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NESTED VALIDATION OF AQUACROP MODEL FOR SIMULATION OF WINTER WHEAT GRAIN YIELD, SOIL MOISTURE AND SALINITY PROFILES UNDER SIMULTANEOUS SALINITY AND WATER STRESS†

M. MOHAMMADI[1], B. GHAHRAMAN[1]*, K. DAVARY[1], H. ANSARI[1], A. SHAHIDI[2] AND M. BANNAYAN[3]

[1]*Ferdowsi University of Mashhad, Faculty of Agriculture, Water Engineering Department, Mashhad, Iran*
[2]*University of Birjand, Faculty of Agriculture, Water Engineering Department, Birjand, Iran*
[3]*Ferdowsi University of Mashhad, Faculty of Agriculture, Mashhad, Iran*

ABSTRACT

Improvement of water management and water use efficiency at field scale is highly important under simultaneous salinity and water stress. The models that can translate the effects of different quantity and quality of water to crop yield, are useful tools for water management and improving water productivity (WP). AquaCrop (v4.0) simulates yield, water requirement, WP, soil water content and salinity under different conditions in the field, including water-limiting and different quality of irrigation water. This study was carried out as split plot design (factorial form) in Birjand, in the east of Iran, in order to evaluate the AquaCrop model. Treatments consisted of three levels of irrigation water salinity (S_1, S_2, S_3 corresponding to 1.4, 4.5, 9.6 dS m^{-1}) as the main plot, two wheat varieties (Ghods and Roshan), and four levels of irrigation water amount (I_1, I_2, I_3, I_4 corresponding to 125, 100, 75, 50% water requirement) as subplot. The model was nested, calibrated and validated separately for each salinity treatment, and also simultaneously for all three salinity treatments. The overall model accuracy was higher for estimating soil moisture profile, as compared to soil salinity profile. For simulation of soil water content, the average values of RMSE, *d*, CRM and R^2 in both calibration and validation were 11.8%, 0.79, 0.05 and 0.61 respectively, while for simulation of soil salinity they were 24.4%, 0.72, 0.19 and 0.57 respectively. The AquaCrop successfully simulated yield, biomass and WP for two wheat varieties under salinity and water-limiting treatments with high accuracy. Average values of NRMSE, *d*, CRM, and R^2 for both calibration and validation of simulated grain yield were 7.1%, 0.97, 0.001 and 0.9 respectively, for the Roshan variety, while these measures were 8.2%, 0.98, −0.004 and 0.87 respectively, for the Ghods variety. Crop transpiration coefficient (Kc_{Tr}), normalized crop water productivity (WP*), reference harvest index (HI_O), volumetric water content at field capacity (θ_{FC}), soil water content at saturation (θ_{sat}), and temperature were the most sensitive parameters.

KEY WORDS: biomass; nested model calibration; plant modelling; sensitivity analysis

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RÉSUMÉ

L'amélioration de la gestion de l'eau et l'utilisation rationnelle de l'eau à l'échelle de la parcelle sont très importantes dans des contextes simultanés de salinité et de stress hydrique. Les modèles qui peuvent traduire les effets de différentes quantités et qualités d'eau sur le rendement des cultures sont des outils utiles pour la gestion de l'eau et l'amélioration de la productivité de l'eau (WP). AquaCrop (v4.0) simule le rendement, les besoins en eau, WP, les teneurs en eau et et en sels dans différentes conditions de terrain, de qualité et quantité d'eau. L'évaluation du modèle AquaCrop a été réalisée à Birjand, dans l'est de l'Iran, avec un plan d'expérience de type split plot (forme factorielle). Les traitements consistaient en trois niveaux de salinité de l'eau d'irrigation (S_1, S_2, S_3 qui correspondent à 1.4, 4.5, 9.6 dS m^{-1}) comme entrée principale, deux variétés de blé (Ghods et Roshan), et quatre niveaux de quantité d'eau d'irrigation (I_1, I_2, I_3, I_4) correspondant à 125, 100, 75, 50% des besoins en

*Correspondence to: Prof B. Ghahraman. Ferdowsi University of Mashhad, Faculty of Agriculture, Water Engineering Department, Mashhad 9177948974, Iran. E-mail: bijangh@um.ac.ir
†Validation du modèle imbriqué AquaCrop pour la simulation de rendement en grain de blé d'hiver, de l'humidité du sol, des profils de salinité sous différentes conditions de salinité et de stress hydrique.

eau). Le modèle a été calibré de manière imbriquée et validé à la fois séparément pour chaque traitement de salinité, et aussi simultanément pour les trois traitements de salinité tous ensemble. La précision globale du modèle est meilleure pour estimer le profil d'humidité du sol que pour estimer le profil de salinité. Pour la simulation de la teneur en eau du sol, les valeurs moyennes de RMSE, *d*, CRM et R^2 dans le calibrage et la validation ont été 11.8%, 0.79, 0.05 et 0.61 respectivement, tandis que pour la simulation de la salinité du sol, elles étaient 24.4%, 0.72, 0.19 et 0.57 respectivement. AquaCrop a simulé avec une grande précision le rendement, la biomasse et WP pour deux variétés de blé et pour les différentes conditions d'alimentation en eau et sels. Les valeurs moyennes des NRMSE, *d*, CRM, et R^2 à la fois pour l'étalonnage et la validation de rendement simulé en grain pour la variété Roshan étaient de 7.1%, 0.97, 0.001 et 0.9 respectivement, et de 8.2%, 0.98, −0.004 et 0.87 respectivement, pour la variété Ghods. Le coefficient cultural de transpiration (K_{cTr}), la productivité normalisée de l'eau (WP*), l'indice de récolte de référence (EIO), la teneur en eau volumique à la capacité de champ (θ_{FC}), la teneur en eau du sol à saturation (θ_{sat}), et la température étaient les paramètres les plus sensibles.

MOTS CLÉS: biomasse; étalonnage du modèle imbriqué; modélisation des plantes; analyse de sensibilité

INTRODUCTION

Irrigated agriculture uses about 72% of accessible water resources on a global scale (Geerts and Raes, 2009). The fast growth of the world's population and the demand for additional water by industries and municipalities have forced the agricultural sector to use its irrigation water more efficiently on the one hand and to produce more food on the other. In the year 2000, Iran was the largest wheat importer from the international market. The amount of imported wheat was 3.53, 6.16 and 6.58 million t for 1998, 1999 and 2000 respectively, and the amounts of imported cereals were 5.18, 8.44 and 9.93 million t (Salemi *et al.*, 2011). The country became self- sufficient in wheat production in 2005. This could have not been achieved without putting more pressure on groundwater withdrawal and replacing other cereals by wheat. Part of the necessary water was supplied through construction of many new dams, improved water management, improved cultivation practices, and other management at the field scale (Salemi *et al.*, 2011). This self-sufficiency, however, was not sustainable and did not last long, and in 2008 Iran had to import wheat again. Developments in water resources management are being sought and implemented in Iran, including change in the structure of the national economic system and demand–supply mechanism for water (Ardekanian, 2005). In spite of all the efforts to alleviate the problem of water scarcity (Bannayan *et al.*, 2010), sensible management and judicious use of available water still need more plans and actions (Roohani, 2006). Various studies have shown that the solutions for the freshwater shortage problem are deficit irrigation and use of saline water (Demir *et al.*, 2006; Igbadun *et al.*, 2008; Malash *et al.*, 2008; Geerts and Raes, 2009; Choudhary *et al.*, 2010; Bannayan *et al.*, 2013). To achieve this goal, a detailed knowledge of the relationship between water use and crop yield is crucial. Agro-hydrological models that quantify the effects of water on yield at the farm level can be valuable tools in making decisions regarding irrigation management (Pereira *et al.*, 2009; Geerts and Raes, 2009; Shafiei *et al.*, 2014). Therefore, to improve management practices, an irrigation management model can be applied to estimate crop water requirement and upgrade irrigation management capability under salinity and water stress. Models allow a combined assessment of different factors affecting yield in order to derive optimal irrigation quantities for different scenarios (Pereira *et al.*, 2002; Liu *et al.*, 2007). All the models should be calibrated and evaluated before they are used (Bannayan *et al.*, 2003, 2007; Nain and Kersebaum, 2007). For calibration, one changes model parameters in order to obtain accurate predictions against observed data. On the other hand, validation is the method whereby the model is run versus independent data, without any adjustment of model parameters (Nain and Kersebaum, 2007; Salazar *et al.*, 2009).

In past decades, many models, including SOYMOD (Meyer *et al.*, 1981), CERES-Maize (Jones and Kiniry, 1986), SOYGRO (Egli and Bruening, 1992), the WOFOST model, CropSyst (Stockle *et al.*, 2003) and APSIM (Marinov *et al.*, 2005), have been introduced and used to study irrigation management at farm level. In these models one of the main criteria is measurement of leaf area index (LAI). Most of these models, however, are quite sophisticated, require advanced modelling skills for their calibration and subsequent operation, and require a large number of model input parameters. Some models are cultivar-specific and not easily amenable for general use. In this context, the recently developed FAO AquaCrop model (Raes *et al.*, 2009a; Steduto *et al.*, 2009) is a user-friendly and practitioner-oriented type of model, because it intends to have an optimal balance between accuracy, robustness and simplicity, and requires a relatively small number of model input parameters. The FAO AquaCrop model predicts crop productivity, water requirement and water use efficiency under water-limiting and saline water conditions (Raes *et al.*, 2009b). This model has been tested and validated for different crops such as maize (*Zea mays* L.) (Hsiao *et al.*, 2009; Mebane *et al.*, 2013), cotton (*Gossypium hirsutum* L.) (Farahani *et al.*, 2009; Hussein *et al.*, 2011), sunflower (Todorovic *et al.*, 2009), potato (*Solanum tuberosum* L.) (Vanuytrecht *et al.*, 2011), wheat (*T. aestivum* L.) (Andarzian *et al.*, 2011; Mkhabela and Bullock, 2012; Kumar *et al.*, 2014) and quinoa (*Chenopodium quinoa* Willd.) (Geerts *et al.*, 2009) under diverse environments. All of these studies have illustrated that the model could accurately simulate the crop biomass and yield as well as soil water dynamics under full and water-deficit irrigation conditions. Besides simulating crop yield, AquaCrop also simulates soil water content and salinity using basic soil and weather data. The importance of obtaining good soil water and salinity estimates in agriculture can never be overemphasized. For the soil profile explored by the root system, AquaCrop performs a water balance that includes evaporation, transpiration, runoff, infiltration, internal drainage, deep percolation, capillary rise from a shallow groundwater table and root uptake (Raes *et al.*, 2009a; Steduto *et al.*, 2009). AquaCrop has also been used to derive and/or optimize irrigation schedules under different levels of salinity and irrigation (Raes *et al.*, 2012). In most arid and semi-arid regions water shortage is associated with reduction in water quality (increasing salinity). Plants in these regions in terms of water quality and quantity may be affected by simultaneous salinity and water stress. Therefore, in this study, the AquaCrop model was evaluated under simultaneous salinity and water stress. In this study, AquaCrop model (v4.0) version which was developed in 2012 to quantify the effects of salinity (Raes *et al.*, 2012) was applied.

The objectives of this study were: (i) evaluation of the AquaCrop model (v4.0) to simulate wheat yield, and soil water content and salinity profiles under simultaneous salinity and water stress conditions in an arid region of Birjand, Iran; (ii) use of different treatments for nested calibration and validation of the AquaCrop model.

MATERIALS AND METHODS

Study location

This study was carried out in 2005–2006 at the research station of the Faculty of Agriculture, University of Birjand (32° 53 N, 55° 13 E, 1480 m + MSL (mean sea level)). Economic cultivation of rainfed wheat is impossible in Birjand region because of the low amount of rainfall, its unsuitable distribution, and high evaporation during the growing season. In this region, wheat production clearly depends on irrigation water. The study region climate is arid with total annual precipitation of 171 mm and it has cold winters and hot summers (Table I).

Field experiments

The experiment was conducted using two varieties of wheat (Ghods and Roshan) during 2005–2006 with three replications as a randomized complete block design with a split plot layout. Treatments consisted of three levels of irrigation water salinity (S_1, S_2 and S_3 corresponding to 1.4, 4.5 and 9.6 dS m^{-1}) as the main plot, two wheat varieties, and four levels of irrigation water amount (I_1, I_2, I_3 and I_4 corresponding to 125, 100, 75, 50% water requirement) as subplot. Wheat was sown by hand on 14 November 2005 in a plot size of 3 × 4 m with a between-row spacing of 20 cm and harvested on 17 (Ghods variety) and 18 (Ghods variety) May 2006. Each plot was planted using 400 seeds m^{-2} as planting density. Irrigation water was applied using the surface flood method (basin irrigation) without runoff. The nutrient requirements were determined based on soil analysis. Standard agronomic practices for fertilizer application were followed with a fertilizer recommendation of N (urea at 46% N), P (triple superphosphate), and K (potassium sulphate) as 300 : 150 : 150 kg ha^{-1}. P, K and one quarter of N were applied before planting and the remaining N was topdressed at the start of the tillering, stem elongation and heading stages. Weeds were effectively controlled

Table I. Monthly average maximum and minimum temperature, sunshine hours and total rainfall at Birjand (over wheat cropping season)

	Temperature (°C)							
	Max		Min		Sunshine (h)		Rainfall (mm)	
Month	1955– 2005	2005– 2006	1955– 2005	2005– 2006	1955– 2005	2005– 2006	1955– 2005	2005– 2006
November	25.3	25.6	−5.0	−2.8	7.6	8.1	7.3	10.3
December	19.9	22.6	−8.3	−7.6	6.4	7.5	21.1	0.5
January	17.5	20.2	−9.9	−11.2	6.3	6.6	32.1	35.2
February	20.3	26.2	−7.7	−5.2	7.0	7.1	30.6	11.8
March	25.2	27.6	−3.7	1.2	6.8	7.4	37.3	10.7
April	30.2	32.4	1.7	3.4	7.9	8.0	27.8	12.7
May	35.8	37.2	7.2	13	9.9	9.8	8.2	5.8

using herbicides, and no pests or disease infestations were observed during the plant growing season. The first irrigation was by the basin method, implemented 2 days after seeding. The date of irrigation was scheduled when accumulated pan evaporation was equal to 70 mm. Then, soil water content was measured gravimetrically in each 0.2 m layer up to 1 m depth, as the effective root depth. The quantity of irrigation water for full irrigation treatment was calculated based on soil moisture content before irrigation, and root zone depth of the plant using Equation 1:

$$SMD = (\theta_{FC} - \theta_i).Bd.D.f \quad (1)$$

where SMD is soil moisture deficit (mm), θ_{FC} is soil water content at field capacity, θ_i is soil water content before irrigation (mass basis), D is depth of root development (mm), Bd is bulk density of the particular soil layer (g cm^{-3}), and f is coefficient for each irrigation treatment levels in the experiment. The coefficient of each treatment f (I_1) = 1.25 (125% FC), f (I_2) = 1 (full irrigation up to FC without any deficit), f (I_3) = 0.75 (75% FC), and f (I_4) = 0.5 (50% FC), was used for different treatments to estimate the quantity of irrigation water. For all other irrigation treatments (50, 75, and 125 % of FC), water was applied on the same day as that of the full irrigation plot (I_2), but with unequal irrigation depths (Table II).

Weather and soil data

Daily maximum (°C) and minimum air temperature (°C), rainfall (mm), sunshine hours data, and wind speed at 2 m above the ground surface were obtained from the synoptic station of Birjand (32° 52 N, 59° 12 E, 1491 m + MSL) (Table I). Reference evapotranspiration (ET_0) was calculated using the Penman–Monteith equation as described in Majidi *et al.* (2014). Physical properties of the soil profile (0–100 cm depth) are presented in Table III. The parameters that were determined include soil texture, bulk density, θ at saturated point (θ_{sat}), field capacity (θ_{FC}), permanent wilting point (θ_{PWP}) and hydraulic conductivity (K_{sat}) of saturated soil. θ_{sat} and K_{sat} were estimated using the RETC model (van Genuchten *et al.*, 1991). θ_{FC} and θ_{PWP} were measured using a mixed sample of all three soil layers (0–100 cm) from four locations in the field. Measured values (i.e. θ_{FC} and θ_{PWP}) were considered for the middle layer. Then, both θ_{FC} and θ_{PWP} were predicted for all three layers indirectly using the RETC model by accounting for sand, silt and clay fractions, and bulk density (Table III). A correction factor was found for the middle layer, with which we corrected the RETC outputs for the other two layers.

Soil water content was measured gravimetrically and the average electrical conductivity of the saturation soil extract (ECe) was determined in the laboratory in each 0.2 m layer up to 1 m depth on days 102, 119, 143 and 185 (end of the growing season) after sowing in all treatments.

Table II. Irrigation scheduling for different treatments

Day after sowing	Date of irrigation	Depth of irrigation (mm)			
		I_1	I_2	I_3	I_4
2	2005/16/11	30	30	30	30
103	2006/24/02	87	70	53	35
117	2006/10/03	95	76	57	38
131	2006/24/03	114	91	68	45
154	2006/16/04	121	97	73	49
165	2006/27/04	113	90	67	45
175	2006/07/05	100	80	60	40
Total		660	534	408	282

Table III. Measured soil properties in Birjand

Soil properties	Depth (cm)		
	0–30	30–60	60–100
Texture	Clay loam	Silty clay loam	Silty clay loam
Sand (%)	29.7	10.1	11.2
Clay (%)	35.7	37.3	53.6
Silt (%)	34.6	52.6	35.2
θ_{FC} (%)	33.6	33.4	31
θ_{PWP} (%)	19.2	19.7	19.5
θ_{sat} (%)	41.8	44.8	45.9
K_{sat} (mm day^{-1})	58.4	65.3	95.2
Bulk density (g cm^{-3})	1.5	1.45	1.39
Organic carbon (%)	0.53	0.42	–
ECe (dS m^{-1})	2.1	2.7	2.9
pH	7.61	7.72	7.78

Model description

The AquaCrop model needs a few, easy accessible parameters, which are readily available or can easily be collected. Input data are divided into four groups: climatic, crop, soil and field management data. AquaCrop calculates a daily water balance that includes all incoming and outgoing water fluxes (infiltration, runoff, deep percolation, evaporation and transpiration) and changes of soil water content. To simulate the redistribution of water into a soil layer, the drainage out of a soil profile, and the infiltration of rainfall and/or irrigation, AquaCrop makes use of a drainage function (Raes *et al.*, 2006). The drainage function describes the amount of water lost by free drainage over time between saturation and field capacity. The function is assumed to be exponential. When field capacity is reached, further drainage of the soil is disregarded (Raes *et al.*, 2006). There are five weather input variables required to run AquaCrop, including daily maximum and minimum air temperatures (T), daily rainfall, daily reference evapotranspiration (ET_0), and mean annual CO_2 concentration in the atmosphere. While the first four are derived from typical agrometeorological stations, the CO_2 concentration uses the Mauna Loa Observatory records in Hawaii. AquaCrop (Steduto *et al.*, 2009) simulates attainable yields of major herbaceous crops as a function of water consumption under rainfed, supplemental, deficit and full irrigation conditions. AquaCrop is a water-driven crop growth model that depends on the conservative behaviour of the biomass per unit transpiration (Tr) relationship (Raes *et al.*, 2009a; Steduto *et al.*, 2009). The model uses canopy ground cover instead of leaf area index (LAI) as the basis to calculate transpiration, and to separate soil evaporation from transpiration. Crop yield is calculated as the product of above-ground dry biomass and harvest index (HI). Crop responses to water deficits are simulated based on the differential sensitivity to water stress of four key plant processes: canopy expansion, stomatal control of transpiration, canopy senescence and HI. HI can be modified negatively or positively, depending on stress level, timing and duration. Crop production might also be affected by soil salinity stress. To describe the effect of soil salinity stress on crop development and production, AquaCrop benefits from four stress coefficients including Ks_{CCx} (stress coefficient for maximum canopy cover), $Ks_{exp,f}$ (stress coefficient for canopy expansion), $f_{CDecline}$ (decline coefficient of canopy cover), and $Ks_{sto,salt}$ (stress coefficient for stomatal closure). Biomass production might be affected by soil salinity stress. To describe this process, a soil salinity stress coefficient (Ks_{salt}) is considered (Raes *et al.*, 2012). The calculation procedure consists of the following five steps: (i) the average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone determines the soil salinity stress (Ks_{salt}); (ii) the relative biomass (B_{rel}) is produced with the salinity stress (Ks_{salt}); (iii) the stress inducing stomatal closure and affecting canopy development is derived from the user-calibrated relationship between relative biomass production and soil salinity stress; (iv) the stress determines the value for: (a) $Ks_{sto,salt}$ (resulting in stomatal closure and affecting crop transpiration, Tr); (b) $Ks_{exp,f}$ (slowing down canopy development), (c) Ks_{CCx} (reducing the maximum canopy cover); (d) $f_{CDecline}$ (triggering canopy decline) resulting in reduced canopy cover and reduced crop transpiration; (v) as a result of the calibration the resulting B_{rel} is identical to the expected B_{rel} in the absence of soil water stress (Raes *et al.*, 2012). AquaCrop has default values for several crop parameters that are used for simulating different crops, including wheat; however, some of these parameters are not universal and thus have to be adjusted for local conditions, cultivars and management practices. More detailed description of AquaCrop may be found in the literature (e.g. Geerts *et al.*, 2009; Hsiao *et al.*, 2009; Raes *et al.*, 2009a; Steduto *et al.*, 2009).

AquaCrop uses the calculation procedure presented in BUDGET (Raes, 2002; Raes *et al.*, 2006) to simulate salt movement and retention in the soil profile. To describe the movement and retention of soil water and salt in the soil profile, AquaCrop divides the soil profile into various soil compartments (12 by default) with thickness Δz. To simulate the convection and diffusion of salts, a soil compartment is further divided into a number of cells where salts can be stored. The number of cells, which may range from 2 to 11, depends on the soil type of the soil horizon. The electrical conductivity of saturated soil paste extract (ECe) at a particular soil depth (soil compartment) was estimated using the arithmetic average of EC_{cell} (electrical conductivity of the soil water in the cell, dS m^{-1}) (Raes *et al.*, 2012).

Sensitivity analysis

Sensitivity analysis (SA) helps us to recognize the parameters that have significant impact on model output (Cao and Petzold, 2006). The agronomic, soil, meteorology and irrigation management data were considered for SA. First, the AquaCrop model was run with the corresponding data of S_1 treatments (for all I_1, I_2, I_3 and I_4) and the results (wheat grain yield, average of soil water content, and ECe) were considered as the 'basic outputs'. After that one of the inputs was changed while the others were kept constant. The interval of variation of the inputs was chosen from −25 to +25% of its median value. After changing the values of the input parameters, the model outputs were compared with the 'basic outputs' using the sensitivity coefficient (S_c, Geerts *et al.*, 2009):

$$\text{Sc} = \left|\frac{P_m - P_b}{P_b}\right| \times 100 \qquad (2)$$

where P_m is output after changing the input value and P_b is output before changing the input value. Generally, S_c is employed before calibration stage. Sensitivity classes were selected as high, moderate and low, if the model response to changes in inputs was greater than 15%, between 15 and 2%, or smaller than 2% respectively (Geerts *et al.*, 2009).

Nested calibration and validation

At first, the agronomic parameters of wheat (Table IV) were applied in the model for each variety. Then, maximum canopy cover (CC_X), canopy growth coefficient (CGC), canopy decline coefficient (CDC) and maximum effective rooting depth (Z_x) parameters were calibrated using a trial and error method for non-saline full-irrigation treatment

Table IV. Selected non-conservative (cultivar specific) and conservative input parameters used in the study for two winter wheat varieties

Parameter description	Roshan variety	Ghods variety	Unit or meaning
Conservative parameters			
Base temperature	0	0	°C
Cut-off temperature	26	26	°C
Canopy cover per seeding at 90% emergence (CC_0)	1.5	1.5	cm^2
Crop coefficient for transpiration at CC = 100%	1.1	1.1	Full canopy transpiration relative to ET_0
Water productivity	15	15	g (biomass) m^{-2}, function of atmospheric CO_2
Leaf growth threshold (*p*-upper)	0.2	0.2	As fraction of TAW, above this leaf growth is inhibited
Leaf growth threshold (*p*-lower)	0.65	0.65	Leaf growth stops completely at this *p*
Leaf growth stress coefficient curve shape (f_{shape})	5	5	Moderately convex curve
Stomata conductance threshold (*p*-upper)	0.65	0.65	Above this stomata begin to close
Stomata stress coefficient curve shape (f_{shape})	2.5	2.5	Highly convex curve
Senescence stress coefficient (*p*-upper)	0.70	0.70	Above this early canopy senescence begins
Senescence stress coefficient curve shape (f_{shape})	2.5	2.5	Moderately convex cure
Coefficient inhibition of leaf growth on HI	Small	Small	HI increased by inhibition of leaf growth at anthesis
Coefficient inhibition of stomata on HI	Moderate	Moderate	HI reduced by inhibition of stomata at anthesis
Non-conservative parameters			
Time from sowing to emergence	11	10	Day
Time from sowing to start of senescence	161	155	Day
Time from sowing to maturity	186	185	Day
Time from swing to flowering	121	120	Day
Length of flowering stage	18	16	Day
Minimum effective rooting depth, Z_x	0.3	0.3	M
Time from sowing to maximum rooting depth	87	86	Day
Reference harvest index, HI_o 40% common for good condition	40	36	Common for good condition
Building up of HI, days (CDD)	65	65	Day

of S_1I_2. The process of calibration continued until the lowest relative error (RE) between simulated and measured grain yield was achieved. The model was calibrated separately for each variety corresponding to S_2I_2 and S_3I_2 treatments using observed green canopy cover (CC) and biomass production (considering S_1I_2 treatment as the reference field, without soil salinity stress, and S_2I_2 and S_3I_2 treatments as the stressed field, without soil salinity stress (Raes *et al.*, 2012). Then, all of the soil moisture and salinity data in different treatments were divided into two groups for calibration and validation of soil parameters. The first group (corresponding to 10, 50 and 90 m depths) was assigned for calibrating soil parameters, while the second group (corresponding to 30 and 70 m depths) was used for validating. Then, θ_{sat}, θ_{FC}, θ_{PWP} and K_{sat} were calibrated using a trial and error method with the first group of soil moisture and salinity data. The calibration proceeded until the lowest root mean squared error (RMSE) between simulated and measured soil moisture and salinity was achieved. The simultaneous RE between simulated and measured grain yield was controlled to be minimal. Since there are four irrigation treatments for each salinity treatment, the model was calibrated using two irrigation treatments for each salinity treatment and validated using the other two irrigation treatments. In fact, six different cases of calibration and validation for each salinity treatment were [(I_3 and I_4), (I_2 and I_4), (I_1 and I_4), (I_2 and I_3), (I_1 and I_3) and (I_1 and I_2) for calibration, and (I_1 and I_2), (I_1 and I_3), (I_2 and I_3), (I_1 and I_4), (I_2 and I_4) and (I_3 and I_4) for validation respectively]. The model was calibrated by changing the coefficients of water stress (i.e. stomata conductance threshold (*p*-upper) stomata stress coefficient curve shape, senescence stress coefficient (*p*-upper), and senescence stress coefficient curve shape) for six different cases. So, the average relative error of the measured and simulated grain yield was minimized for each case of calibration. The default values of the AquaCrop manual appendix (Raes *et al.*, 2009b) were considered for some parameters such as leaf growth threshold (*p*-upper), leaf growth threshold (*p*-lower) and leaf growth stress coefficient curve shape parameters, as the model has minor sensitivity to these parameters. These parameters were presumed to be applicable to a wide range of conditions and not specific for a given crop cultivar (Raes *et al.*, 2009b). After calibrating the model for each salinity treatment, the model was simultaneously calibrated using six different cases for three salinity treatments as a whole.

Model evaluation

The AquaCrop model simulation results for wheat grain yield, biomass, water productivity (WP, yield per amount of irrigation water) and soil water content and salinity were compared with the observed/measured values from the experiment during the validation process. Different statistical indices, including coefficient of determination (R^2), regression 1:1, normalized root mean square error (NRMSE, Equation 3), index of agreement (d, Equation 4) and coefficient of the residual mass (CRM, Equation 5) were adopted for comparison of simulated versus observed data. The NRMSE, d and CRM are defined as follows (Willmott, 1982; Loague and Green, 1991):

$$\mathrm{NRMSE} = \left[\frac{\sum_{i=1}^{n}(S_i - M_i)^2}{n}\right]^{0.5} \times \frac{100}{\overline{M_i}} \tag{3}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(M_i - S_i)^2}{\sum_{i=1}^{n}\left(\left|S_i - \overline{M_i}\right| + \left|M_i - \overline{M_i}\right|\right)^2} \tag{4}$$

$$\mathrm{CRM} = \frac{\sum_{i=1}^{n} M_i - \sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} M_i} \tag{5}$$

where S_I and M_I are simulated and measured data, respectively, $\overline{M}$ is mean value of M_I, and n is the number of measurements.

A simulation can be considered perfect if NRMSE is less than 10%, acceptable if between 10 and 20%, fair if between 20 and 30% and poor if greater than 30% (Jamieson *et al.*, 1991). d is a dimensionless number and ranges from 0 to 1.0, where 0 describes complete disagreement and 1.0 indicates that the estimated and observed values are identical. The CRM presents model tendency to over- or underestimate measured values of parameters.

RESULTS AND DISCUSSION

Sensitivity analysis

Parameters to which the model was not sensitive indicate an over-parameterization, while parameters to which the model was highly sensitive show a high dependence of certain calculation procedures on a limited number of parameters

Table V. Sensitivity coefficient (S_c) of AquaCrop for simulation of winter wheat grain yield

Input parameter			S_c (+25%) %	S_c (−25%) %	Sensitivity level
Agronomic parameters		Crop coefficient for transpiration (Kc_{Tr})	10.7	10.9	Moderate
		planting date	0. 6	0. 4	Low
		CGC	−1.9	−1.2	Low
		WP^*	10.5	10. 8	Moderate
		HI_o	10.6	9. 9	Moderate
		emergence	−0. 3	−0. 2	Low
		Time from swing to maximum canopy cover	−1. 8	−0. 4	Low
		Time from swing to flowering	0. 4	0. 1	Low
		Length of flowering stage	0.0	0.0	Low
		Upper temperature	0.0	0. 1	Low
Soil parameters		θ_{FC}	−11. 9	6. 2	Moderate
		θ_{sat}	-0.1	0.0	Low
		θ_{PWP}	0.0	42. 5	Low-high
		K_{sat}	0.0	0.0	Low
Irrigation management	Depth of irrigation	I_1	0.0	−0. 2	Low
		I_2	0.0	0.0	Low
		I_3	0. 4	1. 2	Low
		I_4	2. 5	3. 7	Moderate
	Water salinity	I_1	−0. 2	−0. 6	Low
		I_2	−0. 2	−0. 5	Low
		I_3	−1. 1	-1. 8	Low
		I_4	−1. 4	−2. 4	Low
Climate parameters		Maximum temperature	0. 3	5. 9	Low- moderate
		Rainfall	0. 2	1. 1	Low

(Geerts *et al.*, 2009). Finally, the SA provides an indication of the most important parameters requiring precise field measurements and model calibration. The results of the SA in simulation of soil moisture and salinity profiles showed that for simulating soil moisture, θ_{FC} had moderate sensitivity, while θ_{PWP}, θ_{sat} and K_{sat} had low sensitivity. For simulating soil salinity, however, θ_{sat} showed moderate sensitivity while low sensitivity was attributed to θ_{PWP}, θ_{FC} and K_{sat}. So, as far as modelling is concerned, more precise determination of θ_{FC} and θ_{sat} is of prime importance.

The results of SA for input parameters of the AquaCrop model in order to simulate grain yield are presented in Table V. Results showed that the model had low sensitivity to the planting date, CGC, emergence, time from sowing to flowering, time from sowing to maximum canopy cover, length of flowering stage, upper temperature, K_{sat}, θ_{PWP}, water salinity and rainfall. The sensitivity of the model to the crop coefficient for transpiration (Kc_{Tr}), normalized water productivity (WP^*), reference harvest index (HI_0), θ_{FC}, θ_{sat} and maximum temperature was moderate. The sensitivity of the model to the depth of irrigation water was different in different irrigation treatments, however. The model's sensitivity increased with decreasing irrigation depth. Similar results were reported by Salemi *et al.* (2011), which presented the sensitivity of the AquaCrop model to WP^*, Kc_{Tr} and maximum temperature had moderate. The sensitivity of the model to the depth of irrigation water was different in different irrigation treatments and model's sensitivity increased with decreasing irrigation depth.

Soil water content and salinity

The calibrated soil hydraulic parameters and the model performance statistics are presented in Tables VI and VII respectively. The model simulations showed good agreement with observed values. The average value of NRMSE, CRM, d and R^2 for soil water content were 11.8, 0.055, 0.79 and 0.61 respectively and for soil salinity were 24.4, 0.195, 0.72 and 0.57 respectively (Table VII). The CRM values were positive, which indicated underestimation of soil water content and salinity by the model. According to Table VII, the model's accuracy for simulation of soil water content was higher than the accuracy for simulation of soil salinity. With increasing irrigation water salinity, soil saturation salinity increases, but this increase is not distributed evenly in the soil profile. Therefore, for any salinity treatment with a specified salinity level, the simple averaging of soil salinity of the different soil layers (0–20, 20–40, 40–60, 60–80 and 80–100 cm) cannot be an accurate measure of salinity distribution. Therefore, the error of the model in simulating soil salinity is greater than that in simulating soil water content. The statistical indices for the calibration and validation of the model were almost the same (RMSE values for soil water content in calibration and validation were 11.2 and 12.3% respectively, and for soil salinity were 23.9 and 24.9% respectively), which indicates that the model has been well calibrated. Mkhabela and Bullock (2012) reported RMSE, R^2 and d values of 49.4 mm, 0.9 and 0.99 respectively, when simulating soil water content using AquaCrop. Similarly, Mebane *et al.* (2013) reported RMSE values ranging from 0.015 to 0.098 $m^3\ m^{-3}$ when simulating soil water content for six soil depths using AquaCrop.

Table VI. The calibrated soil hydraulic parameters for simulation of soil water content and salinity

Depth of soil (cm)	θ_{FC} (%)	θ_{PWP} (%)	θ_{sat} (%)	K_{sat} (mm day^{-1})
0–30	30.7	16.5	35.6	42
30–60	31.0	17.0	36.0	60
60–90	31.0	18.0	42.0	79

Table VII. Statistical comparison of observed and predicted soil water content and salinity (10, 50 and 90 cm depths for calibration and 30 and 70 cm depths for validation) for all treatments

Parameter	Method	NRMSE (%)	d	CRM	R^2
Soil water content	Calibration	11.2	0.81	0.06	0.62
	Validation	12.3	0.78	0.05	0.60
Soil salinity	Calibration	23.9	0.74	0.18	0.58
	Validation	24.9	0.71	0.21	0.55

Table VIII shows the statistical comparison of measured and simulated soil water content and salinity for the different irrigation treatments. The highest and lowest accuracy for soil water content simulation was for the I_2 and I_4 treatments respectively. CRM values show that the model had a tendency to systematically underestimate the soil water content

Table VIII. Statistical comparison of measured and simulated soil water content and salinity for different irrigation and salinity treatments

Parameter	Treatment	NRMSE (%)	d	CRM	R^2
Soil water content	I_1	12.0	0.69	0.07	0.57
	I_2	11.6	0.75	0.04	0.63
	I_3	12.3	0.72	0.05	0.60
	I_4	13.8	0.68	0.07	0.54
Soil salinity	I_1	24.2	0.67	0.21	0.61
	I_2	21.4	0.72	0.16	0.61
	I_3	25.6	0.71	0.19	0.55
	I_4	30.7	0.66	0.22	0.51

and salinity for all treatments (Table VIII). The underestimation of soil water content may be due to an overestimation of actual evapotranspiration, which subsequently may be due to derived estimations of field capacity and the permanent wilting point from the RETC model. Farahani *et al.* (2009) reported that AquaCrop underestimated the amount of soil water content for a full irrigation treatment. Mebane *et al.* (2013) also reported that AquaCrop underestimated the amount of soil water content for rainfed maize in Pennsylvania.

The highest and lowest simulation accuracy of soil salinity was obtained for the I_2 and I_4 treatments respectively (Table VIII). The model accuracy in the I_1 and I_2 treatments was high because of more infiltration and smoother salinity distribution. But the model accuracy in the I_3 and I_4 treatments was low because of simultaneous salinity and water stress, and not enough leaching.

With reference to Table IX, the NRMSE is reduced and the model's performance improves with increasing depth (except 10 cm depth) for simulation of soil water content. But the error increases with depth for simulation of soil salinity. Most of soil moisture and salinity changes are at the surface (e.g. due to evaporation, transpiration, root uptake). It seems that AquaCrop has captured the effects of these factors in this layer and showed better estimation in simulation of soil salinity. The model's accuracy for simulation of soil water content in deeper layers was greater than in the middle one, because generally the range of soil water content variations in the deeper layers is lower than in the middle layers. Farahani *et al.* (2009) reported that the model's accuracy was varied in different layers, while accuracy was increased in the deep layer. Mebane *et al.* (2013) also reported that for simulation of soil water content, model accuracy increased with depth for rainfed maize in Pennsylvania.

Measured and simulated soil water content and salinity profiles for two irrigation treatments of I_2 and I_4 (corresponding to highest and lowest accurate simulation of soil water content and salinity) are presented in Figures 1 and 2. The accuracy of soil moisture simulation was reduced with increasing salinity (Figure 1). One possible reason may be due to error in simulation of soil water content on days 119 and 143 after planting (Figure 1). All salinity treatments (not completely in S_3I_4) tend to underestimate soil salinity. The initial salinity changes in the soil profile were very insignificant on day102 after planting and irrigation with salinity levels of S_2 and especially S_3 increased salinity of the soil profile and separated curves of day 102 from other days (Figure 2).

Table IX. Statistical comparison of measured and simulated soil water content and salinity at different depths for different irrigation and salinity treatments

Parameter	Depth (cm)	NRMSE (%)	d	CRM	R^2
Soil water content	10	12.0	0.74	0.07	0.63
	30	13.9	0.66	0.05	0.56
	50	12.6	0.73	0.05	0.60
	70	11.0	0.76	0.04	0.61
	90	10.2	0.61	−0.04	0.51
Soil salinity	10	20.1	0.73	0.12	0.61
	30	23.5	0.71	0.17	0.60
	50	24.4	0.70	0.19	0.60
	70	26.5	0.65	0.21	0.57
	90	27.9	0.60	0.24	0.51

Soil salinity profiles were more non-uniform under deficit irrigation treatments (Figure 2). Under the most severe deficit irrigation treatment (I_4), non-uniformity of soil salinity profiles increased by increasing salinity (i.e. from S_1 towards S_3). It is probably because there is not enough water for leaching salts from upper layers to deeper ones. So, the upper layers are more saline than deep ones, and such a pattern was well simulated by the model. Figure 3 shows the average soil salinity depth at different sampling dates after planting for I_2 and I_4 irrigation treatments (full irrigation and 50% under-irrigation respectively). In general, the modelled soil salinity follows relatively closely to that of observed ones. The model tended to slightly underestimate soil salinity over the growing season, while the accuracy was higher in I_4 compared to I_2. So, it seems that accuracy is less under simultaneous salinity and water stress.

Grain yield, biomass and WP

Calibrated crop parameters for two wheat varieties (Roshan and Ghods) are presented in Table X. Since CC_X, CGC, CDC and Zr_X parameters were not measured in the field, upper and lower limits for these parameters were adopted from AquaCrop default data (Raes *et al.*, 2009b) and then locally calibrated (Table X).

The values of coefficients CC_X, CGC, CDC and K_{sto} (soil salinity stress coefficient for stomatal closure) for S_2 and S_3 treatments were obtained by calibration of model for salinity conditions (Table X). Table X shows that values of CC_X, CGC and K_{sto} decreased with increasing irrigation water salinity, and value of CDC increased with increasing irrigation water salinity. Similar results were reported by Kumar *et al.* (2014), who presented a similar pattern of CGC and CDC change with increasing irrigation water salinity respectively.

Water stress coefficients obtained through calibration considering the mean absolute relative error (RE) of simulating the grain yield, are given in Tables XI and XII. Results showed that P_{upper} decreased with increasing water salinity, which suggests that the effect of water stress on the crop

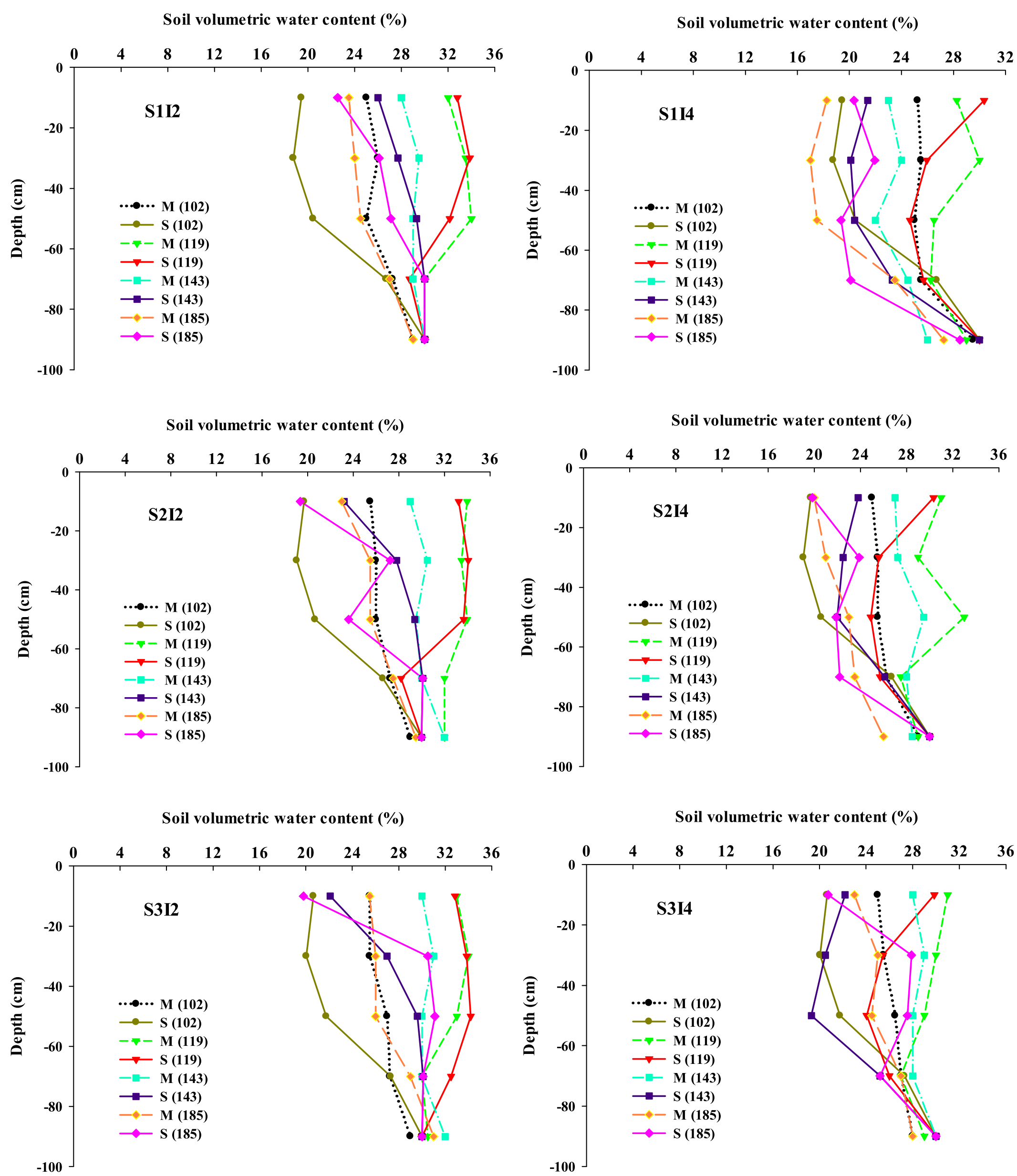

Figure 1. Measured (M) and simulated (S) soil moisture water content profiles at different times (102, 119, 143 and 185 days after planting) for I_2 (left panels) and I_4 (right panels) treatments

initiated earlier as the water is more saline. Under the same applied water, osmotic pressure increased as the water was more saline, so the crop experienced water stress at shorter times (Raes *et al.*, 2012). Water stress coefficients (Table XI) were different from the AquaCrop manual (Raes *et al.* 2009b), because these parameters not only depend on type of crop but also depend on the climate of the region, scenarios of water stress conditions and salinity levels of irrigation water. Kumar *et al.* (2014) reported water stress coefficients under irrigated saline regimes for wheat in New Delhi, India, that were different from the AquaCrop manual. Similarly, Mkhabela and Bullock (2012) reported water stress coefficients for rainfed wheat in western Canada that were different from the AquaCrop manual.

The lowest average RE was obtained when the model was calibrated using I_1 and I_4 treatments and validated using I_2 and I_3 treatments (Table XII). The average RE values for S_1, S_2 and S_3 salinity treatments were 5.2, 3.7 and 6.6% respectively for the Roshan variety and 2.7, 7.5 and 12.9% respectively for the Ghods variety when the model is

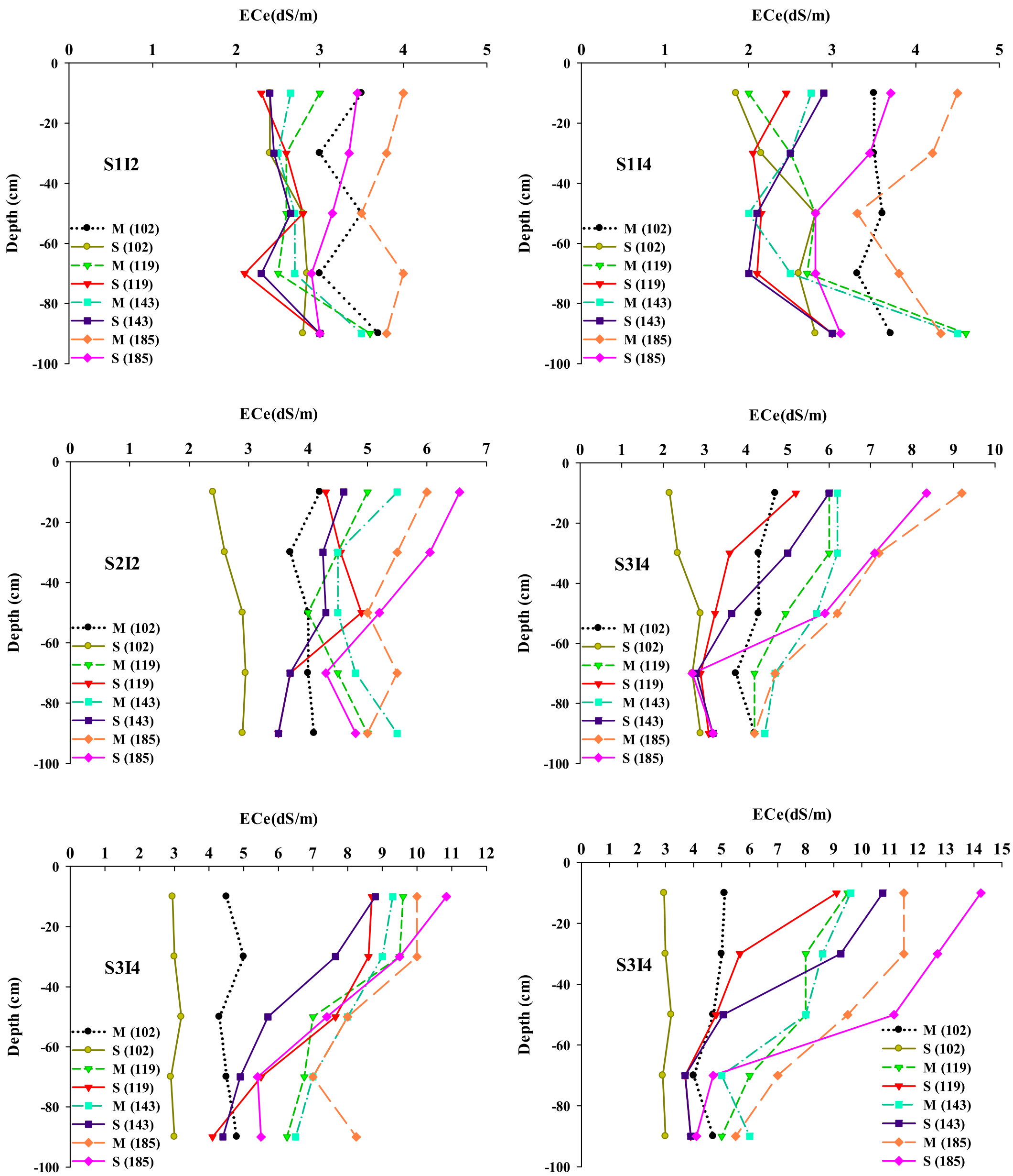

Figure 2. Measured (M) and simulated (S) soil salinity profiles at different times (102, 119, 143, and 185 days after planting) for I_2 (left panels) and I_4 (right panels) treatments

calibrated and validated separately for each salinity treatment (Table XII). On the other hand, the average RE values for the Roshan and Ghods varieties were 6.8 and 10.2 respectively, when the model was simultaneously calibrated and validated for three salinity treatments (Table XII). However, in this case the model's accuracy is slightly lower than when the model is calibrated separately for each salinity treatment. If the model were satisfactorily calibrated for both upper and lower limits of irrigation amounts (I_2 and I_4; full irrigation and maximum deficit irrigation), there is a higher chance of acceptable grain yield simulation for any other irrigation treatment. Such an approach may reduce the cost of field studies for calibrating the model, since only one full irrigation and one deficit irrigation treatment are to be planned in the field.

Mean values of RE (Table XII) show that the model can be calibrated under simultaneous water deficit and salinity treatments and simulate grain yield with relatively high accuracy, especially for the Roshan variety.

The values of measured and simulated grain yield, biomass and WP (grain yield /irrigation water) are presented in Figure 4. The measured grain yield and biomass increased

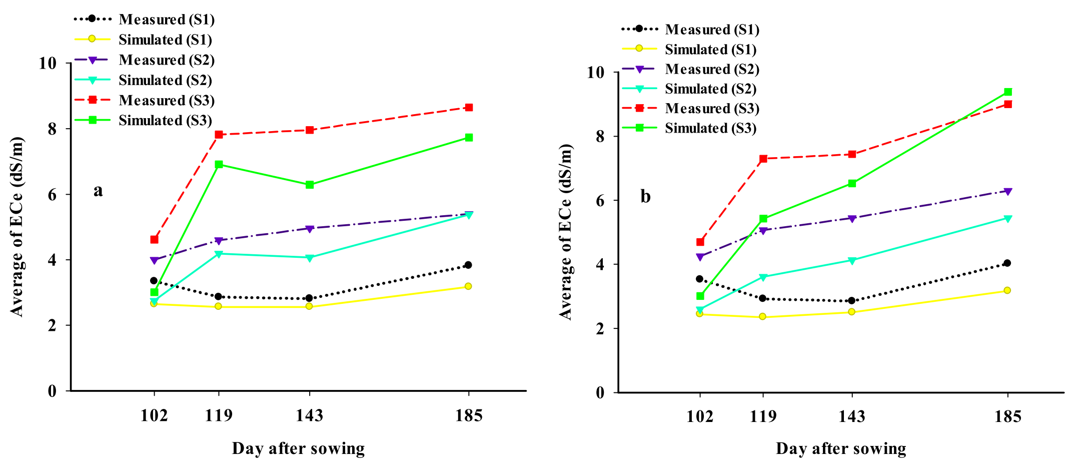

Figure 3. Depth average of measured (M) and simulated (S) ECe at different dates for I_2 (a) and I_4 (b) treatments

Table X. Calibrated crop-type model parameters for simulation grain yield of two winter wheat varieties

Parameter	Treatment	Roshan variety	Ghods variety	Parameter	Treatment	Roshan variety	Ghods variety
CC_X (%)	S_1	90	89	$K_{sto,salt}$	S_1	1	1
	S_2	86	85		S_2	0.65	0.64
	S_3	83	72		S_3	0.55	0.53
	S_1,S_2,S_3	83	72		S_1,S_2,S_3	0.55	0.53
CGC (%)	S_1	6.1	5.5	CDC (%)	S_1	10.1	11.85
	S_2	5.91	5.4		S_2	10.16	11.9
	S_3	5.83	5.25		S_3	10.23	11.85
	S_1,S_2,S_3	5.83	5.25		S_1,S_2,S_3	10.23	11.85
Zr_X (m)	All	1.5	1.5				

Table XI. Calibrated water stress coefficients for simulation of grain yield of two winter wheat varieties

Variety	Treatment	$Ks_{exp,w}$			Ks_{sto}		Ks_{sen}	
		P_{upper}	P_{lower}	f_{shape}	P_{upper}	f_{shape}	P_{upper}	f_{shape}
Roshan	S_1	0.2	0.65	5	0.42	1.8	0.50	1.9
	S_2	0.2	0.65	5	0.40	1.2	0.49	1.7
	S_3	0.2	0.65	5	0.40	0.7	0.49	Linear
	S_1,S_2,S_3	0.2	0.65	5	0.41	1.5	0.46	2.7
Ghods	S_1	0.2	0.65	5	0.39	1.1	0.48	1.9
	S_2	0.2	0.65	5	0.38	0.7	0.42	Linear
	S_3	0.2	0.65	5	0.33	0.2	0.42	Linear
	S_1,S_2,S_3	0.2	0.65	5	0.38	0.6	0.40	Linear

in all treatments by increasing the amount of irrigation water up to 125% level (I_1), except treatment S_3I_1 (Roshan). This trend was also observed in the simulated values. In general, measured and simulated values supported that (Figure 4) the average grain yield and biomass increased as salinity decreased (S_3-S_2-S_1) or applied water increased (I_4-I_3-I_2-I_1). The averages of measured grain yield and biomass for irrigation and salinity treatments were ranked as $I_1 < I_2 < I_3 < I_4$ and $S_1 < S_2 < S_3$ respectively, for two wheat varieties, which were consistent with AquaCrop model simulation (Figure 4). There was 3.1 (2.7) %, reduction in grain yield (biomass) corresponding to every unit increase in salinity, which is approximately supported by the literature. Zamani (2004) reported that wheat grain

Table XII. RE values of measured and simulated grain yield for two winter wheat varieties

Different cases of calibration	Method		Specified treatment							
			S_1[a]		S_2		S_3		S_1, S_2,S_3[b] (simultaneously)	
			Roshan	Ghods	Roshan	Ghods	Roshan	Ghods	Roshan	Ghods
I_2,I_4	Calibration	Average	5.5	2.9	5.3	9.3	7.1	13.8	7.9	11.4
I_1,I_3	Validation									
I_2,I_3	Calibration	Average	9.4	3.0	5.4	8.2	18.2	14.7	12.8	12.9
I_1,I_4	Validation									
I_1,I_2	Calibration	Average	5.7	2.9	4.8	8.4	23.1	18.9	11.1	12.9
I_3,I_4	Validation									
I_1,I_4	Calibration	Average	5.2	2.7	3.7	7.5	6.6	12.9	6.8	10.2
I_2,I_3	Validation									
I_1,I_3	Calibration	Average	9.4	3.0	5.5	8.1	17.9	16.3	12.5	11.9
I_2,I_4	Validation									
I_3,I_4	Calibration	Average	7.5	3.9	4.9	7.9	9.7	14.9	9.7	12.3
I_1,I_2	Validation									

[a]The model was calibrated and validated separately for each salinity treatment using the adopted irrigation treatment (column 1) and then, the average of RE was calculated for two cases of calibration and validation.
[b]The model was calibrated and validated simultaneously for three salinity treatments using the irrigation treatment (column 1) and then, the average of RE was calculated for two cases of calibration and validation and three salinity treatments.

yield (Roshan variety) decreased by 3.9% for every unit increase in salinity in Birjand. Both yield and biomass were successfully simulated by AquaCrop. For two different approaches of separate and simultaneous calibration and validation, the yield decreased by 3.7 and 2.4% respectively for every unit increase in salinity, while the corresponding values for biomass were 3.7 and 2.2% respectively.

As compared to I_2, measured grain yield decreased under I_4 and I_3 treatments by 49.1 and 12.4% respectively, but increased by 2.8% for I_1. There is a similar situation for simulated values: 44.1 and 2.1% reduction, and 0.1% increase for separately calibration and validation and 45.6 and 1.7% reduction, and 0.1% increase for simultaneously calibration and validation processes. The model results for irrigation treatments of more than 75% water requirement resulted in a minor increase in yield. Water requirement in Aquacrop is estimated by the FAO Penman–Monteith approach, while in this study it is estimated in the field through soil moisture analysis of soil samples. These two approaches may not provide identical results.

As compared to I_2, measured biomass decreased under for I_4 and I_3 treatments were 32.9 and 18.9% respectively, but increased by 10.4% for I_1. There is a similar situation for simulated values: 33.6 and 2.2% reduction, and 0.1% increase for separately calibration and validation and 30.7 and 1.8% reduction, and 0.1% increase for simultaneously calibration and validation processes. Both measured and simulated values confirmed that grain yield is more affected by severe water stress than biomass (Figure 4). Comparing two varieties, Ghods was more sensitive to water and salinity stress than the Roshan variety (Figure 4). Afyooni (2005) also reported higher grain yield production by the Roshan variety under salinity stress.

In general, both measured and simulated WP values decreased with increasing water salinity for the two varieties (Figure 4). The maximum WP found to be in the I_3 treatment (75% water requirement), while its minimum was shown to be in the I_4 treatment (50% water stress). Greater WP in I_3 compared to I_1 may be due to difference in their deep percolations (simulated deep percolation for I_1 was 53.7% more than I_3). Lower WP in I_4 compared to I_3 is probably due to high stress in I_4, thus the crop could not respond physiologically to water shortage (relative yields of the two treatments were 49 and 85% respectively). Therefore, a sharp reduction of grain yield resulted in more reduction in WP. WP of the Roshan variety was higher than the Ghods variety for all treatments (Figure 4), which shows the superiority of the Roshan variety under simultaneous salinity and water stress conditions. Analysing 11 different wheat varieties, Fayyaz *et al.* (2006) also reported higher WP in the case of the Roshan variety.

Based on higher WP under deficit irrigation treatments (e.g. I_3) compared to full irrigation treatments (e.g. I_1 and I_2), it seems logical to adopt the I_3 treatment, especially in Birjand as a water-short region, assigning the remaining 25% to another piece of land. By such a strategy, WP would be optimized at the regional scale.

Table XIII shows a statistical comparison of measured and simulated yield, biomass and WP for two winter wheat varieties. The *d* (index of agreement) values were very close to 1 for both varieties, which means that simulated reduction in grain yield and biomass was similar to those of measured

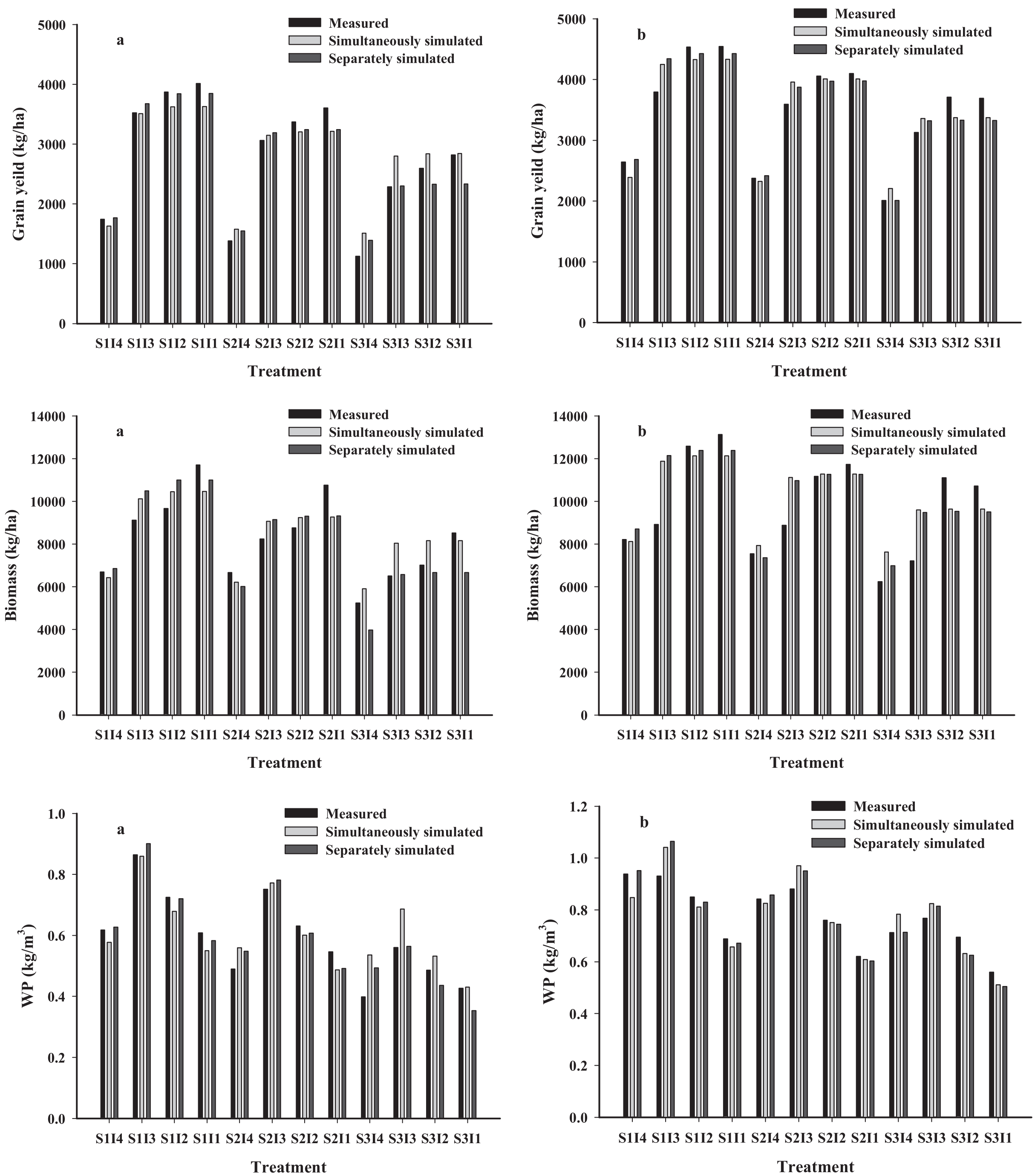

Figure 4. Measured and simulated grain yield, biomass, and WP for Ghods (a) and Roshan (b) varieties for different approaches of separate (only the best case was reported) and simultaneous model calibration and validation

ones. In most cases the R^2 values were about 1.0, confirming a good correlation between simulated and measured values. The NRMSE values in most cases were lower than 10%, which seems good. The CRM values were close to zero (under- and over-estimation were negligible). However, in general, the model's accuracy for simulation yield and WP was better than simulation of biomass. Andarzian *et al.* (2011) reported that the AquaCrop model was able to simulate soil water content of the root zone, crop biomass and grain yield accurately under full and deficit irrigated wheat production in Iran. Similarly, Mkhabela and Bullock (2012) reported that wheat grain yield can be simulated with

Table XIII. Statistical comparison of measured and simulated yield, biomass and WP for two winter wheat varieties, under different approaches of calibration and validation

Variety	Parameter	Salinity treatment	NRMSE (%)	*d*	CRM	R^2
Roshan	Yield	S_1, S_2, S_3 (separately)	7.1	0.97	0.001	0.90
		S_1, S_2, S_3 (simultaneously)	7.4	0.97	0.006	0.89
	Biomass	S_1, S_2, S_3 (separately)	14.9	0.86	−0.039	0.58
		S_1, S_2, S_3 (simultaneously)	15.0	0.84	−0.042	0.57
	WP	S_1, S_2, S_3 (separately)	7.0	0.96	−0.009	0.89
		S_1, S_2, S_3 (simultaneously)	8.1	0.94	−0.002	0.82
Ghods	Yield	S_1, S_2, S_3 (separately)	8.2	0.98	0.021	0.94
		S_1, S_2, S_3 (simultaneously)	10.0	0.97	−0.004	0.87
	Biomass	S_1, S_2, S_3 (separately)	12.6	0.93	0.022	0.78
		S_1, S_2, S_3 (simultaneously)	11.6	0.91	−0.027	0.74
	WP	S_1, S_2, S_3 (separately)	8.0	0.97	−0.001	0.90
		S_1, S_2, S_3 (simultaneously)	11.3	0.93	−0.023	0.76

relative accuracy using AquaCrop. Overall, the agreement between modelled and observed wheat grain yield was satisfactory with R^2 of 0.66, *d* of 0.99, RMSE and MAE of 743 and 611 kg ha^{-1} respectively.

CONCLUSION

In this study, performance of the AquaCrop model was evaluated using field-measured grain yields for two winter wheat varieties in Birjand to determine whether the model could be utilized as a tool to study and model salinity and water stress conditions in Birjand. Sensitivity analysis showed moderate sensitivity to θ_{FC} and θ_{sat} for simulating soil water content and salinity respectively. For simulating grain yield, however, the model showed moderate sensitivity to Kc_{Tr}, WP*, HI_0, θ_{FC}, θ_{sat} and maximum air temperature. AquaCrop was separately and simultaneously nested calibrated and validated for all salinity treatments. The results indicated that the model's accuracy for the simultaneous case was slightly lower than for the separate case. When the model was well calibrated for minimum and maximum irrigation treatments (full irrigation and maximum deficit irrigation), it was able to simulate grain yield for any other level of irrigation treatment. Adopting this approach may reduce the cost of field studies for calibrating the model, since only two irrigation treatments should be conducted in the field. The average values of NRMSE, CRM, *d* and R^2 for soil water content were 11.8, 0.055, 0.79 and 0.61 respectively and for soil salinity were 24.4, 0.195, 0.72 and 0.57 respectively. The NRMSE reduced and the model's performance improved with increasing depth (except 10 cm depth) for simulation of soil water content. However, the NRMSE increased with depth for simulation of soil salinity. In general, the mode's accuracy for simulation of soil water content was higher than the accuracy of simulation of soil salinity, and the modelled total soil water content and salinity values followed relatively closely to the trend of the observed values although there were days within the growing season when the errors were high. Overall, the agreement between modelled and observed wheat grain yield, biomass and WP was satisfactory, with R^2 and *d* close to 1 in most cases, NRMSE values were excellent (lower than 10%) and good (between 10 and 20%) and CRM values were close to zero for both winter wheat varieties. Thus, the AquaCrop model can be considered a valuable tool for modelling winter wheat grain yield, WP, biomass, soil water content and soil salinity, although the latter is less accurate. The simplicity of AquaCrop, as it is less data dependent, makes it more user-friendly. Nevertheless, the performance of the model has to be evaluated, validated and fine-tuned under a wider range of conditions and crops.

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