The effect of winter flood irrigation with saline water on groundwater in a typical irrigation area

Yujiang He, Wenjing Lin and Guiling Wang

ABSTRACT

Flood irrigation in the winter has been widely applied in northwest China for several years, but little attention has been paid to the flood irrigation program to date. In order to seek a reasonable irrigation quota, a flood irrigation experiment using two common quotas (1,800 and 1,200 m³ ha⁻¹) was conducted in an area irrigated by saline water in the Nanjiang basin with shallow groundwater. Soil electrical conductivity in six treatments irrigated by saline water, with various salinity backgrounds, was investigated using Hydra and DDS-307 before and after flood irrigation. The results indicate that the quota of 12.00 m³ ha⁻¹ was small enough to prevent soil salt from leaching out of the root zone. Although the quota of 1,800 m³ ha⁻¹ may guarantee regular plant growth in the following year, it resulted in at least 267.2 g m⁻² of salt entering the shallow groundwater. Therefore, flood irrigation had an important and profound effect on plants, soil environment, and shallow groundwater. The quota of flood irrigation in winter should be determined cautiously according to the hydraulic characteristics and salt background of the soil.

Key words | flood irrigation, groundwater, irrigation area, saline water, soil environment

INTRODUCTION

Flood irrigation in the winter is effective for water storage in soil, the improvement of the soil environment, and the leaching of soil salt (Yang et al. 2009), especially for some areas that are irrigated using saline water (Beltran et al. 1999; Karlberg et al. 2007). Storage irrigation in the autumn as well as irrigation in the winter and early spring (Fan 2001) are conducted to satisfy the water demand of overwintering crops, to regulate the imbalance of water resource supply and requirements, to utilize wastewater, to arrange labor, etc. Each type of the above irrigation methods occurs frequently in early winter and early spring, and the irrigation frequency rises daily with increased contradictions between the supply and requirements of water resources (Li 2007). Furthermore, irrigation was one of the critical measures used to promote cotton yield in the Nanjiang basin in northwest China (He et al. 2010), which lacked fresh water in the summer but not during the winter.

However, irrigation in the winter evoked increased damage, which was evidenced by the groundwater depth of less than 2 m in about 62% of the cotton irrigation area in Nanjiang, China. Secondary salinization was often caused by flood irrigation in areas with lower groundwater levels (Runyan et al. 2010). In addition, excessive irrigation water induced a rise in the water table and the subsequent intense phreatic evaporation that led to the upward movement of salt from groundwater (Sing et al. 2010) and the accumulation in the ground surface (Wang et al. 2014).

Flood irrigation will directly cause serious pollution in shallow groundwater sources in these areas, but little attention has been focused on this issue to date (Malash et al. 2008; Roberts et al. 2009). Hence, using a typical experimental area of the Nanjiang basin as an example (from the intertransform of irrigation water, soil water, and groundwater),
this study examines the basic movement theory of soil water and salt and estimates the pollution of shallow groundwater resulting from flood irrigation.

**METHODS**

**Experimental setup**

The experiment was conducted at the Bazhou Experimental Station of Irrigation in the Nanjiang basin. Both surface water and groundwater were available for irrigation at the experimental farmland. The surface water (F) was from a river, with total dissolved solids (TDS) of 0.90–1.01 g L\(^{-1}\). The TDS of groundwater at the experimental site was 2.98–3.21 g L\(^{-1}\) with the hydrochemical type of ClSO\(_4\)-Na (referred to as S). The groundwater table in the area is located at a depth 1.50–2.00 m below the surface. Furthermore, the soils in the experimental fields were mainly loamy sand, sandy loam, and sand, which were distributed at depths of 0–50, 50–120, and 120–160 cm, respectively. In addition, the field was planted with cotton that exhibited a low yield for several years.

**Treatments**

The irrigation programs were as follows: (1) irrigation with saline groundwater throughout the growth season using three water quantities: 5,250 m\(^3\) ha\(^{-1}\) (5250S), 4,500 m\(^3\) ha\(^{-1}\) (4500S), and 3,750 m\(^3\) ha\(^{-1}\) (3750S); (2) rotation irrigation with fresh water and saline water at a total quantity of 3,750 m\(^3\) ha\(^{-1}\) and three ratios, including 80% saline water and 20% fresh water (80S20F), 67% saline water and 33% fresh water (67S33F), and 50% saline water and 50% fresh water (50S50F); (3) flood irrigation with fresh water at a total quantity of 1,800 and 1,200 m\(^3\) ha\(^{-1}\) for different treatments during the growth season (Figure 1).

**Monitoring**

Soil water content, electrical conductivity (EC), and temperature were automatically monitored *in situ* using a Stevens Hydra Probe Soil Sensor (Stevens, Co. Ltd, Portland, Oregon, USA).

**RESULTS AND DISCUSSION**

The processing analysis of winter irrigation

The results indicate that the soil salt content clearly decreased in 5200S, 4500S, and 80S20F during the irrigation of 1,800 m\(^3\) ha\(^{-1}\). Figure 2 shows that at a depth of 0–60 cm in the soil profile, the soil salt content returned to the background value, which is similar to that during cotton sowing. At a depth of 0–120 cm, the soil salt content
decreased, and soil salt leaching was more obvious at 40–80 cm depths. The figure illustrates that the larger the salt irrigation amount, the greater the salt accumulation in the soil profile before irrigation in winter. For instance, in 5250S, which has the most serious soil salt accumulation, the mean EC of the total soil profile (0–160 cm) was 1,855 μS cm⁻¹ before irrigation in winter and 785 μS cm⁻¹ after irrigation in winter. Therefore, the effect of soil salt leaching was proven to be successful. The salt was leached up to a depth of 120 cm, increasing the EC of the soil below 120 cm.

Compared with the 1,800 m³ ha⁻¹ program, the soil salt leaching effects were unsatisfactory under the irrigation program of 1,200 m³ ha⁻¹ (3750S, 3000S, and 5050F), and the soil salt was leached below 40–50 cm (Figure 3). For example, in 3750S, the change of soil EC was greater at a depth of 0–40 cm, and irrigation in winter had little influence on soil EC. Evidently, the irrigation program was so small that the soil salt could not be leached out of the root zone. The salinification phenomenon is most likely to occur under strong evaporation. Hence, considering the normal growth of cotton, the flood irrigation program should target 1,800 m³ ha⁻¹.

The equilibrium analysis of soil salinity

The soil salt balance refers to the income and expenditures of soil salt during specific periods (equalizing stage) and spatial ranges (equalizing zone). Figure 4 shows the circulant graphs of soil salt in a field. There was no flow in the lateral direction, so there was no soil salt exchange. Therefore, the balanced equation of soil salt is as follows:

$$\Delta S = S_{in} - S_{out} = (S_p + S_i + S_f + S_t) - (S_d + S_c)$$

(1)

where $\Delta S$ is the change in soil salt storage in the profile [ML⁻³], $S_{in}$ is the inflow water amount [ML⁻³], $S_{out}$ is the outflow water amount [ML⁻³], $S_p$ is the inlet salt amount with

![Figure 2](https://iwaponline.com/ws/article-pdf/15/2/356/415189/ws015020356.pdf)

**Figure 2** | Variability of EC for different treatments by WI (1,800 m³ ha⁻¹).

![Figure 3](https://iwaponline.com/ws/article-pdf/15/2/356/415189/ws015020356.pdf)

**Figure 3** | Variability of EC for different treatments by WI (1,200 m³ ha⁻¹).
precipitation \( [\text{ML}^3] \), \( S_i \) is the inlet salt amount with irrigation \( [\text{ML}^3] \), \( S_v \) is the inlet salt amount with the vertical recharge by phreatic water \( [\text{ML}^3] \), \( S_f \) is the inlet salt amount of fertilizer application \( [\text{ML}^3] \), \( S_d \) is the outlet salt amount from soil water leakage \( [\text{ML}^3] \), and \( S_c \) is the outlet salt amount from plants \( [\text{ML}^3] \).

The salt amount entered into the soil was positive, and the flow out of the soil was negative. The observed TDS values of precipitation, irrigation water, fresh water, and groundwater were 0.07, 3.00, 0.98, and 2.73 g L\(^{-1}\), respectively. The salt flowing out from soil water infiltration adopted the average value in the profile at different times. Therefore, the TDS was 8.53 g L\(^{-1}\) in the bud stage, 9.77 g L\(^{-1}\) in the early blooming period, 9.56 g L\(^{-1}\) in the later blooming period, and 5.73 g L\(^{-1}\) during irrigation in the winter. These values were the measured mean values in the study area.

According to the practical planting pattern in the experimental areas, the total salt amount in cotton was 267.0 g m\(^{-2}\) (Gong et al. 2009). In the bud stage, early blooming period, and later blooming period, the outlet salt amounts were 30, 60, and 10% of that measured during the whole year, respectively. The depth of the calculation was the mean buried depth of the groundwater for each period. Therefore, in the cotton growth period, the buried depth of the groundwater was 160 cm, and it was 200 cm during irrigation in winter. For example, note the values recorded for 4500S that are shown in Table 1.

Table 1 indicates that 94% of the inlet salt amount was from precipitation and irrigation, and only a small portion

<table>
<thead>
<tr>
<th>Period</th>
<th>Outlet salt amount by</th>
<th>Inlet salt amount by</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Soil water leakage</td>
<td>Plant</td>
</tr>
<tr>
<td>First-third irrigation (1–21 days)</td>
<td>14.5</td>
<td>80.0</td>
</tr>
<tr>
<td>Fourth–eighth irrigation (22–52 days)</td>
<td>7.8</td>
<td>160.0</td>
</tr>
<tr>
<td>9th–11th irrigation (53–73 days)</td>
<td>2.9</td>
<td>27.0</td>
</tr>
<tr>
<td>Irrigation in winter (74–155 days)</td>
<td>731.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Sum (1–155 days)</td>
<td>756.9</td>
<td>267.0</td>
</tr>
</tbody>
</table>
of the salt came from the vertical recharge by groundwater. For instance, the outlet salt from soil water leakage and cotton were 74 and 26%, respectively. Therefore, it is clear that light saline water irrigation was the main component that introduced salt into the soil. In the first-third and the fourth-eighth periods, irrigation with fresh water was carried out, and it resulted in a soil salt accumulation amount that was lower than that in the 9th-11th period. In the aforementioned periods, the outlet soil salt amount by soil water leakage was very small. The difference in the soil salt storage in the soil profile was 541.3 g m⁻². Furthermore, the soil salt in the soil profile increased by 267.2 g m⁻², and the salt accumulation was concentrated below 80 cm during the period of study. The results indicate that the soil salt was mainly present at depths of 80–140 cm due to irrigation in the winter. Therefore, the soil salt was removed by irrigation and migrated into the groundwater, which eventually led to shallow groundwater pollution.

Three major environmental problems must be considered regarding flood irrigation in the winter. The first is the balance between soil moisture conservation and the deep seepage of soil water. Irrigation in winter was conducted to store soil water for sowing and for seedlings of spring wheat the following year. Combined with the removal of soil salt, irrigation also influenced the agricultural industry and the status of the soil environment the following year in the irrigated region (Wang et al. 2004). After decreasing the deep seepage of soil water, it was feasible to choose the 50 mm depth for the winter irrigation quota (Shang et al. 1997). The ice was pure without salt, so when the soil water transformed into ice, the salt would precipitate and form high-concentration areas. The biological tissues in the high-concentration areas intensely lost moisture. When the frozen soil melted in spring, the soil strength may have been lost entirely. Therefore, irrigation influenced the stability of the soil foundation. Moreover, the melted water seeping to the surface formed spring floods, affected spring plowing, and led to soil nutrient loss.

The second problem is the contamination of shallow groundwater caused by desalinization from flood irrigation. This is particularly important for areas with shallow ground water in that flood irrigation in the winter may make the groundwater severely contaminated. For example, the flood irrigation practices in Punjab (India) that are used to grow paddy crops could induce geochemical conditions that are favorable for the mobilization of arsenic from surface soils, which could eventually elevate arsenic concentrations in the underlying shallow aquifer (Hundal et al. 2013).

The third problem is the drainage salinity effect. For the areas in which the groundwater was shallow with high salinity, the soil salt moved with the groundwater, combined at the surface, and ultimately exacerbated the process of soil salinization. Wang et al. (2014) suggested that winter flood irrigation should use 1,575 m³ ha⁻¹ of fresh water every 2 years in areas that were irrigated by saline water in Nanjiang basin. Moreover, Zhang et al. (2014) proposed that soil salt accumulates above the relatively impermeable layer, which is opposite when compared to the flood irrigation situation in the same area.

Therefore, the irrigation quota should be designed according to the type of irrigation, soil texture, and climatic conditions. This quota has great significance in terms of the comprehensive evaluation of surface water and groundwater resources, the efficient use of water and heat resources in soil, the reasonable determination of technical parameters associated with agricultural irrigation, soil protection, soil salinization prevention, etc.

**CONCLUSIONS**

The results showed that compared with the 1,800 m³ ha⁻¹ quota, the soil salt leaching effects were unsatisfactory under the 1,200 m³ ha⁻¹ quota, which leached soil salt at just 40–50 cm. Obviously, the 1,200 m³ ha⁻¹ quota was so small that the soil salt could not be leached out of the root zone. Moreover, the results would affect the normal growth of cotton in the following year. Therefore, the 1,800 m³ ha⁻¹ irrigation quota should be chosen in most of the local fields for improving the soil environment and the crop production. However, especially the soil water leakage resulted in a large amount of soil salt (267.2 g m⁻² under 4500S) entering the shallow groundwater. To prevent pollution of the groundwater, the flood irrigation quota in the winter should be further designed in a rational way according to the hydraulic characteristics and salt background of the soil in the local field.
ACKNOWLEDGEMENTS

This study was funded by the National Natural Science Foundation of China (41302186). We gratefully acknowledge the Bazhou Experimental Station of Irrigation, Xinjiang, and China University of Geosciences and Prof. Menggui Jin, Prof. Bingguo Wang, and others for their fruitful cooperation on experiments in both the field and laboratory.

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First received 21 July 2014; accepted in revised form 7 November 2014. Available online 20 November 2014