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Modeling and assessing feasibility of long-term brackish water irrigation in vertically homogeneous and heterogeneous cultivated lowland in the North China Plain

Bingxia Liu[a], Shiqin Wang[a,*], Xiaole Kong[a,b], Xiaojing Liu[a], Hongyong Sun[a]

[a] *Key Laboratory of Agricultural Water Resources, Hebei Laboratory of Agricultural Water-Saving, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang, 050021, China*

[b] *University of Chinese Academy of Sciences, 19A Yuquan Road, Beijing, 100049, China*

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ABSTRACT

In the North China Plain (NCP), increased water shortages and food yield increase present serious threats to the sustainability of cultivated lands. Irrigation by brackish or saline water is a possible solution to alleviate freshwater shortages. It is critical to understand the soil salt variations and the characteristics of salt accumulation and leaching under long-term brackish water irrigation in cultivated croplands. In this study, the HYDRUS-1D model was calibrated and validated, and then applied to evaluate that how 20 years of irrigating with brackish water affects soil salinity and soil salt transport in wheat-maize cultivated lands with different texture layers in the lowland of NCP. The results showed that the simulations of soil matric potential and soil salt concentrations fitted well with the measured values. Soil salt dynamics were dominated by seasonal precipitation and hydrological years. Seasonal rainfall distribution determined seasonal characteristics of salt changes in shallow layers (0–100 cm). Soil salt accumulated during the growth period of winter wheat corresponding to the dry season, and was greatest at the harvest. Soil salt leached down to deeper soil layers under abundant rainfall during growth period of maize. The annual soil salt in 300 cm profiles were driven by hydrological years, and soil salt could be accumulated in dry and normal years and leached in wet years, especially in the extremely wet year. Soil salt accumulation was higher under two brackish water irrigations compared to one irrigation for winter wheat, and soil salinity in homogeneous soils was less than in the heterogeneous soil with clay loam interlining. The results showed the effect of irrigation times of brackish water was greater than that of soil texture on soil salt accumulation. Our results demonstrated that wheat and maize could be grown well under one irrigation with brackish water a year. Salt accumulation increased with the number of irrigation events that used brackish water for winter wheat. The brackish water irrigation was evaluated and the results demonstrated that partial substitution of fresh water by brackish water for irrigation is feasible in the lowland area of the NCP. It is more suitable for long-term brackish water irrigation in relatively homogeneous soil than in heterogeneous soil. These simulated results are helpful to provide appropriate management measures for long-term brackish water irrigation and fresh water saving, and provide a basis for assessing the environmental effect under long-term brackish water irrigation.

1. Introduction

The lowland area of the North China Plain (NCP) is an important grain, cotton and fruit production region of China (Zhou et al., 2012). In the region, the winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) cultivated in sequence within one year is the dominant double cropping system. The system requires significantly more water than is available from natural precipitation; wheat is especially at risk of water deficiency because it grows in the winter and spring with little rainfall (Sun et al., 2010). Crops in the region are largely irrigated, but irrigation over uses deep groundwater, resulting groundwater decline and a pervasive water scarcity in the NCP. To restrict the exploitation of freshwater resources, the Chinese government implemented a limited pumping program in 2014 in Hebei Plain. However, there are extensive brackish water resources which account for 36% of the total amount of groundwater resources in the coastal plains of North China (Qian et al.,

* Corresponding author.
E-mail addresses: liubingxia2008@126.com (B. Liu), sqwang@sjziam.ac.cn (S. Wang).

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2014 ; Zhang, 2009). There is 32 billion m^3/a of exploitable saline and brackish water in Hebei province, and 28 billion m^3/a of brackish water (1–3 g/l) is available in the coastal plain (Qian et al., 2014). The combination of adequate shallow brackish groundwater and limited fresh water supply necessitate the development of a proper irrigation mode. The utilization of saline and brackish water resources for crop irrigation not only offers potential to alleviate the water scarcity in the region (Chauhan et al., 2008; Ma et al., 2008; Pang et al., 2010), but also may help renew groundwater resources, increase freshwater stores, and protect ecological environment.

Irrigation using saline groundwater for several years may have negative effects including lower crop production and accumulation of soil salts, which, may damage the balance between local soil water and salt, and gradually cause soil salinization and groundwater quality deterioration (Huang et al., 2011a; Verma et al., 2012; Wang et al., 2015). In a multi-year field experiment on brackish water irrigation of a winter-wheat/summer-maize cultivation system, Ma et al. (2010) showed that soil salinity in the 0–100 cm soil layer was up to 133% higher than the initial conditions in dry years. Selim et al. (2012) observed that salinity in the surface soil layer increased with the increase in salt concentration of irrigation water. Experiments following six-years of saline water irrigation on to fruit trees showed that compared with fresh water irrigation, soil salt content increased significantly under saline water irrigation after the third year (Nicolás et al., 2016). Soil salt accumulation and leaching are highly affected by the hydrological conditions (such as hydrological years and precipitation distribution), soil texture as well as frequency of salt water irrigation and crop patterns. It is recommended that medium or long-term saline water irrigation schemes should consider variations in hydrological conditions, climate conditions and soil features to assure the soil salt is within the range for normal crop growth. Therefore, it is important to study the effects of long-term use of brackish water for irrigation on soil salinity in the NCP.

Several researchers have indicated that brackish or saline water can be used for irrigated crops (Jiang et al., 2012; Kiani and Mirlatifi, 2012; Malash et al., 2012; Singh and Panda, 2012; Sharma et al., 2013). Xue and Ren (2017) studied soil salinity in the root zone did not increase with saline irrigation over time, and they demonstrated that partial substitution of fresh water with shallow saline groundwater for irrigation is feasible in the Hetao Irrigation District. Rasouli et al. (2013) studied the maximum salinity of the irrigation water supply that can be safely used in the long-term (33 years) without impairing wheat production, they determined the maximum safe salinity level to be 6 dS/m in southwest Iran. Saline water irrigation has been widely reported for different crops in the NCP during field experiments over several years (Pang et al., 2010; Sun et al., 2012; Wan et al., 2010). Based on experimental results, saline water irrigation (< 5 g/l) at the jointing stage of winter wheat provided clear benefits to wheat yields compared to no irrigation, as well as insignificant yield losses compared to fresh water irrigation in lowland areas of the NCP (Chen et al., 2016; Liu et al., 2016).

Traditional field-based experiments require considerable time, expense and labor, and long-term trends in the spatial and temporal patterns of variability at the field scale cannot be established. Mathematical models have the advantage of evaluating long-term consequences of saline water irrigation by considering spatial variability in time series, weather, crops, and soil factors (Ramos et al., 2011, 2012; Rasouli et al., 2013; Kumar et al., 2015). A variety of simulation models have been developed to describe the aquifer-soil-vegetation-atmosphere system, including HYDRUS (Šimůnek et al., 2013), SWAP (Kroes et al., 2008) and SIMdualKc (Rosa et al., 2012). Using HYDRUS-1D to analyze the effects of saline irrigation on soil salt accumulation and grain yield in the winter wheat-summer maize double cropping system in the low plain of NCP, Liu et al. (2016) concluded that the risk of long-term accumulation of salts as a result of saline irrigation during the peak of dry season is considered low. Wang et al. (2017) found that winter wheat yield decreased by 10% and soil salinity increased above the initial value as the result of brackish water irrigation using HYDRUS-ID coupled with a crop growth model. Under brackish water irrigation Kanzari et al. (2012) modelled salt balance across a 4-m-depth and showed high salt accumulation and salinity at a clay-silt interface. Considering the importance of using numerical models for a better understanding of salinity processes and for evaluating various irrigation management options, a widely verified and used model HYDRUS-1D was adopted in our study to simulate soil water flow and solute transport processes in irrigated croplands (Min et al., 2015; Ren et al., 2016; Shang et al., 2016). However, few studies have modelled soil salt migration processes considering different soil textures and brackish water irrigation scenarios under long-term period.

In this study, the HYDRUS-1D model was calibrated and validated against experimental data whereby brackish water has been used for irrigation. Further simulations were carried out using the model to obtain a better understanding how 20 years of irrigating with brackish water affects soil profile salinity and soil salt transport in wheat-maize cultivated lands. Our objectives were: (I) to test the feasibility of the HYDRUS-1D model in simulating water flow and solute transport through calibrating and validating the model with observed data; (II) to investigate the characteristics of soil salt accumulation and leaching, and long term trends of soil salinity under different irrigation scenarios and soil texture conditions, and (III) to assess whether it is feasible to irrigate using brackish water for 20 years in wheat-maize croplands under vertical homogeneous and heterogeneous soil profile.

2. Material and methods

2.1. Study area

The study was conducted in Nanpi County, Hebei province, China, which is located in the Hebei Lowland area around the Bohai Sea in the NCP (Fig. 1). The climate is semi-arid monsoon, with hot, humid summer, and a rainy season from July to September. During the period of 1990 to 2016, the average annual precipitation is 562 mm, and about 80% concentrates on the four months (Jun-Sep), with the other months of a year experiencing rather arid conditions. The mean annual temperature is 13.2 °C. The annual evaporation in the region is 1900–2200 mm. The extensive brackish water resources in Nanpi County in the upper aquifer (shallow groundwater) are stored about at a depth of 10–60 m and have total dissolved solids (TDS) ranging from 2 g/L to 5 g/L (electrical conductivity (EC) of 2.8–8.2 ds/m) (MWR, 1998). Historically, saline-alkaline soils account for 0.39 million ha (11.6%) of arable land from the 1960s to 1980s in this study area. The soils are characterized by excessive sodium chloride (NaCl) and sodium sulfate (Na_2SO_4) (Yang et al., 2016). The traditional agricultural system of the area is dominated by a winter wheat-summer maize double cropping agro-system sequence within one year. Winter wheat is usually grown from early October to June of the following year, followed by summer maize from the middle June to the end of September.

2.2. Measurements

The filed experiments were conducted in two irrigated croplands, which cultivated with winter wheat-summer maize. Soil profiles in the two experimental sites were different in soil texture. The soil with clay loam (30–170 cm) and sandy loam (0–30 cm and 170–300 cm) are distributed in an interlayered way at site 1, indicative of the heterogeneous soil structure. While the soil profile is almost consisted with silt loam (30–150 and 170–300 cm) at site 2, and with clay loam only in 0–30 cm and 150–170 cm depth, showing a relatively homogeneous structure.

Soil matric potential data were obtained by tensionmeters and recorded automatically every hour at depths of 10, 20, 30, 50, 70, 100, 150, 200, 250, and 300 cm in two croplands from 14 July to 30