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THEMATIC ISSUE

Regulation of secondary soil salinization in semi-arid regions: a simulation research in the Nanshantaizi area along the Silk Road, northwest China

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Abstract The degradation of soil quality is a common issue in arid and semi-arid regions along the Silk Road. To provide effective measures for controlling secondary soil salinization in irrigated farmland, this article presents a research on the water balance and salt balance in the lowland of Nanshantaizi, northwest China. On the basis of the meteorological, hydrological and hydrogeological data, a 2D transient groundwater flow model was developed to analyze the response of groundwater level to various scenarios of controlling and regulating soil salinization. The results show that the shallow water depth causes strong evaporation, resulting in the accumulation of salt in the area, and is the main controlling factor of secondary soil salinization in the lowland. The effective drainage system in the lowland can efficiently reduce groundwater level and can discharge salt into the river, thus, alleviating the soil salinization in the lowland. The reduction of irrigation water requirement in the high plain as well as in the lowland can lead towards better control of soil salinization in the lowland. The canal leakage is the main source of recharge of groundwater in the lowland. However, the reduction of the canal leakage at the beginning of soil salinization regulation is not recommended, as the reduction of canal water leakage may significantly weaken the efficiency of the new drains to remove salts that have already previously accumulated in the soils of the lowland.

Keywords Soil salinization · Groundwater level · Groundwater modeling · Silk Road

Introduction

Due to human interference, land quality degradation, i.e., soil pollution, soil salinization and land desertification, has become a serious issue along the Silk Road (Li et al. 2015). Soil salinization is a problem due to which the soluble salts accumulate either in the root zone or ground surface (Wu et al. 2014). Soil salinization can be divided into two different categories as per the factors responsible for it: (1) the original salinization that is caused by natural factors and (2) secondary salinization which is the salt accumulation process because of unreasonable utilization of land and water resources (Rengasamy 2006; Owens 2001). Soil salinization is a widespread phenomenon in arid and semi-arid areas where rainfall is inadequate to take salts away from the root zone. The statistics and databases reveal that there is more than 77 mha (million hectares) of land that is affected by salt in the world, of which approximately 43 mha is suffering from secondary salinization (Abbas et al. 2013). It is estimated that approximately one-third of the irrigated land in the major countries is severely affected by soil salinization, thus reducing the productivity of economic plants (Abbas et al. 2013; Carter 1975). It has also been estimated that food production has to increase by 38 and 57 % by the years 2025 and 2050,

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respectively, so that it could be possible to meet the population need, if the current growth rate of population continues (Rengasamy 2006; Owens 2001). Soil salinization, thus, will certainly not provide opportunities to meet this goal and has become one of the most important agricultural problems worldwide.

Extensive research on soil salinization has been carried out. During the 20th century, researchers have invented devices for soil salinity investigation by measurement of electrical resistivity (Wenner 1915). Thereafter, with the rapid development of the science and technology, a detailed investigation on salinization has been carried out using: (1) electrode method (Austin and Rhoades 1979), (2) time-domain reflectometry method (Dalton and Van Genuchten 1986; Topp et al. 2003), and (3) electromagnetic induction techniques (Lesch 1995; Paine 2003; Williams and Baker 1982). During recent years, remote sensing is becoming a popular technique in mapping soil salinization (Abbas et al. 2013; Huang 2010; Wiegand et al. 1994). In addition, many studies have been conducted to evaluate the factors and mechanisms of soil salinization (Wu et al. 2014; Zhang and Wang 2001). Castrignanò et al. (2008) used a mapping technique to evaluate the risk of soil salinization in south-eastern Sardinia in Italy using a probabilistic approach that was based on multivariate geostatistics. Pisinaras et al. (2010) investigated the seasonal and spatial trends for the pattern of soil salinization in irrigated land in Greece. They proposed some management methods, such as hydraulic practices, physical management, chemical practices and biological practices, to alleviate this issue. Acosta et al. (2011) assessed the salinity status of a highly productive agricultural area in Spain. They discovered that the evaporation and the capillary rise by semi-arid climate are the driving factors that cause the seasonal variation in the soil salinity. Zhou and Li (2011) examined the effects of surface water resources, groundwater depth and quantity of soil salinity on soil salinization in the lower reaches of Tarim River, China. Through field monitoring, they determined that the critical depth of groundwater to change the load of salt distribution is 6 m.

The Nanshantaizi area, located in the semi-arid region, is a typical irrigation area in northwest China. Each year, a large volume of Yellow River water is diverted towards this area for irrigation purposes, which causes a significant rise of groundwater level in the lowland of the region, and, thus, becomes a source of secondary soil salinization. Our earlier research (Wu et al. 2014) has found that 53.62 and 27.98 % of the lowland in the area is covered by moderately and severely salinized soils, which seriously restrict the development of agriculture and economy in the area. In this article, a simulation model was developed for studying and controlling the soil salinization in the lowland. Some engineering measures have been introduced for controlling the soil salinization, and various scenarios have been assessed by the simulation model. The results of this study will provide references for the prevention and effective control of soil salinization in the alluvial plain of the Yellow River. They will even be referential for soil salinization control in similar regions of the world.

Study area

Location and climate

The Nanshantaizi area covers approximately 377.75 km^2 and is located to the south of the Yellow River, Zhongwei city, northwest China. It is an essential part of the Silk Road economic belt (Li et al. 2015). According to the geography, it comprises two parts: the Yellow River alluvial plain (lowland) and the Nanshantaizi (high plain in Fig. 1). The lowland is formed by the Yellow River, which covers 79.28 km^2, whereas high plain is formed jointly by the river and flood, which covers 298.47 km^2. The annual average temperature is recorded as 9.37 °C. The highest and the lowest temperatures are usually observed in January and July, respectively. As it is located in a typical semi-arid area, the amount of precipitation is negligible. The annual mean precipitation is approximately 185.18 mm, whereas the annual rate of evaporation is recorded as 1774.25 mm in the area, i.e., approximately 10 times of the recorded precipitation. The major portion (72 %) of the precipitation happens during the monsoon months of June–September, whereas more than 73 % of the annual evaporation is measured during the months from April to September (Wu et al. 2014).

Hydrogeology and hydrology

The detailed hydrogeological settings of the study area have been recorded in Li et al. (2014) and Wu et al. (2014). The study area is a part of the Weining Plain, a famous agricultural region in the northwest of China. Borehole logs indicate that the aquifer of the Weining Plain is mainly composed of sand and gravel formed during the early Holocene and late Pleistocene (Fig. 2). The phreatic aquifer is uniformly distributed over the entire plain, whereas the confined aquifer is not uniformly distributed (Li et al. 2014). The high plain of the study area is formed by the action of meandering and shifting of river as well as due to the deposition of debris during floods. Since the Late Pleistocene, loose sediments composed of sands and gravels interbedded with loess-shaped sticky sands have been deposited in Nanshantaizi area (Fig. 2). Because of the unique geomorphological characteristics of the Nanshantaizi area, the groundwater level in Nanshantaizi is

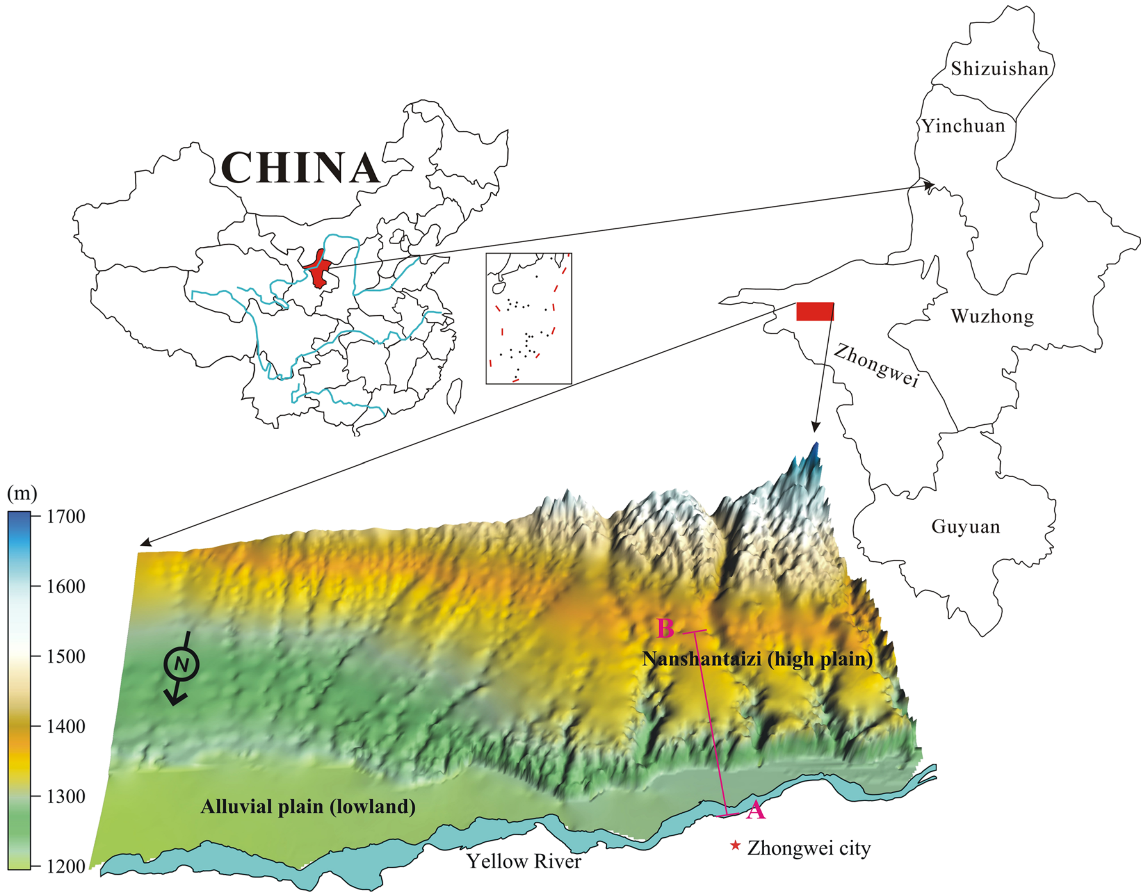


Fig. 1 The location and topographical features of the study area

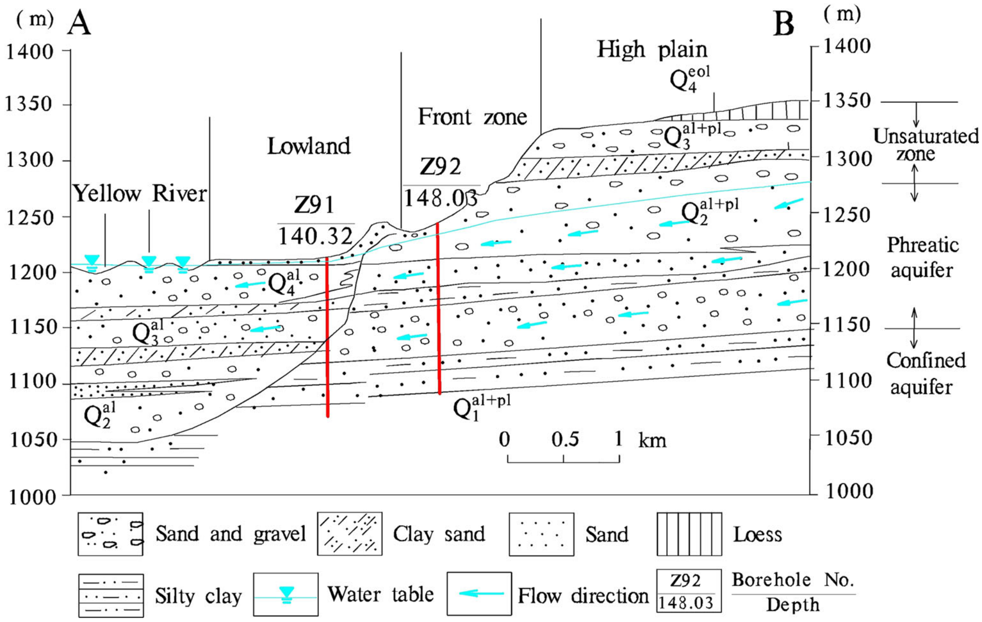


Fig. 2 Hydrogeological cross-section showing the structures of groundwater aquifers in the area (revised after Wu et al. 2014)

much higher than that of the alluvial plain, and therefore, groundwater typically flows from the southwest to the northeast of the study area (Wu et al. 2014). Depth to the groundwater in the alluvial plain is often less than 3 m, which makes the groundwater vulnerable to salt contamination due to extensive evaporation. The Yellow River water is the most important source of water for the purposes of irrigation owing to the limited (local) precipitation. It has been estimated that approximately 6.5×10^7 m^3 of Yellow River water has to be diverted through canals for the irrigated agriculture in the area each year; thus, it elevates the groundwater level, and, thereby, increases the evaporation of the groundwater in the lowland.

In the high plain, depth to the groundwater can be more than 50 m. The thick unsaturated zone contains a large amount of soluble salts. Affected by rainfall and irrigation water, these soluble salts will be likely to dissolve and infiltrate into the aquifers, increasing groundwater salinity underlying the high plain. The total dissolved solids (TDS) in the groundwater underlying the high plain is usually greater than 1 g/L (Wu et al. 2014). Since the groundwater flows from the southwest to the northeast, highly saline groundwater will flow towards the lowland, thus, increasing the possibility of soil salinization in the lowland.

There have already been some drains spreading over the entire lowland to discharge the groundwater to the Yellow River so as to drop the groundwater level to avoid soil salinization. However, these drains apparently do not perform effectively and efficiently, because they are severely clogged by silt, and the soil salinization in the lowland areas is still increasing. In accordance with the field investigations (Wu et al. 2014), soils in the high plain are slightly salinized with soil salinity in the range of 1–3 g/kg, and soils in the lowland, however, are moderately to severely salinized, with soil salinity ranging from 3 to 10 g/kg. Rice is the most popular crop in the alluvial plain of Yellow River, which accounts for approximately 82.84 % of the total farm area of the lowland, whereas the rest of the farmland in the lowland is covered by orchards and woodlands that can resist salt accumulation. In the high plains, the corn and wheat are the most popular crops.

Materials and methods

Groundwater balance and salt balance

The annual groundwater budget of an irrigated area can be estimated using the following equation:

$$\Delta = W_r + W_i + W_c + W_{g_1} - (W_{g_2} + W_d + W_{\mathrm{ex}} + W_{\mathrm{et}}) \tag{1}$$

where, Δ represents the change in the total existing groundwater of the area; W_r, W_i, W_c and $W_{g1,}$ respectively, represent the amount of water recharged by the rainfall, the irrigation, the canal leakage and the lateral groundwater inflow; W_d, W_{g2}, W_{ex} and $W_{\mathrm{et,}}$ respectively, represent the amount of groundwater discharged through the drains, the groundwater outflow, the groundwater extraction and the evapotranspiration. In the present study, groundwater levels were measured during field investigation and data collection was also performed so that these parameters can be calculated easily. Under the existing conditions, the drains do not perform effectively and efficiently to drain water because these are severely clogged by silt. Equation 1, thus, reduces to Eq. 2, and this equation was used in water balance calculation.

$$\Delta = W_r + W_i + W_c + W_{g_1} - (W_{g_2} + W_{\mathrm{ex}} + W_{\mathrm{et}}) \tag{2}$$

As salt is transported with the water, the annual salt balance in the irrigated area can be expressed as follows:

$$\Delta S = W_r C_r + W_t C_c + W_{g_1} C_{g_1} - (W_{g_2} C_{g_2} + W_d C_d + W_{\mathrm{ex}} C_{\mathrm{ex}} + P_s) \tag{3}$$

where, ΔS represents the change in the amount of salt in the area; P_s represents the amount of salt adsorbed or removed by the plants; W_t represents the amount of water diverted by the canals and it comprises the following three parts as shown in Eq. 4: the water loss through canal leakage during the diversion (W_c), the evapotranspiration (W'_{et}), and the water for irrigation (W_i). C_r, C_c, C_{g1}, C_{g2}, C_d and C_{ex}, respectively, represent the salt contents in the rainwater, in the diverted water through canals, the inflow and outflow of the groundwater, the drainage water and in the extracted groundwater. All the other variables have previously been defined. The Eq. (4) can be written as:

$$W_t = W_c + W_i + W'_{ex} \tag{4}$$

The investigations reveal that the water loss through canal leakage during the diversion accounts for 26 % of the total diverted water through canals, and water loss through the evapotranspiration accounts for 10 %, and only the remaining 64 % can readily be used for irrigation.

Because the drains under the current situation are ineffective, the amounts of salt removed by the drain water and the plant adsorption are negligibly small, and Eq. (3) thus reduces to Eq. (5), and this equation was used in salt balance calculation.

$$\Delta S = W_r C_r + W_t C_c + W_{g1} C_{g1} - (W_{g2} C_{g2} + W_{\mathrm{ex}} C_{\mathrm{exs}}) \tag{5}$$

Numerical model

Numerical simulation is an effective tool for the investigation of groundwater. It can be used to predict the variation of groundwater levels due to human interference and natural environment change. Earlier studies have shown that the depth of the water level is a major factor that influences the soil salinization (Wu et al. 2014). Therefore, a 2D numerical model was developed in this study to predict the variation of groundwater level under different scenarios of soil salinization control so that the optimal scheme can be selected for the better control of the soil salinization.

The model domain includes the lowland and high plain that cover approximately 377.75 km^2. During the modeling, the budget was divided into two distinctive zones so that the water budgets of the lowland and the high plain can be simulated and calculated separately. In vertical scale, the model top is the water table and the model bottom is the aquitard below the phreatic aquifer. The Yellow River is situated along the northern boundary and was conceptualized as a constant head boundary, while the other three boundaries were conceptualized as Neumann boundaries. The precipitation infiltration, the irrigation water percolation and the groundwater evaporation can occur through the model top, thus, they can be conceptualized as a water table boundary, and the model bottom can be conceptualized as an impervious boundary. The governing equation of the groundwater flow can be expressed as:

$$\frac{\partial}{\partial x}\left(K(h-B)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K(h-B)\frac{\partial h}{\partial y}\right)+W=\mu\frac{\partial h}{\partial t}\quad (x,y)\in D \tag{6}$$

where, h represents the groundwater level (m), B represents the elevation of the aquifer's bottom (m), W represents the source and sink (m^3/d/m^2), μ represents the specific yield of an unconfined aquifer, K denotes the hydraulic conductivity of an aquifer and D represents the model domain.

The model was solved using MODFLOW-2005, a free finite difference code (Harbaugh 2005). It was, in space, discretized into rectangular grids with a spacing of 100 × 100 m each, whereas temporally it was discretized into multiple stress periods with each representing a month. During the calculation, the Preconditioned Conjugate-Gradient Solver (PCG) was applied, and the maximum outer and inner iterations were set equal to 500 and 250, respectively. The head change criterion and the residual criterion were set equal to 0.001 and 0.0001 m, respectively. The damping factor was set as 1.0. All these parameters were set based on previous modeling experience so that they could yield quick numerical convergence and accurate modeling results. The model was calibrated and verified using the monitoring data in the area, and the results show that the differences between the predicted and the monitored water levels are generally less than 0.5 m (Fig. 3) and the model is stable and accurate, thus can be used for the prediction of the groundwater levels under different scenarios.

Measurement of groundwater salinity

Total dissolved solids (TDS), representative of groundwater salinity, was measured using a drying and weighing approach recommended by the Standard Methods for the Examination of Water and Wastewater, 22th edition (Rice et al. 2012). Samples were first dried at 105 °C and then weighed with an analytical balance. For quality assurance and quality control, duplicates were performed during the analysis.

Results and discussion

Groundwater balance and salt balance under the current situation

Based on practical monitoring and data collection, the groundwater balance and the salt balance for the period from August 2011 to July 2012 have been calculated by Eqs. (2) and (5), respectively, and their results are shown in Tables 1 and 2.

Table 1 shows that, under the current situation, the total annual groundwater recharge in the alluvial plain of the Yellow River is approximately 41.34 million m^3. The main sources of the recharge are the canal water leakage during the diversion, the groundwater inflow and the irrigation infiltration, which account for 50.02, 26.62 and 20.46 % of the total recharge, respectively. As the groundwater flows from the southwest to the northeast in the study area, the groundwater inflow comes mainly from the high plain where groundwater quality is poor with high content of salinity. The high percentage of canal water leakage indicates that the canals over the alluvial plain need further reconstruction or reinforcement so that the diverted water can efficiently be used. The infiltration of irrigation water, accounts for a large percentage of the groundwater recharge, as flood irrigation that may waste a huge quantity of water is widely used in this area. The total groundwater discharge is 40.83 million m^3. Groundwater evaporation and the outflow to the Yellow River are the most dominating discharge patterns, which, respectively, account for 71.89 and 22.67 %. The depth to groundwater is generally less than 3 m in 89.71 % of the alluvial plain, which favors the groundwater evaporation under the semi-arid climate.

The salt balance, as shown in Table 2, indicates that the total salt introduced into the alluvial plain of Yellow River is approximately 55,282 tons annually under the current situation, and the average value is assumed as 697.30 g/m^2. The canal water and the groundwater inflow introduce a huge chunk of the salt, because the amount of canal water is large and the salinity of the groundwater inflow is high.

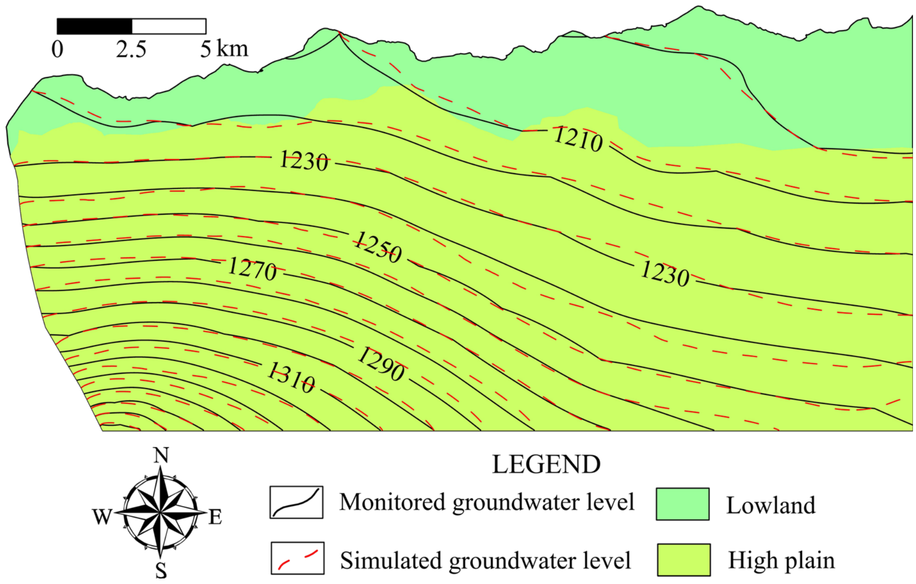


Fig. 3 The fitting curves which indicate the accuracy of the model

Table 1 The groundwater balance for the alluvial plain of Yellow River for a period from August 2011 to July 2012

Recharge items	Amount (10^8 m^3)	Percentage (%)	Discharge items	Amount (10^8 m^3/a)	Percentage (%)
Irrigation infiltration	0.0846	20.46	Groundwater evaporation	0.2972	72.79
Rainfall infiltration	0.0161	3.89	Outflow to the Yellow River	0.0937	22.95
Groundwater inflow	0.1059	25.62	Groundwater extraction	0.0174	4.26
Canal water leakage	0.2068	50.02			
Total	0.4134	100	Total	0.4083	100

Table 2 The results of salt balance for the alluvial plain of Yellow River

Balance items		Amount of water (10^8 m^3)	Water salinity (mg/L)	Amount of salt introduced or discharged		
				Ton	g/m^2	Percentage (%)
Recharge	Canal water	0.8071	452.18	36493	460.31	66.01
	Rain water	0.1468	13.84	203	2.56	0.37
	Groundwater inflow	0.1051	1768.38	18586	234.43	33.62
	Total	1.059		55282	697.30	100
Discharge	Outflow to Yellow River	0.0937	933.35	8745	110.31	80.14
	Groundwater extraction	0.0174	1245.62	2167	27.34	19.86
	Total	0.1111		10913	137.65	100

The salts introduced by the canal water and the groundwater inflow account for 66.01 and 33.62 % of the total salt, respectively. The total amount of salt discharged by the groundwater outflow and the artificial extraction is 10,913 tons annually, with the groundwater outflow as a dominant pathway. The difference between the total salt introduced and the total salt discharged indicates the amount of salts accumulated in the lowland annually, which is approximately equal to 44,369 tons. This will increase the risk of soil salinization.

Simulation of groundwater environment under current conditions

To analyze the variation of groundwater environment under the current situations, the calibrated and verified numerical model was run for 20 years. During the simulation, the environmental conditions such as the precipitation, the groundwater extraction, the water diversion and the irrigation patterns are assumed to be unchanged. The groundwater budgets for the period of 20 years were simulated. The salt accumulation in the alluvial plain was calculated on the basis of the simulated water budget. The results have been shown in Fig. 4.

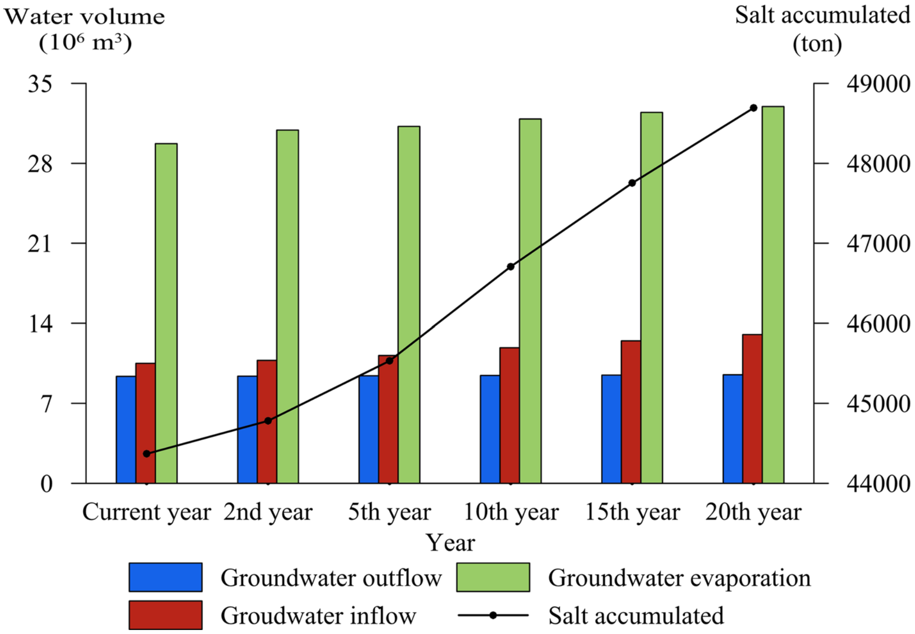
As it has been shown in Fig. 4, the amount of recharge by groundwater inflow from the high plain keeps an increasing trend during the simulated period under the current condition, because flood irrigation continues over the high plain that results in the rising groundwater levels over the high plain. In the 20th year of the simulation, the groundwater inflow will reach up to 13.03 million m^3 and the salt introduced by it will increase to 23,040 tons annually, that is, an increase of 23.96 % as compared to that of the current year (Fig. 4). Meanwhile, the groundwater outflow to the Yellow River shows a tendency of slow increase over the simulated period, as the water level in the lowland is rising due to the increased groundwater inflow from the high plain. In the 20th year of the simulation, the volume of groundwater outflow will be 9.51 million m^3, and the salt discharged is 8877 tons, that is, an increase of 1.51 % as compared to that of the current year. Accordingly, the salt accumulation in the alluvial plain of the Yellow River during each year increases over the period of simulation. The annual salt accumulation for the current year is 44,369 tons, whereas 20 years later it can increase up to 48,692 tons annually, i.e., about 10 % higher than that in the current year. It can be noted that the groundwater evaporation also shows an increasing trend for the same period because of the rising groundwater level. The groundwater evaporation in the 20th year of simulation will be 32.97 million m^3, that is, an increase of 10.94 % as compared to that of the current year. The area with groundwater depth less than 1 m may be increased by 71.93 %, which indicates that the risk of soil salinization in the lowland will become much greater if measures are not being adopted to control the groundwater level and the groundwater evaporation.

Regulation of soil salinization in the lowland

Basic regulation schemes

The shallow groundwater level and the intensive evaporation are the controlling factors for the secondary salinization of soil in the alluvial plain (Wu et al. 2014). To reduce the groundwater evaporation, the groundwater level must be declined. As a way of lowering the groundwater level, it is a logical plan to abstract groundwater for irrigation, as it provides necessary water for crop growth on one hand and drops the groundwater level in the area on the other hand. However, it is not always feasible to dig a lot of wells over the entire lowland due to the economic and societal concerns in the area. As a consequence, alternative measures must be considered to control the groundwater level. In this study, three basic schemes were designed and simulated to control the groundwater level of the lowland so as to regulate the soil salinization. The three regulation schemes are summarized as follows: (1) developing advanced irrigation approaches, i.e., using drip or sprinkle irrigation approaches in the high plain to save water for irrigation, (2)

Fig. 4 The variation of components for the groundwater budget and for salt accumulation over a period of 20 years in the alluvial plain under the current situations



developing advanced irrigation approaches for the entire model domain and reducing canal leakage in the lowland, and (3) constructing new drains over the lowland. The detailed schemes are shown in Table 3. These schemes were incorporated into the numerical model to check their performance on controlling the groundwater level.

Water-saving irrigation The traditional irrigation methods such as flood irrigation not only require a great amount of water, but it may also cause adverse impacts on crop production, soil quality and groundwater environment. Contrary to this, advanced irrigation approaches such as drip irrigation and sprinkle irrigation can save a great amount of water while maintaining a relatively high crop yield. Table 4 shows the annual quota of irrigation water per Chinese acre (mu) (equivalent to 666.7 m^2) for woodland, orchard, dry land, irrigated land and artificial grassland in terms of traditional methods and the advanced approaches.

New drain construction To drop the groundwater level in the lowland, another effective measure, i.e., draining groundwater by drains, can be used to reduce the amount of water recharged from the high plain. In this study, a drain of 4 m in depth was designed along the front zone of the high plain. This drain is referred to as the first type drain in this study. On the basis of the first type drain, other drains (referred to as the second type drains in this paper) were also designed. The second type drains are distributed locally in the locations where groundwater level is high. The first type drains can be effective to constrain the recharge water from the high plain, while the second type drains can be effective to regulate groundwater level in local areas of the lowland. The distribution of the designed drains is shown in Fig. 5.

The model that incorporates the aforesaid basic schemes was run for 20 years. The amounts of groundwater evaporation and salt accumulation under different scenarios were assessed on the basis of the simulation. The results are delineated in Fig. 6.

Under the scheme 1, the groundwater recharge from the infiltration of irrigation water was reduced because less water is used for irrigation. The groundwater levels in the high plain rise slower than that of the current conditions, resulting in the reduction of groundwater recharge to the lowland than that of the current conditions. However, this is insufficient to control the salt accumulation in the lowland, because the recharge from the high plain is still very high and the groundwater evaporation is still intense. In the 20th year of simulation, the groundwater inflow will be increased by 14.23 %, although it is reduced by 9.73 % compared with that under current situation. In the 20th year of simulation, the annual salt accumulation in the lowland will be 46,968 tons, which is only 3.54 % lower than the predicted results under the current conditions. This indicates that the implementation of water-saving irrigation in the high plain without any other company measures cannot efficiently control the groundwater level and the salt accumulation in the lowland.

Table 3 Basic schemes designed for controlling the soil salinization

Schemes	Details
Scheme 1	50 % of the farmlands in only high plain are subject to water-saving irrigation
Scheme 2	50 % of the farmlands over the entire model domain are subject to water-saving irrigation and the utilization efficiency of canal water in the Yellow River alluvial plain is increased from 64 to 80 %
Scheme 3	Additional drains are constructed in the lowland

Under the scheme 2, the advanced irrigation approaches were used over the entire model domain. The efficiency of canal water utilization was also increased. These two measures can reduce the recharge to the groundwater in the lowland and can drop the groundwater level to a great degree, thus reducing the salt accumulation and the groundwater evaporation. As shown in Fig. 6, the salt accumulation is significantly reduced under the scheme 2 as compared to that under the current conditions. In the 20th year of simulation, the salt accumulation will be 38,286 tons, which is 21.4 % lower than that predicted under the current conditions, and is 18.5 % lower than that simulated under scheme 1. However, this scheme is still not able to efficiently control the soil salinization of the lowland, as a great amount of salts still will be accumulated in the lowland over time.

Under scheme 3, the groundwater level in the lowland significantly declines due to the effective performance of the drains. The drain is an effective engineering technique that can lower the groundwater level. It can maintain groundwater level within an acceptable limit. The salt accumulation in the lowland is significantly reduced. In the 20th year of simulation, the annual salt accumulation in the lowland is only 4360 tons, which is tenfold lower than that predicted under the current conditions as well as schemes 1 and 2. The problem of salt accumulation in the lowland can greatly be improved under scheme 3. However, the groundwater recharge from irrigation infiltration and canal percolation is not controlled in scheme 3, which indicates that the source of the salt is not regulated. Besides, it is unclear how it will be if integrated schemes are implemented. The integrated schemes will consider, simultaneously, constructing new drains, increasing efficiency of canal water utilization and implementing advanced irrigation approaches in the study area.

Table 4 Irrigation quotas for different types of land

Land type	Irrigation quota of traditional irrigation methods (m^3/mu)	Irrigation quota of water-saving irrigation methods (m^3/mu)
Woodland	310	70
Orchard	310	70
Dry land	30	17
Irrigated land	280	140
Artificial grassland	295	145
Paddy	800	500

Integrated regulation schemes

To find out the performance of the integrated schemes, other 10 schemes were designed and simulated on the basis of the scheme 3. The details of the new schemes are shown in Table 5. The salt accumulation and the groundwater evaporation in the 20th year of simulation under the 10 schemes were calculated (Fig. 7) and were compared with those predicted under scheme 3. The water volumes of the components of groundwater budget for the 20th year of simulation are shown in Table 6.

As shown in Fig. 7, the annual salt accumulation and the groundwater evaporation for the 20th year of simulation under the schemes 4–9 are found lower than those

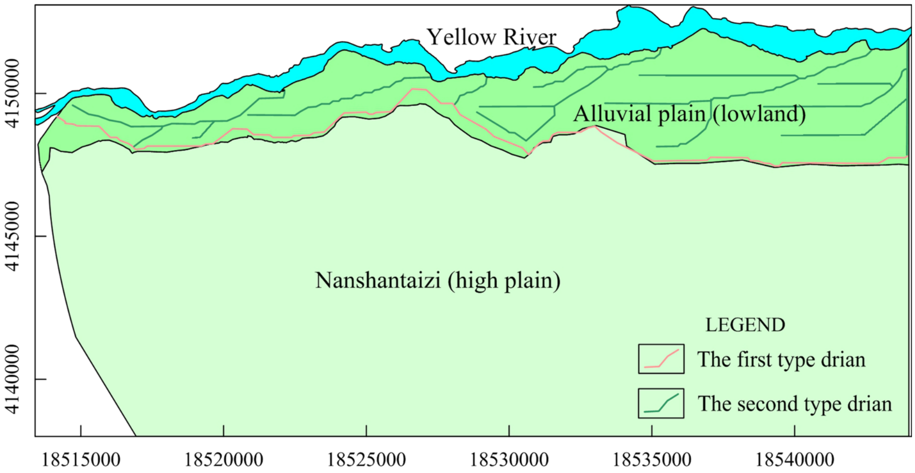


Fig. 5 The location of drains in the alluvial plain of Yellow River

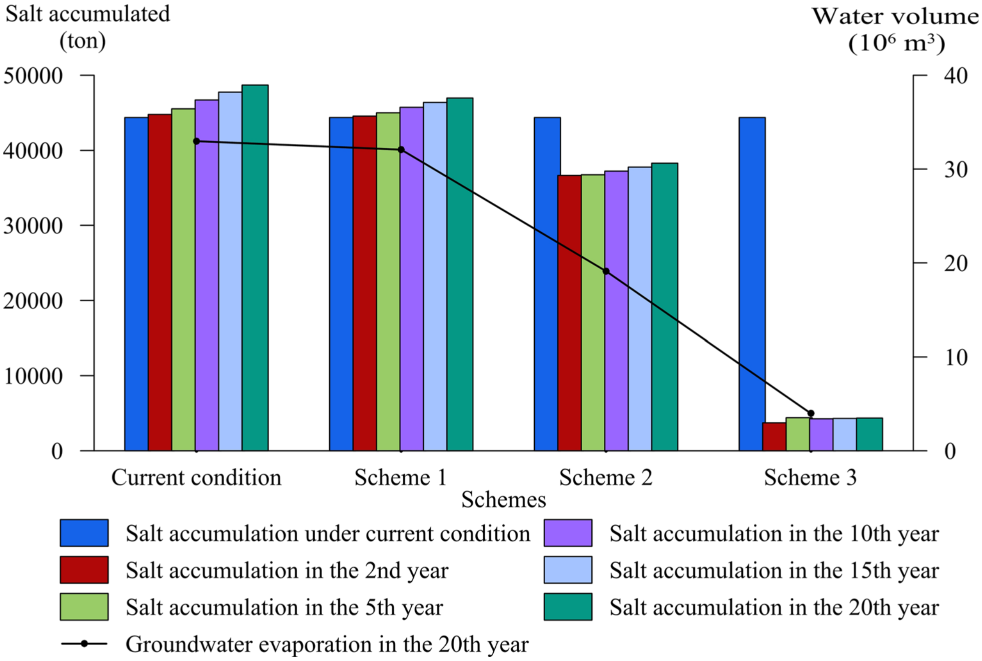


Fig. 6 Groundwater evaporation and salt accumulation in the lowland areas under different basic schemes

Table 5 The integrated schemes to control the soil salinization

Scheme 3		Percentage of area carrying out water-saving irrigation in the lowland.				
		0 %	50 %		100 %	
		Canal water utilization 64 %	Canal water utilization 64 %	Canal water utilization 80 %	Canal water utilization 64 %	Canal water utilization 80 %
Percentage of area carrying out water-saving irrigation in high plain	0 %	Scheme 3	Scheme 6	Scheme 10	Scheme 8	Scheme 12
	50 %	Scheme 4	Scheme 7	Scheme 11		
	100 %	Scheme 5			Scheme 9	Scheme 13

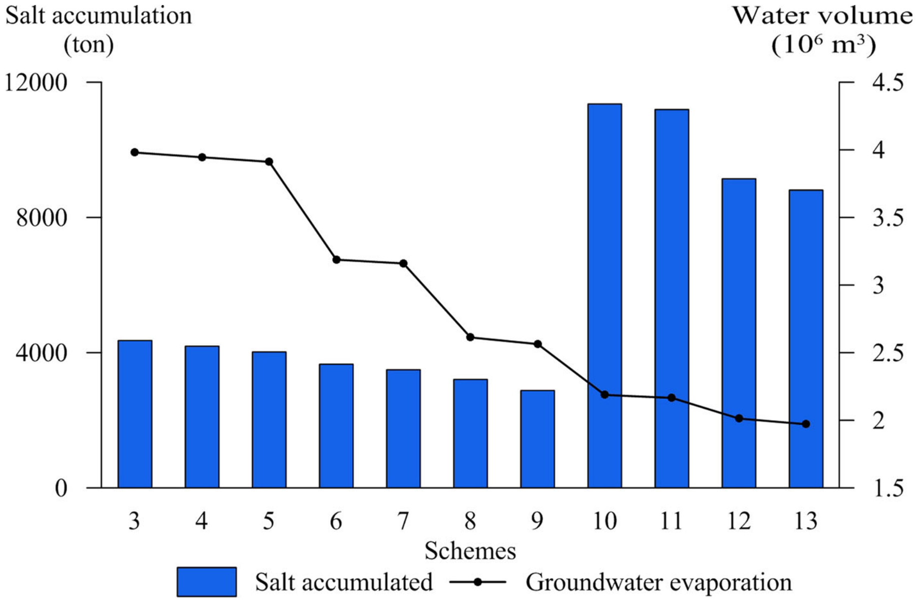


Fig. 7 The salt accumulation and the groundwater evaporation for the 20th year of simulation between the schemes 3–13

predicted under the scheme 3. They show a descending order: scheme 4 > scheme 5 > scheme 6 >scheme 7 > scheme 8 > scheme 9. Compared with the scheme 3, salt accumulation under these schemes are reduced by 3.85, 7.75, 16.08, 19.84, 26.38 and 33.96 %, respectively. Similarly, the reduction in groundwater evaporation is 0.87, 1.72, 19.91, 20.61, 34.35 and 35.58 %, respectively. Especially, the salt accumulation in the lowland for the 20th year of simulation under the scheme 9 is 2879 tons, which is acceptable for the agricultural practices and management in the study area. The areas with water level depth less than 2.5 and 3 m accounts for 11 and 28 %, respectively, under scheme 9, which is also acceptable in terms of groundwater level controlling. To conclude, if there is an efficient drainage system, it is recommended that more irrigated farmland should be irrigated with advanced irrigation techniques to achieve a better effect on the controlling of the soil salinization.

The groundwater evaporation predicted under schemes 10–13 is relatively small, but the problem of salt accumulation becomes more serious than that predicted under schemes 3–9. In the 20th year of simulation, the salt accumulation under schemes 10–13 is approximately 2–2.5 times higher than that under scheme 3. This is because the leakage of the canal water is significantly reduced. As the leakage of canal water is the most important groundwater recharge source in the lowland, its reduction will lower the groundwater level significantly in the lowland, which, in turn, will decrease the amount of groundwater discharged by the drainage system. However, salt removal through drains is the most important salt removal mechanism. The reduction of the groundwater discharge through the drain may weaken the efficiency for the removal of salt that has previously accumulated in the soils of the lowland. In accordance to the data of Table 6, under schemes 10–13, the total volume of the groundwater discharged by the drains is 33–45 % lower than that under scheme 3. This means that salts previously accumulated in the soil of the lowland cannot be removed by the leaching of canal water and then by the drain. This is the main reason of salt accumulation in the lowland under schemes 9–13.

Table 6 Water volumes of changing items for the estimation of salt balance during the 20th year of simulation (unit: $\times 10^6$ m^3)

Schemes	Canal water percolation	Groundwater inflow	Recharge from Yellow River	Discharge by the first type drains	Discharge by the second type drains
Scheme 3	80.7	14.37	0.2	11.36	28.65
Scheme 4	80.7	13.25	0.21	10.47	28.47
Scheme 5	80.7	12.16	0.22	9.61	28.28
Scheme 6	64.56	14.35	0.98	10.43	25.21
Scheme 7	64.56	13.23	0.99	9.55	25.02
Scheme 8	48.42	14.33	1.79	9.49	21.63
Scheme 9	48.42	12.12	1.81	7.78	21.22
Scheme 10	51.65	14.33	2.65	8.8	17.88
Scheme 11	51.65	13.22	2.66	7.93	17.68
Scheme 12	38.74	14.32	3.09	8.31	15.99
Scheme 13	38.74	12.12	3.12	6.62	15.56

Generally speaking, digging and constructing drains is a common practice to lower groundwater level so as to control soil salinization in an irrigation district. However, the feasibility of the irrigation and drainage measures in large area depend on many factors such as hydrogeological settings, soil types, plant types and irrigation patterns as well as societal factors. It seems quite effective in the present study to construct drains to lower the water level because in the study area there are few residents and the main plant is rice in the lowland. However, it is still unclear if the measure is feasible and can be adopted in larger areas, but this certainly is the direction of our future research.

Conclusions

Secondary soil salinization is a serious issue in the alluvial plain of the Yellow River. This study develops a simulation model for studying and controlling the soil salinization. It further introduces some engineering measures for controlling the soil salinization, such as adopting advanced irrigation approaches, increasing utilization efficiency of the diverted water and constructing new drains. These scenarios have been assessed by the simulation approach. The following conclusions have been inferred:

1. There are many factors that can cause soil salinization in the lowland: (1) the shallow depth of groundwater due to increased groundwater recharge, and (2) high salinity in the recharged water, etc. Thus, maintaining groundwater level at a certain threshold level can effectively control soil salinization, because it can reduce the evaporation to a minimum and reduce the accumulation of salt due to high water level.
2. Irrigation-based agriculture in the high plain is an important factor that influences the soil salinization in the lowland. However, the simulation results indicate that implementation of water-saving irrigation in the high plain without any other measure is inefficient for controlling the salt accumulation in the lowland. Although the integration of water-saving irrigation and efficient utilization of canal water can yield much better result for controlling the salt accumulation, yet it cannot completely control salinization. The construction of new drains in the lowland can drain the high salinized water recharged from the high plain and drop the groundwater level in the lowland. It is an effective and efficient measure for controlling the soil salinization in the lowland.
3. On the basis of constructing an effective drainage system, the lesser requirement of irrigation water in the high plain and the lowland, the better that we can control the soil salinization in the lowland. As the canal leakage is the main source of recharge to groundwater in the lowland; therefore, it is unwise to reduce the amount of canal leakage at the very beginning of soil salinization regulation, because the reduction of canal leakage will weaken the leaching of salts that have already previously accumulated in the soils of the lowland.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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