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Evaluating the effects of irrigation water salinity on water movement, crop yield and water use efficiency by means of a coupled hydrologic/crop growth model

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ABSTRACT

Numerical simulation is an efficient approach for investigating the salt and water movement through soil profile and predicting of crop response to soil water deficit and salinity. In this study a coupled model that describes the soil water and solute transport by means of HYDRUS-1D model and crop growth process by means of growth module of EPIC was used. The model was calibrated and validated against field data, collected during two growing seasons in field plots of winter wheat irrigated with four levels of irrigation amount and water salinity of 5 ds m^{-1} at the Fengqiu State Key Agro-Ecological Experimental Station, in North China Plain. The model was also used to evaluate the salinity stress on evapotranspiration (ET), grain yield and water use efficiency (WUE) and long-term use of saline water on grain yield and salt accumulation. Visual inspection and the obtained statistical parameters values showed that good agreement between measured and simulated data of soil water content, salt concentration, ET and grain yield. Evapotranspiration values of winter wheat were reduced under salinity stress conditions, mainly by reducing crop transpiration. The grain yields were reduced due to salinity stress, but the change trend of WUE was associated with precipitation amount. Increasing per saline water irrigation amount is an effective way to reduce the WUE decline rate under the low rainfall growing season as like that in simulation year. The average of ten years grain yield confirmed that a yield potential exceeding 86% could be maintained by saline water with 5 ds m^{-1} when per irrigation volume more than 0.8 E, E denotes evaporation from an uncovered, 20 cm diameter pan positioned 0–5 cm above the crop canopy. There has a slight salt build-up after ten years simulation, and the quantity of salt accumulation decreased with the increase of irrigation volume. Thus, more attention should be paid to the sustainability of irrigated agriculture with low irrigation volume when using saline water irrigation. On the whole, field observations combined with the coupled model could be used to evaluate different agricultural managements on grain yield and soil salinity.

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1. Introduction

A shortage of fresh water limits sustainable agriculture development worldwide (Mantell et al., 1985; Sun et al., 2010; Verma et al., 2012; Chen et al., 2014; Min et al., 2014; Kumar et al., 2015), thus, farmers are forced to explore the possibility of utilizing moderately saline water for agricultural production (Letey and Feng, 2007; Pang et al., 2010; Chen et al., 2014; Lekakis and Antonopoulos, 2015; Mguidiche et al., 2015). However, the salts are added to the soil with saline water irrigation, therefore it may lead to soil salinization and crop yields reduction. Verma et al. (2012) indicated that soil resource health and crop yields are the two parameters of great consequence in the use of saline water for crop production. Management of saline water for irrigation is traditionally based on the application of excess water to maintain minimum root zone salinity and consequently minimize salinity-caused yield reduction (Ayers and Westcot, 1985). However, more water does not necessarily correspond to maximum yield and water use efficiency when using saline water for irrigation (Russo and Bakker, 1987; Amer, 2010).

Numerical simulation is an efficient approach for investigating the salt and water movement through soil profile and predicting of crop response to soil water and salinity (Lekakis and Antonopoulos,

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Table 1
Soil physical properties of experimental area.

Soil depths (cm)	Soil particle percent (%)			Soil classification	Soil bulk density ($g\,cm^{-3}$)	Field capacity ($cm^3\,cm^{-3}$)	Permanent wilting point water ($cm^3\,cm^{-3}$)
	Sand (>0.05 mm)	Silt (0.05–0.002 mm)	Clay (<0.002 mm)				
0–20	10.1	72.0	17.9	Silt loam	1.47	0.32	0.095
20–40	7.1	76.0	16.9	Silt loam	1.46	0.32	0.096
40–60	6.4	81.3	12.4	Silt loam	1.42	0.32	0.089
60–80	0.7	75.2	24.1	Silt loam	1.42	0.35	0.117
80–120	6.8	76.8	16.4	Silt loam	1.43	0.33	0.096

2015; Ghazouani et al., 2016; Karandish and Šimůnek, 2016). In the past several years, various studies have been conducted to analyze water and solute transport, and crop response under different climatic and agronomic conditions by using hydrologic or crop growth models (Hu et al., 2006; Wang and Huang, 2008; Wang et al., 2010; Verma et al., 2012; He et al., 2013; Chen et al., 2014; Rallo et al., 2014; Mguidiche et al., 2015; Ghazouani et al., 2016; Karandish and Šimůnek, 2016). Zhou et al. (2012) indicated that the coupling of hydrologic and crop growth models connects hydrology and agronomy quantitatively and provides a bridge across the boundaries of the two subjects. They also indicated that the coupled modeling approach was better than a single-model method (Eitzinger et al., 2004; Cammalleri et al., 2010; Zhou et al., 2012). Among the hydrologic models, the HYDRUS-1D has been widely used due to its good performance in simulating one-dimensional soil water, heat and solute movement in variably-saturated media (Šimůnek et al., 2008; Sarmah et al., 2005; Šimůnek and Hopmans, 2009; Bah et al., 2009). However, the original version of HYDRUS-1D was developed without considering crop growth module, thus the effect of agricultural managements on grain yield can't be evaluated. Zhou et al. (2012) coupled the HYDRUS-1D and WOFOST crop growth model to improve crop production prediction through accurate simulations of actual transpiration with a root water uptake method and soil moisture profile with the Richards' equation during crop growth. Simultaneously, crop growth module of EPIC was preferred at field production level due to its less demanding data input (Li et al., 2007; Xu et al., 2013; Wang et al., 2014; Wang et al., 2015a), which uses a unified approach to simulate more than 100 types of crops (Williams, 1995). Han et al. (2015) implemented the crop growth module of EPIC into HYDRUS-1D to study the impact of groundwater on cotton growth and soil water dynamics. Xu et al. (2013) and Wang et al. (2014) coupled the crop growth module of EPIC with the SWAP model and CHAIN-2D to assess soil water, soil salinity and crop yield, respectively. Wang et al. (2015a) implemented the crop growth module of EPIC into HYDRUS-1D to simulate the response of soil water, nitrogen movement and crop yield under sprinkler irrigation. Most of the research focused on the effect of agricultural managements on grain yields and soil water dynamics, few of them paid attention to model the root growth algorithm and root water uptake. However, to the best of our knowledge, there are few studies evaluating the water salinity on root water uptake and long-term use of saline water on grain yield and salt accumulation.

The main objectives of this paper were (1) to calibrate and validate the coupled model by field measured data; (2) to evaluate the effect of salinity stress on evapotranspiration, evaporation, transpiration, grain yield and water use efficiency; (3) to assess the long-term use of saline water on grain yield and salt accumulation.

2. Materials and methods

2.1. Experiment design and treatments

Field experiments were conducted from 2011 to 2013 at the Fengqiu State Key Agro-Ecological Experimental Station (35°01′N, 114°32′E), Henan Province, China. The site has a monsoon climate with a mean annual temperature of 13.9 °C and a mean annual precipitation of 615 mm (Ding et al., 2010).The experiment was split-plot design with four levels of irrigation amount equals to 0.8 E, 1.0 E, 1.2 E and 1.4 E, and water salinity of 5 ds cm^{-1} in three replicates. E denotes evaporation from an uncovered, 20 cm diameter pan (Model ADM7, China) positioned 0–5 cm above the crop canopy (Wang et al., 2015b). Each plot measured 1 m × 1 m and was bordered by cement curbs to minimize the effects of lateral water and salt movement between plots. Fertilizer rates were similar to local practices. A total of 500 kg ha^{-1} was applied at preplanting stage in the form of ammonium nitrate, P_2O_5 and K_2O at a rate of (N: P_2O_5:K_2O = 32:4:4%). Urea was applied at a rate of 300 kg ha^{-1} with the first irrigation water for all treatments.

Table 2
Values of van Genuchten model parameters at different soil layers.

Depth (cm)	θ_r ($cm^3\,cm^{-3}$)	θ_s ($cm^3\,cm^{-3}$)	α(cm^{-1})	n (–)	K_s ($cm\,d^{-1}$)
Initial values					
0–20	0.070	0.433	0.0055	1.643	15
20–40	0.069	0.442	0.0058	1.637	16
40–60	0.064	0.452	0.0060	1.652	23
60–80	0.083	0.464	0.0069	1.575	9
80–120	0.068	0.446	0.0057	1.641	16
Calibrated values					
0–20	0.018	0.451	0.0018	1.351	20
20–40	0.018	0.443	0.0035	1.279	15
40–60	0.024	0.442	0.0032	1.276	10
60–80	0.011	0.457	0.0035	1.204	10
80–120	0.017	0.419	0.0026	1.252	10

Note: The detail information of parameters in Table 2 can be found in Šimůnek et al. (2008).

Soil physical properties at the experimental site are listed in Table 1.The soil profile was divided into five layers based on different physical soil properties. The soil layers were 0–20, 20–40, 40–60, 60–80 and 80–120 cm. The particle size distribution was determined on disturbed soil samples collected using a laser particle size analyzer (Malvern MS2000, UK). It was observed that all soils are silt loams. The soil water content at saturation, field capacity, and wilting point, the bulk density and saturated hydraulic conductivity were measured on undisturbed soil samples at different soil layers. The initial soil hydraulic parameters (Table 2) were estimated from bulk density and percentages of sand, silt and clay values using the Rosetta pedotransfer functions (Schaap et al., 2001).

Daily meteorological data were collected from automatic weather stations installed at the experimental field, including air temperature, relative humidity, net radiation, wind speed and precipitation. Total rainfall was 185 and 45 mm during the first and second growing season, respectively. Daily values of precipitation, pan evaporation and irrigation from the reviving stage to the harvest date are presented in Fig. 1.

Flood irrigation was applied to the plots using water meter to record the water used. Five to eight irrigations at 7–10 days interval were applied during the growing season. The first irrigation

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