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Modeling the effects of saline water use in wheat-cultivated lands using the UNSATCHEM model

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Abstract Waters of poor quality are often used to irrigate crops in arid and semiarid regions, including the Fars Province of southwest Iran. The UNSATCHEM model was first calibrated and validated using field data that were collected to evaluate the use of saline water for the wheat crop. The calibrated and validated model was then employed to study different aspects of the salinization process and the impact of rainfall. The effects of irrigation water quality on the salinization process were evaluated using model simulations, in which irrigation waters of different salinity were used. The salinization process under different practices of conjunctive water use was also studied using simulations. Different practices were evaluated and ranked on the basis of temporal changes in root-zone salinity, which were compared with respect to the sensitivity of wheat to salinity. This ranking was then verified using published field studies evaluating wheat yield data for different practices of conjunctive water use. Next, the effects of the water application rate on the soil salt balance were studied using the UNSATCHEM simulations. The salt balance was affected by the quantity of applied irrigation water and precipitation/dissolution reactions. The results suggested that the less irrigation water is used, the more salts (calcite and gypsum) precipitate from the soil solution. Finally, the model was used to evaluate how the electrical conductivity of irrigation water affects the wheat production while taking into account annual rainfall and its distribution throughout the year. The maximum salinity of the irrigation water supply, which can be safely used in the long term (33 years) without impairing the wheat production, was determined to be 6 dS m^{-1}. Rainfall distribution also plays a major role in determining seasonal soil salinity of the root zone. Winter-concentrated rainfall is more effective in reducing salinity than a similar amount of rainfall distributed throughout autumn, winter, and spring seasons.

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Introduction

Waters of poor quality are often used to irrigate crops in arid and semiarid regions, including the Fars Province in southwest Iran. It is well known that due to high concentrations of soluble salts, the use of such waters may result not only in the decrease of crop yield, but also in the reduction in soil water infiltration capacity (e.g., McNeal 1974; Shainberg and Levy 1992; Qadir et al. 2000). A variety of strategies have been adopted to overcome problems associated with soil salinity, including improving the productivity of saline soils mainly through leaching of excess soluble salts, blending and reusing of saline drainage waters, selecting of tolerant varieties of suitable crops, and using appropriate agronomic practices (Rhoades et al. 1992). Adoption of suitable salinity control measures requires determination of salt and water movement through the soil profile and prediction of crop response to soil water

and soil salinity, subject to various climatic, edaphic, and agronomic factors (Ferrer and Stockle 1999).

Wheat is the main winter cereal crop planted over an area of almost 600 thousand hectares in the Fars Province. About 44 % of the total cultivated area in the Fars Province is cultivated with this crop. Wheat is ranked as a moderately salt-tolerant crop (Maas and Grattan 1999) that can be safely irrigated with moderately saline water, although an increase in water salinity may cause a reduction in the wheat grain yield. However, the wheat yield is also affected by several other factors, including soil, crop, and environmental conditions, which interact with soil salinity to cause different yield responses.

Several methods are available for a thorough assessment of what impact water quality and existing farm irrigation management may have on soil salinity (e.g., Kelleners and Chaudhry 1998; Sharma and Rao 1998). By far, the most widely used method for salinity assessment is detailed soil sampling and subsequent laboratory measurement of salinity (Cheraghi et al. 2007). However, the traditional soil salinity assessment method requires considerable time, expense, and effort and cannot fully cover the spatial and temporal patterns of variability at the field scale. There has been considerable success in using ground-based geophysical measurements of the apparent soil electrical conductivity (EC_a) to assess salinity across individual fields, including the electrical resistivity (ER) or electromagnetic induction (EM) surveys (e.g., Corwin and Lesch 2003). However, even these methods are currently too time consuming to be applied cost-effectively at regional scales (Lobell et al. 2010). Therefore, there is a need for the development of more practical (i.e., quicker and cheaper) methods and tools to determine and evaluate soil salinity in order to improve decision-making processes.

Mathematical models that consider and integrate various climate, crop, and soil factors have been suggested as useful tools for assessing the best management practices for saline conditions (e.g., Ramos et al. 2011, 2012). Steady-state and transient water flow and solute transport models are the two main classes of currently available models for the assessment of salinity management. Steady-state models, which assume steady-state water flow through the soil profile and constant soil solution concentrations at any point of the root zone at all times, are not suitable for irrigated lands under saline conditions (Letey and Feng 2007; Corwin et al. 2007; Letey et al. 2011). A large number of transient flow and transport models, including UNSATCHEM (Šimůnek et al. 1996), SWAP (van Dam et al. 1997), HYDRUS-1D (Šimůnek et al. 2008), and HYSWASOR (Dirksen et al. 1993), among many others, have been developed to simulate integrated effects of climate, soil, and plants.

UNSATCHEM is a transient flow and transport model that considers the effects of many variables and factors, such as the initial soil salinity, time and amount of rainfall, water quality, and blending of saline and fresh waters (Bradford and Letey 1992; Kaledhonkar and Keshari 2006; Gonçalves et al. 2006; Ramos et al. 2011, 2012; Kaledhonkar et al. 2012). The UNSATCHEM model can additionally account for chemical reactions, such as aqueous complexation, cation exchange, and salts precipitation and/or dissolution, which are important for assessing the effects of the quality of irrigation water in arid and semiarid regions.

The UNSATCHEM model is a suitable tool for studies evaluating salt movement in soils irrigated with brackish waters because it can accurately predict not only soil water contents and concentrations of soluble ions, but also integral variables, such as electrical conductivity, the sodium adsorption ratio, and sodium exchange percentage (Gonçalves et al. 2006; Ramos et al. 2011). For example, Suarez et al. (2006) modeled the effects of rainfall on the permeability of a soil with a high sodium content. Their simulation results demonstrated that for regions where rainfall is significant, the Na hazard is considerably greater than what would be suggested by a simple application of commonly used EC–SAR hazard relationships.

Studies assessing soil salinity using numerical models are very limited in Iran. For example, Vaziri (1995) evaluated four desalinization models in a field study conducted in two regions of Rudasht and Kangavar. Four different types of models were compared: (1) a serial reservoir model, (2) a theoretical plat-thickness model, (3) a numerical convection–dispersion model, and (4) a numerical model that considered both continuous and intermittent leaching processes. Results showed that the highest accuracy was achieved in both regions and for both conditions using the convection–dispersion model. Droogers et al. (2000) used the SWAP model to evaluate field experimental data from the Isfahan Province. They concluded that the SWAP model can successfully predict water and salt balances in the root zone for different irrigation management scenarios with steady-state conditions.

Considering the importance of using numerical models for a better understanding of salinity processes and for evaluating various salinity management options, the UNSATCHEM model was, in the present study, first calibrated and validated against the experimental data involving the use of saline water for irrigating wheat (Wahedi 1995). Next, further simulations were carried out using the UNSATCHEM model to obtain better understanding about strategies involving the conjunctive use of waters of different qualities, to evaluate the effects of different irrigation water qualities, rainfall amounts, and saline waters and to develop the guidelines for the management of salinity in wheat-cultivated lands.

Materials and methods

Model description

UNSATCHEM is a numerical model for simulating movement of water, heat, carbon dioxide, and solute in one-dimensional, variably saturated media (Šimůnek et al. 1996; Šimůnek and Suarez 1994a, b). The model numerically solves the Richards equation for water flow and convection–dispersion type equations for heat, carbon dioxide, and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K_\theta \frac{\partial h}{\partial z} + K_\theta\right) - S \qquad (1)$$

where θ ($L^3 L^{-3}$) is the volumetric water content, t (T) is time, K_θ ($L\,T^{-1}$) is the unsaturated hydraulic conductivity, h (L) is the soil water pressure head, z (L) is the vertical spatial coordinate, and S (T^{-1}) defines the root water uptake term. Root water uptake is simulated as a function of depth and time, and is a function of the pressure and osmotic heads to account for water and salinity stresses, respectively.

Transport of seven major ions, namely Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-}, and Cl^-, is considered by UNSATCHEM. Solute transport of each aqueous species is simulated using the advection–dispersion equation:

$$\frac{\partial \theta c_k}{\partial t} + \rho_b \frac{\partial \bar{c}_k}{\partial t} = \frac{\partial}{\partial z}\left(D\theta \frac{\partial c_k}{\partial z} - qc_k\right) \quad k = 1,\ldots,7 \qquad (2)$$

where c_k ($M\,L^{-3}$) is the total dissolved concentration of aqueous species k, $\overline{c_k}$ ($M\,M^{-1}$) is the concentration associated with the solid phase (i.e., sorbed and precipitated), ρ_b ($M\,L^{-3}$) is the soil bulk density, D ($L^2\,T^{-1}$) is the dispersion coefficient, and q ($L\,T^{-1}$) is the Darcy water flux. The transport equation is solved in UNSATCHEM using a Galerkin finite-element method (van Genuchten 1987).

The UNSATCHEM model accounts for equilibrium chemical reactions between major ions, such as aqueous complexation, cation exchange, and precipitation–dissolution (Šimůnek and Suarez 1994a, b). Activity coefficients are determined using either modified Debye–Huckel or Pitzer equations to calculate single-ion activities. All cations in the solution are assumed to be in equilibrium with the sorbed cations, which balance the negatively charged sites of the soil. Cation exchange is a dominant chemical process for the major cations in the solution in the unsaturated zone (Suarez 2001). The UNSATCHEM model uses a Gapon-type expression to describe exchange equilibrium between the sorbed and dissolved cations (White and Zelazny 1986):

$$K_{ij} = \frac{\bar{c}_i^{b+}(c_j^{a+})^{1/a}}{\bar{c}_j^{a+}(c_j^{b+})^{1/b}} \qquad (3)$$

where b and a are the valences of species i and j, respectively, and K_{ij} is the Gapon selectivity coefficient (dimensionless). Parentheses indicate ion activity (dimensionless), and $\bar{c}$ in (3) is the concentration of adsorbed cations (mmol$_c$ kg^{-1}).

The model considers a set of solid phases, including calcite ($CaCO_3$), gypsum ($CaSO_4\cdot 2H_2O$), and others. The model allows for precipitation of a mineral whenever the product of molar concentrations of their constituent ions raised to the power of their respective stoichiometric coefficients exceeds the K_{sp} value of the mineral (Šimůnek and Suarez 1994a, b).

Root water uptake is simulated as a function of depth and time, and is a function of the pressure and osmotic heads to account for water and salinity stresses, respectively:

$$S(h,\pi) = \alpha_1(h)\alpha_2(\pi)S_p \qquad (4)$$

where S_p is the potential water uptake rate ($L^3\,L^{-3}\,T^{-1}$) in the root zone, $\alpha_1(h)$ and $\alpha_2(\pi)$ are the pressure and osmotic stress response functions (dimensionless), respectively, and π is the osmotic head (L).

The S-shaped stress response functions proposed by van Genuchten (1987) were used to evaluate the reduction due to pressure and salinity stresses for the rate of water extraction. Reduction functions $\alpha_1(h)$ and $\alpha_2(\pi)$ for pressure and salinity stresses are described by the following pair of functions:

$$\alpha_1(h) = \frac{1}{1 + \left(\frac{h}{h_{50}}\right)^p} \qquad (5)$$

$$\alpha_2(\pi) = \frac{1}{1 + \left(\frac{\pi}{\pi_{50}}\right)^p} \qquad (6)$$

where h_{50} and π_{50} are the pressure and osmotic heads at which the water extraction rates are reduced by 50 % during conditions of negligible osmotic and pressure stress, respectively, and p (dimensionless) is an empirical constant.

Field experiments

The data for calibration and validation of the model were obtained from a research project reported by Wahedi (1995). The field experiment was conducted in Sarvestan, Fars Province (29.12°N, 53.12°E), to study the effects of three irrigation water salinities (2.5, 6.5, and 11.5 dS m^{-1}) and three leaching requirements corresponding to 10, 25, and 50 % reductions in the grain yield of winter wheat (namely $LR_{10\%}$, $LR_{25\%}$, and $LR_{50\%}$). The experiment was conducted in a randomized block design with four replications during three consecutive years (1991–1994). Seeds were planted on November 28 and grain was harvested on June 25, 27, and 21 in the first, second, and third year of the study, respectively.

Irrigation was provided using the basin irrigation system. Two irrigations (with a total of 210 mm) were applied before the vegetative cover reached 50 % during the winter season in the first 2 years of the study. In the third year of the experiment, an additional irrigation was provided in this growth stage (with a total of 310 mm). Six additional irrigations were carried out afterward, with a total of 480 mm plus the amount of leaching required to obtain 10, 25, and 50 % yield reductions as calculated using the leaching requirement equation:

$$LR = \frac{EC_{iw}}{\left(5EC_e^* - EC_{iw}\right)} \qquad (7)$$

where LR is the leaching requirement, EC_{iw} (dS m^{-1}) is the electrical conductivity of irrigation water, and EC_e^* (dS m^{-1}) is the salinity level, at which a particular yield loss is obtained. EC_e^* values that resulted in 10, 25, and 50 % yield reductions in wheat were 7.4, 9.5, and 13 dS m^{-1}, respectively, according to the Maas and Hoffman equation (1977). Leaching requirement, total applied water at different EC_{iw} and desired yield reductions during 3 years of the field experiment are presented in Table 1.

Water samples were analyzed for sodium (Na$^+$), magnesium (Mg^{2+}), calcium (Ca^{2+}), potassium (K$^+$), bicarbonate (HCO$_3^-$), carbonate (CO$_3^{2-}$), chloride (Cl$^-$), sulfate (SO$_4^{2-}$), and water electrical conductivity (EC$_{iw}$). The electrical conductivity of water samples was measured in the field. Na$^+$ and K$^+$ concentrations were measured using the emission flame photometer. Ca^{2+} and Mg^{2+} were measured by EDTA titrimetry. HCO$_3^-$ was determined using titration with HCl and Cl$^-$ was titrated by silver nitrate, while SO$_4^{2-}$ was obtained using the gravimetric method (Richards 1954). The chemical composition of irrigation waters is presented in Table 2. The calcium carbonate content of soil was determined by treating 0.5 g of dried soil with HCl, followed by back titration of unreacted acid with NaOH (Loeppert and Suarez 1996). Cation-exchange capacity (CEC) and exchangeable cations were measured according to Amrhein and Suarez (1990).

The hydrometric method was used to determine the soil texture (Bouyoucos 1962). The soil texture was clay loam between 0 and 50 cm depth with a high percentage of calcium carbonate and a low value of the organic carbon. The soil is classified as Carbonatic, Thermic, Typic Calcixerepts according to soil taxonomy (Soil Survey Staff 1999). Soil texture, calcium carbonate content, cation-exchange capacity, and Gapon's selectivity coefficients were measured before experiment. To assess soil salinity, soil samples were taken from 0–10, 10–30, and 30–50 cm depths three times during the wheat growing season every year over 3 years of the experiment. Averaged salinity during the season was reported for each depth.

Daily meteorological data were obtained from the Sarvestan Weather Station. Total annual rainfall was 309, 276, and 67 mm during the first, second, and third year of the experiment, respectively. Reference evapotranspiration, ET$_o$, was estimated using the FAO Penman–Monteith method (Allen et al. 1998). Crop evapotranspiration was then calculated as the product of ET$_o$ and crop coefficient (K_c) using the AQUACROP model. Crop parameters required for calculating actual evapotranspiration were adopted from Najafi Mirak (2008). The Sarvestan region has two distinct weather periods: a cool, rainy season (winter) from November to April (with about 97 % of the total rainfall) and a hot, dry season (summer) from May to October (with only about 3 % of the total rainfall). Required climatic parameters (ET and rainfall), soil properties, and initial concentrations for simulations are presented in Table 3.

Table 1 Leaching requirement, total applied water at different EC_{iw}, and desired yield reductions during 3 years of field experiment

EC_{iw} (dS m^{-1})	Desired yield reduction (%)	Soil salinity level at which a desired yield reduction is achieved (dS m^{-1})	Applied water before vegetative cover reached 50 % (mm)	Crop water requirements (mm)	Leaching requirements (mm)	Total applied water (mm)
2.5	10	7.4	210[a] (310)[b]	480	34.8	725[a] (825)[b]
2.5	25	9.5	210 (310)	480	26.7	717 (817)
2.5	50	13	210 (310)	480	19.2	709 (809)
6.5	10	7.4	210 (310)	480	102.3	792 (892)
6.5	25	9.5	210 (310)	480	76.1	766 (866)
6.5	50	13	210 (310)	480	53.3	743 (843)
11.5	10	7.4	210 (310)	480	216.5	906 (1,006)
11.5	25	9.5	210 (310)	480	153.3	843 (943)
11.5	50	13	210 (310)	480	103.2	793 (893)

[a] Applied water in the first 2 years, [b] Applied water in the third year

Table 2 Chemical composition of irrigation water

| EC (dS m^{-1})	Ca^{2+} (meq L^{-1})	Mg^{2+} (meq L^{-1})	Na$^+$ (meq L^{-1})	K$^+$ (meq L^{-1})	HCO$_3^-$ (meq L^{-1})	SO$_4^{2-}$ (meq L^{-1})	Cl$^-$ (meq L^{-1})
2.5	5.5	5.0	11.9	0.4	3.7	5.8	12.5
4.0	11.2	12.4	17.1	0.5	1.1	11.3	28.2
6.0	18.5	18.0	22.1	0.5	4.1	17.0	37.2
6.5	18.5	18.0	27.1	0.5	4.1	17.0	46.2
8.0	19.4	21.3	49.3	0.5	5.5	28.5	54.9
10.0	21.1	31.7	54.3	0.4	4.4	34.3	61.4
11.5	21.0	29.1	60.9	0.4	3.9	22.5	92.0

The UNSATCHEM model setup

The UNSATCHEM simulations were conducted using the atmospheric boundary condition (BC) with surface runoff. However, the surface runoff option was insignificant since specified daily precipitation and irrigation fluxes were lower than the infiltration capacity of the upper soil layer. The upper BC consisted of daily values of rainfall and potential evapotranspiration, which was partitioned into potential transpiration and potential evaporation using the modified approach of Ritchie (1972). The AQUACROP model was applied to calculate soil evaporation and crop transpiration separately based on the fraction of green canopy ground cover (Raes et al. 2009).

Free drainage BC was used at the bottom of the soil profile. The root growth was modeled using a logistic growth function, assuming the initial root growth time set at the planting date and 50 % root growth halfway through the growing season. Parameters for the van Genuchten model (van Genuchten 1980) describing soil hydraulic properties were derived from soil textural information and the soil bulk density using the ROSETTA program (Schaap

Table 3 Parameter values used in the UNSATCHEM model

Soil parameter	Value	Unit
Soil classification	Carbonatic, Thermic, Typic Calcixerepts	–
Soil texture	Clay loam	–
Soil bulk density	1.35	g cm^{-3}
Soil hydraulic parameters		
K_s	6.24	cm day^{-1}
α	0.019	cm^{-1}
n	1.31	–
θ_r	0.095	–
θ_s	0.41	–
Cation-exchange capacity	165	mmol$_c$ kg^{-1} soil
Gapon's selectivity coefficients		
Ca–Na exchange	10.3	
Ca–Mg exchange	0.92	
Ca–K exchange	0.41	
Initial dissolved concentrations		–
In plots irrigated with EC$_{iw}$ = 2.5 and LR$_{10 \%}$, LR$_{25 \%}$, and LR$_{50 \%}$	3.7, 4.2, 3.7	dS m^{-1}
In plots irrigated with EC$_{iw}$ = 6.5 and LR$_{10 \%}$, LR$_{25 \%}$, and LR$_{50 \%}$	9.4, 8.9, 8.2	dS m^{-1}
In plots irrigated with EC$_{iw}$ = 11.5 and LR$_{10 \%}$, LR$_{25 \%}$ and LR$_{50 \%}$	13.9, 13.8, 15.7	dS m^{-1}
Initial sorbed concentrations ($\overline{Ca}$, $\overline{Mg}$, $\overline{Na}$, $\overline{K}$)	105, 35, 10, 15	mmol$_c$ kg^{-1} soil
Calcite	400	gr kg^{-1}
Potential ET (1st, 2nd, and 3rd year)	646, 695, 686	mm
Long-term mean potential ET	635	mm
Crop coefficient (initial, developing, and ripening stages)	0.51, 1.05, 0.4	
Rainfall (1st, 2nd, and 3rd year)	309, 276, 67	mm
Long-term mean rainfall	250	mm
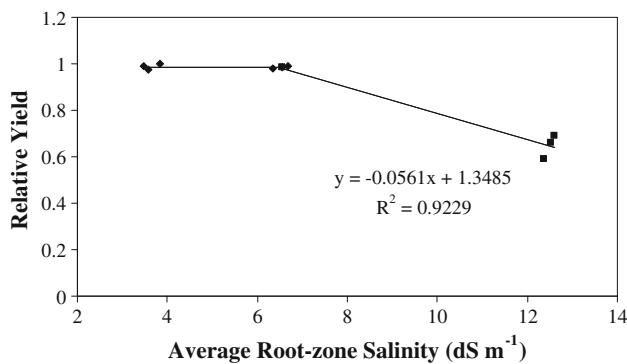
Fig. 1 Relationship between the relative wheat grain yield and the average root-zone salinity

et al. 2001). Since field data related to CO_2 concentrations ($cm^3 cm^{-3}$), fluxes, and production were not available, the CO_2 concentrations were assumed to increase linearly from 0.00033 (the CO_2 concentration in the atmosphere) at the soil surface to 0.022 at the 50 cm soil depth.

The relationship between the relative yield of wheat (the Ghods cultivar) and the mean value of soil salinity during the growing season for 3 years of experiment is illustrated in Fig. 1. The first segment of the relationship shows no change in the relative yield up to a soil salinity threshold of about 6.9 dS m^{-1}. The second segment is given by the following equation:

$$Y_r = -0.0561EC_e + 1.388 \quad R^2 = 0.92 \tag{8}$$

where Y_r is the relative yield (the actual wheat yield divided by the maximum wheat yield) and EC_e is the average root-zone salinity in dS m^{-1}. This equation provides the standard values of threshold and slope for yield reduction due to salt stress (Maas and Hoffman 1977) of 6.9 dS m^{-1} and 5.61 % decrease per 1 dS m^{-1} increase above the threshold, respectively.

Note that the threshold value obtained in our study indicated a slightly higher salt tolerance than reported by Maas and Grattan (1999) (i.e., 6 dS m^{-1}) and lower than recorded by Francois et al. (1986) (8.6 dS m^{-1}). In experiments with different wheat cultivars in an extremely dry region of Iran (the Yazd province), Ranjbar (2005) found that wheat cultivars were less salt tolerant than in temperate regions. A threshold of 5.92 dS m^{-1} and slope of 4.5 % decrease per 1 dS m^{-1} for a Ghods cultivar were proposed. According to the results obtained from 150 farms in 15 provinces in the north, south, and central parts of Iran, the soil salinity threshold, above which wheat yield started to decline, was found to be 6.8 dS m^{-1} (Siadat and Saadat 1998). Differences between different studies can be attributed to different experimental conditions, including genotypes, soils, climate, and/or agronomic practices.

The relationship between the electrical conductivity and the osmotic pressure head is given by:

$$\pi = -3.580EC + 1.366 \quad R^2 = 0.996 \tag{9}$$

where π has units of meters and EC has units of dS m^{-1}. Equation (9) was determined using UNSATCHEM (Šimůnek et al. 1996) to compute the osmotic head π for the solution composition of irrigation water reported by Wahedi (1995).

In the UNSATCHEM model, the water and salinity stresses on root water uptake are defined using the empirical parameters h_{50} and π_{50}. These parameters represent the pressure and osmotic heads, at which the water extraction rate is reduced by 50 % due to water and salinity stresses, respectively. Dehghanian (2004) reported h_{50} for wheat of -29.7 m. According to Wahedi (1995), the soil salinity that causes 50 % loss in the wheat yield is 15.82 dS m^{-1}. According to Eq. (9), this corresponds to the osmotic pressure head π_{50} of -55.3 m.

Data from experimental plots with irrigation water with the salinity of 2.5 dS m^{-1} were used for model calibration and that of 6.5 and 11.5 dS m^{-1} for model validation. For both calibration and validation, simulations were carried out for three leaching requirements in 3 years. Simulated salinities at depths of 0–10, 10–30, and 30–50 cm, averaged over 3 years, were compared with measured salinities at corresponding depths. Three-year average soil salinities were used for calibration and validation based on prior recommendations (e.g., Gan et al. 1997) that 3–5 years of data that include average, wet, and dry years should be used for model calibration and evaluation.

Statistical evaluation

Modeling results were evaluated using both graphical and statistical methods. In the graphical approach, measured values of soil salinity were plotted against simulated values. Agreement between simulated and observed values was evaluated using the root mean square error (RMSE) and the relative error (RE), which are defined as follows (Kobayashi and Salam 2000):

$$RMSE = \left[\frac{1}{n} \sum (Sim_i - Obs_i)^2 \right]^{0.5} \tag{10}$$

$$RE = \left[\frac{RMSE}{Obs_{avg}} \right] \tag{11}$$

where Sim_i and Obs_i are simulated and observed values, respectively; n is the number of data points included in the comparison; and Obs_{avg} is the mean observed value. RE was used to evaluate the quality of the RMSE value. The simulation is considered to be excellent when a relative error is less than 10 %, good if it is greater than 10 % and less than 20 %, fair if it is greater than 20 % and less than 30 %, and poor if it is greater than 30 % (Loague and Green 1991).

Alternative irrigation scenarios

Three alternative scenarios were considered when evaluating the effects of different irrigation waters on the development of salinity using UNSATCHEM. While no rainfall was considered in the first scenario, the other two scenarios considered daily rainfall data. In all alternative simulations, the longitudinal dispersivity of 9 cm obtained by calibration against the field data was used.

Scenario 1   Temporal changes in the quality of irrigation water can significantly influence the salinization process. These changes can occur when farmers get an occasional supply of good quality canal water. In such a situation, saline and canal waters can be used either alternately or mixed (blended), depending on the availability of good quality water. The effects of various options involving either an alternative use of different waters or their blending on soil salinity were investigated using the calibrated UNSATCHEM model. In this scenario, the wheat crop was considered and rainfall events were neglected. Simulations were carried out for six sub-scenarios: for two cases when only either low–salinity (LS) or high-salinity (HS) waters were used, and for four modes of conjunctive use (Table 4), namely LS:HS (alternating irrigations with low- and high-salinity waters, starting with low-salinity water), HS:LS (alternating irrigations with low- and high-salinity waters, starting with highly saline water), 3LS:3HS (initial three irrigations with low-salinity water followed by three irrigations with highly saline water), and Mix (1:1), where LS and HS stands for low and high salinity, respectively. Eight irrigations, each of 9 cm, were applied in each simulation. UNSATCHEM was run with daily values of long-term mean potential evapotranspiration. The EC of irrigation water of 2 (LS), 6 (Mix), and 10 (HS) dS m^{-1} was used.

Scenario 2   In lands cultivated with wheat in the Fars Province, about 35–45 % of applied water percolates below the root zone into deeper soil layers, leaching salts and increasing the wheat yield even when high-salinity irrigation waters are used (Cheraghi and Rasouli 2008). However, applying large amounts of water is not sustainable in arid and semiarid areas (such as in Iran and specifically in the Fars Province). Therefore, optimizing the leaching fraction while preserving the crop yield and minimizing the amount of irrigation water is of primary interest. This scenario involved four practical irrigation treatments (1.1ET, 1.2ET, 1.3ET, and 1.4ET, where ET is the potential evapotranspiration) while considering or ignoring annual rainfall. Water was applied at one-day intervals, such as with a drip irrigation system. The use of pressurized irrigation (e.g., sprinkler or drip irrigation) is one of the goals of sustainable agriculture in Iran. Long-term mean atmospheric data (potential ET and rainfall) and an EC$_{iw}$ of 6 dS m^{-1} were considered in this scenario. Other input data required for simulations are given in Table 3. For each simulation, various salt balance components, including leaching, precipitation (of calcite and gypsum), and final soil salinity were calculated for the soil depth of 0–50 cm.

Scenario 3   This scenario was carried out to evaluate the maximum electrical conductivity of irrigation water (EC$_{iw}$) that can maintain an average root-zone salinity of less than 6.9 dS m^{-1}, while considering annual rainfall and evapotranspiration. Three 3-year time series of rainfall, representing dry, average, and above-average rainfall years, were analyzed. Irrigation waters with EC$_{iw}$ of 4, 6, 8, and 10 dS m^{-1} were tested.

The historical rainfall record over the past 33 years for the Sarvestan area was obtained from the Meteorological statistics of the Fars province (2011). Long-term average precipitation calculated over a time period from 1978 to 2011 was considered a normal year. The year with annual rainfall either 50 % below or above the long-term mean was assumed to be a dry or wet year, respectively. Annual rainfall values were then sorted from the driest year to the wettest year. If the rainfall of the ith year in the ordered series was P_i, then the probability that rainfall was lower than P_i was given by the order number (i) of a year divided by the total number of years (n) plus 1 [Prob($P \leq P_i$) = $i/(n + 1)$]. The rainfall distribution of the ith year was used to determine results with P_i probability.

To evaluate the influence of rainfall distribution, two rainfall records with similar annual rainfall averages but different distributions throughout the year were selected. Two years (2005–2006 and 2010–2011) were compared. Total annual rainfall was almost the same (207 mm) in both years. In 2005–2006, rainfall was concentrated in winter (87 % of rainfall occurred from November to March), whereas in 2010–2011, rainfall was more uniformly distributed throughout the winter and spring (only 38 % occurred from November to March). Irrigation water was assumed to have a salinity of 6 dS m^{-1} in the model.

One additional scenario was carried out to evaluate how particular irrigation water affects the wheat yield over the long term. In this scenario, a 33-year record of historical daily rainfall was considered to determine the effect of irrigation waters with different EC$_{iw}$ on the average root-zone salinity. In this scenario, the quantity of irrigation water was assumed to be 120 % of the potential evapotranspiration. The simulation was run for 33 years and the simulated series of soil salinity was used to establish the probability of obtaining values below or above the threshold value of soil salinity.

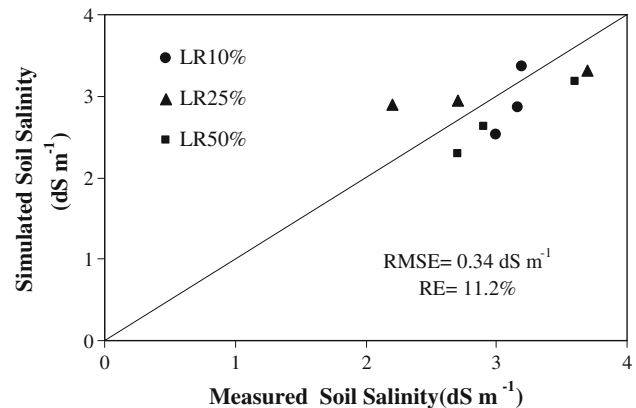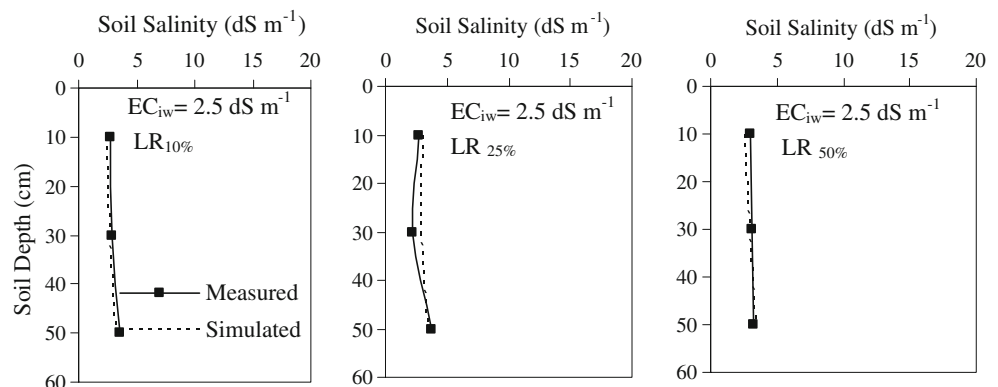## Results and discussion

Calibration and validation of UNSATCHEM for modeling the use of saline water for irrigation

During model calibration, the longitudinal dispersivity was fitted using the trial-and-error method until the simulated and measured soil salinities agreed within acceptable limits. Good agreement between the simulated and measured data was obtained by adjusting the dispersivity value to 9 cm, which is in the range of values suggested by many authors (e.g., Leijnse et al. 1996; Bejat et al. 2000; Vanderborght and Vereecken 2007).

Vanderborght and Vereecken (2007) wrote a review on dispersivities for solute transport modeling in soils (the data base contains 635 entries derived from 57 publications). Data are provided for a wide range of transport distances, flow rates, soil textures, pore water velocities, and scales of experiments (field, column, or core). Dispersivity values ranged between 0.1 and 481.1 cm. Dispersivities obtained for conditions most similar to our study (a relatively heavy soil texture, field condition, and travel distance of 50 cm) were in the range from 2.7 to 13.5 cm. We chose the minimum, maximum, and mean dispersivity values for inverse simulations. In each model run, simulation results were compared against the measured soil salinity data. Differences between measured and simulated values were evaluated by means of the RMSE. Differences between measured and simulated values were minimized with a dispersivity of 9 cm. Therefore, this value was used for remaining simulations in the present study. A comparison between measured and simulated soil salinities for experimental treatments with irrigation water with a salinity of 2.5 dS m^{-1} and three different leaching requirements is depicted in Figs. 2 and 3.

The RMSE of 0.34 dS m^{-1} (11.2 % relative error) shows that the UNSATCHEM model is able to predict soil salinities with an acceptable accuracy. Graphical display of results for the calibration (Fig. 3) and validation (Fig. 4)

Fig. 2 Comparison between measured and simulated (with the UNSATCHEM model) soil salinities for experimental treatments with irrigation water with salinity of 2.5 dS m^{-1} and three different leaching requirements (LR$_{10 \%}$, LR$_{25 \%}$, and LR$_{50 \%}$ are leaching requirements for 10, 25, and 50 % yield reductions, respectively)

periods indicates that the UNSATCHEM model adequately described experimental data, although the calibration results showed a better match than the validation results. RMSE values for the calibration period ranged from 0.31 to 0.38, while RE ranged from 10.5 to 12.3 % (Fig. 5). RMSE values ranged from 0.52 to 1.01 dS m^{-1} and from 1.60 to 2.13 dS m^{-1} for the validation period with water salinities of 6.5 and 11.5 dS m^{-1}, respectively. UNSATCHEM predicted soil salinity with relative errors of 10.6 and 14.9 % when using irrigation water with medium- and high-level salinity, respectively.

Higher differences between simulated and measured salinities for experiments with the highest salinity of irrigation water (11.5 dS m^{-1}) indicate that the model performs better for lower salinity levels. However, RE remained in the range of 10 to 20 %, which, according to evaluation guidelines, indicates a good accuracy of the model simulation. This result suggests that UNSATCHEM provides reasonably accurate predictions of soil salinity for different ranges of water quality and quantity. The

Fig. 3 Graphical comparison between measured and simulated soil salinities for experimental treatments with irrigation water with salinity of 2.5 dS m^{-1} and three different leaching requirements (LR$_{10 \%}$, LR$_{25 \%}$, and LR$_{50 \%}$ are leaching requirements for 10, 25, and 50 % yield reductions, respectively)

Fig. 4 Validation of the UNSATCHEM model for experimental treatments with salinities of irrigation water of 6.5 and 11.5 dS m^{-1} and three different leaching requirements (LR$_{10\%}$, LR$_{25\%}$, and LR$_{50\%}$ are leaching requirements for 10, 25, and 50 % yield reductions, respectively)
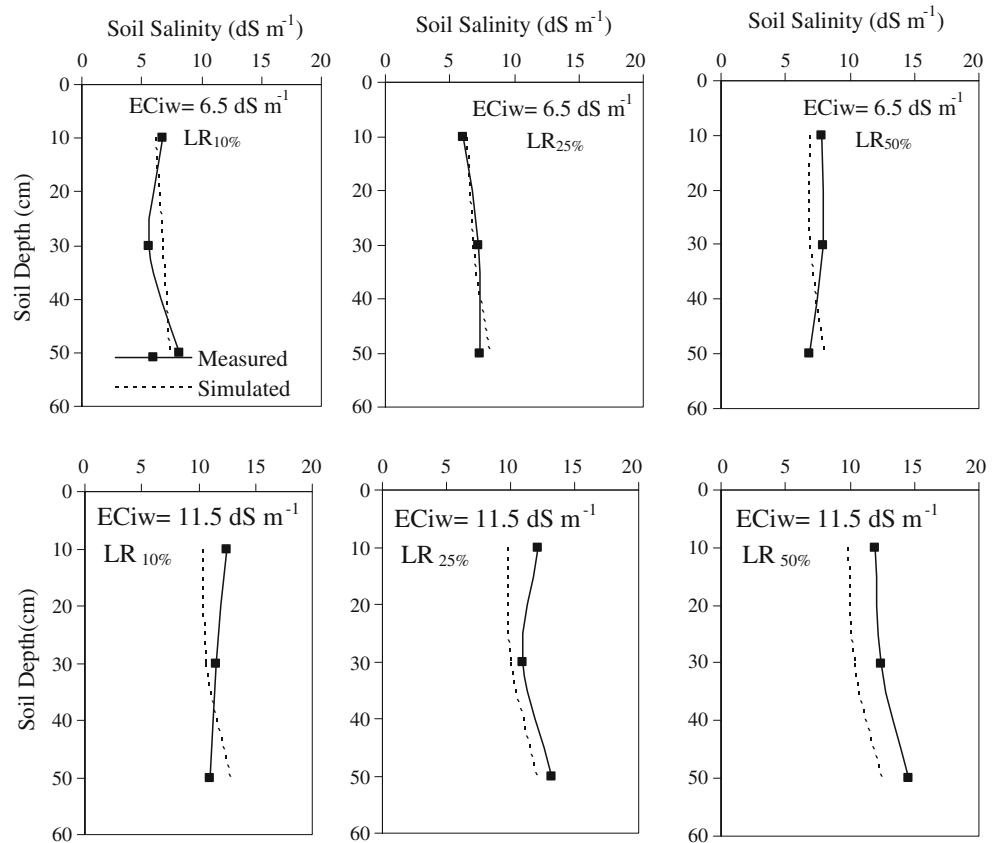
UNSATCHEM model can thus be used to evaluate the effects of various factors on the development of salinity for different situations.

### Scenario 1: Salinization for different modes of conjunctive water use

Different scenarios (Table 4) with cyclic and blending use of irrigation water were evaluated using the UNSATCHEM model. The average root-zone salinity throughout the season for the LS:HS, HS:LS, 3LS:3HS, and mixed (1:1) modes were 6.31, 5.93, 6.04, and 5.56 dS m^{-1},

respectively. The lowest soil salinity was obtained for the mixed (1:1) mode and the highest for the LS:HS mode.

Since the salt tolerance of wheat varies at different stages of its growth, seasonal changes in root-zone salinity can influence the crop yield substantially. Time changes of the average root-zone salinity for different modes of conjunctive water use are shown in Fig. 6. For the 3LS:3HS mode, soil salinity remained lower than 6.9 dS m^{-1} (the threshold limit for yield reduction) up to 120 days after planting. Although for this mode, soil salinity was relatively high during the last 40 days of the growth period (up to 11.2 dS m^{-1}), salinity during this growth phase does not

Table 4 Results simulated using UNSATCHEM for different modes of the conjunctive water use (Scenario 1)

Conjunctive use practice	Description	Soil salinity at different depths (dS m^{-1})			Average root-zone salinity (dS m^{-1})
		0–30	30–60	60–90	
LS	Irrigations with low-salinity water only	3.52	3.88	4.53	3.97
3LS + 3HS	Three irrigations with low-salinity water, followed by three irrigations with high-salinity water	4.88	5.08	8.17	6.04
LS + HS	Alternate irrigations with low-salinity and high-salinity waters	4.28	5.85	8.82	6.31
HS + LS	Alternate irrigations with high-salinity and low-salinity water	4.27	5.19	8.33	5.93
MIX (1:1)	Irrigations with water mixed from low- and high-salinity waters (1:1)	4.26	5.27	8.17	5.56
HS	Irrigations with high-salinity water only	7.73	8.50	13.31	9.85
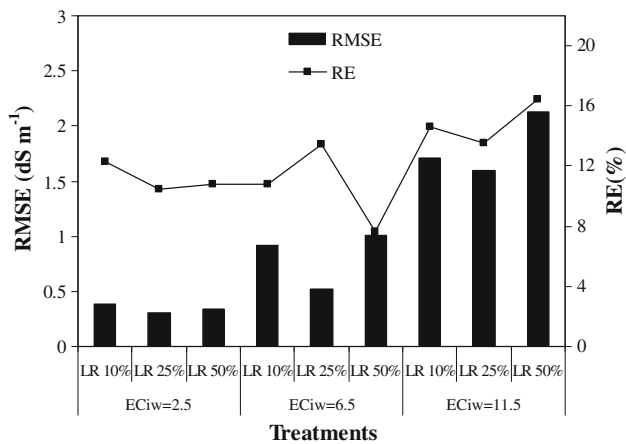
Fig. 5 The performance statistics comparing simulated versus measured data (*RMSE* root mean square error, *RE* relative error)
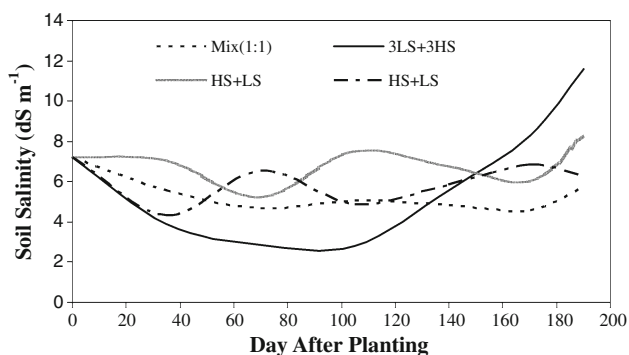
Fig. 6 Seasonal changes in average soil salinity for different modes of conjunctive water use

have a considerable effect on wheat's function and performance. For the LS:HS mode, soil salinity was low during the first 35 days. After that, soil salinity started fluctuating between 4.9 and 6.9 dS m^{-1}, depending on whether good- or poor-quality water was used for irrigation. For the HS:LS mode, high-salinity water was applied during the early stage of the wheat growth. Although soil salinity was then reduced when high-quality water was used for irrigation later on, this practice should not be used because early salinity may adversely affect germination, a growth stage negatively affected by high salinity. For the mix (1:1) mode, soil salinity fluctuated around 5.38 dS m^{-1} from the beginning to the end of the growing season.

The early stages of wheat growth are considered most sensitive to the salt stress, and its salt tolerance increases with growth (Maas and Poss 1989; Ranjbar 2010). In order to minimize the salinity stress, good quality water must be allocated for the most sensitive stages of crop growth. Therefore, the most suitable modes of conjunctive water use with low- and high-salinity waters during the growing season, while controlling initial soil salinity, are 3L:3H, followed by the LS:HS, and mix (1:1) modes. The optimal

strategy of conjunctive water use for the wheat crop is to delay as much as possible the use of saline waters, which may lead to the salinity stress, while always keeping salt concentrations within permissible limits, especially during early crop stages.

Wheat yields reported by Minhas and Gupta (1993a) and Ranjbar (2010) validate this recommendation. Experiments carried out on Iranian wheat cultivars grown in sand containing 200 mM of salt have indicated that the wheat yield was reduced by a half in treatments that exposed wheat to salts during early vegetative growth stages, compared to treatments in which wheat encountered increased salinity during later reproductive stages (Ranjbar 2010). It was concluded that the more delayed irrigation with saline water is, the more water productivity can be achieved. Experiments of Minhas and Gupa (1993a) showed that when irrigations with saline water start at jointing, non-saline/saline waters are used cyclically, and salinity is increased gradually, wheat yield is higher than in other treatments. They estimated that salinity (expressed as EC_{50}) during the salt-tolerant stage (dough to maturity) can be as much as 1.4 times higher than during the salt-sensitive growth stage (seedling to root crown) (i.e., 13.2 vs. 9.3 dS m^{-1}). Simulation results indicate that up to 90 % of the potential wheat yield can be achieved under conjunctive water use when non-saline water is used until the third post-sowing irrigation, while water with an EC_{iw} of 51.4 dS m^{-1} is used thereafter (Minhas and Gupta 1993b).

The above discussion suggests that initial soil salinity, quality of irrigation water applied during an early growth stage, and practices of conjunctive water use have a significant impact on temporal changes in root-zone salinity and that these changes affect the wheat yield.

Scenario 2: Salinization for different amounts of applied water

The salt balance components for different amounts of irrigation water (1.1, 1.2, 1.3, or 1.4 ET) and annual rainfall (no rainfall or average rainfall) are given in Table 5. The soil profile salt balance (initial and final mass of salts) is given for the upper layer of soil (50 cm). The salt balance was significantly affected by the amount of applied irrigation water and the presence of rainfall. Results suggest that salt accumulation was inversely proportional to the quantity of applied water. The less the irrigation water was applied, the higher was the salinization risks of soils under irrigation. Soil salinity increased by 8.6, 23.5, and 58 % when the quantity of applied water decreased from 1.4 ET to 1.3, 1.2, and 1.1 ET, respectively. The corresponding values when annual rainfall of 300 mm was considered in simulations were 2.7, 5.5, and 13.7 %, respectively. Since 140 mm of rainfall (during the growth season) met evapotranspiration needs of

the plants, this quantity of water was subtracted from the total irrigation water used. Thus, the salt input to the soil through irrigation, as given in Table 5, was reduced by 1.4 kg m^{-2}. Furthermore, 53 % (160 cm) of rainfall occurred during the winter months, percolating through soil and leaching salts below the upper soil layer. Hence, the amount of salt stored in the soil was reduced by rainfall.

Chemical precipitation/dissolution reactions also affected the salt balance in the soil profile. Results showed that because irrigation water is high in gypsum and carbonate minerals, salts tend to precipitate in the soil profile in all irrigation treatments. The relative amount of salts that precipitated varied inversely with the amount of applied water and/or rainfall. More salts precipitated when less irrigation water was applied, especially if accompanied by a lack of rain conditions. For conditions without rainfall, 0.89, 0.83, 0.76, and 0.68 kg m^{-2} salts were estimated to precipitate for 1.1, 1.2, 1.3, and 1.4 ET irrigation treatments, respectively. Less salts precipitated when soil received 300 mm of rainfall. The amounts of precipitated salts for sub-scenarios with and without rainfall and for different irrigation quantities during the growing season are shown in Fig. 7. This figure shows that the less the water for irrigation was applied, the earlier the salts started precipitating and the more the salts precipitated during the entire season. Additionally, during the rainy season (from 10 to 150 days after planting), no salt precipitation occurred in the soil profile.

Table 5 shows that salts leaching from the top 50 cm of soil and the amount of applied water were closely related. More leaching of salts occurred when more irrigation water was applied. Under no rainfall conditions, 1.07 and 2.55 kg m^{-2} of salts were leached below the depth of 50 cm when irrigation was equal to 1.1 and 1.4 ET, respectively. A fraction of leached salts below the depth of 50 cm to salt input through irrigation was 0.68, 0.61, 0.52, and 0.36 for irrigation equal to 1.4, 1.3, 1.2, and 1.1 ET. Fraction of leached salts thus decreased with reduced irrigation. A similar trend was also observed for conditions with rainfall. Salt losses under no rainfall conditions were higher than under conditions with rainfall. This can be attributed to the higher quantity of salt input through irrigation in the absence of rainfall.

A combination of chemical precipitation and leaching resulted in favorable root-zone salinity. For sustainable agriculture, irrigation should be managed such that the salt precipitation is maintained at high levels without a significant reduction in the crop production (Bresler et al. 1982). Simulated results showed that 26 and 30 % of salts applied with irrigation water in the 1.2 and 1.1 ET irrigation treatments, respectively, contributed to the precipitation process when no rain was considered. Salt concentrations (Fig. 8) exceeded 7 dS m^{-1} after the 115th and 135th day after planting, respectively, and were continuously increasing until the end of the season. When rainfall was considered, soil salinity for all irrigation treatments remained below 7 dS m^{-1} during the growing season. These results indicate that an application of irrigation water at 1.3 ET (a leaching fraction of 23 %) would guarantee the optimal wheat yield under dry conditions (no rainfall) in the study area. On the other hand, the 1.1 *ET* irrigation treatment (a leaching fraction of 10 %) can be successfully used in normal years with average rainfall of 300 mm.

Scenario 3: Evaluation of the maximum EC$_{iw}$ to maintain the average root-zone salinity below the soil salinity threshold

The maximum EC of the irrigation water (EC$_{iw}$) that maintains an average root-zone salinity below 6.9 dS m^{-1} during the growing season was evaluated for different rates of rainfall (for dry, average, and above-average rainfall years). Simulation results indicate that the seasonal-average root-zone salinity over the 3-year period for sub-average rainfall conditions (annual rainfall of 110 mm) was 4.6, 6.7, 9.1, and 10.1 dS m^{-1} when the EC of irrigation water was 4, 6, 8, and 10 dS m^{-1} (Fig. 9), respectively. Corresponding root-zone salinities for average rainfall conditions were 4.6, 6.8, 9.1, and 10.1 dS m^{-1}—almost the same. Finally, wetter conditions (with average rainfall of 450 mm) resulted in average root-zone salinity of 3.2, 4.8, 6.4, and 7.4 dS m^{-1}, respectively. For all irrigation waters in the above-average rainfall years and for an EC$_{iw}$ of 4 dS m^{-1} in average rainfall years, the seasonal root-zone salinity was lower than the EC$_{iw}$ of

Table 5 Components of the salt balance (kg m^{-2}) for simulations involving wheat crop and various water applications (Scenario 2)

	Rain = 0				Rainfall = 300 mm			
	1.4 ET	1.3 ET	1.2 ET	1.1 ET	1.4 ET	1.3 ET	1.2 ET	1.1 ET
Initial	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Irrigation	3.74	3.47	3.20	2.94	2.35	2.08	1.81	1.54
Leaching	2.55	2.13	1.67	1.07	1.66	1.24	0.91	0.56
Final	0.81	0.88	1.00	1.28	0.73	0.75	0.77	0.83
Precipitation (calcite and gypsum)	0.68	0.76	0.83	0.89	0.26	0.39	0.43	0.45
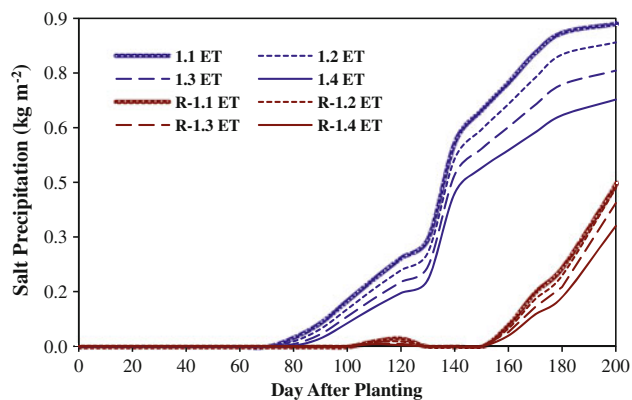
Fig. 7 Changes in salt precipitation during wheat growing season (*ET* evapotranspiration, *R* simulation considering annual rainfall)
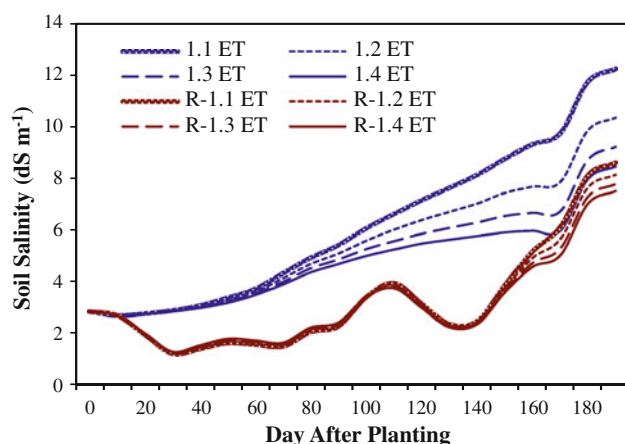
Fig. 8 Changes in soil salinity during wheat growing season (*ET* evapotranspiration, *R* simulations considering annual rainfall)
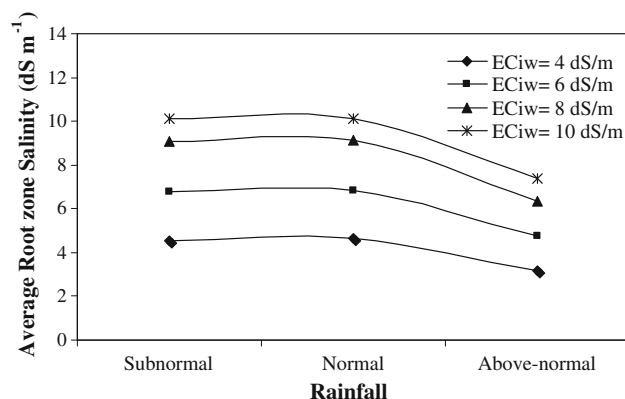
Fig. 9 Simulated root-zone salinity for various rainfall rates and different qualities of irrigation water

irrigation water, due to rain-induced salt leaching during the cool winter rainy season.

During sub-average and average rainfall years, irrigation waters with salinities of 4 and 6 dS m^{-1} can be safely used without any loss in the wheat yield. However, irrigation

water salinities of 8 and 10 dS m^{-1} produced reductions in wheat yield of 12.1 and 12.4 %, and 18.0 and 18.6 % in sub-average and average rainfall years, respectively. For above-average rainfall years, soil salinity remained below the salinity threshold except when irrigation water with salinity of 10 dS m^{-1} was used. However, even this case did not produce a dramatic reduction in wheat yield.

Reduced grain yield can be attributed to osmotic stress. In saline soils, osmotic potential can be so low that plants cannot overcome it and cannot take up enough water, suffering from the effects of osmotic or salinity stress (Heikal and Shaddad 1981). Osmotic stress reduces germination, seedling growth, leaf expansion, and the root growth rate, leading to a reduction in the yield of the wheat crop (Läuchli and Grattan 2007).

The following relationships between permissible irrigation water salinity (EC*$_{iw}$) and the wheat salinity threshold (EC$_t$) for different rainfall series were developed based on simulated results discussed above:

$$EC^*_{iw} = 1.042 EC_t - 0.978 \quad R^2 = 0.978$$
Sub-average rainfall \hfill (12)

$$EC^*_{iw} = 1.069 EC_t - 1.083 \quad R^2 = 0.975$$
Average rainfall \hfill (13)

$$EC^*_{iw} = 1.306 EC_t - 0.704 \quad R^2 = 0.993$$
Above-average rainfall \hfill (14)

These relationships (Eqs. 12–14) can be used to estimate the salinity of irrigation water that will not produce average soil salinity higher that the threshold for wheat production. Considering a soil salinity threshold of 6.9 dS m^{-1} and substituting it into Eqs. 12–14, the maximum salinity of irrigation water for different rainfall conditions can be estimated. The maximum salinity of irrigation water for the optimum production of wheat is 6.21 and 6.29 dS m^{-1} for sub-average and average rainfall years, respectively. Interestingly, the dryer 3-year period resulted in average root-zone salinity values equal to those for the average 3-year period, suggesting that rainfall distribution also plays an important role in determining the soil salinity. Irrigation water with a salinity of up to 8.31 dS m^{-1} can be applied without any reduction in wheat yield in above-average rainfall years.

These results suggest that consideration of rainfall would produce lower leaching requirements or higher permissible EC$_{iw}$, thus allowing farmers to use either less irrigation water or water with lower quality (Letey et al. 2011; Isidoro and Grattan 2011). Data collected from the wheat-cultivated land of the Fars Province indicate that the average wheat yield increases by about 900 kg ha^{-1} in those years, for which annual rainfall is 50 % above its long-term mean (Cheraghi and Rasouli 2008). Saline water was also successfully used in the high-rainfall (>550 mm)

Fig. 10 Temporal changes in simulated root-zone salinity when irrigation waters with EC_{iw} of 2, 4, 6, and 8 dS m^{-1} are used
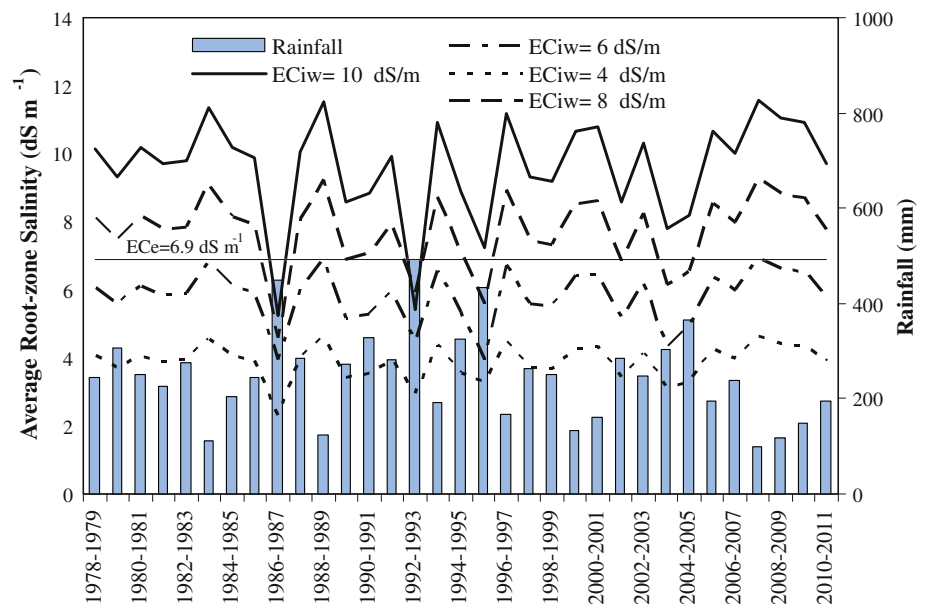

agro-ecological zone of India. Guidelines for utilizing saline water in these areas indicate that allowable EC_{iw} is about 1.8 times larger than that in low-rainfall (<350 mm) regions (Minhas et al. 1998).

Another scenario that was evaluated involved the entire 33-year rainfall series (Fig. 10). Simulations that consider applications of irrigation waters of different salinities for the entire 33-year series of meteorological data should provide the best insight into variations of soil salinity over the long term. If irrigation waters with an EC_{iw} of 4, 6, 8, and 10 dS m^{-1} are used for the entire period of 33 years (from 1978 to 2011), the EC_e seasonal-average root-zone salinity will range from 2.3 to 4.6, 3.9 to 7.0, 4.6 to 9.3, and 5.35 to 11.6 dS m^{-1}, with mean values of 3.9, 5.8, 7.7, and 9.7 dS m^{-1}, respectively (Fig. 10). The salinity threshold value of 6.9 dS m^{-1} for wheat (Wahedi 1995) is never reached over the entire analyzed time period when irrigation water with an EC_{iw} of 4 dS m^{-1} is used. When irrigation water with an EC_{iw} of 6 dS m^{-1} is used, maximum seasonal soil salinity is maintained below 6.95 dS m^{-1}, which translates into a yield of over 99.7 % of the optimal production.

Simulations further show that irrigation water with an EC_{iw} of 8 dS m^{-1} can be safely used only in above-average rainfall years. Annual rainfall of 365 mm or more was found to be adequate to keep soil salinity below the threshold value for wheat. For irrigation water with an EC_{iw} of 8 dS m^{-1}, an appreciable yield loss of more than 10 % would occur in only 5 years. The maximum yield reduction of about 13 % would presumably occur in the 2007–2008 year, which had the lowest amount of annual rainfall on record. The use of irrigation water with a salinity of 10 dS m^{-1} would increase soil salinity above the threshold yield level in all years except in the 2 years
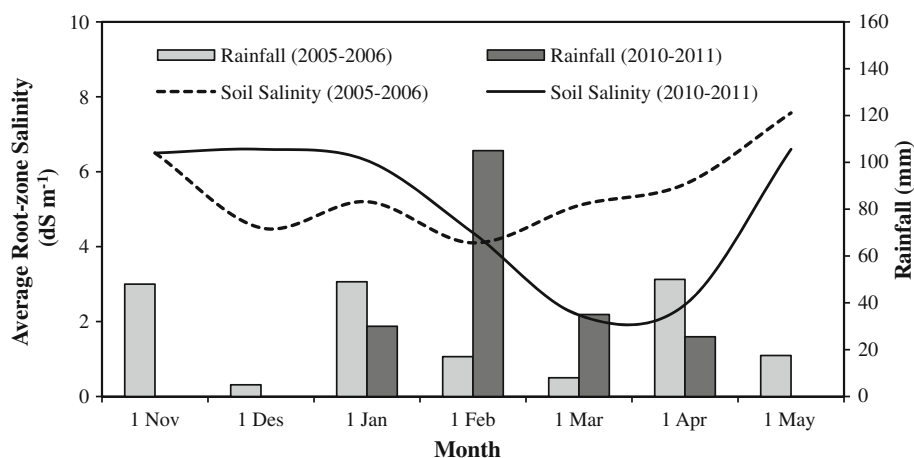
(1986–1987 and 1992–1993) with very high annual rainfall (449 and 491 mm). The buildup in soil salinity would cause a loss in the wheat yield ranging from 3 to 26 %.

Results of the probability analysis for the entire time period of 33 years (Fig. 11) illustrate that all seasonal-average root-zone salinities are below the threshold value of 6.9 when irrigation waters with salinities of 4 and 6 dS m^{-1} are used. On the other hand, there are only seven and 2 years when the seasonal-average root-zone salinity is below 6.9 dS m^{-1} when irrigation waters with an EC_{iw} of 8 and 10 dS m^{-1} are used, respectively. Given these long-term simulation results and taking into account all other factors that may potentially impact the crop yield, using irrigation water of 6 dS m^{-1} as a threshold EC_{iw} value for irrigation water can be considered to be a conservative choice for cultivating wheat in the Sarvestan area.
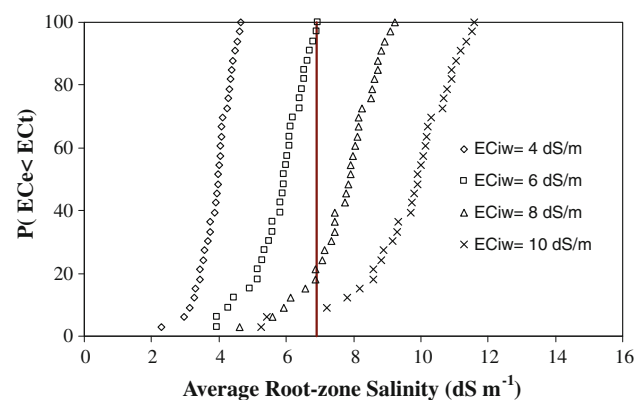
Fig. 11 The probability distribution function of the root-zone salinity (EC_e) being smaller than the wheat yield threshold (EC_t) obtained by simulating the 33-year series with irrigation waters of an EC_{iw} of 4, 6, 8, and 10 dS m^{-1}

Results of the long-term simulations for a given irriga-
tion water salinity (Fig. 10) showed certain variability in
soil salinity not only for different amounts of annual
rainfall, but also for the same amounts of annual rainfall
when rainfall was differently distributed during the year.
To test this phenomenon, simulations for 2 years
(2005–2006 and 2010–2011) with similar rainfall and
irrigation water with salinity of 6 dS m^{-1} were carried out
and compared in Fig. 12. Simulated results showed that the
mean seasonal soil salinity was lower (5.1 dS m^{-1}) in
2010–2011 than in 2005–2006 (5.9 dS m^{-1}). Rainfall that
occurred in a short period of the winter of 2010–2011 was
more effective in reducing the salinity of soil in the root
zone than a similar amount of rainfall distributed
throughout the entire year of 2005–2006. Moreover,
changes in soil salinity during the wheat growing season in
2010–2011 were not consistent with those in 2005–2006.
In the early wheat growth stage of 2005–2006, soil salinity
was lower than in 2010–2011. On the other hand, after
February of 2011, soil salinity dropped dramatically and
stayed continuously below levels reached in 2005–2006.

These results suggest that while winter-concentrated
rainfall has an important influence on seasonal root-zone
salinity, initial soil salinity may be sufficiently reduced by
late autumn rainfall. High initial (during wheat germina-
tion) soil salinity is one of the limiting factors for wheat
production in the Fars Province of Iran (Cheraghi and
Rasouli 2008). Autumn rainfall would thus be very effec-
tive for conditions in which the initial level of soil salinity
is so high that it could adversely influence the wheat
establishment. Research conducted in different parts of the
Fars Province has shown that 30–50 mm of rain would be
sufficient to flush salts out of the top 30 cm depth (Cher-
aghi and Rasouli 2008). In the study area, in 28 years of the
studied time period (33 years), rainfall occurred in late
autumn. The amount of rainfall varied between 12 and
343 mm from November 23 to December 23, a

recommended planting date for wheat in the Fars Province.
Meteorological data illustrate that in 24 years, rainfall was
at least 40 mm during the optimum planting time period. In
other words, rainfall is an important potential salt-leaching
factor in the early stages of wheat growth in 73 % of years.
Hence, irrigation with saline water should be delayed after
December 23, because rainfall may improve conditions for
germination and ensure low salinity in the root zone during
the planting month. If there is not enough rainfall to leach
accumulated salts, non-saline water may need to be applied
to leach salts out of the root zone during stand
establishment.

Conclusions

Numerical simulations with the UNSATCHEM model
were used to evaluate the effects of saline water used for
irrigation of wheat on root-zone salinity and wheat yield.
Based on temporal changes in root-zone salinity simulated
for different modes of conjunctive water use, the following
ranking in the order of decreasing preference (in terms of
yield) was obtained: alternate 3LS:3HS, LS:HS, Mix (1:1),
and alternate HS:LS. Optimal planning of conjunctive
irrigation water use should attempt to delay the salinity
stress to later growth stages as much as possible and to
always keep it within permissible limits.

The balance of salt fluxes and salt storage in the soil
profile was affected by the quantity and quality of irrigation
water, the quantity of rainfall, and by dissolution/pre-
cipitation reactions. Rainfall had a significant effect on soil
desalinization. In addition, precipitation reactions removed
salts from the soil solution and lowered the solution con-
centrations in the root zone, especially when less irrigation
water was used.

The maximum irrigation water EC$_{iw}$ that can be used to
maintain soil salinity below the wheat yield threshold of

6.9 dS m^{-1} throughout the growing season was calculated after taking into account different rates of rainfall. Maximum salinity of irrigation water for a sustainable production of wheat was 6.21 and 6.29 dS m^{-1} for sub-average and average rainfall years, respectively. For above-average rainfall years, saline water with an EC$_{iw}$ of up to 8.31 dS m^{-1} can be applied without any reduction in wheat yield.

For irrigating wheat on a sustainable basis, long-term simulations indicate that it is possible to use saline water with an EC$_{iw}$ of 6.29 dS m^{-1}. Similar types of simulations as these can be used to find a suitable quality of irrigation water for different salinity-sensitive crops. This modeling approach can be valuable not only for policy and decision makers, but also for irrigation managers. Given these results and taking into account other factors that can potentially impact crop yield, the use of 6 dS m^{-1} as the threshold EC$_{iw}$ value for irrigation water can be considered a conservative value for wheat in the study area.

Rainfall distribution also plays a major role in determining the salinity of the soil in the root zone. The winter-concentrated rainfall is more effective in reducing soil salinity than a similar amount of rainfall distributed throughout the autumn, winter, and spring seasons. Autumn rainfall would be very effective in reducing the potentially high initial soil salinity level to levels that would not adversely influence wheat establishment.

Results of this study can help us predict the salinity of water, which can be used on a sustainable and long-term basis for irrigating a clay loam soil. Moreover, the management option for minimizing root-zone salinity during the establishment stage by considering the effects of rainfall was evaluated. There are different climatic zones in the Fars Province, in which weather, water quality, and soil conditions may vary. The long-term simulations can be effectively used to establish safe salinity limits for irrigation waters for different climatic zones.

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