University of Birjand

Water Harvesting Research Vol. 6, No. 2, Autumn & Winter 2023, Original Paper p. 203-212

10.22077/JWHR.2024.7158.1126

Comparison of Virtual Water Amount and Sugarcane Consumption in Water Shortage Conditions of Khuzestan Region, Iran

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Received: 17 December 2023/ **Revised**: 14 February 2024/ **Accepted**: 17 February 2024

Abstract

This study aimed to assess the virtual water of sugarcane under two irrigation scenarios in the Khuzestan province of Iran. The first scenario (S1) reflected current water consumption conditions in sugarcane fields, while the second scenario (S2) involved a 30% reduction in water usage on these farms. In S1, the average virtual water content was 0.42 $m^3.kg^{-1}$, which decreased to 0.32 $m^3.kg^{-1}$ in S2. The virtual water variation among sugarcane units in S1 was 0.62 $m^3.kg^{-1}$, while in S2, it was 0.53 $m^3.kg^{-1}$. In S1, the virtual water contribution of all sugarcane units to the water stress index of Khuzestan's agricultural sector was approximately 20.1%. This indicated that sugarcane production accounted for one-fifth of the water resources in the province's agricultural sector, primarily for export. This contribution decreased by 14.1% in S2. The changes in virtual water were comparable among different sugarcane units in both scenarios. The water stress index, based on the virtual water per total allocated water resources in the agricultural sector in Khuzestan (VKA), revealed high values (2%<VKA) in the Mirza Kochuk Khan, Debal-Khazai, Farabi, Karoon, and Dehkhoda units, moderate values (1% <VKA< 2%) in the Imam Khomeini and Salman Farsi units, and low values (VKA<1%) in the Haft Tappeh and Mianab units. Overall, the virtual water value and cultivated area significantly influenced the share of each sugarcane unit in the total virtual water amount. Notably, the Haft Tappeh and Mianab units had the smallest virtual water share, attributed to their smaller cultivated areas.

Key words: AquaCrop, Sugarcane, Water Deficit, Water Productivity.

1. Introduction

Agriculture holds a significant role in global food production, with Iran being no exception to its crucial importance. In Iran, agriculture contributes to 27% of the GDP and employs 22% of the workforce (Babazadeh and Saraei Tabrizi, 2012). Providing irrigation water is particularly vital in Iran's arid and semi-arid climate, where approximately 90% of the country's water resources are allocated to agriculture (Heidariniya et al., 2012; Ahmadee et al., 2021). With Iran's population projected to reach 100 million by 1410, an annual requirement of over 150 billion cubic meters of water is anticipated to meet the food needs, based on a daily energy intake of around 2600 kcal. Unfortunately, the country's water resources are insufficient to fulfill this demand (Babazadeh and Saraei Tabrizi, 2012).

Sugarcane cultivation plays a crucial role in meeting the nutritional needs of Iran's growing population and is exclusively grown in Khuzestan province. However, sugarcane, being a water-intensive crop, exerts pressure on water sources, with reported water requirements of upto 30,000 cubic meters per year, nearly six times that of strategic crops like wheat (Ahmadee et al., 2021b). Consequently, careful consideration of water usage in sugarcane cultivation becomes a priority in the country's agricultural sector.

The concept of virtual water, denoting the water consumed per kilogram of product, has been introduced to manage water resources at both regional and national levels (Chapagain and Hoekstra, 2004). In agriculture, where water consumption is substantial, the importance of virtual water is heightened. The concept not only considers the virtual water content per kilogram of agricultural produce but also takes into account the overall production volume in the region. For instance, wheat has significantly less virtual water than rice (approximately 50% less), yet it contributes 30% of the world's virtual water, compared to rice's 15% (Mousavi et al., 2009). This emphasizes the significance of applying the virtual water concept to products with extensive cultivation and water-intensive crops to alleviate water resource strain at minimal cost (El-Sadek, 2010; Antonelli et al., 2017).

In some countries, a strategic approach involves reducing the production of high-virtual-water products and importing food from other countries (Alizadeh and Khalili, 2009). However, some countries, including Iran, prefer to produce strategic agricultural products domestically to enhance self-sufficiency. Sugarcane is deemed a strategic crop in Iran, and despite its high virtual water content, it is essential to produce it within the country. Therefore, reducing the cultivated area is not a viable solution to decrease virtual water. Instead, one suggested method is to decrease water consumption in sugarcane fields, with deficit irrigation proposed as a means to achieve this goal (Ahmadee et al., 2021b). However, the impact of reduced water consumption on sugarcane yield must also be considered.

According to literature review, the study of virtual water in sugarcane agro-industry in Iran under the deficit irrigation has not been the attention of researchers. So, this study explores changes in sugarcane virtual water, considering a reduction in water consumption, and compares these findings with the virtual water status under current conditions.

2. Materials and Methods

2.1. Location of farms

This research was conducted in the all sugarcane agro-industry of Khuzestan province, located in the southwest of Iran, latitude between 29° 58' -33° 04' N and longitude between 47° 41' – 50° 39' E. The farms' geographical positions are depicted in Figure (1). Table (1) provides details about these farms, including their location, cultivated area, yield, and the quantity of irrigation water applied. In Iranian sugarcane farms, irrigation is implemented through furrows using a low-pressure irrigation pipe system known as hydroflum tubes. The discharge input into the furrows is established according to the methodology outlined by Ahmadee et al. (2021a).

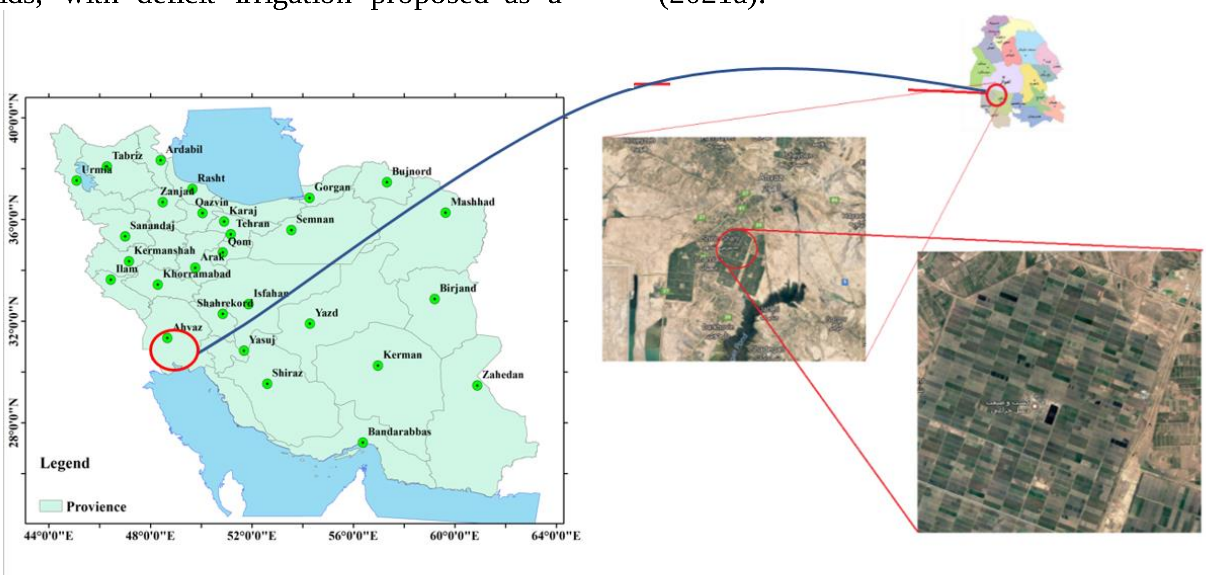

Fig. 1. The position of sugarcane farms in Khuzestan province, Iran

Table 1. Characteristics of sugarcane farms in Khuzestan province, Iran

Row	Agro-industry company	Symbol	Yield ($kg.ha^{-1}$)	Cultivated Area (ha)	Average amount of irrigation water per irrigation ($m^3.ha^{-1}$)
1	Mirza Kochuk Khan	MK	67176	12023	1160
2	Debal-Khazai	DK	67176	9540	1160
3	Farabi	FA	63337	10500	1160
4	Imam Khomeini	IK	63337	9850	954
5	Haft Tappeh	HT	74388	6000	754
6	Karoon	KA	72959	18000	954
7	Salman Farsi	SF	63337	10508	861
8	Dehkhoda	DE	44941	9198	1580
9	Mianab	MA	74388	1500	754

2.2. Virtual water

The virtual water quantity for sugarcane was determined by establishing the ratio of its average water requirement to its average yield, as outlined in equation (1).

$$VWCc = \frac{CWRc}{Tpc} \quad (1)$$

where, *VWCc* denotes the virtual water content of sugarcane ($m^3.kg^{-1}$), *CWRc* represents the irrigation water amount (m^3), and *Tpc* signifies the average yield of sugarcane (kg). Notably, virtual water exhibits an inverse correlation with water productivity. The virtual water exchange for each unit within the sugarcane agro-industry was computed by multiplying the total field yield by the virtual water quantity, as described in equation (2).

$$NVWI = M \times VWCc \quad (2)$$

where, *NVWI* is the total amount of virtual water (m^3), *M* is the total yield of sugarcane (kg) and *VWCc* is the amount of virtual water ($m^3.kg^{-1}$). Based on this concept, the amount of water stress index is calculated using equation (3).

$$V = \frac{NVWM}{TW} \times 100 \quad (3)$$

where, *V* represents the water stress index (%), *NVWM* stands for the total virtual water amount ($Mm^3.yr^{-1}$), and *TW* denotes the total available water resources ($Mm^3.yr^{-1}$). The parameter *V* ranges from 0 to 100, where a value closer to 100 signifies high water stress intensity. Conversely, an approach towards zero indicates a reduction in water stress intensity. This parameter was applied to various water sources in the research, as outlined below:

$$VT = \frac{NVWM}{TW1} \times 100 \quad (4)$$

$$VA = \frac{NVWM}{TW2} \times 100 \quad (5)$$

$$VR = \frac{NVWM}{TW3} \times 100 \quad (6)$$

$$VK = \frac{NVWM}{TW4} \times 100 \quad (7)$$

$$VKR = \frac{NVWM}{TW5} \times 100 \quad (8)$$

$$VKA = \frac{NVWM}{TW6} \times 100 \quad (9)$$

The parameters *VT*, *VA*, *VR*, *VK*, *VKR*, and *VKA* represent water stress indicators based on various water resources in Iran and Khuzestan. Specifically, they denote total water resources of Iran, total extractable water resources of Iran, total surface water resources of Iran, total water resources of Khuzestan, total surface water resources of Khuzestan, and the total allocated water resources in the agricultural sector in Khuzestan. Additionally, parameters *TW1* to *TW6* correspond to the total water resources of Iran, total extracted water resources of Iran, total surface water resources of Iran, total water resources of Khuzestan, total surface water resources of Khuzestan, and the total water consumed in the agricultural sector of Khuzestan.

This study explored two scenarios for evaluating virtual water. The first scenario (S1) reflects the existing conditions of water consumption in sugarcane fields. The second scenario (S2), incorporating a 30% reduction in water consumption for these farms, was considered based on the methodology proposed by Ahmadee et al. (2021b). To assess the impact of reduced water consumption on sugarcane yield, the AquaCrop crop growth model was employed in this research.

2.3. AquaCrop theory

The AquaCrop uses the calculated evapotranspiration (ET) assuming its segregation (Eq.10). Separation of this component into two components, evaporation (E) and transpiration (*Tr*), causes the non-productive consumption of water to be removed from the Equation (Eq. 11) (Raes et al., 2009).

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = K_y\left(\frac{ET_x - ET_a}{ET_x}\right) \quad (10)$$

$$T_r = K_s \times CC \times K_{CTrx} \times ET_0 \quad (11)$$

where, Y_x and Y_a are respectively the maximum and actual crop yield, ET_x and ET_a are respectively the maximum and actual crop evapotranspiration, K_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration, K_s and K_{CTrx} are respectively the water and crop stress coefficients, and *CC* is canopy cover in the crop development stages which is calculated by following equations (Raes et al., 2009).

$$CC = CC_0 \times e^{tCGC} \quad (12)$$

$$CC = CC_x - 0.25\frac{CC_x^{\;2}}{CC_0} \times e^{-tCGC} \quad (13)$$

$$CC = CC_x\left[1 - 0.05\left(e^{\frac{CDC}{CCx}\times t} - 1\right)\right] \quad (14)$$

where CC_0 is the initial canopy cover, *CGC* is the canopy growth coefficient, *CDC* is the canopy decline coefficient, and t is the time after cultivation. Equations (12) to (14) are respectively used to determine canopy cover from the beginning of the growth period to the middle of the development period, from the middle to the end of the development period, and from the beginning of the senescence to the end of the growth period. Biomass is calculated by Eq. (15).

$$B = WP^*\left[\frac{Tr_i}{ET_{0,i}}\right] \quad (15)$$

where Tr_i is the total amount of daily crop transpiration during the crop season, WP^* is the normalized water productivity, $ET_{o,i}$ is the daily reference crop evapotranspiration, and B is the daily biomass. The crop yield is also calculated using the biomass and the harvest index according to Equation (16).

$$Y = B \times HI \quad (16)$$

where *Y* is yield, *HI* is harvest index, and *B* is biomass. To calibrate the AquaCrop model, data obtained from 13 farms within the Farabi agro-industry were utilized, selected based on the availability of essential parameters for AquaCrop simulation. Following the calibration phase, validation of AquaCrop was conducted using data collected from all sugarcane farms, as reported by Ahmadee et al. (2021b). In assessing AquaCrop during both calibration and validation steps, various statistical metrics were employed, including root mean square error (RMSE), mean bias error (MBE), normalized root mean square error (NRMSE), model efficiency (EF), and coefficient of determination (R^2). The expressions for these statistical criteria are provided in Equations (17) to (21), as detailed by Nasrolahi et al. (2024).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (17)$$

$$MBE = \frac{\sum_{i}^{n}\left(P_i - O_i\right)}{n} \quad (18)$$

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}}{\overline{O_i}} \quad (19)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \quad (20)$$

$$R^2 = \frac{\left(\sum(P_i - \overline{P})(O_i - \overline{O})\right)^2}{\sum(P_i - \overline{P})^2\sum(O_i - \overline{O})^2} \quad (21)$$

where, P_i is the simulated value, O_i is the measured value, *P* is the average of the simulated values, *O* is the average of the measured values, and n is equal to the number of data. The value of RMSE statistic is always positive and the closer value to zero, shows low error. The positive value of the MBE indicates that AquaCrop has estimated the parameter value more than the actual value, and the negative values indicate that the crop model has obtained a smaller number in the estimation of the parameter. Values less than 0.1 for the NRMSE statistic indicate excellent accuracy of the model. In addition, the values of this statistic in the ranges of 0.1-0.2, 0.2-0.3, and more than 0.3 indicate good, moderate, and poor accuracy, respectively. The value of EF and d indicates the correctness of the data fitting and varies from a negative value of infinity in the worst case to one when the data is fully fitted. The value of R^2 varies from zero to one, and the closer it is to one, the better the fit of the data (Nasrollahi et al., 2024).

3. Results and Discussion

3.1. AquaCrop evaluation

During the calibration step, the results revealed that the simulated yield in all examined farms was consistently lower than the observed yield. The most difference between observed and simulated yield reached 16 ton.ha^{-1}, while the minimum difference stood at approximately 7 ton.ha^{-1}. The simulated yield exhibited a range of changes compared to the actual yield, fluctuating between 10% and 14%. The Mean Bias Error (MBE) in the calibration step was recorded at -11.3 ton.ha^{-1}, indicating an underestimation by the AquaCrop model (Table 2). To assess the model error, the Root Mean Square Error (RMSE) was employed, yielding a value of about 6.4 ton.ha^{-1}, considered acceptable in comparison to the sugarcane farms' actual yields. The accuracy of the AquaCrop model, as assessed by the Normalized Root Mean Square Error (NRMSE), was less than 0.10, categorizing it within the excellent accuracy range. Results for the Efficiency (EF) and coefficient d statistics also indicated satisfactory performance of the model. The validation results, presented in Table (2), showcased the largest yield difference between simulation and validation in the KA unit, with the DE unit displaying the smallest difference. The simulated and observed yield differences across all farms ranged between 7-14 ton.ha^{-1}, with an average difference of 10 ton.ha^{-1}. As indicated by the MBE statistics in Table (2), the AquaCrop model consistently exhibited an underestimation error, a trend observed during the calibration step. The simulation error, based on the RMSE statistic, was measured at 6.5 ton.ha^{-1}, considered acceptable when compared to the average yield in sugarcane farms (65.6 ton.ha^{-1}). The NRMSE statistic yielded a value of 0.1, positioning it on the border between good and excellent accuracy. The efficiency of the AquaCrop model was also deemed acceptable based on the EF and d statistics.

Table 2. Results for statistical values in the calibration and validation step

Row	Statistical Criteria	Unit	Calibration Value	Validation Value
1	MBE	ton.ha^{-1}	-11.6	-10.4
2	RMSE	ton.ha^{-1}	6.4	6.5
3	NRMSE	-	0.06	0.10
4	EF	-	0.98	0.97
5	d	-	0.99	0.99

The elevated R^2 value indicates the AquaCrop model's strong capability to forecast changes in yield under farm conditions (Fig. 2). Given that AquaCrop operates as a water-driven model (Ahmadee et al., 2021b), significant fluctuations in water levels can substantially impact the accuracy and R^2 statistic. However, under conditions of ample moisture availability, the model demonstrates sufficient accuracy in predicting yield variations on farms. This observation aligns with findings from other researchers, such as Raes et al. (2009) and Katerji et al. (2013). Therefore, the notably high R^2 value in this research instills confidence in the AquaCrop model's outcomes. The dispersion of points below the 1:1 line signifies that observed yield in the field exceeds the corresponding value in the simulation. This pattern mirrors the MBE statistics in Table (2) and underscores the AquaCrop model's tendency to underestimate sugarcane yield. The R^2 statistic maintained a high value during the validation step, further reinforcing confidence in the model's outcomes based on the results from both calibration and validation steps. Consequently, this model was employed to simulate sugarcane yield in the second scenario (S2).

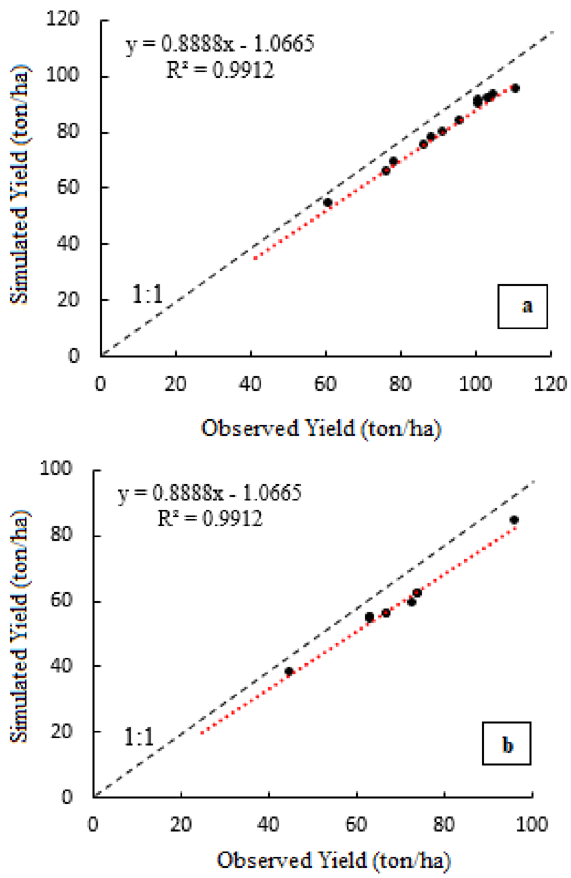

Fig. 2. Correlation of observed and simulated yield in the calibration (a) and validation (b) step

3.2. Virtual water

Under current conditions (S1), the DE unit exhibited the highest virtual water content at 0.8 ($m^3.kg^{-1}$) (Fig. 3), attributable to its lower sugarcane yield. This unit's yield was approximately 31.5% lower than the average yield in Khuzestan province sugarcane farms. Conversely, the HT unit recorded the lowest virtual water at 0.18 $m^3.kg^{-1}$, owing to its higher yield compared to other units and lower irrigation water usage. The overall average virtual water across all sugarcane units was 0.23 $m^3.kg^{-1}$, indicating a water productivity of 4.3 $kg.m^{-3}$. Comparable studies by Zanganeh Yusef Abadi et al. (2021) reported sugarcane water productivity ranging from 1.6 to 2.2 $kg.m^{-3}$. Virtual water for sugar derived from these sugarcane units surpassed sugarcane virtual water, reflecting the lower sugar production relative to sugarcane. The total virtual water consumption for sugarcane in agro-industry units amounted to 1314 MCM, with the MK unit being the highest water consumer in Khuzestan province, constituting 19% of the total virtual water. Subsequently, FA, KA, and DE units were the next highest water consumers, accounting for 17%, 15%, and 14% of total virtual water, respectively. In contrast, HT and MA units placed the least pressure on water resources, contributing 3% and 2%, respectively, to the total virtual water, with HT's low share attributed to its low virtual water quantity and MA's share influenced by its smaller cultivated area.

In S2, virtual water varied between 0.29-0.66 $m^3.kg^{-1}$ across the studied units. The average virtual water decreased to 0.32 $m^3.kg^{-1}$, representing a 9 $m^3.kg^{-1}$ change from S1. Despite uniform water reduction across all units, the HT unit exhibited the lowest virtual water, while the DE unit had the highest. Virtual water for sugar in S2 decreased by 11.7 $m^3.kg^{-1}$ compared to S1 due to reduced yield with lower irrigation water usage (Fig. 4). Although the average yield decreased by 7.7%, water consumption savings were more pronounced, resulting in a 22.9% decrease in virtual water compared to S1. Considering yield changes ranged from 5-15% among the studied units due to water consumption reduction, the virtual water change spanned a relatively wide range. Additionally, since water stress was applied uniformly across all sugarcane units, their virtual water shares remained similar to S1.

In Figures (5), the Water Stress Index Value (WSIV) for sugarcane has been assessed based on various water sources. In S1, the MK unit displayed the highest WSIV, while the MA unit exhibited the lowest. The collective WSIV for sugarcane units, calculated with respect to Iran's total water resources, stood at 1.7%. This value signifies that approximately 1.7% of Iran's water resources are utilized for sugarcane production. Furthermore, about 2.5% of Iran's total extractable water resources are allocated to sugarcane production. When distinguishing between surface and underground water sources, around 9.2% of Iran's surface water resources contribute to sugarcane production. In S2, the VT, VA, and VR values decreased to 1.2%, 1.8%, and 6.4%, respectively.

In S1, the values for VK, VKR, and VKA were calculated at 12.1%, 13.5%, and 20.1%, respectively (Fig. 6). Correspondingly, in S2, these values were reduced to 8.5%, 9.4%, and 14.1%. Although this represents an improvement compared to S1, it remains suboptimal. The challenge lies in the fact that while water consumption has been reduced, the yield has also decreased. Overall, in comparison to S1, approximately 6% of the water resources in the agricultural sector of Khuzestan province were conserved, albeit at the expense of reduced yield. Notably, these values signify the percentage of stress imposed on water sources, indicating a shift of water from primary sources to the commercial sector, indirectly leading to the withdrawal of water resources from Khuzestan province. Despite some studies, like those conducted by Hayatgheibi et al. (2021), which explore the adverse effects of diverting water from rivers in Khuzestan province and emphasize environmental preservation, no research has yet delved into the nuances of indirect water withdrawal from these sources. While some researchers have suggested replacing high-water consumption crops like sugarcane with low-water consumption alternatives such as sesame (Safi and Amirlatifi, 2015), the precise extent of indirect water withdrawal from Khuzestan province remains unknown.

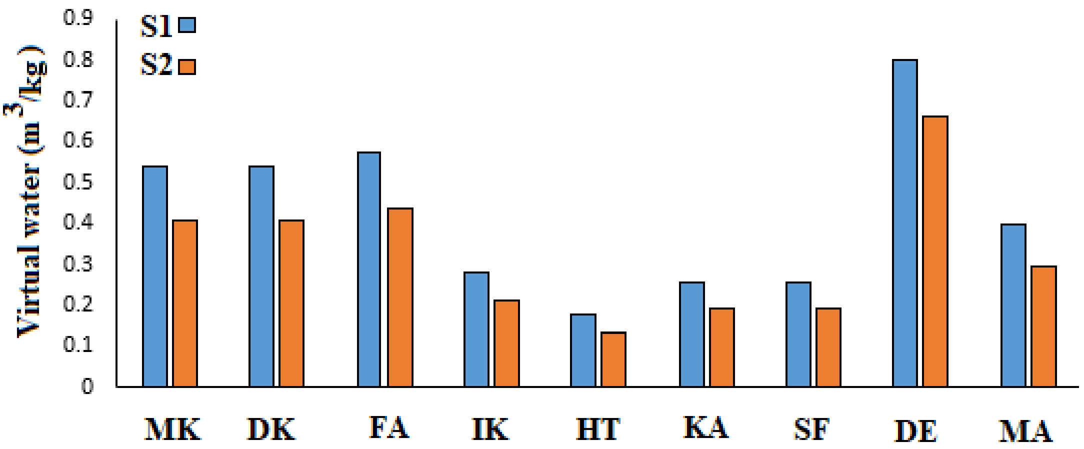

Fig. 3. Comparison of sugarcane virtual water in the S1 and S2

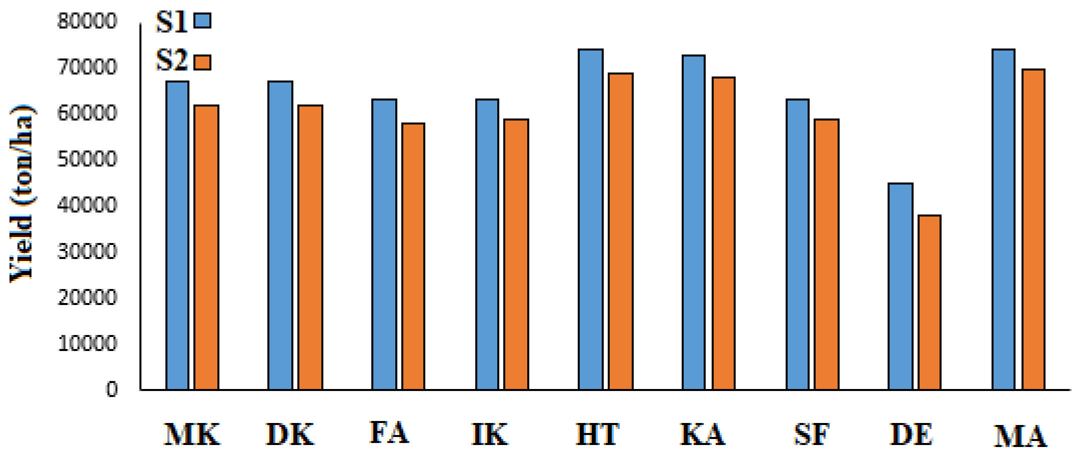

Fig. 4. Comparison of sugarcane yield in the S1 and S2

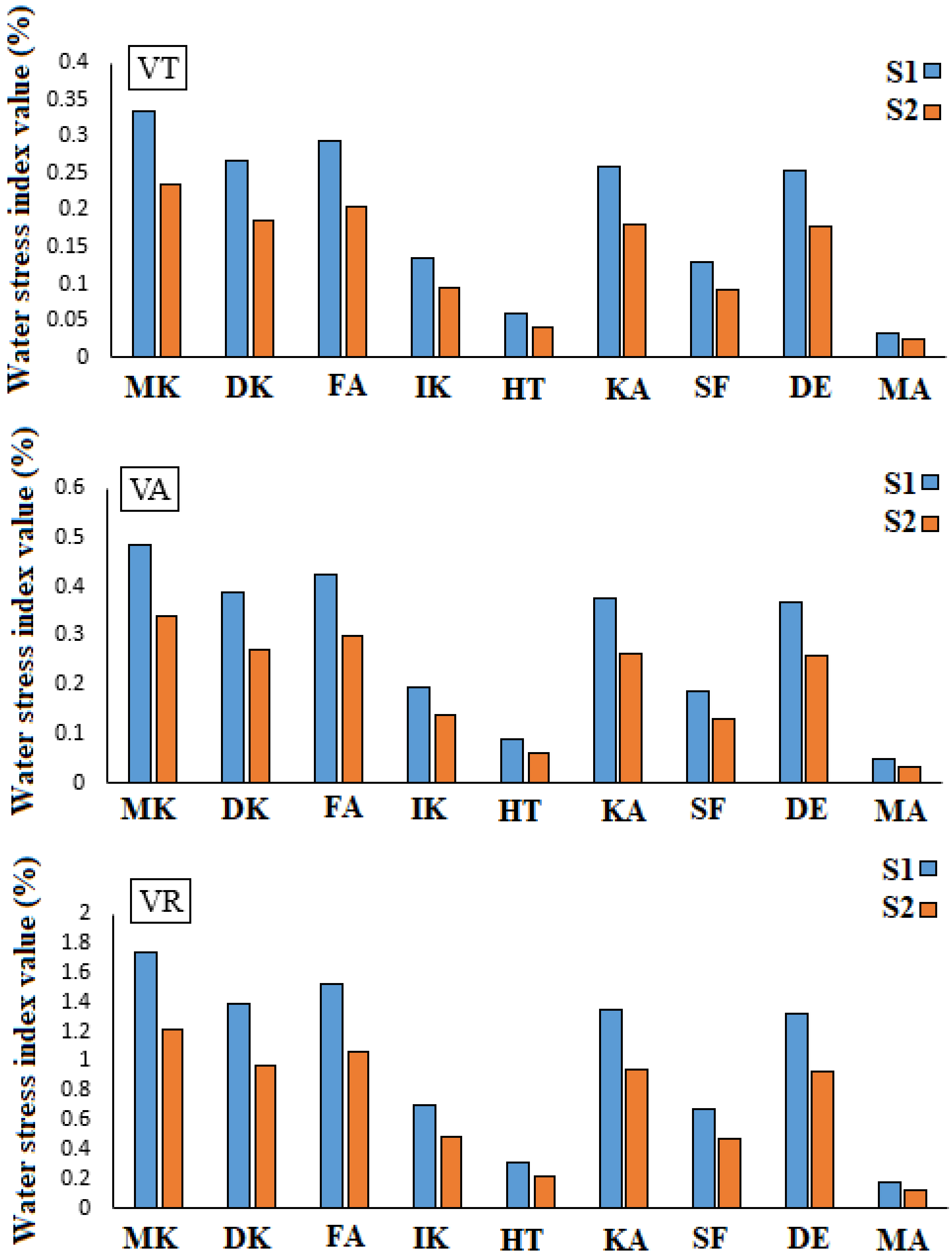

Fig. 5. Water stress index value in sugarcane farms based on the Iran total water resources (VT), the total extractable water resources (VA), the total surface water resources (VR) in the S1 and S2

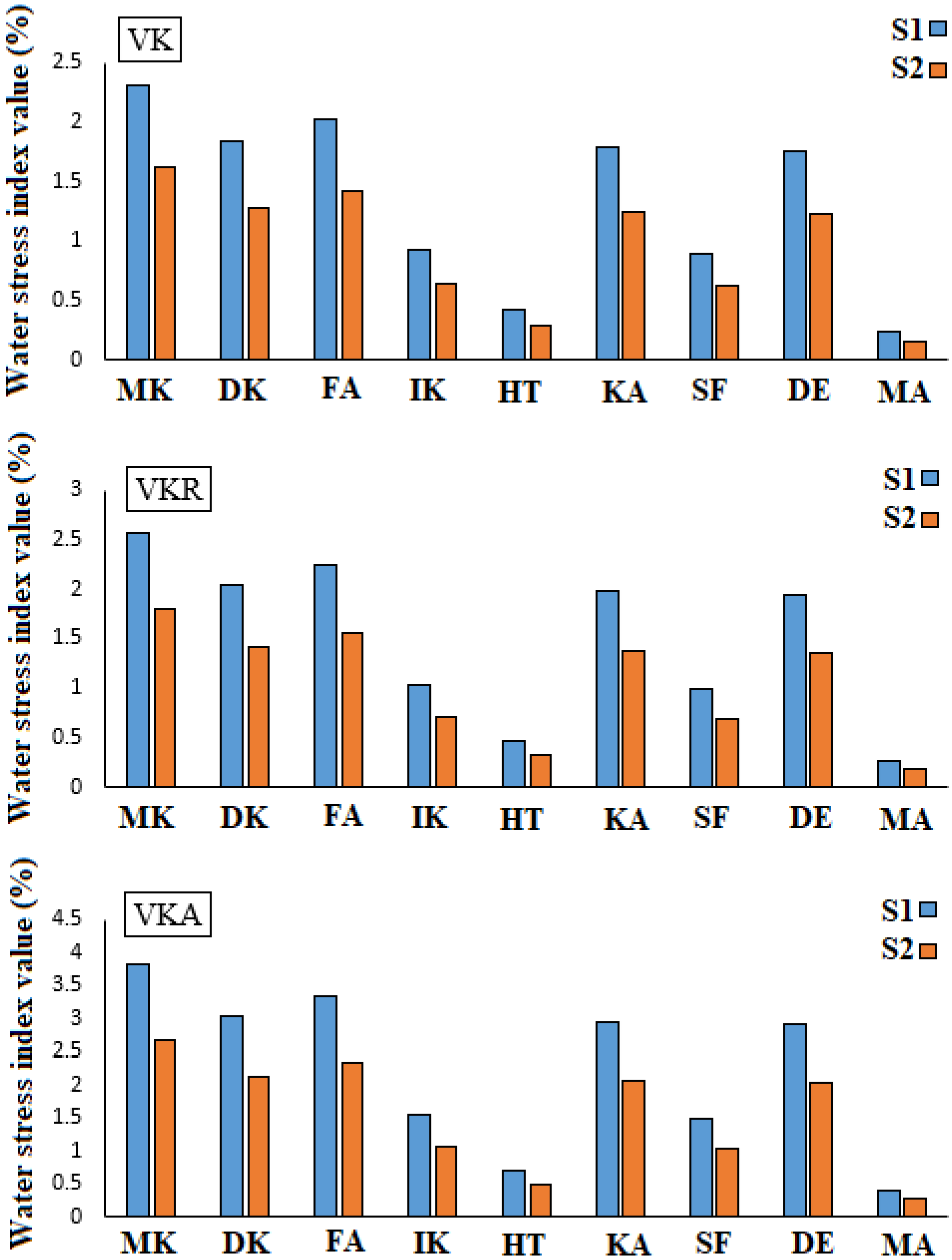

Fig. 6. Water stress index value in sugarcane farms based on total water resources of Khuzestan province (VK), total surface water resources of Khuzestan province (VKR) and total water resources in agricultural sector of Khuzestan province (VKA) in the S1 and S2

4. Conclusion

The AquaCrop model's simulation results in both the calibration and validation steps demonstrated an acceptable error in sugarcane yield (RSME≤6.5 ton.ha^{-1}), even though the model exhibited an underestimation error (MBE<0). Excellent accuracy was maintained throughout both steps (NRMSE≤0.1), with a high correspondence between simulated and observed results (R^2>0.9), instilling confidence in the reliability of the model's simulation outcomes. In S1, the average virtual water quantity was 0.42 m^3.kg^{-1}, decreasing to 0.32 m^3.kg^{-1} in S2. The range of virtual water variations among sugarcane units was 0.62 m^3.kg^{-1}in S1, decreasing to 0.53 m^3.kg^{-1} in S2. In S1, the virtual water share of all sugarcane units in the water stress index of Khuzestan's agricultural sector reached approximately 20.1%. This indicated that around one-fifth of the water resources in the agricultural sector of Khuzestan province were utilized by sugarcane production, primarily for export outside the province. This share decreased by 14.1% in S2. Virtual water changes exhibited similarity among different sugarcane units in both S1 and S2. The water stress index value (VKA) indicated high stress (2%<VKA) in

MK, DK, FA, KA, and DE units, moderate stress (1% <VKA< 2%) in IK and SF units, and low stress (VKA<1%) in HT and MA units. Overall, the virtual water value and cultivated area significantly influenced each sugarcane unit's share in the total virtual water amount. Consequently, the MA and HT units had the lowest share of virtual water, attributable to their smaller cultivated areas.

5. Disclosure Statement

No potential conflict of interest was reported by the authors.

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