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Modification of transient state analytical model under different saline groundwater depths, irrigation water salinities and deficit irrigation for quinoa

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Abstract

Salinization of soil is primarily caused by capillary rise from saline shallow groundwater or application of saline irrigation water. In this investigation, the transient state analytical model was modified to predict water uptake from saline shallow groundwater, actual crop evapotranspiration, soil water content, dry matter, seed yield and soil salinity under different saline groundwater depths, irrigation water salinities and deficit irrigation for quinoa. Considering the effect of salinity on soil saturated hydraulic conductivity and maximum root depth in presence of shallow saline groundwater, the model resulted in good agreement between the measured and predicted saline groundwater uptake, soil salinity increase at different groundwater depths (300-800 mm) and water salinity (10-40 dS m^{-1}). Therefore, the modified model is applicable for quinoa yield and soil salinity prediction and it could be a valuable tool for soil salinity management in presence of shallow saline groundwater. Furthermore, prediction of quinoa yield by the modified model can be used for better irrigation water salinity management under different saline groundwater depths, irrigation water salinities and deficit irrigation.

Keywords: Quinoa; Growth modeling; Groundwater uptake; Water salinity; Deficit irrigation.

Introduction

Salinization of soil is a major problem in arid and semi-arid areas with saline shallow groundwater. This is influenced by climate, soil type, crop, irrigation water quality and management practice, depth to groundwater and salinity of groundwater. Salinization of soil is primarily caused by capillary rise from saline shallow groundwater or application of saline irrigation water.

Crop simulation models have widely been used to assess and understand the effects of environmental parameters and irrigation regimes on plant growth and yield. They also help to manage resources, maximize returns to producer and reduce impacts on water quality. These models differ in complexity and theories that have been used in their development (Hoogenboom, 2000). Less complicated models can estimate crop yield and can be easily used for practical applications using simple equations and fewer input data (Sepaskhah et al., 2006; Sepaskhah et al., 2013; Shabani et al., 2015).

Analytical models to estimate capillary rise from a shallow groundwater could be formulated either with a steady state solution or with a transient solution for Richards' equation. In the study of Prathapar et al. (1992), performance of a quasi steady state analytical model (QSSAM), a transient state analytical model (TSAM) and a numerical model (NM) for predicting capillary rise of a heavy clay soil profile with a saline shallow groundwater was compared. Furthermore, they predicted the capillary rise and the increase in salt content within the soil profile and compared them with measured value in a constant groundwater depth of 1.2 m for wheat in a heavy clay soil. The QSSAM did not satisfactorily predict the capillary rise. The predicted capillary rise estimated by TSAM was reasonably close to the measured values; however, the weekly rates fluctuated considerably. The NM prediction of capillary rise was quite satisfactory except near the soil surface. The electrical conductivity (EC) values predicted by the NM were close to the measured values. However, the application of NM to complex conditions is generally restricted by the limited availability of temporal and spatial data; where as the analytical models are sufficient and easy to use when input data are spare and uncertain.

Jorenush and Sepaskhah (2003) showed that using variable root depth and non-uniform root water uptake pattern in the modified TSAM model for pistachio resulted in good agreement between measured and predicted cumulative and weekly capillary rises. Furthermore, the modified model TSAM accurately predicted the capillary rise and salinity of different soil layers for different groundwater depths (0.3–1.2 m) and salinity levels (0.5–13 dS $m^{-1)}$ under irrigated and non-irrigated conditions for pistachio seedling growth in micro-lysimeter, except for saline groundwater (13.0 dS m^{-1}) and shallow groundwater depth (smaller than 0.6 m). This may be occurred due to the effect of high soil salinity in the root zone on the roots water uptake reduction that was not considered properly in the modified TSAM model.

Many models were developed to predict the effects of water deficit and salinity on crop growth, for example, SWAP (Soil–Water–Atmosphere–Plant, Noory et al., 2011) and SALTMED (Salt-Mediterranean, Ragab (2001); Silva et al., 2013; Rameshwaran et al., 2013) that are either complex or need many input data that are not readily available.

Quinoa is new interesting crop, simulating of quinoa growth and yield with models is rarely found in literature. For example, in quinoa native regions the crop water productivity model AquaCrop (Steduto et al., 2009; Raes et al., 2009) has been calibrated and validated for simulating quinoa production (Geerts et al., 2009a) and the potential of closing quinoa yield gaps in Bolivian Altiplano region (Geerts et al., 2009b) under different water availabilities. In Mediterranean weather conditions, Razzaghi et al. (2011) concluded that the SALTMED model has the ability to simulate seed yield and dry matter of quinoa irrigated with saline and fresh water under no groundwater conditions. In this study the soil surface salinity was not predicted accurately.

The objectives of this study were to modify transient state analytical model (Prathapar et al., 1992) for estimating capillary rise in soil profile and predicting quinoa yield under different saline groundwater depths, irrigation water salinities and deficit irrigation using tipping-bucket algorithm. Furthermore, the accuracy of the model for prediction of plan growth, yield, soil ware content and increase in salt content within the soil profile was studied.

Materials and Methods

Description of model

Root growth

Capillary rise in this study is defined as the volume of water leaving a static groundwater due to soil surface evaporation and plant transpiration. In irrigated soils, most of the roots are found within the soil somewhat above the groundwater level. Thus, the soil profile was divided into a root zone (DRZ) and a subsoil (DSUB). Depth of root for each day of growing season was estimated with Equation (1) (Borg and Grimes 1986) in Table 1. DRZ_i is the root depth for ith day (mm), DRZMAX and DRZMIN are the maximum and minimum root depths (mm), i is the number of days after planting and NDRZMAX is the number of days for maximum root depth. Therefore, $DSUB_i$ was calculated by subtracting DRZ_i from the groundwater depth.

Table 1. The equations described in text.

Equations	Numbers
$DRZ_i = DRZMIN + 0.5 DRZMAX \left(1 + Sin \left(3.03 \dfrac{i}{NDRZMAX} - 1.47 \right) \right)$	(1)
$DR_{i,k} = DR_{i-1,k} + (ETa_i - CR_i)S_k + DP_{i,k} - DP_{i,k-1}$	(2)
$DP_{i,k-1} = IR_i + (P - RO)_i$	(3)
$DP_{i,k} = (P - RO)_i + IR_i - ETa_i \times S_k - DR_{i-1,k}$	(4)
$ETc_i = Kc_i \times ETo_i$	(5)
$ETa_i = Ks_i \times ETc_i$	(6)
$Ks_i = \left[1 - \dfrac{b}{k_y \times 100} (EC_{ei} - EC_{e-thr}) \right] \times \left[\dfrac{TAW_i - DR_i}{(1-p)TAW_i} \right]$	(7)
$\theta_{rz_i} = \theta_{fc} - \dfrac{DR_i}{DRZ_i}$	(8)
$\theta_{sub_i} = \theta_{sub_{i-1}} + \dfrac{\theta_{rz_i} - \theta_{rz_{i-1}}}{2} + \dfrac{DP_i}{DSUB_i}$	(9)
$\Psi = \Psi_e \left(\dfrac{\theta}{\theta_s} \right)^\beta$	(10)
$\Phi(Z,T) = \dfrac{Z\Phi_0}{Z_0} + A(Z - Z_0) + \sum_{n=1}^{\infty} \left\{ A_n \exp \left[-\left(1 + \mu_n^2 \right) T \right] + C_n \right\} w_n(Z)$	(11)
Where:	
$Z = \dfrac{\alpha}{2} z$	(11a)
$T = \dfrac{\alpha^2 D}{4} t$	(11b)
$Z_0 = \dfrac{\alpha}{2} L$	(11c)

Continue Table 1.

Equations	Numbers
$A = \dfrac{-\Phi_0/Z_0 - 2q_0/\alpha}{1 + 2Z_0}$	(11d)
$A_n = \dfrac{-8q_0\mu_n \sin\mu_n Z_0 + 16\mu_n S(2\sin\mu_n Z_0 + \mu_n \exp(-Z_0))/\alpha(1+\mu_n^2)}{(2\mu_n Z_0 - \sin 2\mu_n Z_0)\alpha(1+\mu_n^2)}$	(11e)
$C_n = \dfrac{16\mu_n(q_0 - \Phi_0\alpha - S_x)(2\sin\mu_n Z_0 + \mu_n \exp(-Z_0))}{(2\mu_n Z_0 - \sin\mu_n Z_0)(1+2Z_0)(1+\mu_n^2)^2 \alpha}$	(11f)
$w_n(Z) = \exp(Z)\sin\mu_n(Z_0 - Z)$	(11g)
$S_x = \dfrac{S}{\alpha(1+2Z_0)}$	(11h)
$\mu_n = -\tan\mu_n Z_0$	(11i)
$K(\Psi) = K_s \exp(\alpha\Psi)$	(11j)
$\Phi = \int_{-\infty}^{\Psi} K(\Psi)d\Psi = \dfrac{K(\Psi)}{\alpha}$	(11k)
$\Phi_0 = \int_{-\infty}^{0} K(h)dh = \dfrac{K_s}{\alpha}$	(11L)
$D = \dfrac{1}{\alpha}\dfrac{dK}{d\theta}$	(11m)
$-\dfrac{\partial\Phi}{\partial z} - \alpha\Phi = q_0(t)$ at $z = 0$	
$\Phi = \Phi_0$ at $z = L$	(11n)
$\Phi = g(z) = -z$ at $t = 0$	
$CR = \dfrac{\Phi_0 - \Phi_{rz}}{L - DRZ} - K_{\Phi rz}$	(12)
$S = \dfrac{2aT_c}{DRZ}$	(13)
$T_c = K_{cb}ET_0$	(14)
$ECIWss_{i,k} = \dfrac{ECss_{i,k-1} \times DP_{i,k-1} + ECss_{i-1,k} \times \theta_{rz_{i-1,k}} \times DOL}{DP_{i,k-1} + \theta_{rz_{i-1,k}} \times DOL}$	(15)
$ECIW_{ss_{i,k}} = EC_{ss_{i-1,k}} + \dfrac{EC_{ss_{i,k-1}} \times DP_{i,k-1}}{\theta_{s_k} \times DOL}$	(16)
$ECGW_{ss_{i,k}} = EC_{ss_{i-1,k}} + \dfrac{EC_{GW} \times CAP_i \times \dfrac{S_k}{100}}{\theta_{s_k} \times DOL}$	(17)
$EC_{ss_{i,k}} = ECIW_{ss_{i,k}} + ECGW_{ss_{i,k}}$	(18)
$DM = f \times \dfrac{T}{e_s - e_a}$	(19)

Soil water balance

Water depletion from each soil layer of the root zone for each day was calculated by Equation (2) in Table 1. $DR_{i,k}$ is the depleted soil water depth from kth layer of root zone for ith day (mm), $DR_{i-1,k}$ is the depleted soil water depth from kth layer of root zone at the end of previous day (mm), $DP_{i,k-1}$ is the depth of water entered each soil layer in day i from upper layer (k−1) (mm), S_k is the relative root water uptake in no water and salinity stress conditions that is determined by empirical pattern of root water uptake from soil (40%, 30%, 20% and 10% for each quarter of root depth from top to bottom of root, respectively), ETa_i is the actual crop evapotranspiration (mm) and $DP_{i,k}$ is the deep percolation from each soil layer in day i (mm). In the first soil layer, $DP_{i,k-1}$ was calculated by equation (3) in Table 1. IR, P and RO are the irrigation, rainfall and run-off in day i (mm), respectively. Rain and run-off did not occur in this study in greenhouse conditions. In the first day of simulation, $DR_{i-1,k}$ was zero because initial soil water content was at field capacity.

$DP_{i,k}$ was estimated according to Equation (4) in Table 1. The $DP_{i,k}$ is zero when the soil water content in the root zone is less than the field capacity.

Crop evapotranspiration

Crop evapotranspiration (ETc_i) was determined according to Equation (5) (Allen et al., 1998) in Table 1. Kc_i is the crop coefficient for each day and ETo_i is the reference evapotranspiration for each day (mm d^{-1}). Crop coefficients of different growth stages of quinoa were determined based on measured evapotranspiration (ETc_i) by the water balance equation (Talebnejad and Sepaskhah, 2015a) and calculated reference evapotranspiration (ETo_i) with Hargreaves and Samani (1985) equation because the available meteorological data for evapotranspiration calculation was limited in the greenhouse conditions in our experiment. In the developed model, crop coefficient in different days after planting was determined based on the FAO method (Allen et al., 1998).

Actual crop evapotranspiration

Actual crop evapotranspiration (ETa_i) was determined according to Equation (6) in Table 1. Ks_i is soil water stress coefficient for ith day varies between 0 and 1.0 proposed by Allen et al. (1998). Soil water stress coefficient (K_s) under salinity and water stress conditions was given according to Equation (7) in Table 1. DR_i is the depleted soil water depth from root zone for day i (mm) that was considered to be the summation of $DR_{i,k}$ in the root zone, TAW_i is the total available soil water in day i (mm), K_y is the relative dry matter response factor to water stress that was determined in the developed model for quinoa, EC_{ei} is the soil saturation extract salinity in day i (dS m^{-1}) that was considered to be the summation of soil saturation extract salinity in layer k day i ($EC_{ei,k}$) in the root zone, EC_{e-thr} is the threshold soil saturation extract salinity for dry matter reduction that was considered to be 18.9 dS m^{-1} for quinoa (Talebnejad and Sepaskhah, 2015a), b is the dry matter reduction per unit saturated soil extract salinity under full irrigation condition that was reported to be 3.8 for quinoa by Talebnejad and Sepaskhah (2015a).

Soil water content in the root zone and subsoil

Volumetric soil water content in the root zone (θ_{rz}) was determined according to Equation (8) in Table 1. θ_{rz_i} is volumetric soil water content in the root zone in day i (cm^3 cm^{-3}), θ_{fc} is volumetric soil water content at field capacity cm^3 cm^{-3}.

Volumetric soil water content in subsoil (between the end of root zone and groundwater level) was determined according to Equation (9) in Table 1. where θ_{rz_i} is the volumetric water content of root zone on a day (m^3 m^{-3}) and $\theta_{rz_{i-1}}$ is the volumetric water content of root zone on the previous day (m^3 m^{-3}).

Matric potential in the soil (Ψ) was determined using Campbell (1974) equation Table 1. where Ψ_e is air entry matric potential of the soil profile, θ is volumetric water content (m^3 m^{-3}), θ_s is saturation volumetric water content (m^3 m^{-3}), β is Campbell coefficient. Campbell (1974) equation is a form of van Genuchten (1980) equation when θ_r is very small (nearly equal to zero) in our case. Additionally, groundwater uptake simulation by model was good and it could be concluded that Campbell equation worked well in this model.

Capillary rise

Under transient state condition (as stated by Prathapar et al., 1992), the matric flux potential Φ (L^{2}T^{-1}) (Gardner, 1958; Raats and Gardner, 1974) distribution within a homogenous soil profile with roots above the groundwater level is given by an infinite time series (Brandyk and Romanowicz, 1989) by Equation (11) in Table 1. t is time (T), z is distance from soil surface (L), D is the soil water diffusivity (L^{2}T^{-1}), K$_s$ the saturation hydraulic conductivity (LT^{-1}), α the K(Ψ) versus Ψ decay parameter (Gardner, 1954), L the depth to groundwater (L), t the time (T), q$_0$(t) the surface evaporation or evapotranspiration rate (LT^{-1}), which has been described previously and S the root water uptake rate (LT^{-1}). Practical calculation showed that first 3 part of infinite time series [Equation (11)] is non zero. Subsequently, the daily capillary rise, CR, was calculated using Equation (12) in Table 1. K$_{\Phi rz}$ is the unsaturated hydraulic conductivity at Φ_{rz}.

S in Equation (11h) was determined according to Equation (13) in Table 1 by using Feddes et al. (1976) where a is the coefficient related to soil water content and varies between 0-1 and T$_c$ is the crop transpiration (mm) that was determined according to Equation (14) in Table 1. K$_{cb}$ is the basal crop coefficient. Basal crop coefficients of different growth stages of quinoa were determined based on measured transpiration (Talebnejad and Sepaskhah, 2015b). In the developed model, crop coefficient in different days after planting was determined based on the FAO method (Allen et al., 1998).

Soil salinity

Soil salinity was estimated by salt balance equation in soil. Salt is added to soil by application of saline irrigation water and capillary rise from saline groundwater. Two cases were presumed to estimate the salinity increase caused by application of saline irrigation water to each soil layer:

(i) In the first case, at the time that leaching occurred from a given soil layer due to higher applied water than the soil water holding capacity. In this case, salts were leached to the next layer. To estimate the salinity in each soil layer, it is assumed that total remained salt from previous irrigation event is dissolved in the water entered into the soil layer and resulted in a uniform salt solution. Therefore, salinity of deep percolated water from a given layer is equal to its electrical conductivity of soil solution caused by saline irrigation water ($ECIWss_{i,k}$). The electrical conductivity of soil solution by application of saline irrigation water in a given layer is calculated by Equation (15) in Table 1. $ECIW_{ssi,k}$ is the electrical conductivity of soil solution of layer k in day i caused by saline irrigation water (dS m^{-1}), $EC_{ssi,k-1}$ is the electrical conductivity of water that is entered into the layer from the upper layer that is equal to the electrical conductivity of soil solution in the upper layer (dS m^{-1}), $EC_{ssi-1,k}$ is the electrical conductivity of soil solution in the layer from previous irrigation event (dS m^{-1}), $\theta_{rz\,i-1,k}$ is the soil volumetric water content (m^3 m^{-3}) in layer k in day i, $DP_{i,k-1}$ is the depth of water entered each soil layer from upper layer (k-1) (mm) and DOL is the layer thickness (mm).

(ii) In second case, water entered to a soil layer but leaching did not occur from the layer. Therefore, soil salinity is calculated by Equation (16) in Table 1. θ_{sk} is the saturation soil water content of layer k (m^3 m^{-3}).

The electrical conductivity of soil solution caused by capillary rise from saline groundwater in a given soil layer is calculated by Equation (17) in Table 1. $ECGW_{ssi,k}$ is the electrical conductivity of soil solution of layer k in day i caused by capillary rise from saline groundwater, EC_{GW} is the electrical conductivity of saline groundwater (dS m^{-1}). Salinity of the groundwater was not changed during the crop growth cycle. Therefore, for simplicity it was assumed that the salinity of capillary rise water in each layer was not changed. Furthermore, even with this assumption the model was calibrated and validated with good accuracy.

Therefore, electrical conductivity of soil solution caused by application of saline irrigation water and saline capillary rise is calculated by Equation (18) in Table 1. $EC_{ssi,k}$ is the electrical conductivity of soil solution in layer k in day i (dS m^{-1}).

Dry matter

Total dry matter production was determined using actual transpiration and the difference of saturated vapour pressure and actual vapour pressure according to Equation (19) in Table 1 (Tanner and Sinclair, 1983). DM is the total dry matter (Mg ha^{-1}); f is a constant value that includes the toxicity effects of ions, radiation saturation and temperature stress impacts on DM production (transpiration efficiency in Mg kPa ha^{-1} mm^{-1}), T is the actual transpiration in growing season (mm) and e_s and e_a are the mean saturated and actual vapour pressure in the growing season (kPa), respectively. Actual transpiration for each day was estimated by multiplying the soil water stress (Ks) to crop transpiration (T).

Seed yield

Seed yield was estimated by multiplying harvest index (the ratio of seed yield to aboveground dry matter) by total dry matter.

Statistical analyses

To evaluate the modified model, index of agreement (d) and normalized root mean square error (NRMSE) were used. These parameters were calculated according to Equations (20) and (21) (Willmott et al., 1985) as follows:

$$NRMSE = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{nO_m^2} \right]^{0.5} \tag{20}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - O_m| + |O_i - O_m|)^2} \tag{21}$$

where P_i and O_i are the predicted and observed values, respectively. O_m is the mean of measurement values and n is the number of data. When the value of d is closer to 1.0 and NRMSE is closer to 0.0, the accuracy of the results is higher. The simulation is considered excellent if the NRMSE is less than 10%, good if the NRMSE is greater than 10% and less than 20%, fair if NRMSE is greater than 20% and less than 30% and poor if the NRMSE is greater than 30% (Jamieson et al., 1991).

Field data

The data used in this investigation were obtained from a 3-year experiment in 2011, 2012 and 2013. Some of the physico-chemical properties of the soil are shown in Table 2. Details of the experiment were described by Talebnejad and Sepaskhah (2015a, 2015b). In the first and second experiment (2011 and 2012) the influence of saline groundwater depths, GD (0.3, 0.55 and 0.80 m) with salinity equivalent to irrigation water and irrigation water salinity, WS (10, 20, 30, 40 dS m^{-1}) on growth and yield of quinoa and groundwater contribution to its water use in cylindrical lysimeters in greenhouse conditions was investigated with 3 replications. In the third experiment (2013) the influence of saline groundwater depths, GD (0.3, 0.55 and 0.80 m) and deficit irrigation, DI (80, 55 and 30% of full irrigation, FI) on growth, yield and water productivity of quinoa and groundwater contribution to its water use in lysimeters under greenhouse conditions was investigated with 4 replications. Water salinity in the third experiment was 20 dS m^{-1}.

Table 2. Physical and chemical properties of the soil in lysimeter.

Physical property		Chemical property	
Sand (%)	17	ECe (dS m^{-1})	0.73
Silt (%)	47	pH	7.19
Clay (%)	36	Cl (meq l^{-1})	3.75
Soil texture	Loam	Na (meq l^{-1})	1.30
Field capacity (cm^3 cm^{-3})	0.32	K (meq l^{-1})	0.06
Permanent wilting point (cm^3 cm^{-3})	0.16	Ca (meq l^{-1})	6.80
Bulk density (g cm^{-3})	1.38	Mg (meq l^{-1})	2.2
		SO$_4$ (meq l^{-1})	1.1
		HCO$_3$ (meq l^{-1})	8.0

The actual crop evapotranspiration and actual transpiration for the irrigation intervals were estimated with the water balance procedure as detailed by Talebnejad and Sepaskhah (2015a, 2015b). Before each irrigation event, soil water content at different depths above the groundwater level was measured with Time Domain Reflectometry method. The daily rate of crop water use from the groundwater was determined by replacing the water loss from the Mariotte bottle that maintained a constant groundwater level for the various treatments. To determine electrical conductivity of soil, soil saturation extract was prepared as described by the US Salinity Laboratory Staff (Richards, 1954).

Modeling structure

The flowchart of model is shown in Figure 2. To determine the actual evapotranspiration and actual transpiration, crop coefficients (Kc) and basal crop coefficients (Kcb) of different growth stages of quinoa were determined based on measured evapotranspiration and transpiration by water balance equation (Eq. 2) and calculated reference evapotranspiration by Hargreaves and Samani (1985) equation for the calibration. The measured and predicted seasonal actual evapotranspirations (ETa) based on water stress coefficient [Equations (7)] was determined. The K_c and K_{cb} values were adapted and defined according to the development stages as in Doorenbos and Pruitt (1986) and Allen et al. (1998): initial stage ($K_{c\ ini}$ and $K_{cb\ ini}$), crop development stage, mid-season stage ($K_{c\ mid}$ and $K_{cb\ mid}$) and the late-season stage ($K_{c\ end}$ and $K_{cb\ end}$). In this research K_c values during the initial, mid and late stages were 0.58, 1.2 and 0.8, respectively. However, K_{cb} values during the initial, mid and late stages were 0.50, 1.1 and 0.6, respectively.
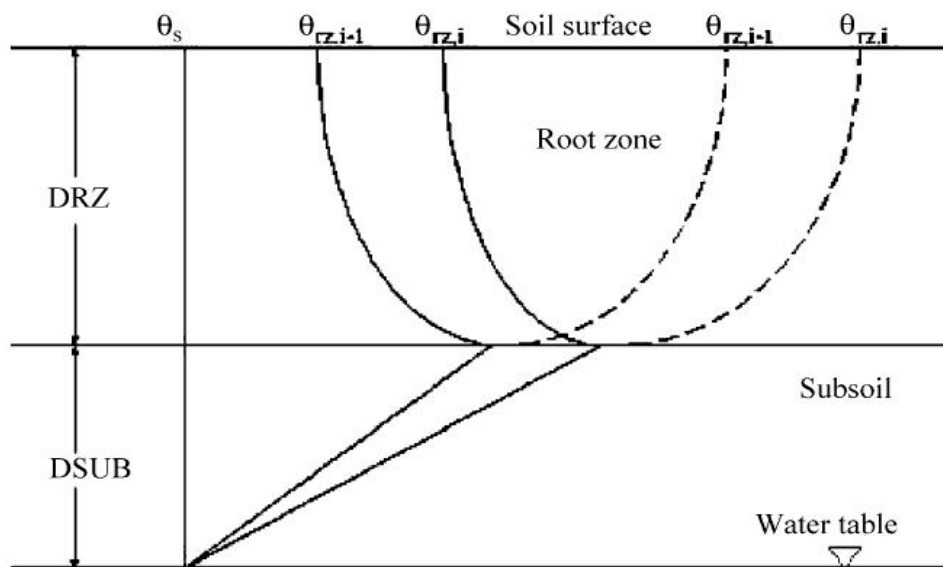

Figure 1. Estimating the change in subsoil water content using a triangular approximation at irrigated (solid lines) and non-irrigated (dashed lines) conditions (Jorenush and Sepaskhah, 2003).
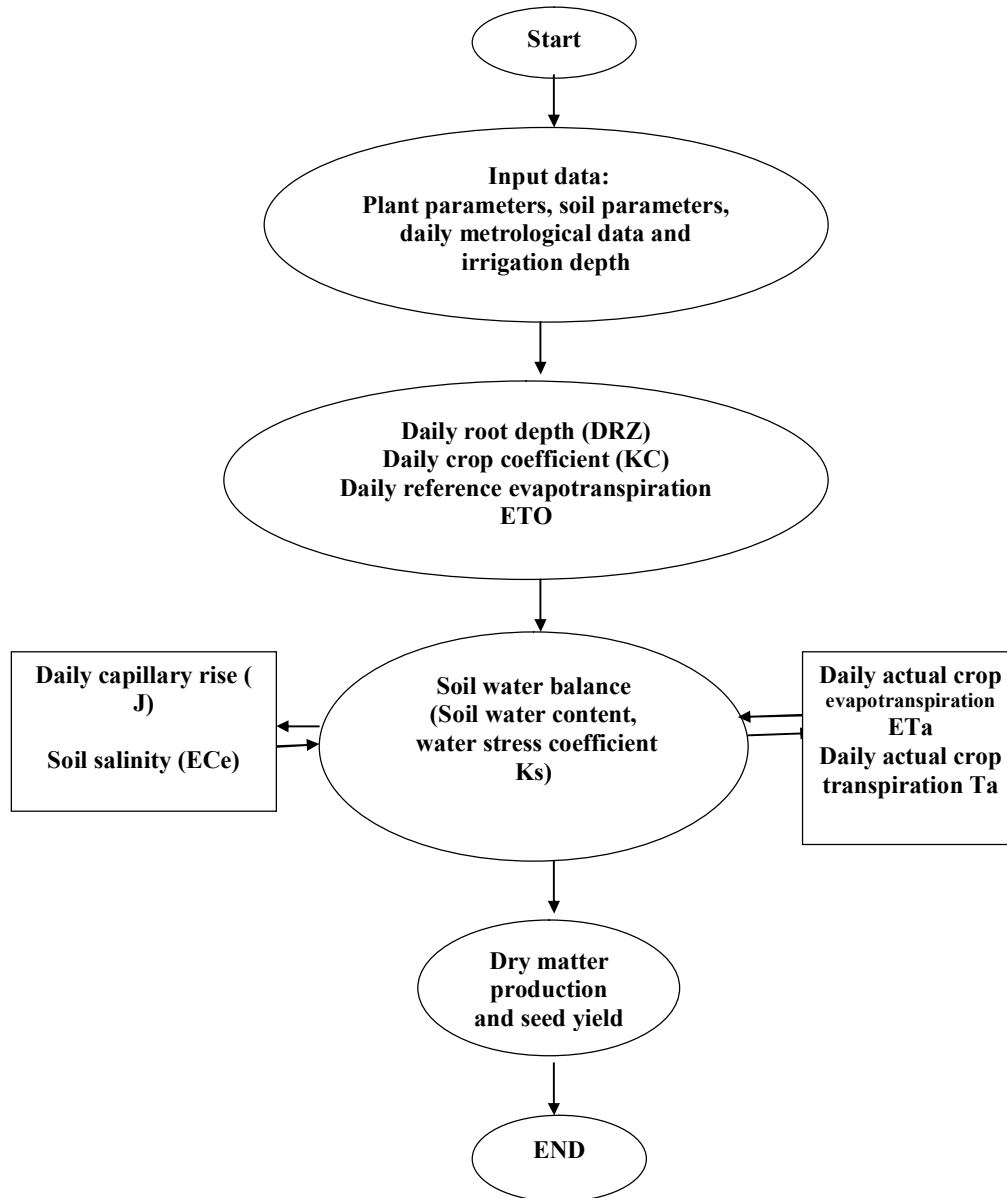
Figure 2. Flow diagram for the proposed model.

Value of K_y is the relative dry matter response factor to water stress that was determined in the developed model for quinoa. For calibration of the model, the measured data of the first year (2011) experiment and the data of two out of four replications of the measured data of the third year (2013) were used. The best calibrated model was achieved due to the fact that the least differences between the measured and predicted parameters were acceptable. According to the results of calibration experiment, the values of K_y were 1.72, 0.97, 0.88 and 0.63 for WS of 10, 20, 30 and 40 dS m^{-1}, respectively. Therefore, the relationship between K_y and salinity of groundwater (WS) obtained by regression analysis as follows:

$$K_y = -0.032 \times WS + 1.8 \tag{22}$$

$R^2 = 0.78 \quad SE = 0.18 \quad n = 5 \quad P = 0.02$

Soil profile was divided into a root zone and subsoil. Soil of the root zone was divided into layers in soil water balance analysis and soil water content at each layer was determined at the end of each day. Volumetric soil water content of the root zone and subsoil were determined based on Equations (8) and (9). Then capillary rise was calculated from Equation (12). Different investigations revealed that soil physical properties such as hydraulic conductivity influenced by water quality (e.g. Tedeschi and Dell Aquila, 2005). Salinity and presence of sodium ion reduced saturation hydraulic conductivity probably because of dispersion and changing in soil structure. In the developed model under different water salinities, the values of soil saturation hydraulic conductivity (K_s) were 210, 185, 132 and 91 mm day^{-1} for WS of 10, 20, 30 and 40 dS m^{-1}, respectively. Therefore, the relationship between the ratio of saturated hydraulic conductivity under non-saline conditions and the saturated hydraulic conductivity under saline conditions and water salinity was obtained by regression analysis as follows:

$$\frac{Ks_s}{Ks_{ns}} = 0.82 - 0.0129 WS \qquad (23)$$

$R^2 = 0.98$ $SE = 0.25$ $n = 54$ $P < 0.001$

Where Ks_s is the saturated hydraulic conductivity under saline conditions in mm day^{-1}, Ks_{ns} is the saturated hydraulic conductivity under non-saline conditions in mm day^{-1} which is 317 mm day^{-1} in this experiment and WS is the electrical conductivity of saline groundwater in dS m^{-1}. K_s determined from Eq. (23) is used in estimation of capillary rise [Eq. (11)]. By using saline water the plot soil could not be turned to sodic soil. Therefore, the soil salinity could not affect the soil saturation water content because soil dispersion could not occur due to fact that the plot soil was not sodic (SAR was lower than 10).

In presence of shallow groundwater, quinoa root growth is restricted by anaerobic conditions near shallow groundwater level (Talebnejad and Sepaskhah, 2015b). Therefore, in calibration of the model for quinoa, maximum root depths were 250, 505 and 755 mm at groundwater depths of 300, 550 and 800 mm, respectively. However, at deficit irrigation strategies, root growth is motivated in order to extract more water from available shallow groundwater. Therefore, max root depth was determined as follows:

$$DRZMAX = 0.989 \times GD - 15.33 \times IF - 29.03 \qquad (24)$$

$R^2 = 0.99$ $SE = 3.2$ $n = 15$ $P < 0.001$

where DRZMAX is the maximum root depth in mm, GD is the groundwater depth in mm and IF is the ratio of applied irrigation water to full irrigation water.

Soil solution salinity of each layer was determined based on Equations (15) and (16). Results showed that the predicted soil solution salinity by Equations (15), (16) and (17) was higher than the measured electrical conductivity of soil saturation extract due to the fact that the ratio of soil water content to soil saturation water content was lower than the ratio of soil water content to soil water content in saturated soil based on US Salinity Laboratory Staff method for saturated soil preparation. Therefore, the predicted soil salinity by the model was multiplied by 0.8. This coefficient is the ratio of soil saturated water content in pot soil to the saturated water content prepared in the laboratory for soil

salinity measurement according to the US Salinity Laboratory Staff method. This coefficient may vary in different soil textures and should be determined as calibration parameters for the model. The soil salinities at different soil layers were averaged in the root zone.

Quinoa is a halophyte with special characteristics in salinity conditions and salt uptake. In halophytes, much of the excess salt is concentrated in the leaves and crystallized in special bladder cells (Adolf et al., 2013). In our experiment, salt bladders on leaf and stem surfaces were observed. However, part of salt uptake in quinoa was accumulated in straw tissues. However, this amount was negligible even at highest water salinity (40 dS m^{-1}) and bladders had the main role in accumulation of salt in plant. Quantitative measurement of salt in bladder cells was not possible in our experiment; therefore, relationship between the measured and predicted soil salinity was obtained by regression analysis for calibration of the model.

Relationship between the measured and predicted electrical conductivity of soil saturation extract ratio and GD and WS was obtained by regression analysis as follows:

$$\frac{EC_{e,m}}{EC_{e,p}} = 0.70 + 0.00164GD - 0.0238WS \qquad (25)$$

$R^2=0.84$ SE=0.18   n=54   P<0.001

where $EC_{e,m}$ is the electrical conductivity of soil saturation extract determined in laboratory in dS m^{-1}, $EC_{e,p}$ is the electrical conductivity of soil saturation extract determined by Equation (17) multiplied by 0.8 in dS m^{-1}, GD is the groundwater depth in mm and WS is the electrical conductivity of groundwater (dS m^{-1}).

Seed yield was estimated by multiplying HI (the ratio of seed yield to aboveground dry matter) by total dry matter. Relationship between harvest index, depth and salinity of groundwater and irrigation fraction obtained by regression analysis as follows:

$$HI = 0.159 + 6.5 \times 10^{-5} GD - 0.004WS - 0.39IF^2 + 0.45IF \qquad (26)$$

$R^2=0.72$ SE=0.03   n=54   P<0.001

where GD is the groundwater depth in mm, WS is electrical conductivity of groundwater (dS m^{-1}) and IF is the ratio of applied irrigation water depth to full irrigation water depth.

Model calibration and validation

For calibration of the model, the measured data of soil water content, evapotranspiration, dry matter and yield, groundwater uptake and soil salinity of the first year (2011) experiment and two out of four replications of the measured data of the third year (2013) were used. Equations (22, 23, 24, 25 and 26) were determined by mentioned calibration data. In validation of the model, the measured data of the second year (2012) experiment and other half of the measured data of the third year (2013) experiment were used.

Results and Discussion

Model calibration

Soil water content

   The measured and predicted soil water contents at different soil layers for different experimental treatments were compared for different GDs and WSs and for different GDs and DIs. Examples are shown in Figure 3. Agreement between the measured and predicted soil water contents by the modified model was good (NRMSE= 0.12) except for 0.3 m GD at 0.10 - 0.20 m soil layer. The modified model underestimated soil water content in 0.3 m GD for all WSs. However, this did not occur in 0.3 m GD with deficit irrigation (DI). Relationship between the measured and predicted mean soil water content at the root depth is presented in Figure 4a. The value of NRMSE was 0.12 which showed a good estimation of soil water content by the model based on Allen et al. (1998) equation [Equation (7)] for soil water stress coefficient. Time domain reflectometery method was used in measuring the soil water content. Although special coated TDR probes were used in the soil water content measurement, it is possible that soil salinity increasing by application of saline irrigation water and capillary rise from saline shallow groundwater influenced the accuracy of soil water content measurement in saline soil columns. Furthermore, to estimate the amount of water uptake by root at different soil layers, an empirical pattern (40, 30, 20 and 10% for each quarter of root depth from top to bottom of root, respectively) was assumed. This assumption was in accordance with root development which is completely explained in Talebnejad and Sepaskhah (2016). However, it is recommended to estimate soil water uptake by root by other sink functions, i.e. an empirical model described by Jarvis (1989). Using this method could improve the model performance.

Evapotranspiration

   The measured and predicted cumulative actual evapotranspiration (ET_a) during the growing season for different experimental treatments were compared for different GDs and WSs and for different GDs and DIs. Examples are shown in Figure 5. It was concluded that the modified model slightly overestimated ET_a particularly in 0.80 m GD with different DIs. In general, prediction of ET_a by the modified model during the growing season was good. Relationship between the measured and predicted seasonal quinoa actual crop evapotranspiration (ET) is presented in Figure 4b. The values of NRMSE (0.09) and d (0.93) showed that the developed model could estimate seasonal ET with high accuracy. In this experiment, reference crop evapotranspiration was calculated by Hargreaves and Samani (1985) equation, because it is the most appropriate method when only temperature data is available in our experimental conditions in greenhouse (Razzaghi and Sepaskhah, 2010). Therefore, for application of the model in different regions, suitable and calibrated reference crop evapotranspiration equation should be used.
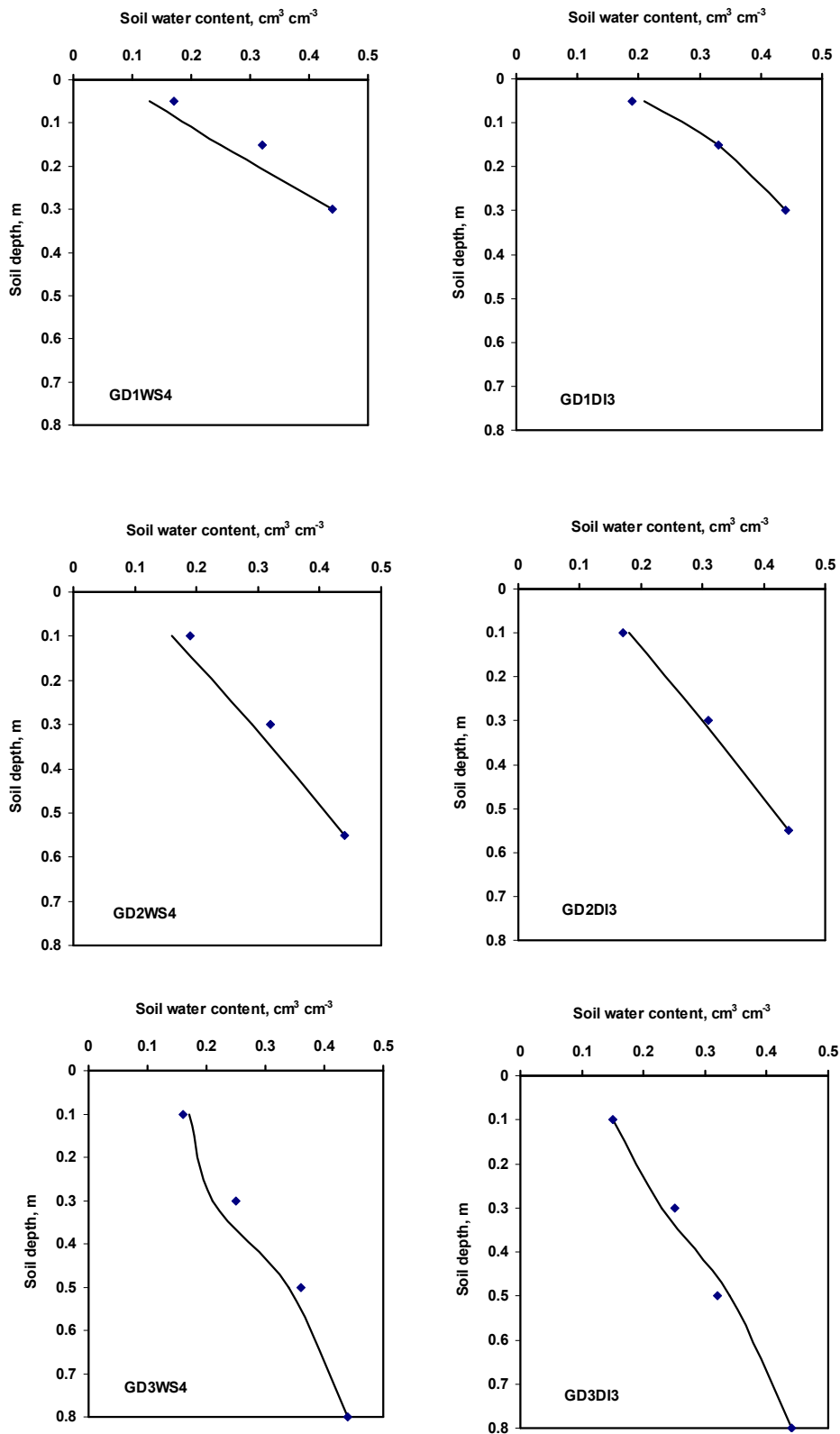
Figure 3. The measured (♦) and predicted (solid line) soil water contents (cm³ cm⁻³) by the model for calibration at different soil depths. GD1, GD2 and GD3 are 0.30, 0.55 and 0.80 m groundwater depth, WS4 is 40 dS m⁻¹ water salinity and DI3 is 0.80FI irrigation treatment.
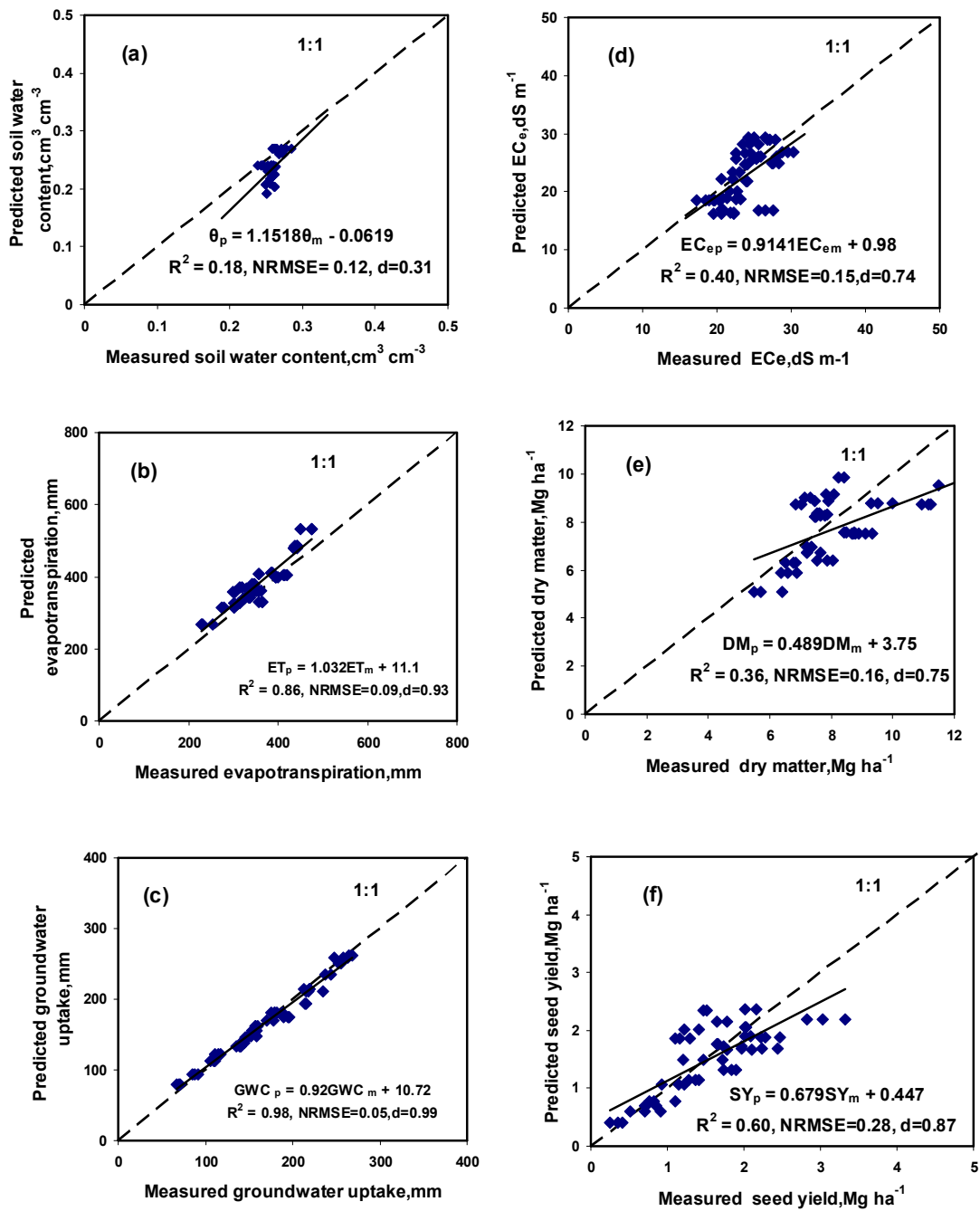
Figure 4. Relationship between the predicted and measured (a) soil water content, (b) seasonal evapotranspiration, (c) groundwater uptake, (d) soil saturation extract salinity, EC_e, (e) dry matter and (f) seed yield (calibration).
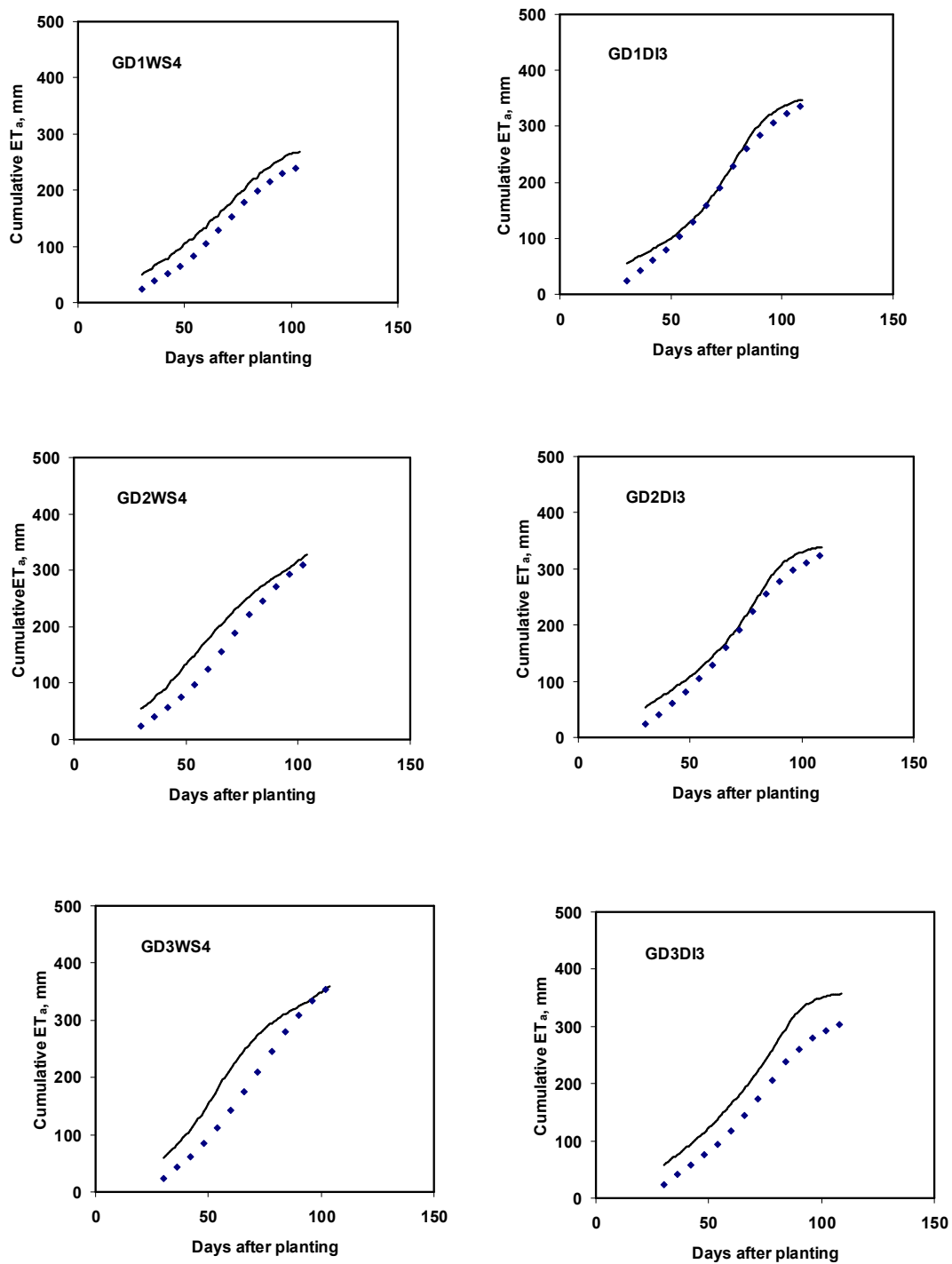
Figure 5. The measured (♦) and predicted (solid line) cumulative actual evapotranspiration (ET$_a$), mm by the model for calibration as a function of days after planting. GD1, GD2 and GD3 are 0.30, 0.55 and 0.80 m groundwater depth, respectively. WS4 is 40 dS m^{-1} water salinity and DI3 is 0.80FI irrigation treatment.

Groundwater uptake

The measured and predicted cumulative uptakes of groundwater during the growing season for different experimental treatments were compared and examples were shown in Figure 6. Agreement between the measured and predicted groundwater uptake by the modified model was very good. However, this agreement between the measured and predicted cumulative groundwater contribution to crop water use (GWC) for 0.55 m GD with 0.30FI was not as good as those for other treatments. In the other word, the modified model slightly underestimated GWC for mentioned treatment. Relationship between the measured and predicted groundwater uptake is presented in Figure 4c. The value of index of agreement was high (0.98) and NRMSE was low (0.05). Excellent estimation of groundwater uptake is probably due to good estimation of saturated hydraulic conductivity under saline conditions in Eq. (23) and also good estimation of root depth by using Eq. (24) for maximum root depth estimation. Previous studies on using Eq. (11) for capillary rise estimation (Prathapar et al., 1992; Jorenush and Sepaskhah, 2003) emphasized the noticeable influence of root depth estimation in accuracy of the capillary rise determination in analytical model [Eq.(11)]. However, our study revealed the influence of physical soil properties (K_s) at high water salinity on the capillary rise estimation from saline shallow groundwater which is intensified by application of irrigation water with high salinity.

Soil salinity

The measured and predicted soil saturation extract electrical conductivity (EC_e) at different soil layers for different experimental treatments was compared for different GDs and WSs and for different GDs and DIs. Examples are shown in Figure 7. Agreement between the measured and predicted EC_e by the modified model was good except for 0.3 m GD with 40 dS m^{-1} WS at all soil layers. Similar underestimation of EC_e by the modified model was observed for 0.3 m GD with 0.30FI. Relationship between the measured and predicted soil salinity was determined by linear regression analysis (Figure 4d). The values of NRMSE and d for this comparison were 0.15 and 0.74, respectively that indicated an acceptable estimation of soil salinity by the proposed model. There are many sources of errors in process of soil sampling and soil salinity measurements. For higher accuracy, it is recommended to provide the soil water salinity extract by suction cup apparatus from the soil. However, determination of soil salinity in each soil layer by application of Eqs. (15, 16 and 17) in each soil layer at high water salinity in this experiment (10 to 40 dS m^{-1}) resulted in acceptable estimation of soil salinity.
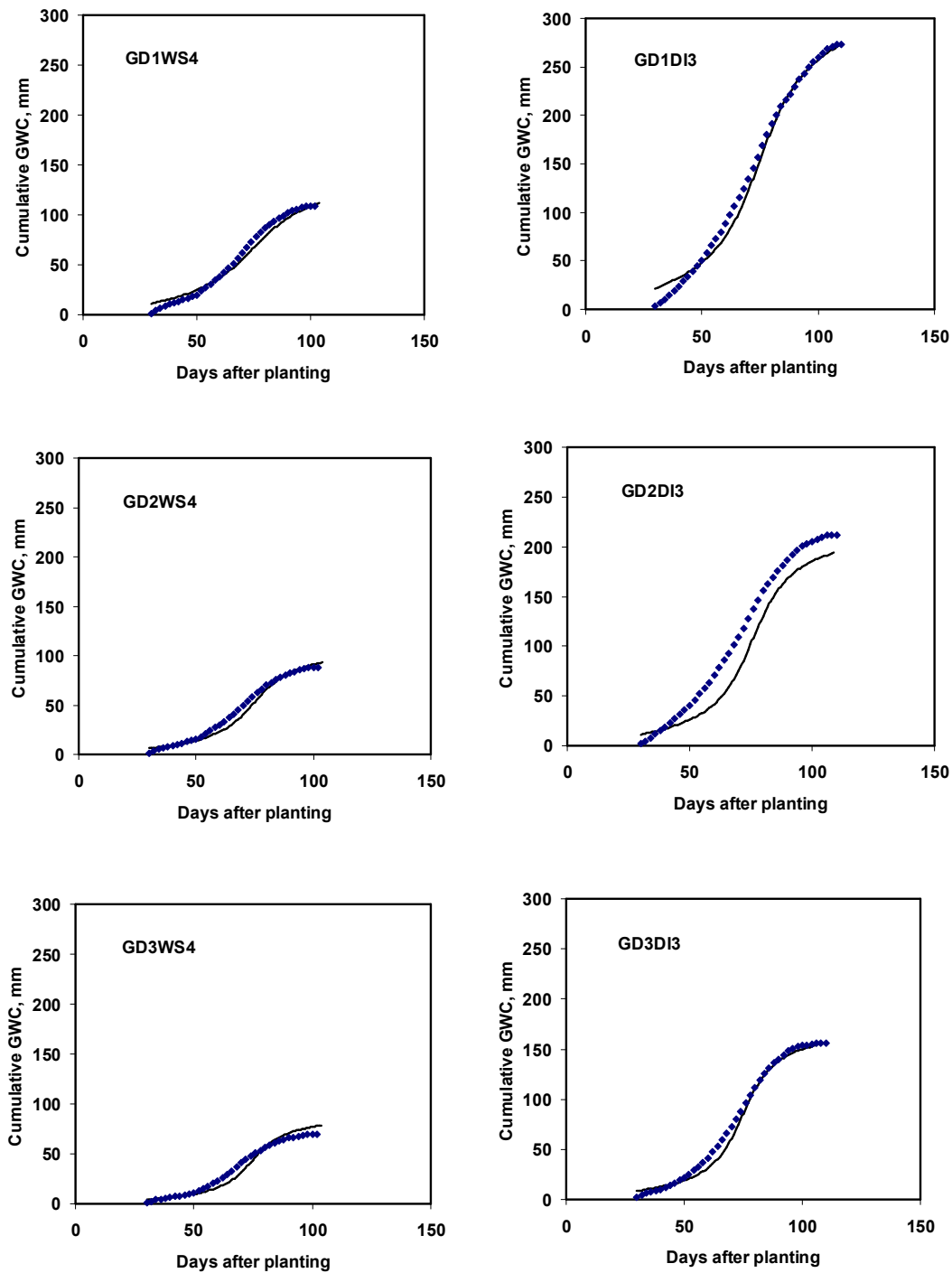
Figure 6. The measured (♦) and predicted (solid line) cumulative groundwater contribution to crop water use (GWC), mm by the model for calibration as a function of days after planting. GD1, GD2 and GD3 are 0.30, 0.55 and 0.80 m groundwater depth, respectively. WS4 is 40 dS m^{-1} water salinity and DI3 is 0.80FI irrigation treatment.

Figure 7. The measured (♦) and predicted (solid line) soil saturation extract salinity (EC_e), dS m^{-1}by the model for calibration at different soil depths. GD1, GD2 and GD3 are 0.30, 0.55 and 0.80 m groundwater depth, respectively. WS4 is 40 dS m^{-1} water salinity and DI3 is 0.80FI irrigation treatment.
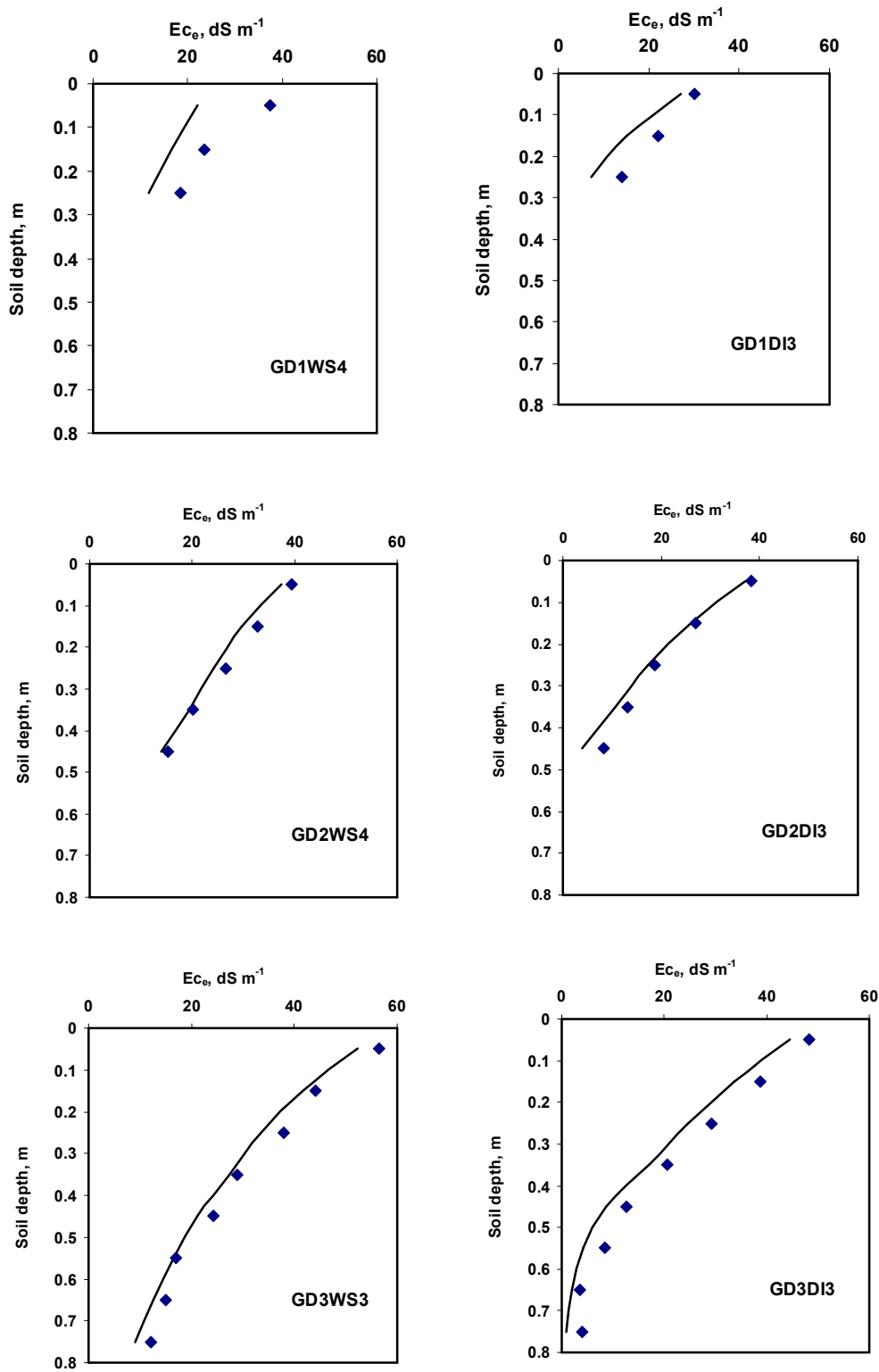
Dry matter and seed yield

The measured and predicted dry matter and seed yield for calibration and validation is presented in Table 3. It is indicated that the model underestimated the dry matter in calibration, particularly for different water salinities. However, the model slightly overestimated the dry matter in deficit irrigations. Maximum dry matter was measured as 12.5 Mg ha^{-1} for groundwater depth of 0.80 and WS of 10 dS m^{-1}, whereas it was predicted as 9.52 Mg ha^{-1} by the model in calibration. However, the model prediction of seed yield was closer to the measured seed yield in calibration (Table 3). Maximum seed yield was measured as 2.09 Mg ha^{-1} for groundwater depth of 0.80 and DI of 0.80FI (full irrigation), whereas it was predicted as 2.37 Mg ha^{-1} by the model in calibration. Relationship between the measured and predicted dry matter is presented in Figure 4e. The values of NRMSE (0.16) and d (0.75) showed that the proposed model could estimate dry matter of quinoa with fair accuracy. Transpiration efficiency in Eq. (16) for dry matter estimation was 0.08 Mg ha^{-1} kPa mm^{-1} in calibration of the model for quinoa which indicated that quinoa transpiration efficiency is higher than other C3 crops. However, the relationship between the dry matter and ratio of transpiration to the difference of saturated vapour pressure and actual vapour pressure may be different in different environmental conditions that should be considered in the model for various environmental conditions.

Table 3. The measured (m) and predicted (p) dry matter and seed yield (Mg ha^{-1}) in different experimental treatments.

Treatments	Calibration				Validation			
	Dry matter		Seed yield		Dry matter		Seed yield	
	P	M	P	M	P	M	P	M
GD1*WS1**	7.53	8.71	1.49	1.47	9.15	8.56	1.82	1.42
GD1WS2	6.70	7.35	1.06	1.09	8.14	7.32	1.29	1.04
GD1WS3	5.89	6.60	0.69	0.76	7.15	6.44	0.85	0.76
GD1WS4	5.10	5.86	0.40	0.34	6.22	5.57	0.49	0.36
GD2WS1	8.73	11.11	1.87	2.32	10.61	10.78	2.28	2.43
GD2WS2	7.52	9.11	1.31	1.83	8.83	8.91	1.54	1.72
GD2WS3	6.38	7.81	0.86	1.18	7.51	7.74	1.01	1.14
GD2WS4	6.28	6.70	0.60	0.71	7.46	6.54	0.71	0.68
GD3WS1	9.52	12.4	2.20	3.06	11.61	12.44	2.68	3.17
GD3WS2	8.78	9.6	1.68	2.21	10.22	9.56	1.95	2.19
GD3WS3	7.56	8.54	1.14	1.35	8.74	8.34	1.32	1.32
GD3WS4	6.94	7.2	0.77	0.90	8.01	7.41	0.89	0.96
GD1DI1***	8.28	7.72	1.73	1.84	8.28	7.76	1.73	1.88
GD1DI2	8.29	7.76	1.89	2.05	8.29	7.78	1.89	2.04
GD1DI3	8.34	7.56	1.66	1.94	8.34	7.85	1.66	1.99
GD2DI1	9.16	7.95	2.06	2.02	9.16	8.09	2.06	2.04
GD2DI2	8.85	7.70	2.16	1.74	8.85	7.65	2.16	1.69
GD2DI3	8.22	7.48	1.76	1.65	8.22	7.41	1.76	1.54
GD3DI1	9.84	8.33	2.37	2.09	9.84	8.21	2.37	2.07
GD3DI2	9.04	7.22	2.35	1.50	9.04	7.41	2.35	1.54
GD3DI3	8.73	6.94	2.02	1.32	8.73	7.10	2.02	1.34

* GD1, GD2 and GD3 are the groundwater depth of 0.30, 0.55 and 0.80 m.
** WS1, WS2, WS3 and WS4 are the water salinity of 10, 20, 30 and 40 dS m^{-1}.
*** DI1, DI2 and DI3 are different irrigation treatments as 080FI, 0.55FI and 0.80FI; Full irrigation.

Relationship between the measured and predicted quinoa seed yield is presented in Figure 4f. The value of NRMSE was 0.28 which shows a fair estimation of seed yield by the model. However, the value of index of agreement (d) was high (0.87). The slopes and intercepts of the linear relationships between measured and predicted dry matter and seed yield were analyzed statistically. The slope of linear equations for dry matter and seed yield were not statistically different from 1.0 (P<0.05).

Model validation

Soil water content

The measured and predicted soil water contents at different soil layers for different experimental treatments were compared for different GDs and WSs and different GDs and DIs in validation of the modified model. Similar as the calibration, agreement between the measured and predicted soil water contents by the modified model was good except for 0.3 m GD at 0.10 - 0.20 m soil layer for all WSs; however, the underestimation was lower than the calibration and the modified model prediction was more accurate in validation. Relationship between the measured and predicted mean soil water content at root depth by the model was determined by linear regression analysis (Figure 8a). The value of NRMSE was 0.086, which showed a good estimation of soil water content. Results showed that the model slightly underestimated the soil water content in comparison with the measured values.

Evapotranspiration

The measured and predicted cumulative actual evapotranspiration (ET_a) during the growing season for different experimental treatments were compared for different GDs and WSs and different GDs and DIs in validation of the modified model. The modified model slightly overestimated ET_a at 0.80 m GD with different DIs. Relationship between the measured and predicted seasonal quinoa actual crop evapotranspiration (ET) is presented in Figure 8b. The values of NRMSE (0.09) and d (0.92) showed that the proposed model could estimate ET of quinoa with excellent accuracy. The results of transpiration behavior were similar to the results of evapotranspiration. Therefore, it was not presented here to be brief.

Groundwater uptake

The measured and predicted cumulative groundwater uptake during the growing season for different experimental treatments was compared for different GDs and WSs and different GDs and DIs in validation of the modified model. Model prediction was good for groundwater uptake during the growing season. Relationship between the measured and predicted groundwater uptake is presented in Figure 8c. The value of index of agreement (d) was high (0.98) and NRMSE was lower than 10%. These statistical parameters indicated that the accuracy of estimated groundwater uptake was excellent and their results were statistically close to the measured

values. Results of Jorenush and Sepaskhah (2003) showed that analytical model [Eq. (11)] accurately predicted the capillary rise of different soil layers for different groundwater depths (0.3–1.2 m) and salinity levels (0.5–13 dS m^{-1}) under irrigated and non-irrigated conditions for pistachio seedling growth in micro-lysimeter, except for saline groundwater (13.0 dS m^{-1}) and shallow groundwater depth (smaller than 0.6 m). However, in the proposed model for quinoa at high water salinity (10–40 dS m^{-1}), accurate groundwater uptake were obtained by considering the effect of salinity on saturated hydraulic conductivity and maximum root depth according to Eqs. (23) and (24).

Soil salinity

The measured and predicted EC$_e$ at different soil layers for different experimental treatments was compared in validation of the modified model. In validation, the model underestimated of EC$_e$ for 0.30 m GD with 40 dS m^{-1} WS. Relationship between the measured and predicted mean soil salinity of root zone with the model is shown in Figure 8d. The value of index of agreement (d) was acceptable (0.74) and NRMSE was 0.15 (between 10% and 20%). These statistical parameters indicated that the accuracy of the estimated mean soil salinity is good. The analytical model for capillary rise estimation from shallow saline groundwater and different soil salinities increase were not well estimated on high water salinity as reported by Prathapar et al. (1992) and Jorenush and Sepaskhah (2003). However, in the proposed model for quinoa at high water salinity (10–40 dS m^{-1}), accurate soil salinity was obtained by good estimation of salinity increase caused by capillary rise from saline groundwater and application of saline irrigation water. Therefore, this model is applicable for salinity prediction and could be a valuable tool in soil salinity management in presence of shallow saline groundwater.

Dry matter and seed yield

The model prediction in validation was more accurate than calibration for dry matter and seed yield. Maximum dry matter was measured as 12.44 Mg ha^{-1} for groundwater depth of 0.80 m and WS of 10 dS m^{-1}, whereas it was predicted as 11.61 Mg ha^{-1} by the model in validation (Table 3). Furthermore, maximum seed yield was measured as 3.17 Mg ha^{-1} for groundwater depth of 0.80 m and WS of 10 dS m^{-1}, whereas it was predicted as 2.68 Mg ha^{-1} by the model in validation.

Relationship between the measured and estimated dry matter and seed yield by the model is shown in Figure 8d and 8e, respectively. The value of NRMSE for dry matter was between 10 and 20%, which indicated that the accuracy of estimated dry matter was good (Jamieson et al., 1991). However, the value of NRMSE for seed yield was 0.21, which indicated that the accuracy of estimated seed yield was acceptable. This model was applicable to determine quinoa yield and it could be a valuable tool for farm irrigation water management under different irrigation salinities and deficit irrigation in presence of shallow saline groundwater.
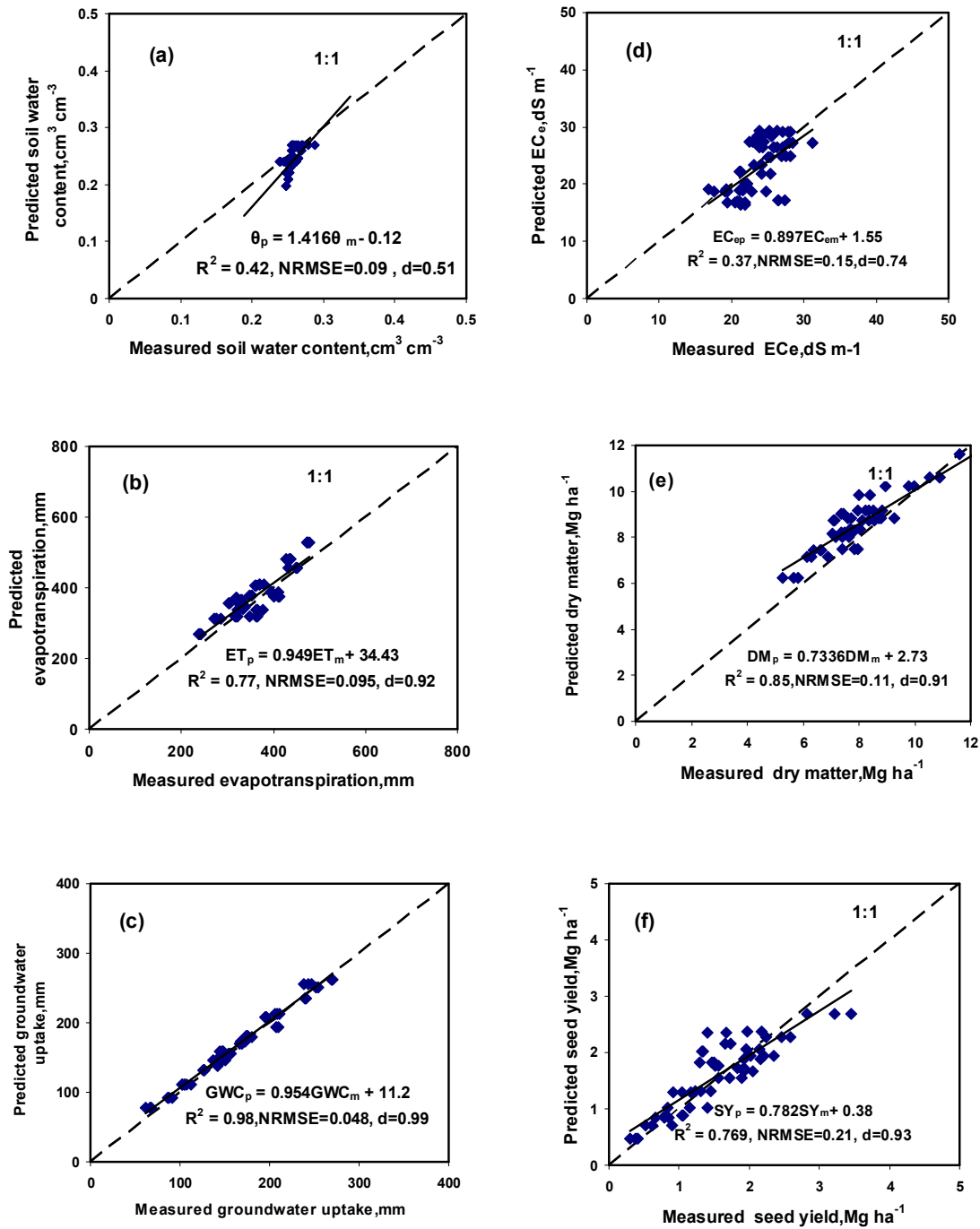
Figure 8. Relationship between the predicted and measured (a) soil water content, (b) seasonal evapotranspiration, (c) groundwater uptake, (d) soil saturation extract salinity, EC_e, (e) dry matter and (f) seed yield (validation).

Conclusions

In this investigation, the transient state analytical model was modified to predict the groundwater uptake, actual crop evapotranspiration, soil water content, dry matter, seed yield and soil salinity under different saline groundwater depths, irrigation water salinities and deficit irrigation for quinoa. Considering the effect of the salinity on the saturated hydraulic conductivity and maximum root depth in presence of shallow saline groundwater resulted in good agreement between the measured and predicted groundwater uptake and soil salinity increase at different groundwater depths (300-800 mm) and water salinity (10-40 dS m^{-1}). According to the NRMSE parameter, validation results showed that the proposed model presented excellent estimation of groundwater uptake, seasonal evapotranspiration, mean soil water content and mean soil salinity and acceptable estimation of dry matter and seed yield. Therefore, this model is proposed to be used for irrigation and soil salinity management in presence of shallow saline groundwater.

Acknowledgement

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