively. The total amount of the rainfall during the study period was recorded at 80.1 mm. Also, the average annual wind speed was 15.02 m S-1 and the average monthly ETo ranged between 155 mm (November 2016) and 530 mm (July 2016), with a mean daily ETo of 11.0 mm. The CWR varied across the crop type and length of growth period; however, the temporal dynamics of ETo played a major role in the variability of CWR. For the summer cultivated silage maize, the CWR was high (1686 mm) compared to the spring crop (1304 mm). Similarly, the CWR of carrot cultivated in summer (2015 mm) was superior to that of winter crop (620 mm).

The CWU (green, blue and grey) of carrot and silage maize crops changed dramatically across the seasons. The green, blue and grey components of CWU for the carrot fields were 0%, 77-79% and 20 – 29%, respectively. For silage maize crop, these values were 0 - 0.14%, 77 - 93% and 7 – 23%, respectively.

The recorded average yield of silage maize crop was 29.6 t ha-1, while carrot yield was about 32.4 t ha-1. Models for the prediction of silage maize and carrot yields were developed based on the values of the Soil Adjusted Vegetation Index (SAVI). A linear relationship between the Landsat-8 derived SAVI and the actual yield was prepared for both carrot and silage maize crops (Figure 2). The Landsat-8 estimated yield (YP) ranged from 22.7 t ha-1 (maize) to 28.2 t ha-1 (carrot). For silage maize and carrot crops, the values of RMSE between YA and YP, were 9.6% and 10.2%, respectively.

Among the four silage maize investigated fields, the field number TE-9 showed the lowest values of WF (3540 m3 t-1); while the highest WF (4960 m3 t-1) was recorded for the field number TE-11. On the average, the contribution of WFgreen, WFblue and WFgrey for silage maize was estimated at 0.74%, 83.28% and 15.98%, respectively. Results also revealed that the WF of carrot crop ranged between 2970 m3 t-1 (field number 3-5N) and 5020 m3 t-1 (field number 5-5S), with an average of 3750 m3 t-1 over the entire study period. The WFgreen, WFblue and WFgrey contributed with 0.5%, 77.31% and 22.19%, respectively. To understand the spatial variation in the WF, Landsat-8-based CWUBlue of the two crops was predicted. The predicted values of CWUBlue were underestimated for silage maize by 6% (in winter) and 14% (in summer). For the carrot crop, the CWUBlue was overestimated by 12% for both summer and winter seasons compared to empirical method. The remote sensing (RS) based WFblue varied across the crops from 3010 m3 t-1 (carrot) to 2552 m3 t-1 (silage maize).

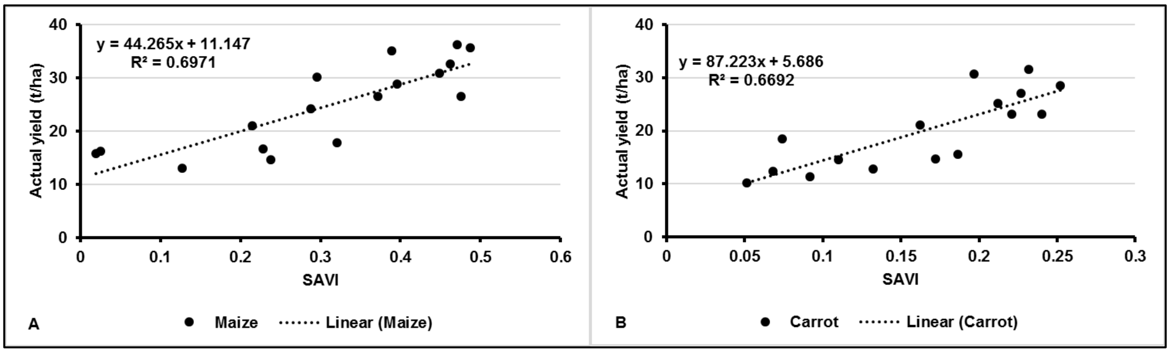

Figure 2. Relationship of actual yield and SAVI for (A) maize crop and (B) carrot crop.

Discussion

The obtained empirical yield models were validated for their accuracy, and the best relationship was observed between the crop yield and SAVI values extracted when the crops were in the mid-stage of development. In the case of silage maize, the best response was observed on the Julian days of 162 (SAVI = 0.456) and 272 (SAVI = 0.462) for summer and spring seasons, respectively; i.e. when the crops were at their peak growth stage. The best response for carrot fields; however, was observed on the Julian days of 68 (winter) and 146 (summer), when the values of SAVI were estimated at 0.416 and 0.398, respectively. Landsat-8-based CWUBlue of the two crops was predicted with a seasonal variation estimated at 4% (winter) and up to 23% (summer) for silage maize, while for carrot crop, it was about 5% for both summer and winter seasons.

The blue water represented the predominant fraction of the WF, with up to 94% for silage maize and 82% for carrot. The grey water, however, which corresponded to the local salinity and crop salt tolerance, ranged from 15% (maize) to 20% (carrot). The total WF values of silage maize (4012 m3 t-1) and carrots (397 m3 t-1) obtained in this study were higher than that of earlier studies. For example, the carrot crop obtained WF was 1.2 times greater than that reported by Multsch et al. (2013). Results of silage maize; however, indicated that the obtained WF was 2.5 times lower than that reported by Chowdhury et al., (2013). Moreover, the WFgrey determined in this study was observed to be 24% and 56% higher than the reported values of both silage maize and carrot crop, respectively.

Conclusion

A field study was conducted to investigate the Water Footprint (WF) for carrot and silage maize crops cultivated in Saudi Arabia during the period from December 2015 to December 2016. The specific conclusions drawn from this study are as follows:

1. Water footprint (WFBlue) was accurately mapped out using remote sensing data from Landsat-8 multispectral imagery.

- The utility of Landsat-8 data in mapping CWUBlue showed reliable seasonal estimates of 1199 mm (summer) and 761 mm (spring/winter), which were in accordance with the Eddy covariance measured ET of 939 mm and 750 mm for summer and spring/winter growth periods, respectively.
- Among the six experimental fields, Landsat-8 determined WFBlue of silage maize was 2552 m3 t-1. For carrot, the WFBlue value determined from Landsat-8 data was 3010 m3 t-1, and showed a highly significant relationship with the empirical WFBlue (R2 = 0.77, P>F = 0.001).

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