Soil salt balance and simulation in a high efficiency film-mulched drip irrigation and subsurface pipe drainage system

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Abstract

Soil salinisation is vital factor limited crop yield in dryland oasis cropland. A film-mulched drip irrigation and subsurface pipe drainage (MDI-SPD) system has been proved its high efficiency all over the world. However, soil salt balance and simulation in time and spatial dimension are unclear in this system. Based on four-year observation data, we use HYDRUS-2D model to simulate the soil salt balance in a MDI-SPD system in western China. We conducted a set of MDI-SPD experiments three times in a field in Manas River Basin, western China: The laying depth of the subsurface pipe was 1 m, and drain spacing was 15 m. Three treatments were set at 0, 5, and 7.5 m horizontal from the subsurface pipe. Results after four years indicated that the total salt output in the irrigated area was 260.16 t, with 103.4 t salt drained by the subsurface pipe (39.74% of the total salt output in the irrigation area). Soil salt balance indicated desalination state. Soil EC response ranged from 8.33 to 11.21 dS m^{-1}. The mineralization of subsurface pipe drainage was positively correlated with drainage flow and salt discharge, and negatively correlated with drainage discharges and time ($P<0.05$). If salinity leaching stops, 0−200 cm depth soil salt balance will achieve critical value in 8 years. Thus, we recommend salinity leaching once every three years. An increase in shaft drainage would also reduce the deep seepage of salt.

Keywords: Soil salinisation; Salinity leaching; film-mulched drip irrigation; Subsurface pipe drainage; HYDRUS-2D

1. Introduction

More than 80 countries with predominantly agricultural economies are located in arid areas worldwide (Cristóbal and José, 2008). Soil salinization threatens the sustainability of irrigated agriculture in arid and semi-arid regions since salt accumulation degrades soil quality. (Zhang et al., 2016). Currently, there are about one billion ha of saline-alkali soil worldwide, and this area was increasing at one million ha per year, mainly in inland arid continental regions (Ren et al., 2012). Xinjiang, China is located in the center of the Eurasian continent, with a saline-alkaline soil area of about 2.81×10^7 ha (Li et al., 2015). Xinjiang is the largest cotton-producing area in China, with a cotton yield accounting for 30% of the total global yield in 2019 (Chen et al., 2020). In addition to the damage caused by soil salinisation, the threat of water shortage is also severe in this region (Nabi et al., 2019), mainly owing to low rainfall and high evaporation. The rainwater infiltration through the soil is challenging to preserve naturally in Xinjiang (Kribaa et al., 2001). Thus, film-mulched drip irrigation is more suitable than furrow irrigation, sprinkler irrigation, and flood irrigation in arid areas (Tiwari et al., 2003; Yang et al., 2020), and can save water by 30%40%, increase yield by 20%, and save fertiliser by up to 7%−15% of cultivated land area (Luo et al., 2018). By 2019, the application area of film-mulched drip irrigation in Xinjiang was 3.76 × 10^6 ha (Heng et al., 2018), and its use has extended to more than 15 central Asian and African countries.

Film-mulched drip irrigation is suitable for use on saline-alkali soil. Dorta et al. (2016) found that long-term drip irrigation concentrates soil EC toward the edge of the wetting front. Additionally, Liu et al. (2010) concluded that film-mulched drip irrigation could make the soil EC accumulate at an annual rate of 0.36 g kg^{-1} in root areas. Several studies have shown that drip irrigation with salinity leaching after the growth period can efficiently and significantly reduce salt accumulation within the soil profile. Tian et al. (2013) indicated that salinity leaching could effectively prevent surface crust salt deposition. Meanwhile, Danierhan et al. (2012) showed that the accumulation of soil salt was relieved by increasing drip irrigation water. Moreover, Wang et al. (2014) found that the salt accumulated by film-mulched drip irrigation can be offset by salt leaching after the growth period. However, salinity leaching consumes large amounts of water resources, which is limited in arid areas. Long-term leaching may lead to an imbalance of water and salt, and damage to the ecological environment of farmland. Kevda and Wu (1959) highlighted that if leaching led to a 5−8-m rise of the groundwater table, then there would be a need for new drainage systems within two years. Irrigation without drainage systems caused natural disasters in Xinjiang in the early 1960s, a decrease in the availability of crop fields across large areas, and widespread farmland abandonment.

Salinity leaching combined with subsurface drainage was essential for saline-alkali soil improvement in Xinjiang. Current subsurface drainage research has mainly focused on pipe parameters and water-salt balance during drainage. Kladivko et al. (2004) analysed the effect of subsurface pipe spacing on nitrate nitrogen (NO_3^--N) concentration and drainage flow to develop appropriate management strategies. Furthermore, Radu and Onet (2013) carried out MDI-SPD experiments on meadow soils in Moldova. They pointed out the best laying depth for subsurface pipe drainage, i.e. 1 m. Yuan et al. (2011) used the annualised agricultural non-point source model (AGNPS) to delineate the spacing of subsurface pipe drainage in Maumee River Basin, Ohio, and pointed out that when changing drain spacing from 12 to 15 m, non-point source nitrogen loading would be reduced by 35%. Akram et al. (2013) also reported that subsurface pipe drainage was an effective drainage solution for sustainable agricultural production in an area of southwestern Iran where secondary salinisation had been a problem.In recent years, the HYDRUS model is useful in solving several numerical simulation problems of subsurface pipe drainage. Roberts et al. (2009) used HYDRUS-2D to analyse soil moisture content and solute transport under drip irrigation conditions, and validated the accuracy of this classification model. Mante et al. (2018) used HYDRUS-2D to compare soil strength between drained and undrained sandy-loam fields (0.9 m depth and 15 m spacing). Subsurface pipe drainage systems can significantly improve shallow soil moisture content. Moreover, Han et al. (2015) simulated root water uptake (RWU) under different drip irrigation and soil texture, with satisfactory accuracy.

The original aim of subsurface pipe drainage was to lower the groundwater level, remote the excess water from tillage-layer soil, and improve soil physical and chemical properties (Salo et al., 2017; Yang et al., 2017). It was commonly used in the semi-humid coastal, river, basin, and swamp areas (Yao et al., 2017; Sellner et al., 2017). However, affected by the intense evaporation in arid regions, capillary water rise was the main route of salt accumulation. At present, there has been no detailed investigation of soil salt balance during irrigation leaching and drainage system. Few studies have reported the efficacy of 0−2 m profile soil improvement in the most severe salinisation areas (Sloan et al., 2017; Manninen et al., 2018). Furthermore, the performance of subsurface pipe drainage and salt deep seepage issues have not received much attention. Therefore, the objective of our study was to investigate the salt migration of saline−alkali cultivated land under long-term irrigation and drainage patterns. The soil EC was analysed in three typical soil layers (0−20, 60−80, and 180−200 cm) at three locations, i.e., 0, 5, and 7.5 m away from the subsurface pipe, and the precision and accuracy of HYDRUS-2D were verified. We quantitatively analysed the relationship between drainage parameters and salt desalination performance. This study provides a scientific basis for the saline-alkali farmland restoration and reconstruction in arid regions.

2 Materials and methods

2.1 Site description

A long-term experiment was carried out over four years (2015–2019) in the northwest of Shawan County, Xinjiang, China (85°21′E, 44°36′N). The test field was located on the edge of Gurbantunggut Desert (Fig. 1). The average climate data were obtained from the China Meteorological Network (http://data.cma.cn/) for the period 2015–2019. The climate in this region is that of a typical continental arid desert, with average annual sunshine of 2,447.9 h. Throughout the whole monitoring period, the average minimum and maximum temperatures were -19.4 and 31.4 °C, respectively (Fig. 2). The average annual precipitation is only 182.5 mm, while annual evaporation reaches 1,720 mm. The groundwater depth was 2−3 m during the non-irrigation period. The abandoned agricultural field was selected as the experimental field site (3.4 ha). The elevation in the southeast of the site is 385.1 m, and in the northwest of the site is 383.5 m. The soil textures were sandy loam and silt loam, and soil pH ranged from 7.51 to 8.53. The soil EC of the 0−20 and 60−80 cm soil layer at the beginning of the study was 14.3−16.1 and 12.9−15.5 dS m^{-1}, respectively. The main soluble salts in the soil were sulphate and chloride.

Figure 1 is here

Figure 2 is here

2.2 Experimental design

2.2.1 Experimental Area

The drainage system of the experimental site was repaired prior to the start of the experiment, including the seepage control of the access roads, diversion ditch, drainage ditch, and reservoir. The native plants were by wormwoods (Artemisia spp.) and, in particular, by Artemisia anethifolia Weber ex Stechm. Construction of the subsurface drainage systems started in March 2016 and was completed in April 2016. Details of the experimental installation process were as follows: a soil profile was excavated using a hydraulic excavator (Doosan 331), the subsurface pipes were then placed horizontally in the soil profile. The subsurface pipes were covered with sand and gravel (particle size = 4 cm) to a thickness of 20 cm. Subsurface pipes were backfilled with soil, layer by layer, to complete the construction. The opening gap was 1 mm, and the opening area was 250 cm^2 m^{-2}, with a design slope of 0.4%. High-quality resin integrated drainage wells were set at the end of each subsurface pipe, and the wells through the catchment pipe flowed directly to the drainage tile. The 90-mm subsurface pipe diameter was wrapped by a double geotextile. Polypropylene woven fabrics were the main raw materials used in the geotextile, with a density of 450 g m^{-2}. The catchment pipe was a hard polyvinyl chloride plastic pipe with a 250 mm diameter and 0.3% slope. The spacing and depth of subsurface pipe were designed using the water balance principle and Hooghoudt's equation (Cook et al., 2006; Gerke et al., 2016; Kirkham and Zeeuw, 1952), as shown in Eq. (1). Experimental design drain spacing was 15 m, and the Laying depth and length of each subsurface pipe were 1.0 m and 200 m, respectively.

$$\begin{cases} H = H_k + \Delta h + d \\ L^2 = \dfrac{4K_a h_t^2}{q} + \dfrac{8K_b e h_t}{q} \end{cases} \tag{1}$$

where H (m) represents the buried pipe depth; H_k (m) represents the critical depth of groundwater, depth of drainage, or depth of soil improvement; h (m) is retained head, and d (m) represents the pipe diameter. h_t (m) represents the head of water midway between drains, K_a and K_b (m day^{-1}) are the soil hydraulic conductivity of above-drain and below-drain level, respectively, q (m day^{-1}) is the design drainage rate (Gerke et al., 2016), L (m) is the drain spacing, and e (m) is the Hooghoudt's equivalent depth.

2.2.2 Leaching and planting experiments

Plots were irrigated with surface water (salt content was 0.8 dS m^{-1}). We conducted four leaching tests (one for flood irrigation leaching and three leaching), and the selected leaching dates were 8 June 2015, 8 June 2016, 8 September 2017, and 18 April 2017, respectively. The irrigation scheme was based on the local crop water requirement, including irrigation quota, date, and time (Table 1).

Table 1 is here

Leaching water demand was determined by soil EC and the critical salinity of the allowed crop growth (Nasiev and Eleshev, 2014).

$$D_W/D_S=-C\lg[(EC_a-2EC_i)/(EC_s-2EC_i)] \quad (2)$$

where D_W (m) is leaching water demand, D_S (m) is leaching need of soil layer depth, EC_a (dS m^{-1}) is the critical salinity of the allowed crop growth, EC_i (dS m^{-1}) is the irrigation water salinity, EC_s (dS m^{-1}) is initial soil EC, and C is salt leaching coefficient (C = 1.06).

Drip irrigation was adopted during the crop growing period from 2015 to 2019 (Fig. 3). Cotton (Gossypium hirsutum L. var. Xin Luza 9112) seed was planted in 2015; the seedling emergence rate of cotton under salt stress was less than 30%. Sunflower (*Helianthus annuus* L.) was the best of salt-tolerant crops through the field investigation, so sunflower was planted in 2016, and cotton was also planted for the remaining years. Both cotton and sunflower were salt tolerant. A narrow-wide-row planting pattern was used. For sunflower cultivation, the narrow and wide row spacings were 30 and 60 cm, respectively, and the transparent plastic film mulch width was 140 cm (Fig. 3). For cotton cultivation, the narrow and wide row spacings were 25 and 50 cm, respectively, and the transparent plastic film mulch width was 140 cm. The single-hole flow of drip irrigation tape was 2.6 L h^{-1}, with dripper spacing of 30 cm and operating pressure of 0.09 MPa.

Figure 3 is here

2.3 Data measurement

2.3.1 Soil physical measurements

The undisturbed field soil of 0−20, 20−40, 40−60, 60−80, 80−100, 100−120, and 120−140 cm soil layers were sampled before planting. The random sampling was repeated three times, and samples were taken back to the laboratory to determine their physical parameters (Table 2). The soil samples collected with the ring knife, soil bulk density, and total porosity were obtained using drying method in the laboratory. Soil permeability coefficient was measured by Guelph 1800 K infiltration metre (Soilmoisture, Santa Barbara, CA, USA). Measurements of soil particle size distribution were conducted using a LSI3320 Laser particle size analyser (Beckman Coulter, Indianapolis, IN, USA). Field capacity, soil water content at lower and upper limits, and saturated hydraulic conductivity were determined for each soil layer following Saxton et al. (1986).

Table 2 is here

2.3.2 Soil EC

Soil sampling points were set at 0, 5, and 7.5 m horizontal from the subsurface pipe. The maximum sampling depth was 200 cm. Only three typical soil layers (shallow layer 0−20 cm; root layer 60−80 cm; deep layer 180−200 cm) were considered in this study. The soil was sampled before and after salinity leaching and once a month during the crop growth period (May to September), and at two-month intervals during the winter (October to April). Soil EC was determined using a conductivity meter (DDSJ-319L Shanghai Leichi®). Soil desalination ratio was calculated using the Eq. (3).

$$N = \left[\left(EC_1 - EC_2\right) / EC_1\right] \times 100\% \quad (3)$$

where N is the desalination ratio (%), EC_1 is the initial value of soil EC (dS m^{-1}), and EC_2 is the final value of soil EC after an irrigation (dS m^{-1}).

2.3.3 Drainage dynamics

A system was set up to monitor subsurface pipe drainage flow and mineralization during drip irrigation leaching. A water tank (capacity 10,000 mL) was placed in the drainage well. Then, the water tank was connected to the subsurface pipe water outlet and time-lapse recording was started. After 10 s, the water tank was lifted from the well, and the water volume was measured using graduated cylinders (500, 1,000, and 2,000 mL). Finally, the collected water samples were brought back to the laboratory in a cooler and stored at 4 °C for drainage mineralization analysis within 48 h. This sampling process was monitored every 4−6 h and repeated four times until the end of the experiment, when the last well stopped drainage and monitoring was completed.

2.3.4 Salt balance

The concept of salt balance was first introduced by Wilcox and Resch (1963); the concept is defined as the relation between the quantity of dissolved salts carried to an area in irrigation water, and the quantity of dissolved salts removed by the drainage water. Thus, in our study, salt balance included the following five parts: subsurface pipe drainage, deep seepage, plant absorption, groundwater recharge, and surface water.

(i) Soil EC carried by subsurface pipe drainage (D_{dw}), i.e. the amount of residual salt that was drained through subsurface pipes after salinity leaching.

(ii) Loss of soil EC during deep seepage (D_{dp}).

(iii) Soil EC supplied by surface water including rainfall (G_{rn}), irrigation (G_{ir}), and leaching (G_{lh}).

(iv) Groundwater recharge (G_{ss}, i.e. soil EC carried by capillary water rises).

(v) Soil EC absorbed by plants (D_{pt}). Before the autumn ploughing every year, soil EC was obtained from 10 randomly selected samples. In addition, sunflowers were ploughed and flattened as a salt input.

The salt balance equation (△SB) at the field scale was calculated using Eq. (4):

$$\triangle SB = \sum_{i}^{e} \left(D_{dw} + D_{dp} - G_{ir} - G_{rn} - G_{ss} + D_{pt}\right) \quad (4)$$

where i and e represent the different start and end dates (months). All units are in tonnes. When $\triangle SB > 0$, the soil profile is in the desalination state; when $SB < 0$, the soil profile is in a salt-accumulating state.

2.4 Model calibration and validation

2.4.1 Simulation of soil profile salinity changes due to different drain spacing

The HYDRUS-2D model (Šimůnek et al., 2011) was used to assess the impact of MDI-SPD on soil profile salinity. It is based on the Windows software package for simulating the temporal variations in soil water distribution, solute transport, and RWU (version 2.05). Among them, soil water flow was described based on the 2-D Richards equation for Galerkin finite-element method to appropriate initial and boundary conditions (Celia et al., 1990), while RWU was calculated using Feddes et al. (1978). RWU model was described as a sink term, and the solute transport was solved numerically using Fickian-based convection dispersion equation (Eq. 5).

$$R\frac{\partial c}{\partial t}=D_T\frac{\partial^2 c}{\partial x^2}+D_L\frac{\partial^2 c}{\partial y^2}+\mu c+\lambda \tag{5}$$

Where λ and μ are zero-order and first-order degradation constants, respectively; R is solute retardation factor; D_L and D_T are the longitudinal and transverse dispersion coefficients, respectively; and x and y are the spatial coordinates perpendicular to the flow direction. Soil profile hydrological process properties were described using the van Genuchten functions, Eq. 6 (van Genuchten, 1980).

$$\begin{cases} K(\theta)=K_s\theta_e^l\left[1-\left(1-\theta_e^{\frac{1}{m}}\right)^m\right]^2 \\ \theta_e=\dfrac{\theta(h)-\theta_r}{\theta_s-\theta_r}=\left(1+|\alpha h|^n\right)^{-m} \\ m=1-\dfrac{1}{n},0<m<1 \end{cases} \tag{6}$$

Where K_s is the saturated hydraulic conductivity, cm day^{-1};θ_e is the soil water retention;θ_s is the saturated water content (cm^3 cm^{-3}); θ_r is the residual water content (cm^3 cm^{-3}); l is a pore connectivity parameter (equal to 0.5); α, n, and m are the fitting parameters (dimensionless); and m is assumed to be 1 - 1/n. Details are summarised in Table 3.

Table 3 is here

2.4.2 Soil profile and drain tile representation

To mimic the actual field conditions, the simulation area size of 60 m^2 (30 × 2, width × depth), the depth of subsurface pipes drain was 1.0 m. The soil was divided into three layers (layer 1, layer 2, layer 3), each of them with associated parameters. Layer 1 was the surface layer (Sandy Clay Loam, 0−60 cm), and the main consideration is field management and RWU. Layer 2 was the layer in which the drainage pipes were buried (Silty Loam, 60−140 cm). Layer 3 was the deepest layer (Silty Loam, 140−200 cm).

2.4.3 Initial and boundary conditions

The triangular finite-element grid was used to create the model area; each grid cell was 0.33 cm in the vicinity of the subsurface pipes and 2.16 cm in other areas. Initial conditions were defined according to the initial soil water and soil EC at the start of the first salinity leaching in the experiments. Boundary conditions were chosen as follows: the soil surface was set as variable flux (drip irrigation) and atmospheric boundary, subsurface pipes were set as seepage drainage boundary. We also used the no-flux boundary as the lateral-dorsal, and the lower boundary as the free drainage (Fig. 4).

Figure 4 is here

Finally, the accuracy of HYDRUS-2D was quantitatively evaluated using the root mean square error (*RMSE*), criteria indices such as mean bias error (*MAE*), and r-squared (R^2), through Eqs. 7: (Nash and Sutcliffe, 1970).

$$\begin{cases} MAE = \dfrac{\sum \left| P_i - O_i \right|}{n} \\ RMSE = \sqrt{\dfrac{\sum_{i=1}^{n} \left(P_i - O_i \right)^2}{n}} \\ R^2 = 1 - \dfrac{\sum_{i=1}^{n} \left(P_i - O_i \right)^2}{\sum_{i=1}^{n} \left(O_i - O_m \right)^2} \end{cases} \quad (7)$$

where P_i and O_i are the predicted and observed data; O_m is the average of observed and simulated data; and *n* is the observations number.

3 Results

3.1 Comparison between simulated and observed soil EC

The simulated values of soil EC during the simulation period were graphically compared with the observed results for different profiles corresponding to those of the experimental observations (Fig. 5). Although differences were observed between the measured and simulated values, the trends of soil EC obtained from the model were generally in agreement with the observations. MDI-SPD of soil desalination performance were significantly better than flood leaching, according to both the observation and simulation ($P < 0.05$). Flooding leaching (June 2015) was effective in reducing the soil EC of the 0–20 cm soil layer, whereas 60–80 and 180–200 cm soil layer were not significant, and the overall decline was 0.75–3.06 dS m^{-1}. Strong salt-resalinisation occurred in the 0–20 cm soil layer after irrigation, whereas this did not occur during MDI-SPD, with an overall decline of 6.34–13.69 dS m^{-1}.

Figure 5 is here

During drip irrigation leaching and drainage (June 2016 to April 2017), the soil EC presented a significant stepwise downward trend for the drip irrigation hydrodynamic drive. After the third drip irrigation leaching (April 2017), the overall soil profiles showed that soil EC decreased from 14.42–15.74 to 2.86–6.91 dS m^{-1}, and the soil desalination ratio followed the trend 60–80 cm > 0–20 cm > 180–200 cm soil layer, which may be explained by the root region being more complex than the shallow layer (0–20 cm) with respect to salt-stress response. These results indicate that the variation of soil EC was controlled not only by the surface-groundwater compound recharge but also by RWU and salt drainage of the subsurface pipes. Moreover, salt accumulation of the root region only occurred within 5−7.5 m horizontal distance from the subsurface pipe.

The soil desalination ratio was largest in the soil immediately adjacent to the subsurface pipe drainage under drip irrigation and smallest at the mid-point between drainage pipes (7.5 m from the subsurface pipe drainage), indicating that the further away from the water suction pipe, the lower the soil desalination rate (Table 4). The observed and simulated values of soil EC from May 2017 to December 2019 revealed a slowly rising trend. The 60−80 cm soil layer showed a slightly poorer performance at points 5 and 7.5 m away from the subsurface pipe, and simulation trajectories coincided with those of other soil layers. This deviation revealed the complexity of soil EC in the natural state in arid farmland. Nevertheless, for statistical comparison, the difference between simulated and measured soil EC, i.e. RMSE and MAE, were 0.149−0.264 and 0.172−0.349 g L^{-1}, respectively. Based on these results, we conclude that the model reliably reproduces salt transport under field conditions.

Table 4 is here

3.2 Drainage and salt discharge performance of subsurface pipe drainage

The salt output during salinity leaching was quantitatively converted to drainage flow and mineralization (Fig. 6). In June 2016, September 2016, and April 2017, the drainage duration of the subsurface pipe during drip irrigation leaching was 77, 72, and 79 h, respectively. No temporary cut-off of the subsurface pipes occurred during drainage, and the water sludge concentration was maintained at 4.5−5.5 g L^{-1}, and the total hardness was 40−50 mg L^{-1} (Ca). The drainage dynamic of the subsurface pipe changed in different periods. For the first, second, and third drip irrigation leaching events, drainage flow was 1.16, 1.94, and 1.22 m^3 h^{-1}, respectively; average mineralization was 164.58, 142.51, and 122.56 g L^{-1}, respectively; total drainage discharge was 195.08, 291.7, and 222.44 m^3, respectively, and total salt discharge was 33.01, 42.87, and 27.52 t, respectively. The above-mentioned parameters of the subsurface pipe drainage system were evaluated using multiple linear regression analysis (Eq. 8). Overall, the mineralization (Y) of subsurface pipe drainage was positively correlated with drainage flow (X_1) and salt discharge (X_3), and negatively correlated with drainage discharges (X_2) and drainage times ($P < 0.05$).

$$Y=0.301\cdot X_1-0.802\cdot X_2+55.259\cdot X_3+142.222\left(R^2=0.891\right) \tag{8}$$

Figure 6 is here

3.3 Salt balance

The soil salt balance (the relation between salt output in drainage water and salt input in irrigation water) at the experimental site is illustrated in Fig. 7. The salt output includes D_{dw} (salt in subsurface drainage), D_{dp} (salt in deep seepage), and D_{pt} (salt absorbed by plants).Salt input in surface-groundwater compound recharge, including G_{rn} (salt in rainfall), G_{ir} (salt in irrigation), G_{lh} (salt in leaching), and G_{ss} (salt in groundwater recharge). Obviously, only G_{ss} values cannot be measured under field trial conditions. Even with embedded salt sensor probes in the soil profile, or with laboratory salt flux experiments (Yang et al, 2020), it has not been possible to accurately measure G_{ss} values under field conditions.Therefore, we present two possible hypotheses. OR change Hypothesis to Assumption in the next paragraph.

Hypothesis 1: The difference between soil salt balance and water balance in arid areas was caused by soil water content entering the atmosphere through evapotranspiration, while salts were arrested in soil. Evapotranspiration is known to be mainly composed of surface-groundwater compound recharge and variations of soil water storage, and so we assume that the interannual variation of soil water storage was 0, i.e. input water fluxes that could be obtained by field trial G_{ss} value based on surface-groundwater compound recharge. *Hypothesis 2*: Since the salt concentration of G_{ss} was unknown, it was convenient to consider the variations of soil EC (Fig. 5). Assuming that G_{ss} was 0, 5, 10, 15, and 20 g L^{-1} respectively, we could obtain the value range of salt balance equation.

Cumulative water input and salt output during ten months were 260.16 t, respectively (Fig. 7a, c). When G_{ss} was 0, 5, 10, 15, and 20 g L^{-1}, cumulative salt input was 38.75, 106.08, 173.42, 240.75, and 308.08 t, respectively (Fig. 7b). D_{dp} was 32.36 t higher than D_{dw}, and obviously, salt output was still dominated by D_{dp}. D_{dw} accounted for 39.74% of the total salt output.

Moreover, when G_{ss} was 0, 5, 10, and 15 g L^{-1} (Fig. 7d, e), soil salt balance indicated desalination state ($\triangle SB > 0$), and at 20 g L^{-1}, it indicated accumulation ($\triangle SB < 0$). When G_{ss} was 10 and 15 g L^{-1}, soil profile was about to reach a salt balance state ($\triangle SB = 0$), and when it was 0 g L^{-1}, $\triangle SB$ tended to slowly rise within each soil sampling period. At this stage, the field trial soil EC tended to increase slowly (May 2017 to December 2019). However, it cannot be accumulated to the initial value (June 2015) in the short-term. Therefore, we considered only G_{ss} = 5 g L^{-1} (i.e. *Hypothesis 1* did not hold true for 0, 10, 15, and 20 g L^{-1}).

After the first drip irrigation leaching (June 2016), soil salt balance went from a state of accumulation ($\triangle SB<0$) to a state of desalination state ($\triangle SB>0$). Salt output presented a significant stepwise upward trend (Fig. 7e), which was consistent with the characterisation of soil EC (Fig. 5). Linear regression analysis results showed that the estimated coefficients of salt input and output were 0.967 and 0.971, respectively (Fig. 7f). After three leaching events (April 2017), soil salt input and output were expected to achieve equilibrium on 26 May, 2027 ($\triangle SB = 0$), and the average annual total salt input was 24.68 t. Thereafter, without salinity leaching, the study site will continue accumulate salt ($\triangle SB < 0$).

Figure 7 is here

4. Discussion

4.1 Effects of salinity leaching on soil desalination

The salinity leaching curve (D_W/D_S) can reflect the soil desalination effect and describes the empirical relationships between the soil EC and leaching quota (Fig. 8). During the initial stage of leaching, the desalination effect was higher in the high salinity environment, and it decreased as the soil EC was decreased during the later stages of the leaching. At this point, a greater D_W was needed to substitute the same amount of soil EC. The wetting front was constantly overlapping around the dripper. Meanwhile, soil EC moves to drainage pipes under the hydrodynamic drive of drip irrigation. Moreover, drip irrigation leaching consumed less water than flood leaching over time. Hanson et al. (2006) demonstrated that drip irrigation leaching that partially wets the soil surface area was highly efficient only under conditions of severe irrigation deficit, and the leaching fraction decreased over time. The D_W/D_S regression analysis results showed that the estimated coefficient of drip irrigation leaching and flood leaching was 0.976 and 0.621, respectively. The high efficiency of MDI-SPD (R^2 = 0.976) had a significant contribution to the improvement of field drip irrigation. This tendency was highly consistent with the drainage characteristics of subsurface pipes. Yang et al. (2019) conducted an experiment in California and also showed that drip irrigation has the highest salinity leaching efficiency.

Figure 8 is here

4.2 The salinity leaching plan

In a previous study. Yang et al. (2019) concluded that the salinity of the 0−150 cm soil layer will reach a steady-state in 10 years. In the current study, in the non-salinity leaching case, if salinity leaching stopped, 0−200 cm depth soil salt balance will reach a critical value in 8 years (△SB = 0). A rational leaching plan should be developed that considers the trends in salt balance trends (Fig. 7f). D_{dw} and D_{dp} are the main pathways of the salt discharge, and the sums of the two components were 84.67(8 June 2016), 88.94 (8 September 2016), and 65.55 t (18 April 2016) during drip irrigation leaching; these were 2.65 to 3.60-fold of the predicted average annual salt input (i.e. 24.68 t). The amount of salt discharged by a single leaching corresponds to about three years of salt accumulation. Therefore, Therefore, we recommend that a salinity leaching plan should be created and then updated every three years (assuming that there no changes in the leaching quota).

4.3 Effects of soil EC on cotton yield

In the arid area, soil salinisation was the main factor inhibiting cotton growth. Dong et al. (2012) confirmed that when the soil EC was greater than 7 dS m^{-1}, the yield and quality of cotton would be suppressed. Additionally, Akhtar et al. (2010) concluded that the critical value of soil EC affecting cotton was 8 dS m^{-1} during seed germination. In this study, the initial soil EC in 2015 was 15.5−16.1 dS m^{-1}, which inhibited normal germination. The more salt-tolerant sunflower varieties were planted after the first drip irrigation leaching in 2016. After the first drip irrigation leaching EC decreased to 10.46−12.71 dS m^{-1}, and the sunflower germination rate was maintained below 50%, with no economic value. From 2017 to 2019, the soil EC of the shallow layer (0−20 cm) was 5.17−8.23 dS m^{-1}, and cotton yields were 3,300, 4,150, and 4,515 kg ha^{-1}, respectively, still below the non-salinised field (in 2019, 5900 kg ha^{-1}). Thus, cotton yields increased gradually from year to year for the drip-irrigated crops. The soil EC requires further reduction through MDI-SPD.

4.4 Effects of groundwater recharge and deep seepage on salt balance

It is very difficult to measure salt input and salt output in arid areas in a comprehensive and accurate way. In this study, during non-salinity leaching, G_{ss} (groundwater recharge) contributed to 63.5% of the total salt discharge, whereas the sum of G_{ir} (irrigation) and G_{rn} (rainfall) only accounted for 8.2%. Therefore, G_{ss} played a key role in soil salt balance during non-salinity leaching.

Deep seepage affected soil salt balance mainly in the salinity leaching period, accounted for 52.2% of the total salt discharge. Surface water recharge (G_{ir}, G_{lh}, and G_{rn}) could only moisten the root-zone soil during non-salinity leaching. The subsurface pipes did not generate drainage in the meantime, and there was also no deep seepage generation. The above-mentioned phenomena were fully differentiated salinisation in arid areas from salinisation in the semi-humid coastal, river, and swamp areas (Corwin et al., 2007; Turfgrass et al., 1995). In our view, with the further intensification of salt accumulation, more salinity leaching would be required through regular sampling surveys. This observation was in agreement with Souto et al. (2016). However, there are still aspects of the soil salinisation that require further study (for example, deep seepage). The following aspects require further study: (i) the spatiotemporal variability of root-zone soil EC; (ii) quantification of the soil salt carried by shallow groundwater evaporation; and (iii) coordination of subsurface pipe drainage engineering with shaft drainage engineering to reduce the deep seepage of salt.

5. Conclusions

The main conclusions of this research were as follows:

(1) During drip irrigation leaching, subsurface pipe drained 103.4 t salt, accounting for 39.74% of the total salt discharge. The average decrease in soil EC was 8.33−11.21 dS m^{-1}. The soil layer at 60−80 cm depth responded more sensitively to salinity than other soil layers. Overall, the mineralization of subsurface pipe drainage was positively correlated with drainage flow and salt discharge, and negatively correlated with drainage discharges and times ($P < 0.05$).

(2) Surface water recharge (G_{ir}, G_{lh}, and G_{rn}) could only moisten the root-zone soil, with subsurface pipes not generating drainage and no deep seepage generation in the meantime. Groundwater recharge (G_{ss}) played a determining role in soil salt balance during non-salinity leaching.

(3) Results of HYDRUS-2D simulation and observed soil EC values showed differences in the horizontal area 5−7.5 m away from the subsurface pipe in the root-zone soil (60−80 cm). The observed value of salt accumulation in the root-zone occurred only in the horizontal region 5−7.5 m from the subsurface pipes.

(4) When G_{ss} was assumed as 5 g L^{-1}, total salt discharge and observed soil EC showed a similar trend in most cases. Furthermore, if salinity leaching stops, soil salt balance will reach a critical value in 8 years ($\triangle SB = 0$). Assuming no change in the leaching quota, we recommend salinity leaching once every three years.

Author contributions

Tong Heng: Conceptualisation, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualisation. **Lili Yang**: Data curation. **Xinlin He**: Conceptualisation, Supervision, Project administration, Funding acquisition. **Guang Yang**: Methodology, Validation, Data curation, Writing – original draft. **Fadong Li**: Investigation, Resources, Supervision. **Xuan Xu**: Software, Formal analysis, Data curation. All authors have read and agreed to the published version of the manuscript.

Acknowledge

This research was funded by the National Natural Science Foundation of China [grant number U1803244, 51969027]; Key Technologies Research and Development Programme [grant number 2017YFC0404303]; Xinjiang Production and Construction Corps [grant numbers 2018CB023, CZ027204 , 2018AB027, 2018BC007]; and Shihezi University [grant number CXRC201801, RCZK2018C22]. We also acknowledge the support of the Xinjiang Production and Construction Group Key Laboratory of Modern Water-Saving Irrigation and the China Scholarship Council.

Conflict of Interest

The authors declare no competing financial interests.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1

Irrigation and Leaching schedule during the cotton growing season.

Cotton Growth stage	Irrigation date	Irrigation time (h)	Irrigation quota (mm)	Sunflower Growth stage	Irrigation date	Irrigation time (h)	Irrigation quota (mm)
Squaring	20 May	30	52.7	seedling	8 June	33	66.2
	10 June	24	53.4				
	25 June	25	53.4		25 June	30	65.5
Flowering	5 July	25	53.4	Squaring	5 July	31	65.5
	11 July	24	53.4		16 July	30	65.5
	20 July	24	53.4		25 July	30	65.5
Bolling	5 August	25	53.4	Flowering	8 August	31	65.5
	10 August	24	53.4		13 August	30	65.5
Boll opening	19 August	25	53.4	Maturity	26 August	31	65.5
Total quota			479.8	Total quota			524.7

Leaching scheme	1st Leaching Flooding irrigation	2nd Leaching Drip irrigation	3rd Leaching Drip irrigation	4th Leaching Drip irrigation
Leaching date	8 June 2015	8 June 2016	8 September 2016	18 April 2017
Total quota (mm)	1,000	1,230	1,150	1,000
Leaching time (h)	24	60	64	56

Definitions of cotton and sunflower phenological stages (Munger et al., 1998; Yu et al., 2007).

Table 2

Physical properties of the soil

Soil Layer	Bulk density g cm^{-3}	Soil particles (%)			Porosity (%)
		Sand	Silt	Clay	
0−20 cm	1.58	61.8	35.1	3.1	54.99
20−40 cm	1.66	63.3	34.1	2.6	55.53
40−60 cm	1.75	51.6	44.1	4.3	52.62
60−80 cm	1.67	52.7	44.8	2.5	54.33
80−100 cm	1.57	53.1	43.9	3.0	55.19
100−120 cm	1.62	53.1	44.7	2.2	55.45
120−140 cm	1.59	45.8	52.2	2.0	53.57

Table 3

Soil hydraulic parameters estimated from the inverse modelling method.

Soil Layer	θ_r(%)	θ_s(%)	θ_e(%)	n	K_s (cm day^{-1})	l
0−60 cm	0.1	0.39	0.059	1.48	31.44	0.5
60−140 cm	0.067	0.45	0.02	1.41	10.8	0.5
140−200 cm	0.034	0.46	0.016	1.37	6	0.5

K_s saturated hydraulic conductivity; θ_e, effective saturation; θ_s and θ_r, saturated and residual water content; *l*, pore connectivity; *n*, fitted parameter.

Table 4

Summary of values for the model evaluation parameters comparing the simulated and field-measured soil desalination ratio.

Horizontal Level (m)	Depth (cm)	Soil desalination ratio (%)					MAE (g L^{-1})	RMSE (g L^{-1})	R^2
		T1	T2	T3	T4	T5			
0	0−20	-3.28 ^{c}	81.83 ^{a}	20.98 ^{b}	-39.38 ^{cd}	4.13 ^{e}	0.159	0.207	0.69
	60−80	-10.28 ^{d}	56.60 ^{b}	9.93 ^{c}	-93.29 ^{d}	42.99 ^{a}	0.264	0.320	0.53
	180−200	7.60 ^{b}	32.12 ^{cd}	35.53 ^{a}	10.79 ^{b}	7.03 ^{d}	0.149	0.172	0.45
5	0−20	8.80 ^{b}	62.89 ^{b}	-4.60 ^{d}	-7.41 ^{c}	-5.39 ^{e}	0.235	0.283	0.69
	60−80	3.21 ^{bc}	70.58 ^{a}	6.68 ^{c}	-91.03 ^{d}	27.10 ^{b}	0.228	0.277	0.53
	180−200	17.55 ^{a}	38.13 ^{c}	19.79 ^{b}	-4.06 ^{c}	26.89 ^{b}	0.201	0.349	0.69
7.5	0−20	9.78 ^{b}	77.24 ^{ab}	27.70 ^{ab}	-23.49 ^{cd}	-6.57 ^{e}	0.176	0.197	0.53
	60−80	1.86 ^{bc}	11.55 ^{d}	7.06 ^{c}	-185.88 ^{e}	12.15 ^{c}	0.246	0.331	0.45
	180−200	-15.57 ^{d}	72.32 ^{ab}	8.90 ^{c}	22.94 ^{a}	17.95 ^{bc}	0.257	0.320	0.69

T1−T5 (time node): T1 (8 June, 2015 to 8 June, 2016), T2 (8 June, 2016 to 23 April, 2017), T3 (23 April, 2017 to 21 April, 2018), T4 (21 April, 2018 to 14 April, 2019), T5 (14 April, 2019 to 21 December, 2019). Different lowercase letters in the same column represent significant differences among treatments (sampling sites or points) at $P<0.05$ level.