Evaluating the impact of flood irrigation on spatial variabilities of soil salinity and groundwater quality in an arid irrigated region

Nengzhan Zheng, Mengshen Guo, Weifeng Yue, Yanguo Teng, Yuanzheng Zhai, Jie Yang and Rui Zuo

ABSTRACT

Soil salinization is a key problem limiting the sustainable development of agriculture in arid areas. To explore the quantitative influence of irrigation on soil salinity and groundwater quality, spatial variability of salt at different soil depths and total dissolved solids in groundwater before and after irrigation was analysed in the Hetao Irrigation District, China. The spatial variability of soil salinity before and after irrigation was moderate, with high coefficients of variation observed in shallow soil. After irrigation, amounts of salt were transferred into the groundwater, leading to the deterioration of groundwater quality, the average salt flux through each interface was -153.66, 169.12, 130.13 and 318.48 g/m^2, for 20, 50, 100 and 150 cm soil depths, respectively. All salt moved downward vertically except for 0–20 cm soil layer, and the average soil salt flux of shallow layers was significantly lower than that of deep layers. Compared soils of different depths and land types, salt discharge occurred in cultivated land, while salt accumulation occurred in shallow soil in wasteland after irrigation. Irrigation could help remove salt from cultivated land and deeper soil; however, it had almost no effect on shallow soil of other land uses.

Key words | depth to groundwater table, Hetao Irrigation District, soil salinity, spatial variation

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HIGHLIGHTS

- There was a positive correlation between variations in soil moisture and salinity at the shallower depths.
- Irrigation activities had more effect on the spatial variability of shallow soil but less on the salinity of deep soil.
- The average salt storage showed that salt accumulation still existed in the shallower soil layer.
- The ions Cl$^-$ and Na$^+$ played the dominant role in the variation of soil salinity.

INTRODUCTION

Soil salinization in arid and semi-arid regions has become an urgent challenge to agricultural production globally

(Odeh & Onus 2008). To maintain crop growth, it is essential to supplement soil moisture through different means (Wang et al. 2016), among which irrigation is a more effective way. Thus, soil salt content and irrigation water quality are important factors that determine the sustainability of agriculture in arid and semi-arid areas (Zhu et al. 2013).

Crop growth and production is closely related to changes in the soil environment (Wang et al. 2019a), high soil salt content and low water content appear frequently in irrigation areas after a period of agricultural activities, which has significant negative impacts on the utilization of agricultural land. Although the following irrigation cycle can quickly replenish soil moisture to satisfy the needs of crop growth, the increase in groundwater level simultaneously with irrigation can cause salt accumulation in the shallow soil layer and change the salt distribution in soil and groundwater. The spatial variation of soil and groundwater salinity and the interaction between them in arid and semi-arid regions have now become a key research direction in the field of agricultural production and ecological environment restoration in arid regions (Xia et al. 2016; Yinglan et al. 2019). Particularly for arid irrigation areas, large amounts of surface water will be diverted for irrigation several times a year to leach the soil salt, so as to ensure the sustainability of agricultural production activities in the irrigated areas; therefore, water conservation and salt control are two prominent topics in the sustainable development of regional agricultural economies (Sun et al. 2019).

Previous studies have shown that soil salinization is not only related to natural environments with low precipitation and high evaporation but also closely related to irrigation measures and depth to groundwater table (Benyamini et al. 2005). Groundwater in arid areas is a significant source of soil water (Wang et al. 2019c), which indirectly affects the interaction of dissolved salts and the transfer and redistribution of soil salt. Shallow groundwater deeply influences soil salt migration, accumulation and release (Xia et al. 2016); the distribution and evolution of saline soil are closely linked to groundwater dynamics, and the deterioration of soil salinization is related to the rise in the water table and the increase in total dissolved solids (TDS) in the groundwater. By building a conceptual model of soil water transport, Dou et al. (2019) analysed the spatial and temporal variation characteristics of dissolved salts and the impact of groundwater level on salt in the irrigation area; with increasing soil depth, the variability in moisture content and salinity decreased, and there was a linear relationship between regional soil salinity and depth to groundwater table. Other studies found that the depth to groundwater table had a significant impact on soil salinity, soil with a shallow groundwater level resulting in high soil salinity (Wakindiki & Tirop 2003; Dou et al. 2019; Abd El-Wahed et al. 2020). There was a significant correlation between groundwater salinity and soil salinity under shallow groundwater table conditions (Shah et al. 2011). Therefore, appropriate development and utilization of groundwater to control the groundwater level can effectively alleviate soil salinization.

To solve the problem of soil salinization and guarantee food safety, it is necessary to explore the intensity and influence of soil water salinity interactions based on field monitoring data (Chang et al. 2018). Calculating and exploring the spatio-temporal pattern of soil salinity after irrigation with the appropriate methods are useful for improving management strategies and the efficiency of drainage systems (Forkutsa et al. 2009). The objective of this study was to: (1) analyse the spatial variability of salinity at different soil depths and TDS in groundwater before and after irrigation in the study area; (2) calculate the salt storage and flux between different soil layers as well as between soil and groundwater; (3) explore the impact of depth to groundwater table and TDS on soil salinity and moisture in different layers and (4) provide further insights into understanding the qualitative and quantitative interactions between groundwater and soil.

MATERIALS AND METHODS

Study site

The Hetao Irrigation District (HID), a typical arid irrigated area, is located in western Inner Mongolia, China (Figure 1), with an area of ~1.12×10^4 km². The largest irrigation sub-district of the HID is the Yichang Irrigation Sub-district (YISD), which covers a land area of approximately 3,353 km², 56% of which is irrigated to grow various crops. The main crops in the YISD are oil sunflower (32% of the cultivated area) and spring wheat (30%), with other crops including summer maize, sugar beets and oil seeds. The topography in this area is flat with a regional slope of <0.02%. The primary soil textures in the southern part of
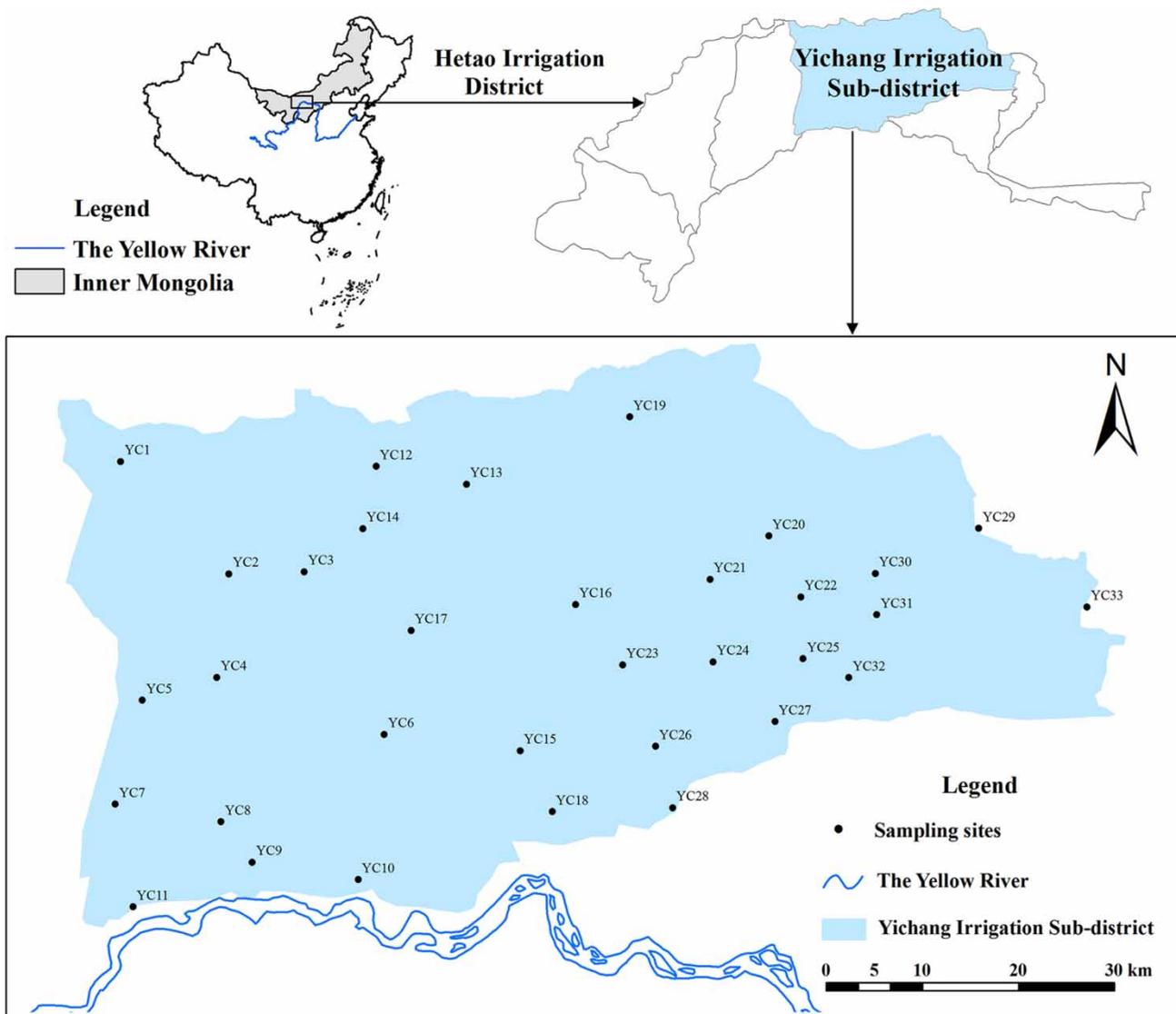
Figure 1 | The distribution of sample sites in the study area.

the YISD are silty loam and sandy loam formed by alluvial sediments, while silty clay in the northern part is formed by lake sediments (Yue *et al.* 2016). With an arid continental monsoon climate, the mean annual precipitation in this area is approximately 173 mm (with >70% of rainfall occurring from July to September), and the mean annual pan evaporation is 2,067 mm (about 60% of which occurs from May to August; Figure 2). An average of 1.38 billion m³/year of irrigation water is almost entirely diverted from the Yellow River during the irrigation period (from April to November). Under the influences of irrigation and evaporation, there

exists a regular fluctuation in depth to groundwater table, with an annual average of 2.04 m.

Data

The irrigation activity in the research area is mainly concentrated in the crop growing period (April–September) and the autumn irrigation period (October–November). During the autumn irrigation period, approximately 35% of the total irrigation water is diverted to leach soil salt, with the aim of providing a suitable soil environment for
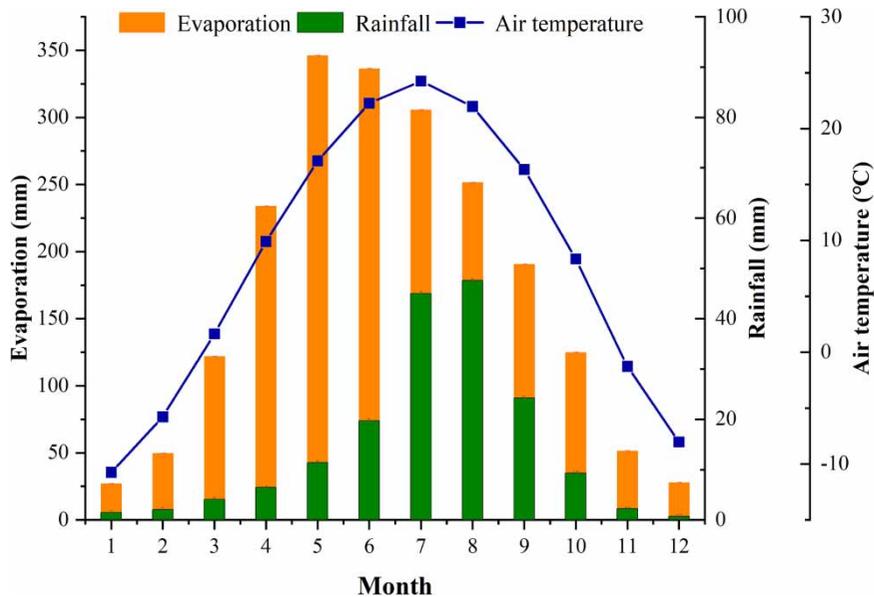
Figure 2 │ Mean monthly changes in evaporation, rainfall and air temperature in the Yichang Irrigation Sub-district.

crop growth in the following year. In this study, soil and water samples from 33 sample sites in the YISD before and after autumn irrigation were collected in October and November 2012, respectively, and the depth to groundwater table was systematically measured. Soil was stratified with depths of 0–20, 20–50, 50–100 and 100–150 cm, and the soil layer above the depth of 50 cm was defined as shallow soil in this study.

Three hundred and thirty groups of sample data (including 264 groups of soil data and 66 groups of groundwater data) before and after irrigation were obtained and analysed in the soil laboratory of Beijing Normal University for a range of parameters, including pH, soil salinity, TDS, anions (Cl^-, SO_4^{2-} and HCO_3^-), cations (K^+, Na^+, Ca^{2+} and Mg^{2+}) and soil moisture content. The groundwater levels were recorded through 33 monitoring wells, and groundwater pH and TDS were measured by the calibrated Portable Multiparameter Rapid Water Quality Analyser (HANNA-HI9828). Soil moisture content was measured through an oven drying method. The ions $K^+ + Na^+$, Ca^{2+} and Mg^{2+} were measured by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES), HCO_3^- with the neutralization titration method (NT), Cl^- with the mercury nitrate titration method (MNT), and SO_4^{2-} with the EDTA titration method.

Statistical analysis

The statistical methods were used to calculate the standard deviation and coefficient of variation of soil salinity and groundwater TDS and to analyse the correlation between them. The spatial variability of soil salinity and groundwater TDS and the impact of other variables on soil salinity were analysed. To further quantify the change in soil and groundwater salinity, soil salt storage and salt flux in different layers were calculated based on salt content.

According to the measured salinity and thickness of different soil layers at different sampling sites in the irrigation area, the soil salt storage is estimated as in Equation (1):

$$S_{i,j} = 10h_{i,j}\gamma_{i,j}c_{i,j}$$
$$S'_{i,j} = 10h_{i,j}\gamma_{i,j}c'_{i,j}$$

$$(1)$$

where $S_{i,j}$ refers to the soil salt storage in the j layer at the i monitoring site before irrigation, g/m^2; $h_{i,j}$ is the thickness of the j layer at the i site, cm; $\gamma_{i,j}$ is the dry bulk density of the j layer at the i site, averaged 1.49 g/cm^3; $c_{i,j}$ refers to the measured soil salinity in the j layer at the i site before irrigation, g/kg, and $S'_{i,j}$ and $c'_{i,j}$ correspond to the soil salt storage

and the measured salinity at the corresponding sites and soil layer after irrigation.

Because of the slow horizontal flow, only one-dimensional vertical flux was considered at each site. The variation in soil salt storage should be equal to the difference between the salt influx and outflux, which is calculated as in Equation (2):

$$S'_{i,j} - S_{i,j} = Q_{i,j-1,k} - Q_{i,j,k} \tag{2}$$

where $Q_{i,j,k}$ is the salt flux per unit area at the lower boundary of the soil, i represents the monitoring site, j represents the layer number and k represents the type of land ($k = 1$ for cultivated land, $k = 2$ for wasteland), g/m^2, and the downward direction is positive; $Q_{i,0,k}$ is the salt flux at the upper boundary of the first layer of type i, g/m^2, because irrigation is only carried out in cultivated areas, $Q_{i,0,2} = 0$. The irrigation water was mainly diverted from the Yellow River, with a salinity of 0.6 g/L (Chang *et al.* 2018). The amount of salt input at the surface of the cultivated land (Q_0) was 148.41 g/m^2.

RESULTS AND DISCUSSION

Descriptive statistics of salinity in soil and groundwater

Through sampling and testing the soil and groundwater before and after autumn irrigation, key indicators like depth to groundwater, TDS, soil moisture and soil salinity were selected to illustrate the spatial variation of soil and groundwater before and after irrigation. Table 1 shows the statistical results of soil salinity and TDS of groundwater to reflect their difference between before and after irrigation.

The average salinity in the shallow soil layers (0–20 and 20–50 cm) was significantly higher than that in the deep soil layers (50–100 and 100–150 cm). With the increase in depth, the average soil salinity first decreased significantly and then increased slightly. Before irrigation, the maximum CV was 93.47% (20–50 cm) and the minimum CV was 61.89% (50–100 cm), the CV of soil salinity in each soil layer ranged between 10 and 100%, which was a moderate level of variation. However, by comparing the CV of soil salinity

Table 1 │ Statistical analysis results of soil salinity and TDS of groundwater

Layers	Time	Max	Min	Mean	SD	CV (%)
S1 (g/kg)	BI	27.75	0.84	9.77	7.79	79.70
	AI	26.27	1.18	9.98	5.9	59.07
S2 (g/kg)	BI	25.46	1.12	5.03	4.7	93.47
	AI	12.37	0.61	4.31	3.18	73.91
S3 (g/kg)	BI	10.61	0.46	3.17	1.96	61.89
	AI	8.64	0.62	3.22	2.16	67.13
S4 (g/kg)	BI	11.36	0.98	3.25	2.55	78.55
	AI	10.86	0.56	3.00	2.22	74.07
GW (g/L)	BI	12.51	0.56	3.54	2.66	75.16
	AI	22.99	0.74	4.46	5.18	114.06

Note: S1, S2, S3 and S4 represent 0–20, 20–50, 50–100 and 100–150 cm soil depth, respectively; GW is groundwater; BI and AI refer to before and after irrigation, respectively; SD is standard deviation; CV is coefficient of variation.

in different soil layers, it was found that the CV of soil salinity in shallow soil layers before irrigation was relatively high, and the difference in salinity between different sample sites was substantial. The TDS varied significantly among different sample sites and the variation in groundwater TDS in the study area was moderate before irrigation.

When compared with the variability before irrigation, the spatial variation of soil salinity was reduced after irrigation. The soil salinity decreased with increasing depth, with the average salinity in all soil layers ranging from 3.00 to 9.98 g/kg. After irrigation, the maximum CV was 74.07% (100–150 cm) and the minimum CV was 59.07% (0–20 cm). The CV among different soil depths showed no specific pattern and moderate variation. The largest difference in the CV of soil layers before and after irrigation was observed for the 0–20 cm soil layer, which declined from 79.7 to 59.1%, with the 20–50 cm soil layer also declining from 93.5 to 73.9%. The soil salinity distribution of different layers in the study area tended to be more uniform and the variability declined significantly after irrigation; the CV of salinity in the 50–100 and 100–150 cm soil layers showed relatively small changes after irrigation, indicating that deep soil salinity was minimally influenced by irrigation activities. The increasing average value of TDS in the groundwater revealed that the groundwater received a large amount of salt from the soil layer, and the CV of TDS reached 116.18%, which was high when compared with that before irrigation.

Nonlinear fitting was applied to the salinity in each soil layer and TDS in groundwater before and after irrigation to investigate the vertical change in soil and groundwater salinity for all sample sites in the study area (Figure 3).

Either before or after irrigation, the vertical one-dimensional variation in soil and groundwater salinity presented an overall downward trend in the YISD. From the surface layer (0–20 cm) to the second layer (20–50 cm), there was a substantial reduction in salinity when compared with the differences among other adjacent layers, with the lowest variation occurring in the deeper layers. Nonlinear function fitting was effective in this situation to avoid the influence of a small number of outliers on the analysis results.

There were great differences in the salinity of different soil layers in the study area and the overall trend was that the salinity gradually decreased from shallow to deep soil layers. This finding is consistent with those of Cetin & Kirda (2003) on the salinity CV and Dou et al. (2019) on the spatial variability of saline soil. Cetin & Kirda (2003) analysed soil samples to a depth of 30 cm, while in this study, we sampled to soil depths of up to 1.5 m, which was below the groundwater level at some sites. Sampling to this depth can better reflect the connection between soil and groundwater salinity, and the one-dimensional vertical change in soil salinity.

Spatial variation of soil salinity and groundwater TDS

The YISD is in arid and semi-arid regions, and perennial precipitation is small, the average depth to groundwater table in the 33 points before irrigation was 2.77 m, which rose to 2.08 m after irrigation. Because of the great difference between evaporation and precipitation, soil salinization is a major problem for local agricultural production and development. Data from the YISD soil samples before and after autumn irrigation were analysed according to the evaluation standard of Guo et al. (2018) to determine the soil salinity classification in arid areas (Figure 4).

With the increase in soil depth, the classification of soil salinization in the study area changed dramatically: Extremely saline-alkali land and severe saline-alkali land in the northwest disappeared rapidly, and the area of extremely saline-alkali land in the south of the YISD gradually decreased. Shallow soils are at great risk of salinization. When the soil depth exceeded 100 cm, the level of soil salinization in most regions did not exceed slight saline-alkali. After irrigation, the salinity of the 0–20 cm soil layer was still much higher than that of the other soil layers. A large area of extremely saline-alkali land appeared in the middle of the study area and a small area appeared in the southeast; as the soil depth increased, the soil salinity of the YISD showed a continuous downward trend. This was particularly evident for the 20–50 cm soil layer in the central and south-
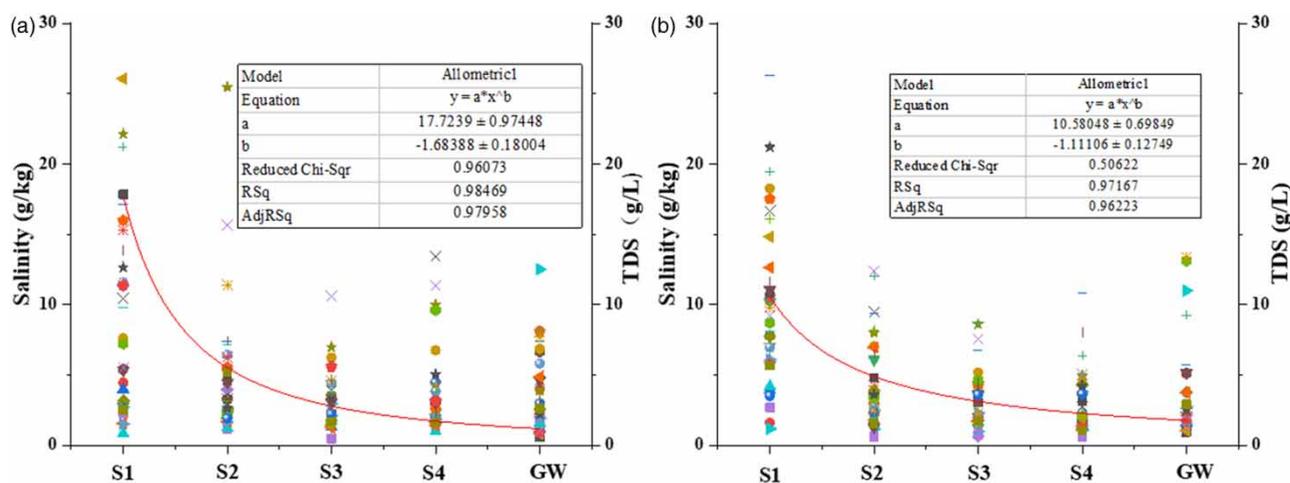

Figure 3 | Nonlinear fitting results of salinity in different soil layers (g/kg) and groundwater (g/L). *Note:* (a) before irrigation and (b) after irrigation. RSq, the coefficient of determination; AdjRSq, the adjusted value of RSq; TDS, total dissolved solids. See Table 1 footnote for sample codes.
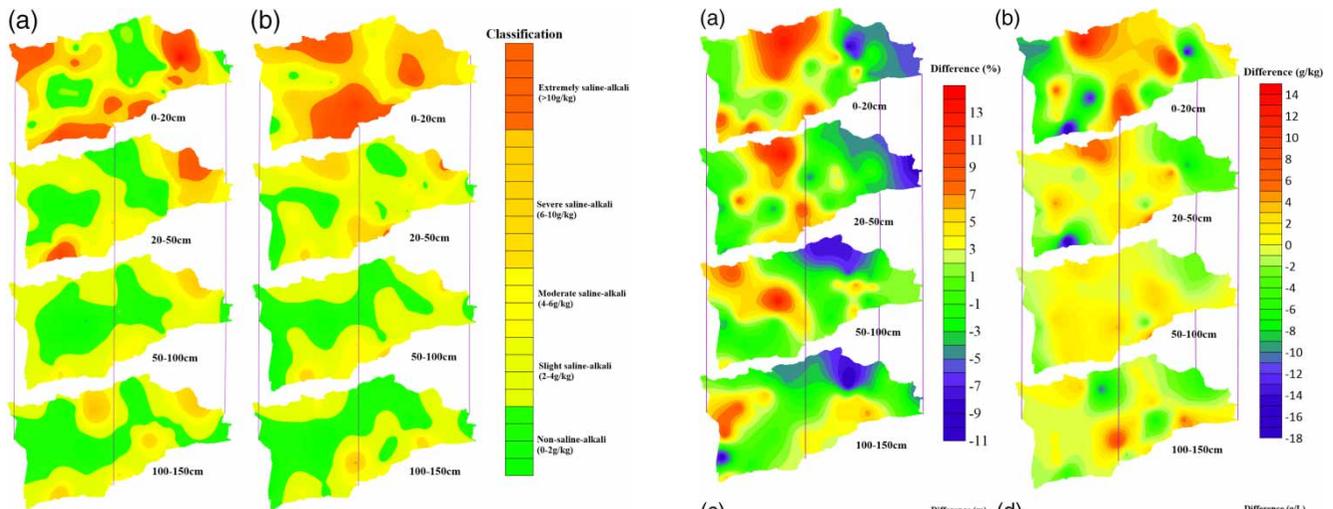
Figure 4 | The soil salinity classification in the study area: (a) before irrigation and (b) after irrigation.

Figure 5 | Differences in (a) soil moisture content, (b) soil salinity, (c) groundwater level and (d) total dissolved solids before and after irrigation.

eastern regions, where the average salinity of all sample sites was much lower than that of the 0–20 cm soil layer. Generally, the soil salinity in the western and north-eastern regions of the study area was lower than the threshold value of moderate saline-alkali (3 g/kg). In contrast to the upper soil layers, soil in the 50–100 cm layer in the north largely changed from severe saline-alkali into moderate saline-alkali or slight saline-alkali, while the area of severe saline-alkali land in the east was greatly reduced. Overall, the spatial distribution of salinity in the 0–50 cm soil layer changed significantly before and after irrigation. The area of extremely saline-alkali land in the irrigated area had a scattered distribution, appearing mainly in the northeast, northwest and south before irrigation, however mostly in the middle and a few in the southwest after irrigation. The salinity in the deep soil layer (50–100 cm) showed no evident characteristics of temporal and spatial variation.

The moisture content of shallow soil in the YISD increased after autumn irrigation (Figure 5(a)). Especially in the north of the irrigation area, there was a widespread increase in soil moisture content, which corresponded to the general increase in soil salinity after irrigation. As the soil depth increased, the area of land with increasing moisture content in the middle of the study area became smaller; the soil salinity in this area also changed from a large decrease to a continuous increase, with the decrease in salinity of some sites exceeding 10 g/kg.
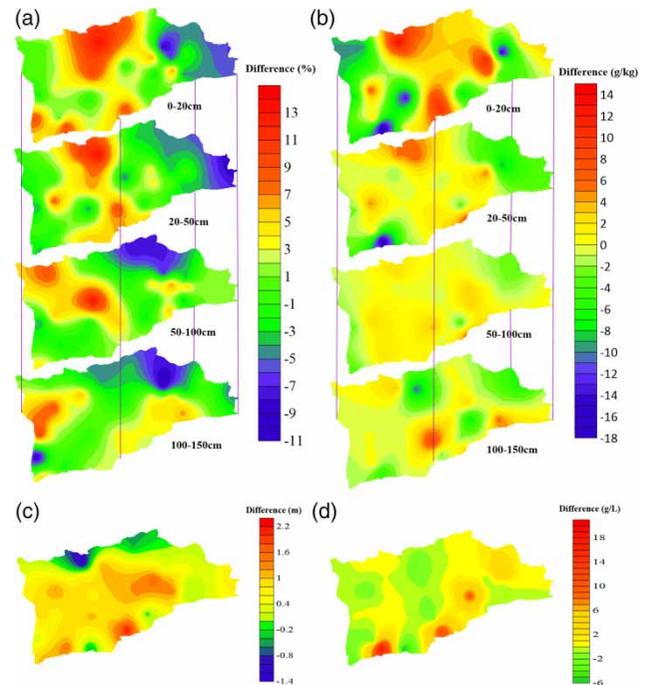
In terms of the changes in salt salinity in different areas before and after irrigation, the differences among these areas were significant. As shown in Figure 5, the rising trend of soil salinity in the middle of the YISD at the depth of 0–20 cm soil layer was obvious. For example, at the sites of YC12, YC18 and YC22, soil salinity increased dramatically (the increment was 13.69, 10.64 and 11.08 g/kg, respectively). Meanwhile, soil salinity at the sites YC12, YC14 and YC15 showed an increase of more than 5 g/kg. However, at the sites of YC06, YC09 and YC30 and the surrounding areas located in east and west of the YISD, the significant decrease in soil salinity after irrigation also existed (the decrement at these sites was 11.24, 15.02 and 12.76 g/kg, respectively). Combine the changes in regional moisture content, there was a positive correlation between the soil moisture content and soil salinity in the middle of the study area, but there was no evident correlation between them elsewhere. In general, after irrigation, the salinity of shallow soil in the YISD irrigation area increased, but it decreased with the increase in soil depth (Figure 5(b)). In the eastern and western irrigation areas, soil salinity declined, and the decline was greater in shallow than in deep soil.

Changes in ions of different soil layers

The soil in the study area appeared alkalescent before and after irrigation. The pH value of each site before irrigation was 7.2–9.9, with an average of 7.9. After irrigation, the pH value was 7.1–9.6, with an average of 8.0. The cations were mainly $Na^+ + K^+$, and the anions were primarily Cl^-, SO_4^{2-} and HCO_3^- (Figure 6). For different soil layers, there were almost no changes in the concentrations of Ca^{2+}, Mg^{2+} and $K^+ + Na^+$, contributing to soil salinity by 4.7–5.3%, 4.1–4.3% and 22.0–23.7% before irrigation, and 4.0–4.8%, 3.6–4.1% and 24.8–26.2% after irrigation, respectively. The concentration of HCO_3^- in the shallow layer seemed significantly lower than that in the deep layer, and the contribution ratio to soil salinity at 0–20 cm depth was the lowest with 11.1 and 8.7% before and after irrigation, respectively. However, in the deep soil layer, the corresponding contribution ratio increased up to 19.5% (before irrigation) and 20% (after irrigation). In all soil layers, the contribution ratio of Cl^- increased simultaneously after irrigation, the largest increase existed in the 100–150 cm soil layer from 23.5 to 27.5%. However, the contribution ratio of SO_4^{2-} fluctuated greatly in different soil layers, especially at 100–150 cm depth it decreased from 25.1 to 20.0% after irrigation.
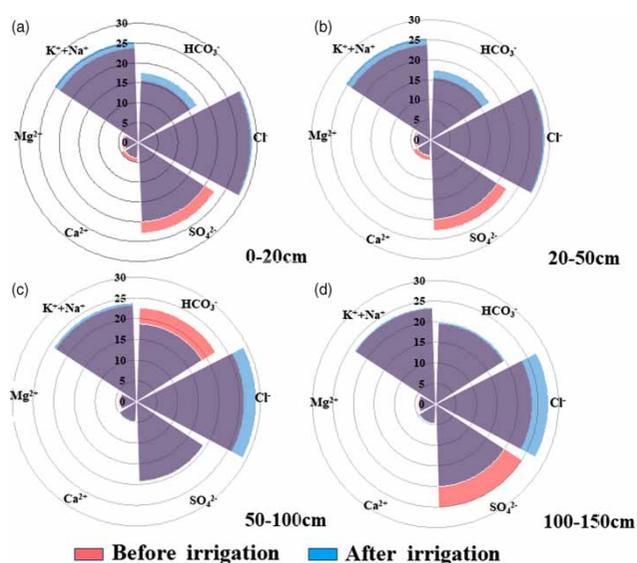

Figure 6 │ The changes in the contributing ratio (%) of each ion to soil salinity before and after irrigation.

Given the contribution ratio of the above-mentioned ions, Cl^-, SO_4^{2-}, HCO_3^- and $K^+ + Na^+$ were chosen for further analysis, and the relationship between the change values of these ions (shown as ΔHCO_3^-, ΔCl^-, ΔSO_4^{2-}, $\Delta[K^+ + Na^+]$) and soil salinity (shown as ΔS) was calculated by the correlation analysis shown in Figure 7. The closer the Pearson correlation coefficient r is to 1, the more significant the correlation between two variables is (Wang *et al.* 2018, 2019b).

Obviously, there was no significant correlation between the changes in HCO_3^- and soil salinity, while Cl^-, SO_4^{2-} and $Na^+ + K^+$ had significant correlation with the change in soil salinity. Thus, it can be concluded that these ions played the dominant role in the variation of soil salinity induced by irrigation; moreover, the correlation coefficients revealed that Cl^- and $Na^+ + K^+$ had more effect on the changes in soil salinity in the study area. Combined with Figure 6, it was considered that the increase of salinity in 0–20 cm soil layer after irrigation was mainly induced by the increase of $Na^+ + K^+$ and Cl^- concentration (from 2.10 to 2.67 g/kg for $Na^+ + K^+$ and 3.04 to 3.46 g/kg for Cl^-), while the decline of soil salinity in the deeper layer was almost affected by the decrease of SO_4^{2-} concentration (from 0.98 to 0.61 g/kg). Furthermore, the averaged SO_4^{2-} concentration in groundwater increased from 554.75 mg/L before irrigation to 976.61 mg/L after irrigation, also verifying that a large amount of SO_4^{2-} in the deep soil layer migrated downward into groundwater by irrigation.

The salt flux in different soil layers

Salinity was highly variable along the vertical plane in shallow soil in the YISD and exhibited a marked change in spatial distribution after irrigation. To explore the causes of this change after irrigation, salt flux can provide important evidence (Schoups *et al.* 2005). The soil salt storage of all sample sites in the study area is calculated by Equation (1), and the soil salt flux of different layers at each site is calculated by Equation (2).

The average soil salt flux of each interface in different soil layers were −153.66 (20 cm), 408.9 (50 cm), 369.96 (100 cm) and 558.31 g/m² (150 cm), respectively. According to the calculated results of soil storage, they were 225.62 (0–20 cm), −322.78 (20–50 cm), 38.99 (50–100 cm) and
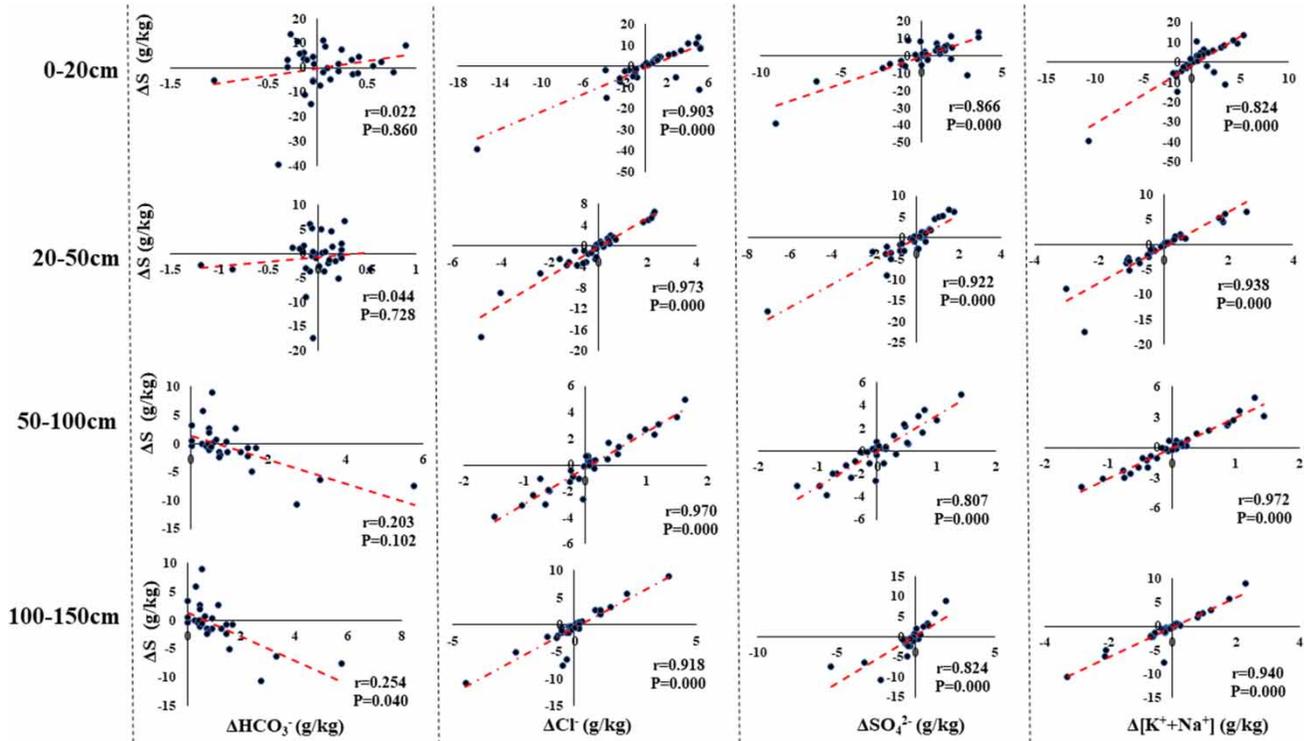
Figure 7 | The relationships between the concentration changes in main ions and soil salinity (ΔS).

−188.35 g/m² (100–150 cm), respectively, revealing that salt accumulation appeared in the shallower soli layer and salt discharge occurred in the deeper layer. Several sites had large salt flux and were connected with the spatial distribution of soil salinity variation before and after irrigation (sites YC09, YC11, YC12, YC15, YC28, YC30 and YC31; Table 2). Two sites corresponded with extremely saline-alkali land in the southwest of the study area (sites YC09

and YC11) and two sites corresponded with extremely saline-alkali land in northeast area (sites YC30 and YC31). These four sites in the southwest and northeast were in the area of cultivated land and the huge downward salt flux indicated that a large amount of salt moved downward during the autumn irrigation, which effectively changed the salinization of shallow soil in the region. The sum of salt discharge from 0 to 20 and 20 to 50 cm soil layers at sites YC09

Table 2 | Salt flux of several sampling sites in each soil layer

Sites	Q_0	Q_1	Q_2	Q_3	Q_4	ΔS_1	ΔS_2	ΔS_3	ΔS_4
YC09	148.41	4,624.00	12,435.93	11,201.16	14,934.02	−4,475.59	−7,811.93	1,234.76	−3,732.86
YC11	148.41	1,528.64	3,196.24	5,457.65	6,589.94	−1,380.23	−1,667.60	−2,261.41	−1,132.29
YC12	0.00	−3,930.20	−6,171.99	−7,910.15	−10,358.93	4,078.61	2,241.79	1,738.16	2,448.78
YC15	0.00	−2,585.17	−3,470.59	−6,154.86	−12,826.23	2,733.58	885.42	2,684.27	6,671.36
YC28	0.00	664.87	−2,291.45	−5,967.13	−7,913.97	−516.46	2,956.32	3,675.68	1,946.83
YC30	148.41	3,951.22	7,926.75	9,628.09	11,378.03	−3,802.81	−3,975.53	−1,711.34	−1,739.95
YC31	148.41	645.18	2,950.71	4,394.82	5,198.41	−496.77	−2,305.54	−1,444.11	−803.59

Note: Q_0, Q_1, Q_2, Q_3 and Q_4 represent the salt flux at the soil interface of 0, 20, 50, 100 and 150 cm soil depths, respectively, in g/m²; ΔS_1, ΔS_2, ΔS_3 and ΔS_4 represent the changes in salt storage before and after irrigation in the 0–20, 20–50, 50–100 and 100–150 cm soil layers, respectively, in g/m².

and YC30 accounted for 83.10 and 69.23% of the total salt discharge, respectively. For the monitoring sites in the wasteland, YC12, YC15 and YC28 had large upward salt flux, which directly increased the depth of soil salinization in this area. The salinity in each soil layer of YC12 and YC15 increased, indicating the phenomenon of 'salt return', which is defined as the accumulation of salt in the surface soil.

Different land types and soil utilization stages will affect the evapotranspiration of soil water (Fang et al. 2018), resulting in soil water and salt changes. This study was conducted in the period between agricultural plantings. When there are no crops planted in the soil, the difference in evapotranspiration between the two land types is small, which highlights the impact of irrigation on soil salinity. Irrigation activities in the YISD resulted in the rapid infiltration of a large amount of water from the Yellow River into the soil of the irrigated area by flood irrigation. The salt input to the shallow soil (0–20 cm soil layer) of the irrigation area was higher than the salt excretion, so the salinity of shallow soil trended upwards.

During the autumn irrigation period, a large amount of salt entered the groundwater system along with the irrigation water, which led to a 28.3% increase in the groundwater TDS of the study area (Figure 5(d)), and simultaneously raised the water level, the average groundwater level of the study area increased by 0.68 m (Figure 5(c)). Thus, there was a strong water–salt interaction between the groundwater system and soil (Wang et al. 2015). The moisture content of the 0–20 cm soil layer increased from 21.4 to 23.0% after irrigation and the moisture content of the other layers also increased to varying extent; this benefited the groundwater because it resulted in a high TDS content to transport salt in the soil through the vadose zone capillary water (Shah et al. 2011). Because of the strong evapotranspiration in the arid desert climate zone of the north temperate zone, the salt eventually remained in the shallow soil and increased the soil salinity, resulting in secondary salinization (Akça et al. 2020). This finding is similar to that of Forkutsa et al. (2009) in the Khorezm region of Uzbekistan in the Aral Sea Basin and Han & Zhou (2018) in the northwest plain of the Junggar Basin, Xinjiang, China. In this study, we chose to sample and analyse samples during the period between crop plantings, while

Han & Zhou (2018) carried out their study during the growing period of cotton, so the soil of the irrigation area was influenced by biological effects. It is clear that the salinity of shallow soil in arid areas increases during irrigation, but the importance of irrigation for agricultural production is self-evident. To secure the agricultural production and soil utilization value of an irrigation area, it is necessary to strike an appropriate balance between allowing irrigation and avoiding excessive secondary salinization of soil. To deal with this problem, Forkutsa et al. (2009) proposed that the irrigation and drainage systems should be improved, but because of the potential cost of this strategy, we recommend changing the irrigation pattern and strengthening the development and utilization of groundwater. When combined with the results of nonlinear fitting of salinity in the different soil layers, it was found that the increasing depth to groundwater table and TDS had different degrees of impact on the salinity of each soil layer. The average salt flux of shallow soil was upward, indicating that the capacity for salt migration downward was poorer than that of other deeper soil layers. Therefore, under conditions of elevated groundwater level and TDS, shallow soil salinity increased.

CONCLUSIONS

Soil salinity in the YISD decreased with increasing soil depth. There was a moderate level of variation in the soil salinity of each layer in the irrigation area and the variability of deep soil was lower than that of shallow soil. After irrigation, the variation in shallow soil salinity decreased markedly. Irrigation activities affected the spatial variability of shallow soil but had a much smaller effect on the salinity of deep soil.

The salinization of shallow soil in the irrigation area was severe, especially in the northeast and southwest of the study area. With the increase in soil depth, the area of extremely saline-alkali land decreased rapidly and the level of soil salinization reduced. By comparing the interpolation maps of salinity and water content in different soil layers, it was found that irrigation had a great impact on the spatial distribution of shallow soil salinity; after irrigation, there was a positive correlation between soil moisture content and soil salinity in the middle of the study area. Irrigation activities led to the disappearance of extremely saline-alkali land in

shallow soil in the northeast. After irrigation, the salinity of cultivated land decreased sharply, while the phenomenon of 'salt return' occurred in wasteland.

Irrigation affected soil salinity in the YISD, but the salt-leaching effect on soil in the 0–20 cm layer was poor. Because irrigation resulted in an increase in the groundwater level and TDS, a large amount of high salinity groundwater passed through the vadose zone and accumulated in the shallow soil, resulting in secondary salinization of the shallow soil. To effectively alleviate this problem, the traditional irrigation pattern needs to be improved. Instead of flood irrigation, drip irrigation or other methods suitable for soil irrigation in arid areas should be applied, and groundwater should be properly extracted as a water source for irrigation, so as to reduce the groundwater level, prevent secondary salinization of the soil in the irrigation area, and promote sustainable agricultural production in the irrigation area.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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