Modeling salinity risk response to irrigation practices for cotton production under film mulched drip irrigation in Xinjiang

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ABSTRACT

Predicting the impacts of the irrigation amount (IA), water salinity (WS), and antecedent soil salinity (AS) on soil salinization, the crop yield, and water productivities (WPs) are important for precision agriculture. We used a calibrated HYDRUS – 2D model coupled with a validated crop water production function to quantitatively determine the response of a soil – cotton system to three factors (IA, WS, and AS) in 30 scenarios under film mulched drip irrigation. These scenarios included five IAs, two ASs, and three WSs. Under the same IA and WS, the transpiration, evapotranspiration, yield, and WPs were lower, whereas the evaporation, drainage, soil water storage, and leached salt were higher under higher AS (over the salt tolerance threshold of cotton) scenarios. Under lower AS scenarios, desalination processes (20.2 to 166.8 g m\(^{-2}\)) occurred in freshwater (0.38 dS m\(^{-1}\)) irrigation scenarios and salt accumulated (425.8 to 1,442.4 g m\(^{-2}\)) in saline water (3.10 and 7.42 dS m\(^{-1}\)) irrigation scenarios. Desalination processes (2,273.4 to 4,692 g m\(^{-2}\)) occurred in the higher AS scenarios. Salinity risk warning should be the focus for cotton fields with lower AS and saline water irrigation. Our results may help to identify the salinity risk to support sustainable cotton production in Xinjiang.

Key words: evapotranspiration components, HYDRUS – 2D, intelligent irrigation, saline water irrigation, soil water/salt balance, water productivity

HIGHLIGHTS

- Desalination occurred in cotton fields under higher soil salinity scenarios.
- Cotton fields with lower antecedent soil salinity and irrigated saline water poses a salinity risk.
- Water/salt balance components, yield, and water productivities functions of irrigation amount and water salinity.

1. INTRODUCTION

Salinization is recognized as a threat to global food security and agricultural productivity, mainly in arid and semiarid regions (Al-Tabbal & Al-Zboon 2021). This process is accelerated by human activities, such as inadequate irrigation management. All water used for irrigation contains soluble salts, and thus there is an inherent salinity risk under irrigation due to unavoidable changes in the soil water/salt balance (Ning et al. 2020, 2021).

The saline–alkali soil area of Xinjiang comprises about one–third of that in China (Chen et al. 2010) and 37.72% of the existing cultivated land has been affected by salinization. In Xinjiang, soil salinization reduces the grain output by 8.6% and the cotton output by 9%. The economic loss caused by soil salinization accounted for about 8% of the annual planting industry output. Xinjiang is the largest cotton growing region in China with about 78% of the planted area and 87% of the yield, and nearly half of the local farmers are engaged in cotton growing (Ning et al. 2013, 2015, 2021). The film mulched drip irrigation (FMDI) technique has been implemented widely for cotton production in Xinjiang, but the sources of irrigation water are often brackish due to the scarcity of fresh water for agriculture (Chen et al. 2010; Liu et al. 2012, 2013).

Sustainable cotton productivity in Xinjiang is challenged severely by the growing risk of salinization due to FMDI. Ning et al. (2014) reviewed the effects of the irrigation regime under FMDI on the soil water and salt movement characteristics.

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in cotton fields. To achieve higher cotton yields, greater water productivities (WPs), and promote salt leaching, the recommended irrigation amount (IA) is about 370 mm with a high irrigation frequency of 5 days under FMDI in northern Xinjiang (Liu et al. 2013; Ning et al. 2021). Chen et al. (2010) reported that irrigation with brackish water significantly increased the accumulation of salt in the root zone. Liu et al. (2012, 2013) reported the effects of the irrigation regime and water quality on the soil salinity, soil moisture, and cotton yield based on field experiments, where the results showed that the cotton yield and WPs decreased as the irrigation frequency and water quality decreased. Compared with irrigation using freshwater, Wang et al. (2017) found that irrigation using brackish water at a reasonable timing and duration were beneficial for the cotton yield. Ning et al. (2021) evaluated the effects of the irrigation schedule (IA and irrigation frequency) and antecedent soil salinity distribution (AS) on the soil water/salt balance and WPs under FMDI. However, little information is available regarding the quantitative effects of the AS profile, IA, and irrigation water salinity (WS) on the response of the soil–cotton system under FMDI.

In order to facilitate intelligent irrigation, managers and researchers require adequate assessment of the effects of irrigation on cotton production and the soil environment under FMDI. Unfortunately, it is still very problematic to systematically determine the soil water and salt balance in the root zone, cotton yield, and WPs under typical irrigation schedules in cotton fields. Ning et al. (2021) investigated the probable reasons for these difficulties and proposed a validated hydrological model coupled with a crop water production function to successfully address this problem. The validated HYDRUS – 2D model with a modified root water uptake (RWU) function coupled with a validated crop water production function was used to estimate the effects of the IA and irrigation frequency and AS on the soil water/salt balance, plant water status, and leaching fraction (LF), as well as the cotton yield and WPs under FMDI in 36 scenarios based on a two-year field experiment conducted previously by Ning et al. (2015). Moreover, the irrigation schedules in typical cotton fields were also optimized to increase the yield and water productivities under FMDI (Ning et al. 2021).

Predicting the effects of irrigation on the soil salinity risk and agricultural ecosystem is crucial for sustainable agricultural development in arid and semi-arid areas. In the present study, we systematically investigated the effects of IA, WS, and AS on the response of the soil–cotton system and the salinity risk under FMDI. Understanding the impacts of FMDI should help to effectively predict and reduce the soil salinity risk to allow sustainable cotton production in Xinjiang. Thus, in this study, we established the quantitative relationships for the soil water/salt balance components, cotton yield, water productivities as functions of irrigation amount and water quality in typical saline–alkali cotton fields.

2. MATERIALS AND METHODS

2.1. Site description

Field experiments were conducted during 2011 and 2012 in moderate–severe saline soil at Manas Cotton Breeding Station (44°18’N, 86°22’E, 438 m above sea level), which is located in the Manas Oasis on the southern alluvial plain, Xinjiang, China (Figure 1).

The experimental site has a typical continental arid climate, with a mean annual temperature of 6.6 °C, average annual rainfall of 147 mm, and annual evaporation ranging from 1,500 to 2,100 mm. The groundwater table is around 4 m below the surface.

2.2. Field experiment

In 2011, cotton (Gossypium hirsutum L. cv. 07–5) was planted using the traditional ‘one film, two tapes, and four rows’ planting mode. Four treatments were tested comprising two IA values of 300 and 375 mm with two irrigation WS values of 0.38 dS m\(^{-1}\) from a deep aquifer (25 m from the soil surface) and 3.10 dS m\(^{-1}\) from a shallow aquifer (5 m). In 2012, cotton was planted using the ‘one film, three tapes, and six rows’ mode. The treatments tested comprised two IA values of 450 and 500 mm with two irrigation WS values of 0.38 and 3.10 dS m\(^{-1}\). Every experiment was replicated three times with irrigation, 10 times in total. Cotton under FMDI was sown in April and harvested in September. Further details of the field experiment were described previously by Ning et al. (2015).

Soil samples were collected at depth intervals of 10 cm at five locations perpendicular to the drip tape or planting row. Samples were collected 10 times and once before each irrigation event. The sampled soil was measured to determine the soil water (gravimetrically) and salinity. Soil profiles (0–150 cm) were obtained for three soil layers (Table 1). Soil water retention curves were determined for the three soil layers by using the pressure membrane method with undisturbed soil samples collected from the field. The soil hydraulic parameters used in this study are presented in Table 1.
Root samples were collected four times (squaring, early bloom, full-bloom, and boll stages) in each growing season using an auger with an inner diameter of 8 cm and height of 10 cm. Root length and rooting depth measurements were interpolated using the Kriging method to generate root distributions in different growth stages (Ning et al. 2015). Shoot and leaf samples were collected every 10–20 days.

2.3. Numerical modeling, and initial and boundary conditions

The HYDRUS–2D model described by Šimůnek et al. (2011) was employed to simulate the two-dimensional soil water flow and solute transport under FMDI. Based on the field experiment conducted in 2011, the HYDRUS–2D model was employed to simulate a rectangular flow domain, comprising the soil profile from the middle of the film to the center of the bare soil surface, and the vertical distances was 150 cm (Figure 2).

**Table 1** | Soil hydraulic parameters and solute parameters for the field experiments used in the simulations (Ning et al. 2015)

| Depth (cm) | Texture class   | \( \theta_r \) (cm\(^3\)/cm\(^3\)) | \( \theta_s \) (cm\(^3\)/cm\(^3\)) | \( \alpha \) (cm) | \( n \) (-) | \( K_s \) (cm d\(^{-1}\)) | \( \alpha_L \) (cm) | \( \alpha_T \) (cm) |
|-----------|----------------|-----------------------------------|-----------------------------------|-----------------|--------|-----------------|-----------------|-----------------|
| 0–20      | Silt clay loam | 0.063                             | 0.388                             | 0.086           | 1.69   | 40              | 30              | 3               |
| 20–80     | Silt loam      | 0.058                             | 0.358                             | 0.092           | 1.46   | 28              | 20              | 2               |
| 80–150    | Loam           | 0.073                             | 0.418                             | 0.093           | 1.48   | 65              | 10              | 1               |

Note: \( \theta_r \) and \( \theta_s \) are the residual and saturated water contents; \( \alpha \) and \( n \) are the fitting parameters of the van Genuchten (1980) equation; \( K_s \) is the saturated hydraulic conductivity; \( \alpha_L \) is the longitudinal dispersivity; \( \alpha_T \) is the transverse dispersivity.

Root samples were collected four times (squaring, early bloom, full-bloom, and boll stages) in each growing season using an auger with an inner diameter of 8 cm and height of 10 cm. Root length and rooting depth measurements were interpolated using the Kriging method to generate root distributions in different growth stages (Ning et al. 2015). Shoot and leaf samples were collected every 10–20 days.

**Figure 1** | Location of the experimental site.
A time-variable flux boundary representing drip irrigation was imposed in the surface saturated zone of the film-mulched soil surface. The remaining mulch-covered upper regions were considered as a zero flux boundary. A time-dependent atmospheric boundary condition was used to represent the soil surface without mulch cover. Zero flux boundary conditions were set through the vertical edges of the flow domain. A free drainage boundary was specified at the base of the flow region. Third-type Cauchy (with the daily evaporation rate) boundary conditions were imposed in the flow domain. All of the specified boundary conditions are illustrated in Figure 2.

The measured soil water and salinity distributions were used as the initial conditions. The measured irrigation WS was used as a time variable input for soil salinity prediction. The normalized root density distribution function of cotton under FMDI determined by Ning et al. (2015, 2019) was used to describe the root distribution in HYDRUS–2D.

### 2.4. Model validation

It is commonly accepted that numerical models should be first calibrated and validated for the specific field conditions to obtain higher confidence in the outcomes predicted. We used previously calibrated and validated input parameters described in previous studies by Ning et al. (2015, 2021), because the same field was considered in the present study. Thus, we previously calibrated and validated the HYDRUS–2D model for the specific meteorological, location, soil, and crop conditions in the study region. The soil hydraulic parameters and solute parameters used as inputs (Table 1) were taken from the study by Ning et al. (2015), who employed the HYDRUS–2D model to simulate the two-dimensional soil water flow and solute transport in cotton fields under FMDI with a modified RWU function. Similarly, the critical values of the water and salinity stresses for water uptake by cotton were taken from our previous investigation of cotton production under FMDI in the study area (Ning et al. 2015). The simulated soil moisture results agreed well with the field measurements, where the root mean square error (RMSE) was less than 0.03 cm$^3$ cm$^{-3}$, and the coefficient of determination ($R^2$) was greater than 0.65. The simulated and measured soil salinity distributions were also in good agreement, with a maximum RMSE of
8.84 dS m\(^{-1}\) and minimum \(R^2\) of 0.65. Further details were provided by Ning et al. (2015). Furthermore, the calibrated HYDRUS–2D model coupled with a validated crop water production function was derived from Ning et al. (2021), who used the coupled model to simulate the effects of the irrigation schedule (\(IA\) and irrigation frequency) and \(AS\) on the soil water/salt balance, plant water status, LF, cotton yield, and \(WPs\) under FMDI.

Thus, in the current study, we evaluated the impacts of irrigation practices (such as \(IA\), WS, and \(AS\)) in the same region considered in our previous studies.

### 2.5. Simulation scenarios

To quantify the impacts of three interacting factors (\(AS\), \(IA\), and \(WS\)) on the soil water/salt balance, cotton yield, and \(WPs\) under FMDI, 30 scenarios were established in this study.

The 30 scenarios were defined as combinations of two different \(AS\) distributions with five \(IA\) values and three \(WS\) values. The two typical measured \(AS\) profiles were derived from Chen et al. (2010) and Ning et al. (2021), and they are shown in Figure 3. Moreover, the recommended regional \(IA\) is equal to 70% evapotranspiration by cotton (70%ETc) in the Shihezi area (Liu et al. 2013; Ning et al. 2021), so five \(IA\) values were set as 60%ETc, 70%ETc, 80%ETc, 90%ETc and 100%ETc (Ning et al. 2021). The measured irrigation WS in the Shihezi area usually ranged from 0.38 to 7.42 dS m\(^{-1}\) (Chen et al. 2010; Liu et al. 2012; Ning et al. 2015), and thus three irrigation WS values were set as 0.38, 3.10, and 7.42 dS m\(^{-1}\). The measured soil water distribution on 11 June, 2011 was used as the initial condition. The measured irrigation WS was used as a time variable input for soil salinity prediction. All simulations were performed from 11 June to 2 September, 2011. The combinations considered in the different scenarios are shown in Table 2.

### 2.6. Modeling soil water/salt balance, cotton yield, and \(WPs\)

#### 2.6.1. Water balance components

During the irrigation season, the actual evapotranspiration (\(ET_a\), mm) was calculated as follows (Ning et al. 2021):

\[
ET_a = Ea + Ta = I + P - \Delta S - D
\]

where \(I\) is the irrigation amount (mm), \(P\) is the precipitation (mm), \(\Delta S\) is the change in the soil water storage in the root zone from 0 to 100 cm (mm), and \(D\) is the drainage (mm). Moreover, \(ET_a\) comprises the actual soil evaporation (\(E_a\)) and actual transpiration (\(T_a\)).

![Figure 3](image-url)  
**Figure 3** | Two measured lower and higher antecedent soil salinity profiles (Ning et al. 2021).
2.6.2. Salt balance components

The simplified salt balance can be represented as follows (Ning et al. 2021):

\[ \Delta SS = S_w - S_d \]  

(2)

where \( \Delta SS \) is the change in the salt storage in the root zone (g m\(^{-2}\)), and \( S_w \) and \( S_d \) are the quantities of salt added in irrigation water and leached by the percolation water (g m\(^{-2}\)), respectively. The salt storage in the root zone is in equilibrium when \( \Delta SS \) equals 0, soil salt is accumulated when \( \Delta SS > 0 \), and more salt leaves the root zone when \( \Delta SS < 0 \).

2.6.3. Cotton yield and WPs

In our previous study (Ning et al. 2021), the cotton yield (\( Y \), kg hm\(^{-2}\)) was calculated using \( ET_a \) based on a verified water production function under FMDI in the same field, as follows:

\[ Y = -1.48 \times 10^{-2} \times ET_a^2 + 21.566 \times ET_a - 2,639.5 \]  

(3)

The WPs for cotton (\( WP_{ETa} \)) and for irrigation (\( WP_I \)) were the cotton yield (\( Y \)) produced per \( ET_a \) and per unit amount of irrigation water (\( I \)), separately (Ning et al. 2021):

\[ WP_{ETa} = \frac{Y}{ET_a} \]  

(4)

\[ WP_I = \frac{Y}{I} \]  

(5)

**Table 2 | Combined scenarios modeled by the HYDRUS–2D model**

| Scenario | Lower antecedent soil salinity profile | Irrigation amount (\( IA \)) | Irrigation water salinity (\( WS, \text{d Sm}^{-1} \)) | Scenario | Higher antecedent soil salinity profile | Irrigation amount (\( IA \)) | Irrigation water salinity (\( WS, \text{d Sm}^{-1} \)) |
|----------|---------------------------------------|-----------------------------|-----------------------------------------------|----------|---------------------------------------|-----------------------------|-----------------------------------------------|
| 1        | 60%\( ETc \)                          | 0.38                        |                                               | 16       | 60%\( ETc \)                          | 0.38                        |                                               |
| 2        | 60%\( ETc \)                          | 3.10                        |                                               | 17       | 60%\( ETc \)                          | 3.10                        |                                               |
| 3        | 60%\( ETc \)                          | 7.42                        |                                               | 18       | 60%\( ETc \)                          | 7.42                        |                                               |
| 4        | 70%\( ETc \)                          | 0.38                        |                                               | 19       | 70%\( ETc \)                          | 0.38                        |                                               |
| 5        | 70%\( ETc \)                          | 3.10                        |                                               | 20       | 70%\( ETc \)                          | 3.10                        |                                               |
| 6        | 70%\( ETc \)                          | 7.42                        |                                               | 21       | 70%\( ETc \)                          | 7.42                        |                                               |
| 7        | 80%\( ETc \)                          | 0.38                        |                                               | 22       | 80%\( ETc \)                          | 0.38                        |                                               |
| 8        | 80%\( ETc \)                          | 3.10                        |                                               | 23       | 80%\( ETc \)                          | 3.10                        |                                               |
| 9        | 80%\( ETc \)                          | 7.42                        |                                               | 24       | 80%\( ETc \)                          | 7.42                        |                                               |
| 10       | 90%\( ETc \)                          | 0.38                        |                                               | 25       | 90%\( ETc \)                          | 0.38                        |                                               |
| 11       | 90%\( ETc \)                          | 3.10                        |                                               | 26       | 90%\( ETc \)                          | 3.10                        |                                               |
| 12       | 90%\( ETc \)                          | 7.42                        |                                               | 27       | 90%\( ETc \)                          | 7.42                        |                                               |
| 13       | 100%\( ETc \)                         | 0.38                        |                                               | 28       | 100%\( ETc \)                         | 0.38                        |                                               |
| 14       | 100%\( ETc \)                         | 3.10                        |                                               | 29       | 100%\( ETc \)                         | 3.10                        |                                               |
| 15       | 100%\( ETc \)                         | 7.42                        |                                               | 30       | 100%\( ETc \)                         | 7.42                        |                                               |
3. RESULTS AND DISCUSSION

3.1. Water balance components

The effects of changes in the AS, IA, and WS values on the water balance components; that is, evaporation ($E_a$), transpiration ($T_a$), drainage ($D$), and soil water storage change ($\Delta S$) in the root zone, were obtained from the HYDRUS–2D model, as shown in Table 3. Regression equations for the water balance components as functions of IA and WS are presented in Table 4.

3.1.1. Evaporation ($E_a$)

Compared with the mean $E_a$ (96.2 mm) under the higher AS scenarios, the mean $E_a$ value (88.8 mm) decreased by 7.63% in scenarios 1–15. The different values of IA and WS had little effect on the values of $E_a$. As IA increased from 60 to 100%ETc, the mean $E_a$ increased in a narrow range from 95.5 to 96.8 mm in scenarios 16–30. The mean $E_a$ raised in a narrow range from 95.9 to 96.5 mm in scenarios 16–30 as WS increased from 0.38 to 7.42 dS m$^{-1}$. Similarly, the increase in the mean $E_a$ was small under the lower AS scenarios (scenarios 1–15) as IA or WS increased.

Under the different AS scenarios, the mean ratios of $E_a$ relative to $ET_a$ all decreased as IA or WS increased, where 21.58 to 22.86% and 31.83 to 38.27% of $ET_a$ occurred at the soil surface under the lower and higher AS scenarios, respectively. The results indicated that a field under higher soil salt stress exhibited greater evaporation from the soil surface. IAs and WSS had relatively insignificant effects on $E_a$ and the ratios of $E_a$ to $ET_a$, thereby suggesting that $E_a$ and the ratios of $E_a$ to $ET_a$ may be mainly affected by the film mulch. Ning et al. (2021) also found that the irrigation amount and frequency had little effect on $E_a$ and the ratios of $E_a$ to $ET_a$ by using numerical modeling methods.

3.1.2. Transpiration ($T_a$)

The $T_a$ (root water uptake) values decreased as IA reduced or WS increased (Figure 4). In scenarios 1–15, $T_a$ increased from 281.7 to 329.2 mm. Compared with the transpiration with 60%ETc, the mean values of $T_a$ with IA ranging from 70 to 100% ETc increased by 4.41%, 6.21%, 7.15%, and 7.09%, respectively.

The $T_a$ values in scenarios 16–30 were lower than those in scenarios 1–15 under the same IA and AS (Figure 4). The lower $T_a$ values in scenarios 16–30 ranged from 134.9 to 231.9 mm due to the higher salt stress. The mean values of $T_a$ decreased by 8.62% and 22.09% as WS increased from 3.10 to 7.42 dS m$^{-1}$, compared with WS = 0.38 dS m$^{-1}$. This result suggests that the excess salt in the root zone may have reduced the soil water availability to crops and reduced transpiration by applying

### Table 3 | Simulated components of water balance (mm) and salt balance (g m$^{-2}$)

| Scenario | Lower antecedent soil salinity profile | Higher antecedent soil salinity profile |
|----------|--------------------------------------|---------------------------------------|
|          | $E_a^*$ | $T_a^*$ | $D^*$ | $\Delta S^*$ | $S_a^*$ | $\Delta S\Delta S$ | $E_a$ | $T_a$ | $D$ | $\Delta S$ | $S_a$ | $\Delta S\Delta S$ |
| 1        | 91.2    | 307.8   | 36.6  | −34.4        | 90.7    | −26.7               | 95.3  | 172.8 | 99.6 | 33.4        | 2,809.2 | −2,745.2         |
| 2        | 87.4    | 305.1   | 32.2  | −23.6        | 79.8    | 425.8               | 95.4  | 157.1 | 111.4 | 37.1        | 3,031.4 | −2,525.8         |
| 3        | 87.5    | 281.7   | 32.6  | −0.7         | 81.0    | 1,161.8             | 95.7  | 135.0 | 130.8 | 39.6        | 3,516.2 | −2,273.4         |
| 4        | 91.2    | 320.6   | 36.9  | 2.4          | 94.2    | −20.2               | 95.6  | 191.3 | 123.8 | 40.4        | 3,329.8 | −3,255.8         |
| 5        | 87.4    | 320.8   | 44.9  | −1.9         | 107.7   | 476.9               | 95.9  | 173.5 | 140.1 | 41.7        | 3,610.9 | −3,026.3         |
| 6        | 87.5    | 292.7   | 47.8  | 23.1         | 118.9   | 1,313.9             | 96.1  | 147.4 | 163.4 | 44.2        | 4,153.8 | −2,721.0         |
| 7        | 91.3    | 327.4   | 64.4  | 18.0         | 150.4   | −66.4               | 96.0  | 207.8 | 153.5 | 43.8        | 3,878.6 | −3,794.6         |
| 8        | 87.5    | 324.4   | 65.0  | 24.3         | 154.7   | 508.9               | 96.3  | 189.5 | 170.8 | 44.5        | 4,137.9 | −3,474.3         |
| 9        | 87.7    | 298.3   | 76.4  | 38.7         | 210.1   | 1,412.7             | 96.6  | 161.7 | 197.0 | 45.8        | 4,720.1 | −3,097.4         |
| 10       | 91.3    | 329.2   | 96.8  | 33.8         | 207.7   | −113.7              | 96.2  | 220.9 | 186.5 | 47.6        | 4,365.8 | −4,271.8         |
| 11       | 87.7    | 328.3   | 97.5  | 37.6         | 234.6   | 508.0               | 96.6  | 202.7 | 205.0 | 46.9        | 4,620.8 | −3,878.2         |
| 12       | 87.9    | 301.0   | 115.8 | 46.4         | 370.3   | 1,442.4             | 96.9  | 173.3 | 233.3 | 47.6        | 5,257.1 | −3,424.3         |
| 13       | 91.3    | 328.1   | 132.6 | 49.2         | 270.8   | −166.8              | 96.4  | 232.0 | 222.9 | 49.8        | 4,796.0 | −4,692.0         |
| 14       | 87.8    | 327.7   | 140.7 | 44.9         | 344.1   | 477.5               | 96.8  | 213.6 | 241.3 | 49.5        | 5,044.0 | −4,222.4         |
| 15       | 88.2    | 302.2   | 160.7 | 50.1         | 574.6   | 1,292.4             | 97.2  | 181.0 | 271.2 | 51.8        | 5,705.5 | −3,838.6        |

Note: * and # represent the water balance components and salt balance components, respectively.
osmotic stress. This result also reflects the self-adaptability of the crops to salt stress conditions. Selim et al. (2012) reported a similar trend where the RWU decreased as WS increased due to the effects of salt stress. The transpiration decreased as IA of drip irrigation reduced (Ning et al. 2021).

### 3.1.3. Evapotranspiration (ETa)

In the lower and higher AS scenarios, the mean values of ETa varied from 386.9 to 408.4 mm and 250.4 to 305.6 mm as IA ranged from 60 to 100%ETc, respectively (Figure 5), thereby indicating a significant decrease in evapotranspiration under salt-stressed conditions. Ning et al. (2021) also reported that the cotton evapotranspiration was less under salt stress than that without salt stress. The average ETa reduced from 413.8 to 408.4 mm and 300.8 to 256.2 mm as WS increased from 0.38 to 7.42 dS m⁻¹, respectively. Compared with the higher AS scenarios, ETa increased significantly as IA increased under the lower AS scenarios.

Similarly, the measured cotton evapotranspiration under FMDI was 277 to 438 mm in an adjacent area according to Cai et al. (2002) and Wu et al. (2014). The relationship between IA and ETa was proposed by Ning et al. (2021). The regression equations for ETa as functions of IA and WS are shown in Table 4.

### Table 4 | Regression equations for water balance components as functions of IA and WS

| Scenario | Regression equation | RSME | R² |
|----------|---------------------|------|----|
| 1–15     | \( E_a = 93.16 - 0.01 \times IA - 2.25 \times WS + 0.20 \times WS^2 \) | 0.05 | 0.99 |
|          | \( T_a = 136.11 + 0.80 \times IA + 2.32 \times WS - 0.79 \times WS^2 \) | 1.10 | 0.99 |
|          | \( ET_a = 229.28 - 0.80 \times IA - 0.08 \times WS - 0.59 \times WS^2 \) | 1.09 | 0.99 |
|          | \( D = 226.84 - 1.27 \times IA - 8.60 \times WS + 0.02 \times IA \times WS + 0.22 \times WS^2 \) | 2.30 | 0.99 |
|          | \( \Delta S = -375.0 + 1.47 \times IA - 8.52 \times WS - 0.021 \times IA \times WS - 0.001 \times IA^2 + 3.74 \times WS^2 \) | 2.25 | 0.99 |
| 16–30    | \( E_a = 91.13 + 0.02 \times IA + 0.04 \times WS - 0.0002 \times IA \times WS - 0.005 \times WS^2 \) | 0.03 | 0.99 |
|          | \( T_a = 7.66 + 0.66 \times IA - 2.86 \times WS - 0.009 \times IA \times WS + 0.015 \times WS^2 \) | 0.72 | 0.99 |
|          | \( ET_a = 98.78 + 0.67 \times IA - 2.83 \times WS - 0.009 \times IA \times WS + 0.01 \times WS^2 \) | 0.74 | 0.99 |
|          | \( D = -51.64 + 0.135 \times IA + 11.887 \times WS + 0.012 \times IA \times WS - 0.231 \times WS^2 \) | 0.75 | 0.99 |
|          | \( \Delta S = -12.53 + 0.19 \times IA + 1.64 \times WS - 0.003 \times IA \times WS + 0.013 \times WS^2 \) | 0.76 | 0.97 |

![Figure 4](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.270/931829/ws2021270.pdf)
3.1.4. Drainage (D)

The applied irrigation water was less than or equal to the cotton ET<sub>a</sub>, but D occurred below the root zone under FMDI. As expected, the highest D values occurred under the largest IA and WS levels. A lower mean D of 78.7 mm occurred in scenarios 1–15 than the mean D of 176.7 mm in scenarios 16–30. Thus, higher soil salt stress limited the RWU, so some fractions of the irrigation water subsequently drained away. Ning et al. (2021) also reported similar conclusions that D was higher under salt stress than that without salt stress in a cotton field under FMDI. Moreover, a considerable amount of D occurred under drip irrigation according to a previously reported numerical model (Phogat et al. 2013; Ning et al. 2021). D raised as IA or WS increased. In scenarios 16–30, compared with the mean D with 60%ETc, the mean values of D with IA ranging from 70 to 100%ETc increased by 24.98%, 52.51%, 82.75%, and 115.12%, respectively. The mean D increased by 10% and 26.61% for WS = 3.10 and 7.42 dS m<sup>-1</sup>, compared with WS = 0.38 dS m<sup>-1</sup>. Similar results were obtained in scenarios 1–15.

LF is defined as the ratio of D relative to IA, and it is usually used to quantify the leaching rate (Ning et al. 2020, 2021). In the lower and higher AS scenarios, the LF values ranged from 9.97 to 30.90% (mean = 17.67%) and 31.13% to 52.15% (mean = 41.58%), respectively, thereby indicating that LF was higher under salt stress than that without salt stress in the cotton field under FMDI. LF raised as IA or WS increased. Specifically, the mean LF values in 1–15 scenarios were 10.56%, 11.67%, 16.33%, 21.99%, and 27.82% when each IA value ranged from 60 to 100%ETc, respectively. The relative increases compared with 60%ETc were 16.57%, 54.62%, 108.19%, and 163.34% when IA ranged from 70 to 100%ETc, respectively. The relative decreases in LF were 3.14% and 16.90% for WS = 3.10 and 7.42 dS m<sup>-1</sup>, respectively, compared with WS = 0.38 dS m<sup>-1</sup>. Similar results were obtained in scenarios 16–30. Hanson et al. (2008) reported that 7.7%–11.3% of the irrigation water leached from the root zone after the application of 60% of the potential ET (severe deficit irrigation).

3.1.5. Water storage change (ΔS)

The ΔS values depleted in scenarios 1–3 and 5 (2.4–50.3 mm), and increased (2.4–50 mm) in scenarios 4 and 6–15. In scenarios 16–30, the ΔS values were compensated (33.4–51.8 mm) by the irrigation water. When IA was fixed, larger WS values led to higher ΔS values. Similarly, when WS was fixed, a larger IA value led to an increase in ΔS.

3.2. Salt balance components

Table 3 shows the salt balance components for each scenario; that is, leached salt (S<sub>d</sub>) and salt storage change (ΔS<sub>S</sub>). In general, the initial soil salt storage (S<sub>I</sub>) values in the root zone were 1,080.8 and 13,601.7 g m<sup>-2</sup> under the lower and higher AS scenarios, respectively. As IA increased from 60 to 100%ETc, the salt (S<sub>I</sub>) added with the irrigation water increased by 64, 74, 84, 94, 104, and 114 g m<sup>-2</sup> (WS = 0.38 dS m<sup>-1</sup>) respectively, as well as by 505.6, 584.6, 663.6, 742.6, and 821.6 g m<sup>-2</sup> with...
WS = 3.10 dS m\(^{-1}\), and by 1,242.8, 1,432.8, 1,622.8, 1,812.7, and 1,866.9 g m\(^{-2}\) with WS = 7.42 dS m\(^{-1}\). Regression equations for the salt balance components as functions of \(IA\) and WS are presented in Table 5.

| Scenario | Regression equation | RMSE | \(R^2\) |
|----------|---------------------|------|--------|
| 1–15     | \(S_d = 1,010.15 - 4.97 \times IA - 91.45 \times WS + 0.22 \times IA \times WS + 0.007 \times IA^2 + 1.74 \times WS^2\) | 16.72 | 0.98  |
| ΔSS      | \(= -1,498.87 + 7.26 \times IA + 122.64 \times WS + 0.21 \times IA \times WS - 0.009 \times IA^2 - 1.36 \times WS^2\) | 34.47 | 0.99  |
| 16–30    | \(S_d = -1,939.65 + 17.74 \times IA + 16.35 \times WS + 0.135 \times IA \times WS - 0.009 \times IA^2 + 5.77 \times WS^2\) | 14.65 | 0.99  |
| ΔSS      | \(= 1,450.75 - 15.45 \times IA + 14.85 \times WS - 0.30 \times IA \times WS - 0.007 \times IA^2 - 5.39 \times WS^2\) | 25.43 | 0.99  |

3.2.1. Leached salt (\(S_d\))

The mean \(S_d\) value of 4,197.1 g m\(^{-2}\) in scenarios 16–30 was higher than that of 205.9 g m\(^{-2}\) in scenarios 1–15 due to the higher soil salt stress. Figure 6 shows that increases in \(IA\) and WS accelerated the leaching of salt in the root zone (Ning et al. 2021). In scenarios 16–30, the mean values of \(D\) when \(IA\) ranged from 70 to 100\%ETc increased by 18.57\%, 36.12\%, 52.01\%, and 66.14\%, respectively, compared with the mean \(S_d\) under 60\%ETc. The mean \(S_d\) values increased by 6.60\% and 21.66\% for WS = 3.10 and 7.42 dS m\(^{-1}\), respectively, compared with the mean \(S_d\) with WS = 0.38 dS m\(^{-1}\). Increasing \(IA\) or WS could promote the leaching of salts from the root zone. Similar results were obtained in scenarios 1–15. Two linear relationships between \(S_d\) and \(IA\), and \(S_d\) and \(D\) are presented in Figure 7.

3.2.2. Salt storage change (\(ΔSS\))

Under the lower AS scenarios, desalination and salt accumulation processes always occurred during the irrigation season. Specifically, salt accumulated (425.8 to 1,442.4 g m\(^{-2}\)) in the scenarios under irrigation with saline water at 3.10 and 7.42 dS m\(^{-1}\). The amount of accumulated salt increased as \(IA\) and WS raised. Compared with the mean accumulated salt amounts with 60\%ETc for WS = 3.10 and 7.42 dS m\(^{-1}\), the mean accumulated salt amounts when \(IA\) ranged from 70 to 100\%ETc for WS = 3.10 and 7.42 dS m\(^{-1}\) increased by 12.80\%, 21.04\%, 22.85\%, and 11.48\%, respectively. The mean accumulated salt amounts were 479.4 and 1,324.6 g m\(^{-2}\) for WS = 3.10 and 7.42 dS m\(^{-1}\), respectively. Phogat et al. (2011) noted that the mass of salt in the root zone increased under drip irrigation with deficit irrigation. In addition, soil salinization was

![Figure 6](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.270/931829/ws2021270.pdf)
avoided by applying irrigation with freshwater ($WS = 0.38 \text{ dS m}^{-1}$), and desalination ($20.2$ to $166.8 \text{ g m}^{-2}$) occurred in these scenarios. The desalination amount increased as $IA$ increased. As $IA$ increased from $60$ to $100\%ETc$, the average amounts of salt leaving the root zone were $26.7, 20.2, 66.4, 113.7,$ and $166.8 \text{ g m}^{-2}$, respectively. Adequate leaching was important for the removal of salts from the root zone and for the long-term sustainability of the irrigated cotton field.

Moreover, desalination processes ($2,273.4$ to $4,692 \text{ g m}^{-2}$) occurred in scenarios $16$–$30$ during the irrigation season. The desalination amounts increased as $IA$ raised or $WS$ decreased. As $IA$ increased from $60$ to $100\%ETc$, the amounts of stored salt in the root zone were $2,514.8, 3,001.0, 3,455.4, 3,858.1,$ and $4,250.9 \text{ g m}^{-2}$, respectively. The mean $\Delta SS$ values decreased by $8.70\%$ and $18.15\%$ for $WS = 3.10$ and $7.42 \text{ dS m}^{-1}$, respectively, compared with the mean $\Delta SS$ when $WS = 0.38 \text{ dS m}^{-1}$.

Based on an extensive field survey in a nearby region, Luo (2014) observed that the amount of salt accumulated in the cotton root zone was $321.2 \text{ g m}^{-2}$ under a lower soil salinity distribution, whereas the desalination amount was $1,182.6 \text{ g m}^{-2}$ in the root zone under a higher soil salinity distribution. Ning et al. (2021) also reported natural desalination amounts of $12.0$ to $231.6 \text{ g m}^{-2}$ and $2,739.7$ to $5,291.9 \text{ g m}^{-2}$ under lower and higher $AS$ profiles, when using the current irrigation freshwater ($WS = 0.38 \text{ dS m}^{-1}$) schedule under FMDI. Ning et al. (2021) also showed that increasing $IA$ could promote soil desalination during the irrigation season. These results are consistent with those obtained in the present study.

### 3.3. Cotton yield ($Y$)

Salt stress affects the transpiration and evapotranspiration by crops, and it will inevitably affect the crop yield. Overall, $Y$ was smaller under the higher $AS$ scenarios ($1,548$ to $2,846 \text{ kg hm}^{-2}$) than the lower $AS$ scenarios ($3,505$ to $3,812 \text{ kg hm}^{-2}$) due to the higher soil salt stress. $Y$ increased as $IA$ raised or $WS$ decreased. In scenarios $16$–$30$, the mean $Y$ raised by $12.20\%$, $23.96\%$, $33.12\%$, and $40.07\%$ as $IA$ increased from $70$ to $100\%ETc$, compared with the mean $Y$ with $60\%ETc$. For a given $WS$ value (i.e., $0.38 \text{ dS m}^{-1}$), the mean $Y$ decreased by $8.95\%$ and $23.68\%$ for $WS = 3.10$ and $7.42 \text{ dS m}^{-1}$, respectively. Similar results were found in scenarios $1$–$15$. Regression equation for $Y$ as functions of $IA$ and $WS$ are shown in Figure 8.

In the same region where our study was conducted, Zhang et al. (2004) reported that the measured cotton yields under FMDI were $2,100$ to $2,685 \text{ kg hm}^{-2}$ in a severely high salinity field with $8 \text{ g salt per kg of soil}$. This result is close to the calculated $Y$ value of $1,548$ to $2,846 \text{ kg hm}^{-2}$ under the higher $AS$ scenarios. Moreover, the simulated cotton yields of $3,505$ to $3,812 \text{ kg hm}^{-2}$ were between the cotton yields under FMDI measured in the field by Wang et al. (2016) of $2,620$ to $3,567 \text{ kg hm}^{-2}$, and by Zhang et al. (2004) of $4,815$ to $4,920 \text{ kg hm}^{-2}$ in a low salinity field ($0.8 \text{ g salt per kg of soil}$). Under the lower $AS$ scenarios, the simulated cotton yields were also similar to the cotton yields of $3,608$ to $3,828 \text{ kg hm}^{-2}$ estimated by Ning et al. (2021).
3.4. WPs

The WPs (WPETa and WPI) indicates the necessity of improving irrigation management. A larger mean WPETa value of 0.90 (0.90 to 0.91) kg m$^{-3}$ was obtained in scenarios 1–15 than scenarios 16–30 with an average WPETa of 0.79 (0.67 to 0.87) kg m$^{-3}$. Ning et al. (2013, 2021) reported similar WPETa values of 0.89 to 1.04 kg m$^{-3}$ for cotton under FMDI in the same region. WPI ranged from 0.68 to 1.13 (mean of 0.89) kg m$^{-3}$ and 0.43 to 0.65 (mean of 0.54) kg m$^{-3}$ under the lower and higher AS scenarios, respectively. WPI raised as IA or WS decreased. The mean WPI values in scenarios 1–15 were 1.09, 0.98, 0.87, 0.79, and 0.71 kg m$^{-3}$ for each IA ranging from 60 to 100%ETc, respectively. The relative decreases in WPI were 1.3% and 8.12% for WS = 3.10 and 7.42 dS m$^{-1}$, respectively, compared with WS = 0.38 dS m$^{-1}$. Similar results were also obtained in scenarios 16–30. Wang et al. (2015) also reported similar results where the values of WPI were 1.0 ± 0.3 kg m$^{-3}$ based on 34 years of data obtained from a cotton field in the same area.

3.5. Identifying the salinity risk of cotton fields under FMDI

The salinity risk was analyzed based on the water and salt balances. There is a potential risk of soil salinization in cotton fields under FMDI. In general, desalination and salt accumulation processes coexisted in the cotton fields under FMDI during the irrigation season when IA and AS were different. Luo (2014) reported that salt accumulated in farmland under drip irrigation with a lower AS profile. Chen et al. (2010) indicated that the mean soil salinity profile in the root zone was 336 and 547% of the original soil profile based on a 3-year experiment under irrigation with saline water at 3.10 and 7.42 dS m$^{-1}$, respectively. In the present study, our results supported the previous conclusion that irrigating a cotton field with a lower AS profile (i.e., below crops salt tolerance threshold) using saline water (3.10 to 7.42 dS m$^{-1}$) will lead to salt accumulation in the root zone. The current irrigation schedule with saline water (3.10 and 7.42 dS m$^{-1}$) under FMDI for cotton in Xinjiang is not sustainable and it cannot satisfy the requirements for salt leaching. Thus, the key areas for warning and monitoring the potential salinity risk are these fields. We also suggest the alternate use of saline and freshwater for irrigation during the irrigation season or regular flood irrigation after the harvest to reduce the risk of soil salinity in the root area under FMDI.

By contrast, desalination occurred in the cotton field under the higher AS profile (i.e., above the crops salt tolerance threshold) using the current irrigation schedule (including saline water). Thus, the current irrigation practices in salt-affected fields could meet the requirements for salt leaching and crop growth during the irrigation season. As a consequence, flood irrigation after the harvest to leach salt may not be required under FMDI. Based on a four-year sentinel surveillance study under FMDI with the current irrigation schedule, in the same region where our study was conducted, Wang et al. (2014) and Li et al. (2016) reported that the soil salt in the root zone in cotton fields decreased in a salt–affected area.
which was beneficial for cotton production. The results obtained in the present study may help farmers and irrigation water management departments to identify and reduce the risk of soil salinity under FMDI in Xinjiang.

4. CONCLUSION

In this study, a calibrated HYDRUS–2D model coupled with a validated crop water production function was used to assess the interactive effects of IA, WS, and AS on the soil water and salt balance, cotton yield and WPs under FMDI. 30 scenarios were investigated with two AS values (lower and higher), five IA values (60%ETc, 70%ETc, 80%ETc, 90%ETc, and 100% ETc), and three WS values (0.38, 3.10, and 7.42 dS m⁻¹). The water balance components (i.e., Ta, ETa, D, and ΔS) were significantly affected by IA, WS, and AS. The values of IA and WS had little effect on Ea. Lower Ta and ETa values, and higher Ea, D, and ΔS values occurred in the higher AS scenarios due to the higher salt stress. The Sa values were greater in the higher AS scenarios than the lower AS scenarios under the same IA and WS values. Under the lower AS scenarios, desalination and salt accumulation processes occurred throughout the irrigation season. Desalination processes (2,273.4 to 4,692 g m⁻²) occurred in the higher AS scenarios. The Y values were smaller under the higher AS scenarios (1,548 to 2,846 kg hm⁻²) than the lower AS scenarios (3,305 to 3,812 kg hm⁻²). Higher WPs values were gained under the lower AS scenarios. The Y and WPs values increased as IA increased or WS decreased.

It should be noted that cotton field with a lower AS profile (e.g., below the salt tolerance threshold of cotton) and irrigated with saline water (3.10, 7.42 dS m⁻¹) resulted in salt accumulating in the root zone (425.8 to 1,442.4 g m⁻²). The key areas for warning and monitoring the risk of salinization are these fields under FMDI. Effective management strategies (such as alternate irrigation using saline and freshwater, etc.) to reduce the secondary salinity risk are also recommended in these cotton fields. The current irrigation practices in salt-affected fields could meet the requirements for salt leaching and crop growth. The results obtained in this study may facilitate the accurate identification and reduction of soil salt accumulation, and sustainable agricultural development in arid regions.

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DECLARATIONS OF INTEREST

None.

DATA AVAILABILITY STATEMENT

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

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