

COMPREHENSIVE SIMULATION OF COTTON PRODUCTION UNDER INITIAL SOIL SALINITY SPATIAL VARIABILITY CONDITIONS: ASSESSING THE EFFECT OF DRIP HYDRAULIC PERFORMANCE AT THE SUBUNIT LEVEL

SIMULATION GLOBALE DE LA PRODUCTION DE COTON DANS DES CONDITIONS DE VARIABILITÉ SPATIALE DE LA SALINITÉ INITIALE DU SOL: ÉVALUATION DE L'EFFET DES PERFORMANCES HYDRAULIQUES DU GOUTTE-À-GOUTTE À L'ÉCHELLE DE LA SOUS-UNITÉ

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ABSTRACT

Highly initial soil salinity is a critical factor constraining agricultural sustainability in arid regions. Field soils generally exhibit substantial spatial variability in salinity at the drip subunit level, but appropriate design standards for drip hydraulic performance under this condition remain to be explored further. Multiple process at the subunit level, including water delivery in drip networks, soil water/solute transport, and crop growth, were simulated through a coupled model under conditions of spatial variability in soil salinity. The results indicated that the spatial distributions of the soil water content, EC_e , and cotton yield within the subunits exhibited spatial structures similar to those of drip hydraulic performance under low initial soil salinity. As the initial soil EC_e and its variability increase, the initial soil salinity conditions progressively become the dominant factor governing the distribution patterns of the three indices. The increase in initial salinity exacerbated the nonuniformity of the EC_e during the irrigation period, with an average 27% decrease in salinity uniformity as the initial EC_e variability increased from 20% to 60%. The deterioration of initial salinity conditions severely restricts cotton production, with both the subunit yield and yield uniformity beginning to decline significantly when the initial salinity level and its variability exceed 6.78 dS m^{-1} and 33%, respectively. The increase in drip hydraulic performance optimized the spatial distribution of soil water/salinity during the irrigation period, with the uniformity of the soil water content and EC_e increasing by 5% and 7%, respectively, when the drip hydraulic performance improved from 72% to 93%. A well-designed drip irrigation system created an optimal soil water/salt environment for cotton growth, achieving up to a 5% (6%) improvement in yield (yield uniformity) at the subunit level. In summary, the optimization of drip hydraulic performance remained highly adaptable for enhancing cotton production in subunits with severe initial soil salinity conditions, with a hydraulic uniformity of 83% recommended as the design standard under such conditions.

Keywords: Drip subunit; Coupled model; Spatial variability; Distribution uniformity; Design standard.

RÉSUMÉ

Une salinité initiale élevée du sol constitue un facteur critique limitant la durabilité de l'agriculture dans les régions arides. Les sols agricoles présentent généralement une forte variabilité spatiale de la salinité à l'échelle de la sous-unité de goutte-à-goutte, mais les normes de conception appropriées pour les performances hydrauliques du goutte-à-goutte dans ces conditions doivent encore être approfondies. Plusieurs processus à l'échelle de la sous-unité, notamment l'acheminement de l'eau dans les réseaux de goutte-à-goutte, le transport de l'eau et des solutés dans le sol et la croissance des cultures, ont été simulés au moyen d'un modèle couplé dans des conditions de variabilité spatiale de la salinité du sol. Les résultats indiquent que, lorsque la salinité initiale du sol est faible, les

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distributions spatiales de la teneur en eau du sol, de l' EC_e et du rendement du coton au sein des sous-unités présentent des structures spatiales similaires à celles des performances hydrauliques du goutte-à-goutte. À mesure que l' EC_e initiale du sol et sa variabilité augmentent, les conditions initiales de salinité du sol deviennent progressivement le facteur dominant qui régit les modes de distribution des trois indices. L'augmentation de la salinité initiale a accentué la non-uniformité de l' EC_e pendant la période d'irrigation, l'uniformité de la salinité diminuant en moyenne de 27 % lorsque la variabilité initiale de l' EC_e passait de 20 % à 60 %. La dégradation des conditions initiales de salinité limite fortement la production de coton : le rendement de la sous-unité et son uniformité commencent tous deux à diminuer de manière significative lorsque le niveau initial de salinité et sa variabilité dépassent respectivement 6,78 dS m⁻¹ et 33 %. L'amélioration des performances hydrauliques du goutte-à-goutte a optimisé la distribution spatiale de l'eau et de la salinité du sol pendant la période d'irrigation ; l'uniformité de la teneur en eau du sol et celle de l' EC_e ont augmenté respectivement de 5 % et 7 % lorsque les performances hydrauliques du goutte-à-goutte sont passées de 72 % à 93 %. Un système d'irrigation goutte à goutte bien conçu a créé un environnement hydrique et salin optimal pour la croissance du coton, permettant une amélioration allant jusqu'à 5 % du rendement et 6 % de son uniformité à l'échelle de la sous-unité. En résumé, l'optimisation des performances hydrauliques du goutte-à-goutte demeure très adaptée à l'amélioration de la production de coton dans les sous-unités soumises à des conditions sévères de salinité initiale du sol ; une uniformité hydraulique de 83 % est recommandée comme norme de conception dans de telles conditions.

Mots-clés : Sous-unité de goutte; Modèle couplé; Variabilité spatiale; Uniformité de distribution; Standard de conception.

1. INTRODUCTION

Drip irrigation is widely used in arid regions because of its ability to enable crop intensification while ensuring high water-use efficiency (Al-Ghobari et al., 2018; Gautam et al., 2025). A single drip irrigation system has been reported to cover up to several thousand hectares, demonstrating its scalability in large-scale farming operations in China with rapid development of drip irrigation (Guan et al., 2022). The subunit is the most fundamental unit in drip irrigation systems, and inherent irrigation nonuniformity exists within it due to hydraulic losses across the network (Ayars et al., 2023). Furthermore, salt accumulation in the root zone is still common under drip irrigation in fields where salts are inherited from the parent materials of soil (Wang et al., 2019). Although both drip hydraulic performance and initial soil salinity may affect multiple processes in drip irrigation systems and even lead to yield reduction, few studies have been reported at the subunit level.

The issue of soil water/salt under drip irrigation has consistently been a focal point for researchers. Several studies have indicated that drip irrigation maintains high soil moisture levels in the root zone while creating a desalinated area, with salts being leached to the wetting front periphery where root activity is significantly reduced (Kachanoski et al., 1994; Palacios-Díaz et al., 2009). Moreover, some researchers have suggested that the characteristics of frequent irrigation with low amounts of water used in drip irrigation may lead to insufficient salt leaching, potentially causing salt accumulation in the crop root zone and yield reduction (Chen et al., 2010; Wang, Z.M. et al., 2014). Several field experiments have been conducted to optimize drip design parameters, including emitter design, lateral patterns, irrigation depths and frequency, for sustainable crop production in high initial soil salinity fields (Hu et al., 2025; Liu, K et al., 2025; Liu, X et al., 2025). The above studies focused mainly on plot experiments in a small field, but the inherent spatial variability in soil salinity cannot be ignored for subunits with relatively large areas. The existing evidence indicates that the spatial variability of soil properties at the subunit scale may be greater than that at the lateral scale (Garten et al., 2007). Yang et al. (2024) reported that water-saving irrigation retrofitting induced the formation of extreme soil salinity values, thereby exacerbating the spatial variability of soil salt in farmlands. Lin et al. (2022) investigated the spatial distribution of soil salinity after irrigation periods in a typical drip subunit, and quantified the influences of irrigation and initial soil salinity patterns. Owing to field experiment constraints, most studies at the subunit level have focused on analyzing spatial variability patterns and sources of soil salinity during representative periods, whereas research on multi-process, including

soil water–salt dynamics and crop growth responses during the drip irrigation period, has been inadequate.

A well–designed drip irrigation system should exhibit high hydraulic performance, ensuring uniform water application across the field (with equal water allocation to each plant) while avoiding both overirrigation and underirrigation throughout the field (Benouniche et al, 2014). The traditional design of drip subunits has been primarily examined from a hydraulic performance point of view, focusing on the diameters of the manifolds/laterals or their maximum lengths under specified diameters, whereas these solutions were deduced from equations of energy state via numerical or analytical methods (Bralts and Segerlind, 1985; Dandy and Hassanli, 1996; Baiamonte et al., 2015). The design and operating costs, which results result from hydraulic requirements rather than design criteria, have gained research attention as key objectives in subunit design (Carrión et al., 2013; Ma et al., 2019). In recent years, there has been expanding research interest in exploring the relationships among drip hydraulic performance, field soil water/fertilizer dynamics, and crop growth processes. Field experiments conducted by Li et al. (2012) indicated that drip hydraulic performance had no statistically significant effect on soil moisture, nitrate content or electrical conductivity, suggesting that design uniformity standards can be moderately relaxed. Wang et al. (2014b) reported that rainfall patterns exert a stronger influence on nitrate leaching than system performance, and the design of drip system uniformity could be appropriately reduced in semi–humid regions. Or and Hanks (1992) demonstrated that maize plant height and yield exhibited spatial distribution patterns similar to those of drip hydraulic performance, whereas yield variability was substantially lower than system performance variability. These studies have improved the practical adaptability of drip hydraulic performance and advanced the development of drip system design. However, research evaluating drip hydraulic performance in saline farmlands in arid regions remains limited, and the adaptability of drip system performance under such conditions is currently unclear.

Field experiments at the subunit level usually require a number of plots with similar soil salinity variabilities to meet the demands of experimental design and replication, which usually cannot be found or used for experiments, as well as increasing the input of manpower and resources. With advancements in computer technology, numerical simulation models have achieved great progress in process analysis and mathematical description under drip irrigation conditions. For example, hydraulic analysis models assist designers in evaluating system performance, whereas hydrological models and crop models can further evaluate soil water/solute movement processes and crop growth responses under drip irrigation (González Perea et al., 2020; Grecco et al., 2019; Sarmah et al., 2005). However, most existing models focus on individual processes under drip irrigation, and integrated models capable of simulating the entire production process remain scarce. Sun et al. (2025) developed a coupled model capable of simulating multiple processes including hydraulic analysis, soil water/solute transport, and crop growth at the subunit level. The purpose of this work was analyze the multiple processes of cotton production in a subunit under initial soil salinity spatial variability conditions through modeling strategies and to evaluate the adaptability of drip hydraulic performance under high–salinity conditions.

2. MATERIALS AND METHODS

2.1 Modelling approach

In this study, a coupled model was used to assess the effects of soil salinity and drip system uniformity on crop growth in drip irrigation subunits. A detailed description of the coupled model can be found in our previous paper (Sun et al., 2025). In this section, we briefly reiterate the basic information about the model to keep the readers more comfortable if they read this part only. Figure 1 presents the different modules of the simulation software. A short description of the model modules follows:

Hydraulic analysis module: This module determines the hydraulic behavior of the drip irrigation system. The design parameters of drip irrigation system, such as the shape and dimensions of the subunit, network layout pattern, hydraulic parameters of the network and emitter design parameters, are externally input. The module automatically generates drip irrigation network information based on

external input parameters, performs hydraulic analysis through EPANET and determines the discharge rates, irrigation duration and irrigation depths for each emitter within the subunit.

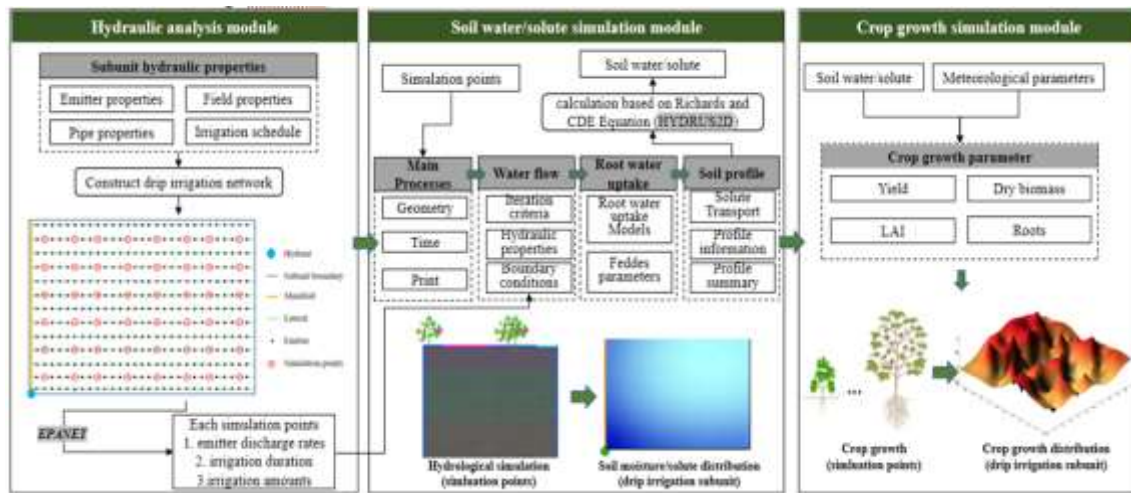


Figure 1. Overview of the coupled simulation model and three main modules.

Soil water/solute simulation module: Distributed simulation methods were used to assess the spatial soil water/salinity variability of the drip irrigation subunits in this module. The drip irrigation subunit is discretized into multiple simulation units with unique initial soil salinity. The HYDRUS-2D model, which has been integrated into the modeling framework, was used to simulate soil water dynamics, salt transport and root uptake during the crop growth season. The results were further used to simulate crop growth.

Crop growth simulation module: The model calculates daily crop growth indices throughout the growing season based on meteorological inputs and simulated soil water/solute dynamics. The simulated results from multiple simulation units are aggregated to comprehensively characterize the crop growth status across the entire drip subunit.

2.2 Model settings and parameters

2.2.1 Subunit geometry and drip network parameters

A rectangular drip irrigation subunit, which is the most common shape in southern Xinjiang, China, was studied in this work. The length and width of the subunit are 80 and 60 m, respectively, with a total area of 0.48 ha (Figure 2a). The drip network was consisted of one hydrant near a corner, one manifold running along a boundary, and a number of laterals perpendicular to the manifold. Cotton (*Gossypium hirsutum* L.) was chosen for mulched drip irrigation in the subunit, and the mulch was 2 m wide, covering six rows of cotton, which were irrigated by two laterals (Figure 2d). Table 1 summarizes the input parameters required for the hydraulic analysis module of the coupled model.

Figure 2 Form of the simulated drip irrigation subunit and the layout of the irrigation networks (a). Discretizing subunits into uniformly sized simulation subunits (b). The simulation unit configuration with water application derived from the emitters in the corresponding zone and unique initial soil salinity conditions (c). The cotton field planting patterns and modeling domain/boundary conditions of the soil water/solute simulation module for the simulation unit (d).

Table 1. Description of the characteristics of drip irrigation subunits.

Parameters	Description	Unit	Value
S_e	Spacing between emitters	m	0.2
S_{l1}	Spacing between two laterals in a film	m	0.76
S_{l2}	Spacing between two laterals located in two adjacent film	m	1.57
q_n	Nominal emitter discharge rate	L h ⁻¹	3.4
D_m	Internal pipe diameter of manifold	mm	66
D_l	Internal pipe diameter of lateral	mm	16
x	Emission exponent	-	0.5
C_l	Roughness coefficient of lateral	-	135
C_m	Roughness coefficient of manifold	-	105
L_m	Manifold length	m	60
L_l	Lateral length	m	80
a	The length of subunit	m	80
b	The width of subunit	m	60
H_0	Working pressure of hydrant	m	10

2.2.2 Field material and boundary conditions

The drip subunit is subdivided into 48 simulation units (n) with unique initial soil salinity to enable distributed simulation, each with a dimension of 10 m × 10 m (Figure 2b c). The simulation domain in soil water/solute simulation module (HYDRUS-2D) for each unit is set as rectangular with a length of 117 cm and a depth of 100 cm (Figure 2 d). We used atmospheric boundary condition for the top of bare soil area (17 cm), free drainage for the bottom (117 cm), no flux for the sides (100 cm), and variable flux for the emitter's element (40 cm). The soil texture of the drip irrigation subunit was categorized as a sandy loam. The simulated domain was divided into three materials (0–20 cm, 20–40 cm, and 40–80 cm), with the hydraulic parameters (θ_s , θ_r , α , n , and K_s) and solute transport parameters (D_L , D_T , D_w , K_d , μ_w , μ_s , and μ'_w) for each layer set according to the calibration by Sun et al. (2025) (Table 2). The initial soil water content contents of the 0–20 cm, 20–60 cm and 60–100 cm soil layers for each units are set to 0.17, 0.19, and 0.18 cm³ cm⁻³, respectively. The reduction in root water uptake caused by salt stress was calculated according to the Maas and Hoffman (1977) model, and the salt threshold (h_ϕ) was set as 6.45, 6.60 and 9.20 dS m⁻¹ at the seed stage, bud stage and flowering stage (boll opening stage), respectively, and the slope was set at 5.2%.

2.2.3 Crop growth parameters

The crop parameters used in this study were obtained from Sun et al. (2025) (Table 3). The simulation periods were from April 16 to September 28, 2019 (165 d). The meteorological data used in this work were obtained from the HOBO Weather Station (Onset, Bourne, MA, USA), which was installed at the Soil and Water Conservation Monitoring Station of the First Division of the Xinjiang Production and Construction Corps (81°11'43"E, 40°37'22"N, altitude 1017 m above mean sea level) (Figure 3).

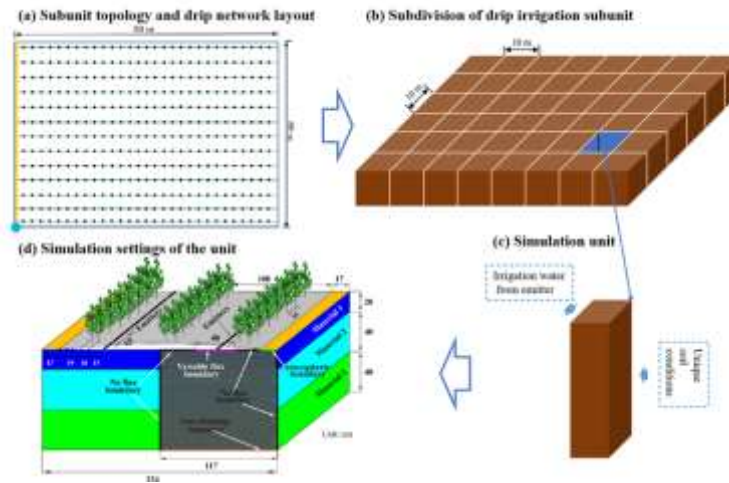


Figure 2. Form of the simulated drip irrigation subunit and the layout of the irrigation networks (a). Discretizing subunits into uniformly sized simulation subunits (b). The simulation unit configuration with water application derived from the emitters in the corresponding zone and unique initial soil salinity conditions (c). The cotton field planting patterns and modeling domain/boundary conditions of the soil water/solute simulation module for the simulation unit (d).

Table 2. Description of the calibrated soil hydraulic parameters of the soil water/solute simulation module (HYDRUS-2D).

Parameter	Description	Unit	Soil depths (cm)		
			0~20	20~60	60~100
θ_r	Residual soil water content	$\text{cm}^3 \text{ cm}^{-3}$	0.0270	0.0260	0.0231
θ_s	Saturated soil water content	$\text{cm}^3 \text{ cm}^{-3}$	0.3940	0.3897	0.3817
α	Parameter in the soil water retention function	-	0.026	0.046	0.045
n	Parameter in the soil water retention function	-	1.7	1.7	1.6
K_s	Saturated hydraulic conductivity	cm h^{-1}	2.21	1.88	1.08
l	Tortuosity parameter in the conductivity function		0.5	0.5	0.5
θ_i	Initial average soil water content of subunit	$\text{cm}^3 \text{ cm}^{-3}$	0.17	0.19	0.18
D_L	Longitudinal dispersivity	cm	100	50	20
D_T	Transverse dispersivity	cm	10	10	10
D_w	Molecular diffusion coefficient in free water	$\text{cm}^2 \text{ h}^{-1}$	0.1458	0.1458	0.1458
K_d	Adsorption isotherm coefficient	$\text{cm}^3 \text{ mg}^{-1}$	1	1	1

Table 3. Main crop parameters in crop growth simulation module.

Parameters	Description	Unit	Default value	Adjusted
T_b	Minimum threshold temperature for crop growth	$^{\circ}\text{C}$	12.5	15
T_0	Optimal temperature for plant growth	$^{\circ}\text{C}$	27.5	27.5
BE	Crop parameter for converting energy to biomass	$(\text{kg/ha}) (\text{MJ/m}^2)^{-1}$	24	34
DLAI	Heat unit index at the LAX decline point	-	0.95	0.72
$\text{LAI}_{\max}$	Maximum leaf area index	-	6	6
$\text{RD}_{\max}$	Maximum root depth	cm	60	50
$\text{HI}_{\max}$	Harvest index	-	0.55	0.55
PHU	Heat units required for maturation	$^{\circ}\text{C}$	2000	2000

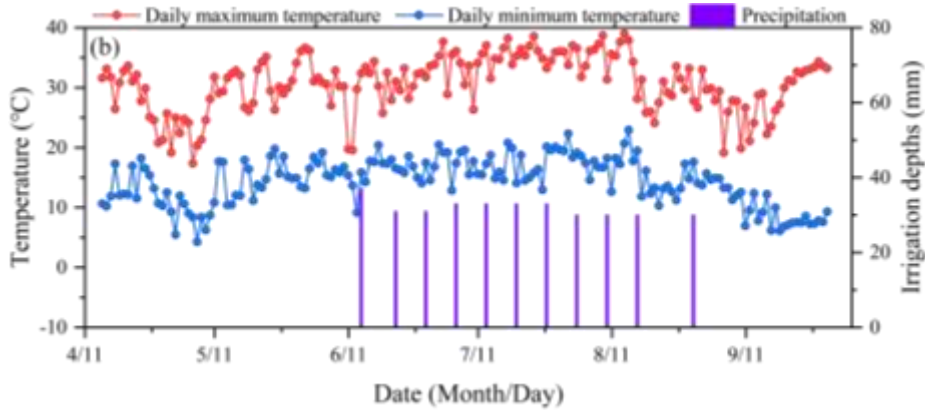


Figure 3. Meteorological conditions and irrigation schedule in the simulation scenario.

2.3 Simulation scenario design

2.3.1 Design of initial soil salinity

Field soil salinity is one of the most important factors affecting plant growth (Patell et al., 2001). The initial soil salinity within an actual drip subunit will demonstrate a certain degree of spatial variability, which means that the salinity values of simulation units are not uniform and are correlated with their specific locations. In this work, considering the spatial variability of initial soil salinity, the Monte Carlo (M-C) method and Kriging interpolation techniques were combined to develop a procedure for modeling soil salinity for drip irrigation farmland. It consists of the next five steps:

Stochastic generation of initial soil salinity (average value of 0~100 cm soil layer) using the M-C method Based on the geometry (length and width) of the subunit, the number n of simulation units to be randomly generated is determined. The soil salinity data in farmlands often can be assumed to follow an approximately normal distribution (Yang et al., 2025). Consequently, based on the given mean value (E_{ave}) and standard deviation (S_d) of the subunit soil salinity, it is first generated n evenly distributed random numbers r_i [0, 1], then the EC_e values E_{i0} corresponding to each r_i are computed through the normal distribution:

$$F(z) = \int_{-\infty}^z \frac{1}{S_d \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{E - E_{ave}}{S_d}\right)^2\right] ds \quad (1)$$

This results in a set of generated EC_e values for all the field simulation units.

Establishing a spatial dependence for the generated EC_e values The generated EC_e shows a spatial structure different from that of the actual initial soil salinity, which do not consider the proximity relationships of soil salinity between neighboring simulation units. Kriging interpolation is then used to establish a spatial dependence of the generated EC_e that considers the observed spatial structure of the EC_e . New values at each unit i (E_i^0) are therefore estimated from the EC_e values at the neighbor units around unit i but assume the above-defined range of variation. Thus, the E_i^0 values are replaced by E_i^1 according to the relation:

$$E(E_i^1) = \sum_{j=1}^m \lambda_j (E_j^0) \quad (2)$$

where m is the number of units surrounding the unit i , and λ_j is the weighing coefficients relative to the j neighbor units whose EC_e values are E_j^0 .

The semivariogram is a key component in Kriging because it quantifies how the spatial dependence between values with distance. Yang et al. (2025) demonstrated that the spatial dependence of soil salinity in field conditions can be well modeled by a spherical semivariogram:

$$\gamma(h) = \begin{cases} C_0 + C \left[\frac{3h}{2a} - \frac{1}{2} \left(\frac{h}{a} \right)^3 \right], & 0 \leq h \leq a \\ C_0 + C, & h > a \end{cases} \quad (3)$$

where C_0 is the nugget; C is the structural variance; a is the range, m. Using the soil salinity data, which observed in a subunit from Lin et al. (2022), to fitted spherical semivariogram and determined the above parameters as $C_0 = 1.10$, $C = 4.02$, and $a = 26.90$ m.

Adjusting the generated EC_e to maintain the original statistical characteristics The generation and adjustment procedures referred to above cause the statistical characteristics of EC_e to change relative to the initial given values of E_{ave} and S_d . Therefore, the generated EC_e must be corrected to ensure that their mean values and standard deviations are conserved. First, they are corrected for the mean values, second, they are corrected for the standard deviation:

$$E_i^2 = \frac{E_{ave}}{E_{ave1}} E_i^1 \quad (4)$$

$$E_i^3 = \left(E_i^2 - E_{ave} \right) \frac{S_d}{S_{d2}} + E_{ave} \quad (5)$$

where E_i^2 and E_i^3 are the EC_e values of the field simulation units after the respective corrections for E_{ave} and S_d , dS m⁻¹; E_{ave1} is the mean value of E_i^1 , dS m⁻¹; and S_{d2} is the S_d of E_i^2 , dS m⁻¹.

Finally, the EC_e of the different soil layers was generated based on the observed relationships from the field data of Lin et al. (2022), which was shown in Table 4.

Table 4. Linear regression relationships between the average soil EC_e (0~100 cm) and the EC_e of the different soil layers in the subunit.

Parameters	Soil depth (cm)	Linearity regression relationship	R^2
E_{20}	0~20	$E_{20}=E \times 0.672 - 0.145$	0.345
E_{40}	20~40	$E_{40}=E \times 1.090 - 0.936$	0.705
E_{60}	40~60	$E_{60}=E \times 1.078 + 0.011$	0.728
E_{80}	60~80	$E_{80}=E \times 1.131 + 0.069$	0.790
E_{100}	80~100	$E_{100}=E \times 1.029 + 1.001$	0.727

2.3.2 Simulation scenario design for drip subunits

The initial soil salinity (EC_e) and the design of the drip system network are essential factors influencing the spatial distribution of soil water/salt and crop yield in drip irrigation subunits. Under a certain drip irrigation network system, the selection of the pipe diameter is closely related to friction losses during irrigation, thereby affecting drip system performance (Wu et al., 2010). By varying the manifold diameter of the field subunit, five different designs of drip networks are studied in this work. For the initial soil salinity of the subunit, five levels of subunit average salinity, S1 (2.87 dS m⁻¹, non-salinized soil), S2 (5.27 dS m⁻¹, lightly salinized soil), S3 (7.67 dS m⁻¹, lightly salinized soil), S4 (10.00 dS m⁻¹, moderately salinized soil) and S5 (12.47 dS m⁻¹, moderately salinized soil), were designed according to the Xinjiang saline soil standards (Department of Agriculture and Rural Affairs of Xinjiang, 1996).

Five initial salinity variability conditions (H1 to H5) with the variation coefficients (CV) of 20%, 30%, 40%, 50%, and 60%, respectively, were set up according to the study of Lin et al. (2022). Therefore, based on the multiple levels of these factors, this study determined 105 simulation scenarios (Figure 4). The initial soil salinities of the drip irrigation subunit under the different simulation scenarios were generated via a stochastic modeling program (Figure 5). Under a given subunit average soil salinity, the soil salinity variability (CV) level determines the initial soil salinity of each simulated field unit. Increasing the design level of salinity variability exacerbates the spatial heterogeneity of soil salinity in the field, resulting in extremely high or low initial soil salinity concentrations at localized simulated units. For example, the maximum and minimum soil salinity values at the simulated units under the S5 scenario were 25.10 dS m⁻¹ and 0.33 dS m⁻¹, respectively. There were 11 irrigation events in different scenarios during the peak period of crop water requirements (June to August), with a total irrigation depth of 350 mm (Figure 3).

Drip network design (Inner diameter of manifold <i>D_m</i> , mm)					Scenarios		Initial soil salinity of subunit (<i>EC_e</i>)																																																																																																						
							2.87 dS m ⁻¹ (S1)			5.27 dS m ⁻¹ (S2)			7.67 dS m ⁻¹ (S3)					10.00 dS m ⁻¹ (S4)					12.47 dS m ⁻¹ (S5)																																																																																						
							20% (H1)	40% (H3)	60% (H5)	20% (H1)	40% (H3)	60% (H5)	20% (H1)	30% (H2)	40% (H3)	50% (H4)	60% (H5)	20% (H1)	30% (H2)	40% (H3)	50% (H4)	60% (H5)	20% (H1)	30% (H2)	40% (H3)	50% (H4)	60% (H5)																																																																																		
79.2 (C5)	61 (C4)	55.4 (C3)	49 (C2)	44 (C1)	C5S1H1	C4S1H1	C3S1H1	C2S1H1	C1S1H1	C5S1H3	C4S1H3	C3S1H3	C2S1H3	C1S1H3	C5S1H5	C4S1H5	C3S1H5	C2S1H5	C1S1H5	C5S2H1	C4S2H1	C3S2H1	C2S2H1	C1S2H1	C5S2H3	C4S2H3	C3S2H3	C2S2H3	C1S2H3	C5S2H5	C4S2H5	C3S2H5	C2S2H5	C1S2H5	C5S3H1	C4S3H1	C3S3H1	C2S3H1	C1S3H1	C5S3H2	C4S3H2	C3S3H2	C2S3H2	C1S3H2	C5S3H3	C4S3H3	C3S3H3	C2S3H3	C1S3H3	C5S3H4	C4S3H4	C3S3H4	C2S3H4	C1S3H4	C5S3H5	C4S3H5	C3S3H5	C2S3H5	C1S3H5	C5S4H1	C4S4H1	C3S4H1	C2S4H1	C1S4H1	C5S4H2	C4S4H2	C3S4H2	C2S4H2	C1S4H2	C5S4H3	C4S4H3	C3S4H3	C2S4H3	C1S4H3	C5S4H4	C4S4H4	C3S4H4	C2S4H4	C1S4H4	C5S4H5	C4S4H5	C3S4H5	C2S4H5	C1S4H5	C5S5H1	C4S5H1	C3S5H1	C2S5H1	C1S5H1	C5S5H2	C4S5H2	C3S5H2	C2S5H2	C1S5H2	C5S5H3	C4S5H3	C3S5H3	C2S5H3	C1S5H3	C5S5H4	C4S5H4	C3S5H4	C2S5H4	C1S5H4	C5S5H5	C4S5H5	C3S5H5	C2S5H5	C1S5H5

Figure 4. Simulation scenario design. C represents the design of the drip irrigation network; S represents the design of the subunit average soil salinity; H represents the design of the subunit soil salinity variability (CV).

2.4 Calculation procedures

The detailed simulation calculation process of the coupled model is as follows:

Parameter initialization was performed for all three modules. The drip irrigation network information was automatically generated from the design parameters and exported as an input file (.inp). The initial input files of HYDRUS-2D are read. The soil salinities of different layers generated via stochastic modeling were used to update the initial conditions of HYDRUS-2D.

The hydraulic analysis module was subsequently executed to compute the emitter hydraulic performance during operation, with the irrigation duration and irrigation depths per irrigation event being determined on the basis of the prescribed schedule.

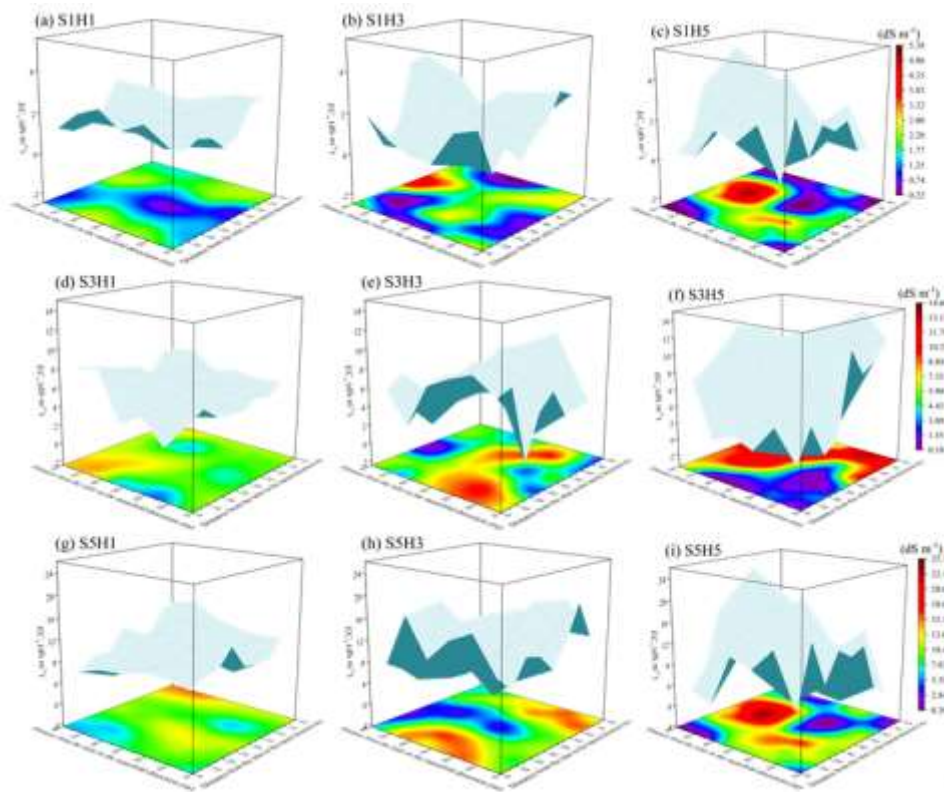


Figure 5. Distribution of the initial soil salinity within the root depth (0~40 cm) under partial scenarios.

The simulation time steps are set to 1 d. For each simulation day i , the soil water/solute simulation module is iteratively coupled with the crop growth module. The external coupling codes allow HYDRUS-2D to receive the emitter discharge rate and irrigation duration, which are calculated by the hydraulic analysis module, to update the input files of each simulation unit. After calculation, the output information, including evaporation, transpiration and rooting depth, is transferred to HYDRUS-2D to update the initial conditions of the next simulation day $i+1$.

Step 3 is repeated until the calculation of the simulation periods (165 d) ends. Then, the calculation process of the growth period for one simulation unit ends. The results of the output files, including the water and solute distributions of the soil profile and the daily crop growth output results, are printed after the completion of the daily calculations.

(1) Steps 3 and 5 are repeated until the calculations of all simulation units (n) are completed.

2.5 Calculation procedures

The Christiansen Uniformity Coefficient (CU, %) is used to evaluate the drip hydraulic performance, and the uniformity of soil moisture/salinity distribution and yield distribution:

$$CU = \left(1 - \frac{\sum_{i=1}^n |M_i - M_{ave}|}{nM_{ave}} \right) \times 100\% \quad (6)$$

where n is the number of simulation units; M_i is the evaluation variable (irrigation depth, soil water content, EC_e , and cotton yield) of simulation unit; and M_{ave} is the average value of each evaluation variable.

The SPSS software version 21.0 (SPSS Inc., Chicago, USA) was used to conduct statistical analysis. The ANOVA was conducted to analyze the differences in the distributions of soil water content, EC_e , and cotton yield in response to the drip hydraulic performance and initial soil salinity.

3. RESULTS

3.1 The drip hydraulic performance of the subunit

Figure 6 shows the simulated emitter discharge rates within the subunit under different scenarios. The results showed a similar pattern under different simulation scenarios: the emitter discharge decreases with increasing distance from the subunit inlet. Increasing the pipe diameter reduces hydraulic loss in the manifold, accompanied by an increase in the emitter discharge rate and a more uniform discharge rate distribution within the subunit. The results showed that, compared with C1, C5 achieved a 113% increase in q_{mean} and a 229% increase in q_{min} . Owing to the variations in emitter discharge during irrigation, marked disparities in irrigation depth were observed among the simulation units (Table 5). The maximum difference in irrigation depth between simulation units was found in C1, with a value of 424 mm. Poor drip network design led to decline in drip hydraulic performance, accompanied by localized overirrigation and underirrigation which severely compromising the irrigation uniformity of the drip subunit. The results demonstrated that, compared with C1, C5 achieved an increase of 21% in drip system uniformity.

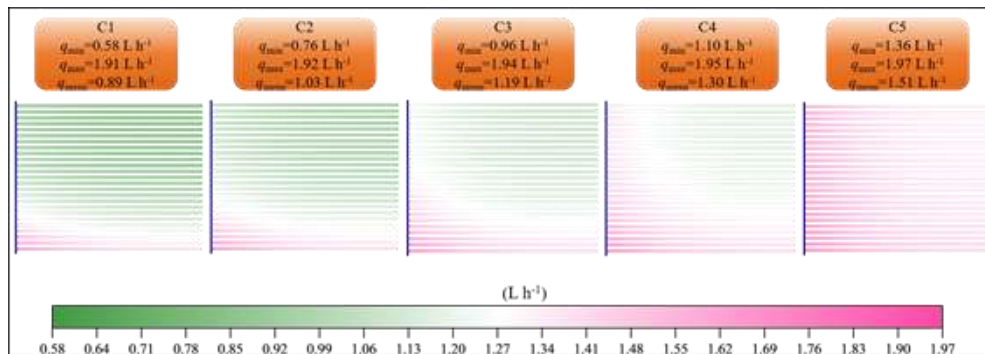


Figure 6. Distribution of emitter discharge rates in the drip irrigation subunit under different scenarios.

Table 5. Description of the cumulative irrigation depths and drip system uniformity under the different scenarios.

Scenarios	Min (mm)	Max (mm)	Mean (mm)	Std (mm)	SK	KU	CU (%)
C1	229	653	349	118	0.97	-0.19	72
C2	258	579	349	85	0.96	-0.01	80
C3	283	517	350	58	0.93	0.25	87
C4	297	482	350	45	0.88	0.38	90
C5	316	431	350	30	0.90	-0.09	93

3.2 The soil water content (SWC) of subunit during irrigation period

The spatial distribution of simulated average SWC within the root zone during the irrigation period is shown in Figure 7. Owing to the effects of non-uniform irrigation caused by drip networks, the SWC showed a similar trend: the highest values occurred near the inlet, whereas it progressively decreased

with increasing distance from the hydrant, and this pattern became more pronounced in scenarios with lower initial EC_e (Figure 7 a and b). The increasing initial soil EC_e level resulted in a relatively high SWC, with the average SWC of subunit consistently followed the pattern $S5 > S4 > S3 > S2 > S1$, and S5 exhibited a 6% increase compared with S1 (Figure 9a). Soil salinity variability led to localized extremes EC_e (high/low) within subunits, further altering SWC distribution patterns influenced by drip hydraulic performance, and this effect was more pronounced under elevated background salinity conditions (Figure 7c and d). In general, Increasing the initial soil salinity variability level exacerbated spatial heterogeneity in SWC distribution, for instance, a 3% improvement of SWC distribution uniformity (CU) was observed in C5S5H1 compared to C5S5H5 (Figure 9b).

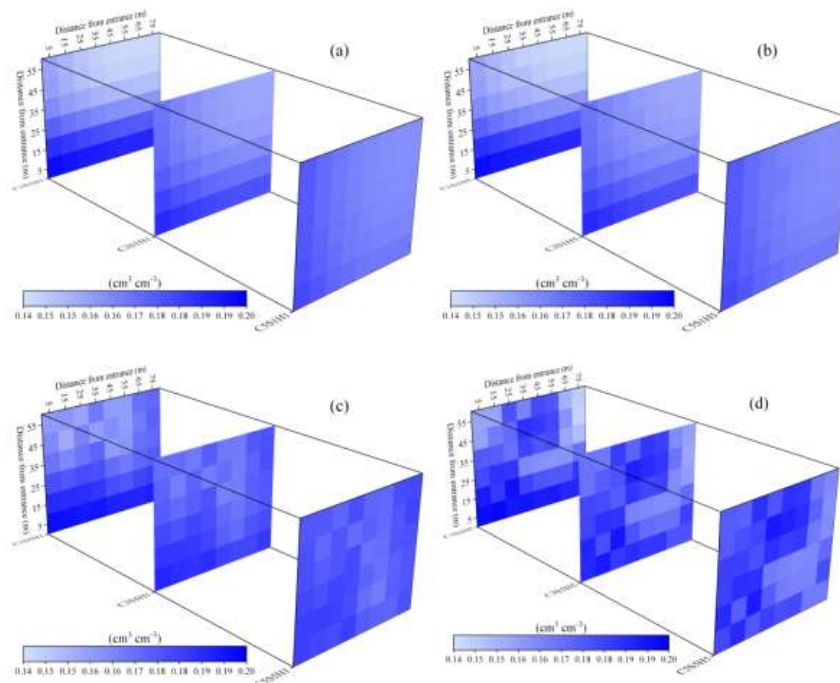


Figure 7. Spatial distributions of the average SWC within the cotton root zone during the irrigation period under partial scenarios.

The enhancing in drip hydraulic performance significantly improved the consistency of water allocation across different simulation units during the irrigation period, which avoided overirrigation (underirrigation) in the local area and led to a more homogeneous SWC distribution (Figure 7). The average SWC of subunit consistently followed the pattern $C5 > C4 > C3 > C2 > C1$, under the different scenarios, whereas C5 presented a $0.02 \text{ cm}^3 \text{ cm}^{-3}$ increase compared with C1 (Figure 9a). Furthermore, improvements in the drip hydraulic performance led to better SWC uniformity, a maximum increase of 7% was found between C5 and C1 (Figure 9b). Overall, the SWC of the subunit was influenced by drip hydraulic performance and initial soil salinity conditions. Under low-salinity conditions, the SWC and its spatial distribution closely align with the hydraulic performance characteristics of the drip network; as elevated salinity levels, SWC was increasingly influenced by initial soil salinity variability, which will led to decrease in SWC uniformity.

3.3 The soil EC_e of subunit during irrigation period

The simulation EC_e exhibited an inverse spatial distribution pattern to that of the SWC, characterized by lower values proximal to the subunit inlets and higher values in distal regions during the irrigation period (Figure 8). This phenomenon becomes particularly pronounced under scenarios of higher initial soil salinity combined with lower salinity variability (for example, C1S5H1). In arid regions, irrigation serves as a pivotal factor affecting spatiotemporal variations in soil salinity, with its impact on salinity fluctuations being particularly pronounced under high-salinity conditions, consequently exacerbating

the spatial distribution of EC_e (compared with initial conditions). As the initial soil salinity level increased, the leaching effect of irrigation on soil salts increased, leading to increased uniformity of the EC_e during the irrigation period (Figure 9d). For example, compared with S1, S5 exhibited an average increase of 15% in EC_e uniformity. Overall, the initial soil salinity level was the predominant factor affecting the EC_e within the root zone during the irrigation period, with simulated values ranging from 1.64 to 7.31 dS m⁻¹ across all the scenarios (Figure 9c). The EC_e uniformity was primarily influenced by the initial soil salinity variability. The EC_e uniformity of the different scenarios ranged from 34% to 84%, with H5 showing an average 27% increase compared with H1.

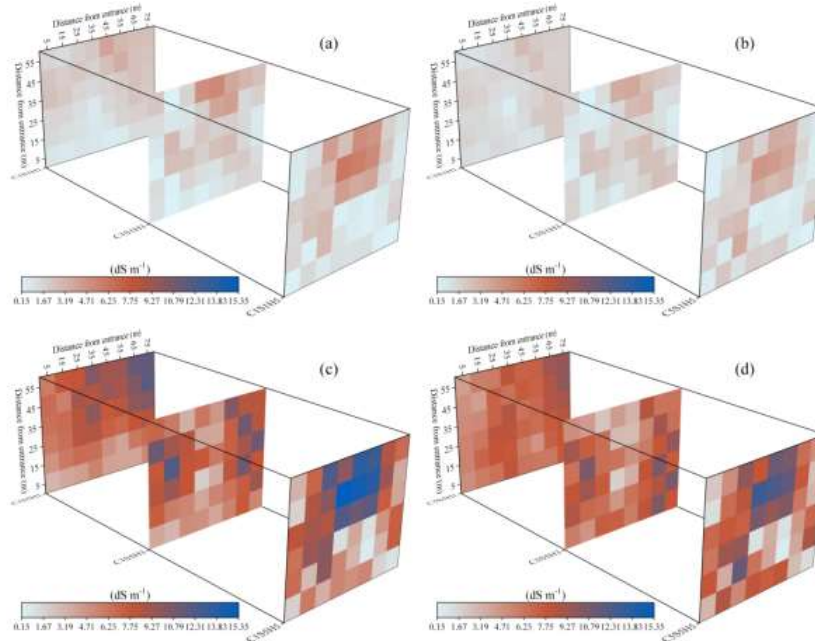


Figure 8. Spatial distributions of the average EC_e within the cotton root zone during the irrigation period under partial scenarios.

The nonuniform water application of drip irrigation caused a dramatic reduction in soil salinity in fields adjacent to the inlet but resulted in insufficient salt leaching in distal zones, with this disparity being exacerbated under scenarios with lower drip hydraulic performance (Figure 8). As the drip hydraulic performance increased, the spatial distribution of EC_e exhibited characteristics that more closely resembled the initial salinity distribution, while this phenomenon was pronounced in scenarios with higher initial soil salinity and variability (Figure 8d). Improving drip hydraulic performance enhanced irrigation uniformity across the field, thereby increasing the overall leaching efficiency at the subunit scale and promoting a reduction in soil salinity within the root zone (Figure 9c). Compared with C1, C5 achieved an average 7% reduction in EC_e . Moreover, optimizing the drip hydraulic performance increased the soil salinity uniformity to varying degrees across all the tested salinity scenarios (Figure 9d). Compared with C1, C5 achieved up to an 11% improvement in salt distribution uniformity.

3.4 Spatial distribution of cotton yield

Figure 10 shows the spatial distribution of cotton yield within the subunit under different scenarios. Owing to the effects of spatial variations in the SWC/ EC_e within the subunit, the cotton yield exhibited similar spatial distribution characteristics: under scenarios with low initial soil salinity or salinity variability, higher yields were observed near the subunit inlet and progressively decreased with increasing distance from the inlet (Figure 10 a, b, and c); As increasing of both initial soil salinity and spatial variability, locally elevated EC_e inhibited cotton growth and yield formation, resulting in a more complex spatial distribution of cotton yield (Figure 10 d). Overall, the increase in initial soil salinity significantly suppressed yield formation in the subunit, with S5 exhibiting a maximum yield reduction of

863.37 kg ha⁻¹ relative to S1 (Figure 9e). Moreover, the soil salinity variability resulted in a localized extreme initial EC_e , which not only decreased cotton yield uniformity but also contributed to an overall decline in subunit-scale yield (Figure 9e and f). The simulation results revealed a maximum 6% difference in cotton yield uniformity between H1 and H5 under the different scenarios.

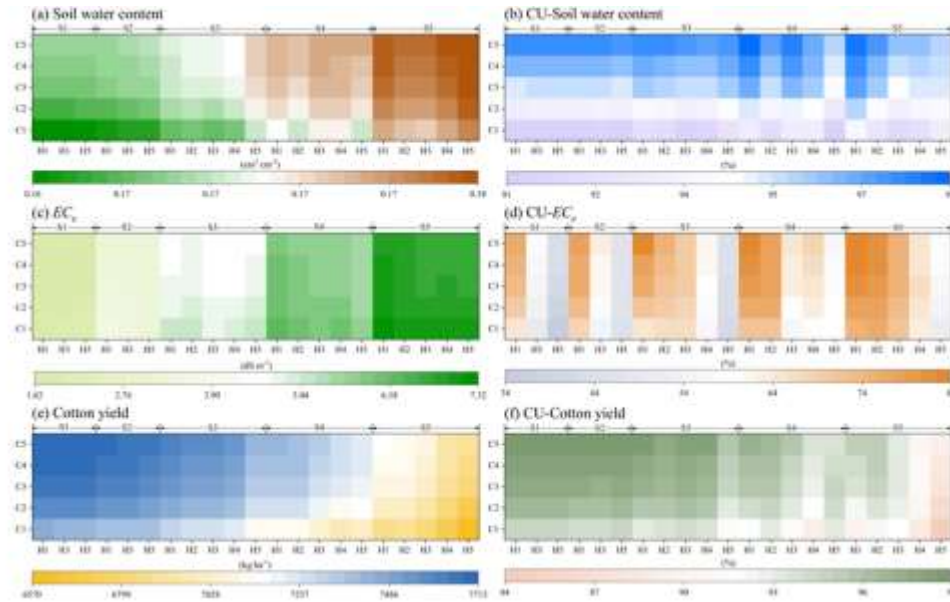


Figure 9. The average SWC of the subunits during the irrigation period under the different scenarios (a). The SWC uniformity (CU) of the drip irrigation subunit during the irrigation period under the different scenarios (b). The average EC_e values of the subunits during the irrigation period under the different scenarios (c). EC_e uniformity (CU) of the drip irrigation subunits during the irrigation period under the different scenarios (d). The average cotton yield of drip irrigation under the different scenarios (e). Cotton yield uniformity (CU) of the drip irrigation subunits under the different scenarios (f).

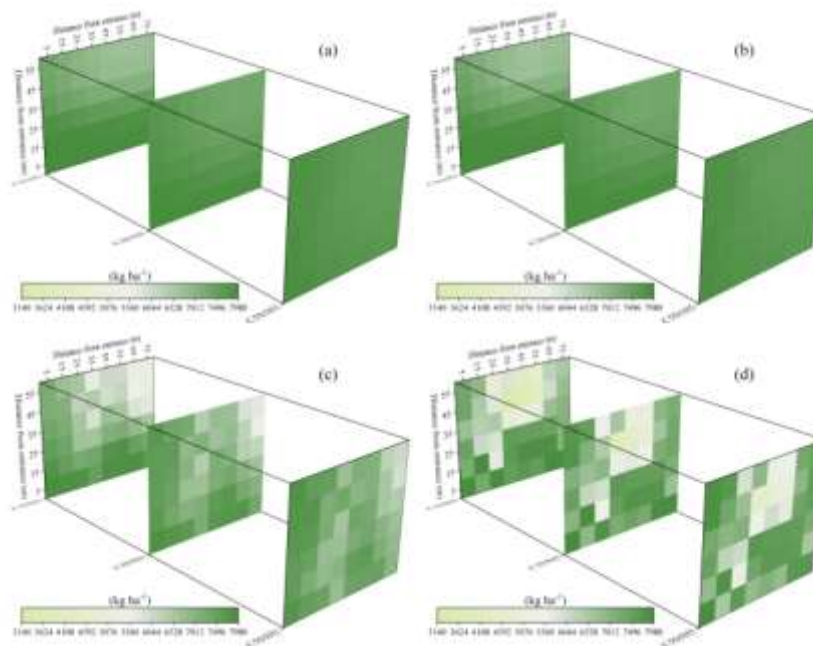


Figure 10. Spatial distributions of the cotton yield under partial scenarios.

4. DISCUSSION

4.1 The spatial distribution of SWC/ EC_e under the interaction effects of irrigation-salinity-crop at drip subunit level

Generally, the SWC in farmland shows non-gaussian patterns due to the effect of several factors, including drip hydraulic performance or spatial distribution of soil properties, potentially leading to significant SWC spatial variability at the drip subunit level (Rodríguez-Sinobas et al., 2021). The SWC exhibited a distinct spatial distribution pattern under subunits of low initial soil salinity, in which the higher emitter discharge rates maintained greater SWC at local area (Figure 7 a, b). Given the scarcity of water resources in arid regions, it follows that irrigation is virtually the sole means of replenishing soil moisture, which explains the observed consistency in the spatial distribution between SWC and the hydraulic performance of drip emitters (affecting the actual irrigation depths). For subunits with a large areas, the drip hydraulic performance is crucial for maintaining both adequate SWC and its spatial uniformity, as it guarantees a consistent level of soil moisture replenishment throughout the field (Table 6). However, the established hydraulic uniformity-dependent distribution patterns of SWC was altered under subunits with higher initial soil salinity and its variability (Figure c, d). This phenomenon can be attributed to the involvement of root activity in the soil hydrological cycle, as under mulch drip irrigation, water depletion of the 0-40 cm soil layer primarily results from root uptake and evapotranspiration (Brighenti et al., 2024; Li et al., 2016; Man et al., 2024). Salt stress suppresses normal root water uptake and consequently reduces transpiration, which leads to the observed increase in SWC associated with locally elevated initial salinity (Bazihizina et al., 2012; Yin et al., 2023). The ANOVA results indicated that the initial soil salinity variability was another significant factor influencing the SWC uniformity at the subunit scale. Under conditions of agricultural water scarcity, the spatial variability of SWC arised from the above factors will significantly affect the formulation of precision irrigation scheduling at subunits level based on soil moisture.

Table 6. ANOVA of drip irrigation parameters on SWC, EC_e , and cotton yield of subunit.

Factor	SWC	SWC (CU)	EC_e	EC_e (CU)	Yield	Yield (CU)
C	0.00**	0.00**	0.52	0.32	0.08	0.01*
S	0.00**	0.09	0.74	0.92	0.59	0.38
H	0.41	0.00**	0.78	0.01*	0.48	0.16

Note: * indicates that it is significant at the level of 0.05; ** indicates that it is significant at the level of 0.01, C the design of drip irrigation network, S is the design of subunit average soil salinity, H is the design of subunit soil salinity variability (CV).

Soluble salts (primarily Na^+ and Cl^-) in the soil exhibit high mobility with water flow; therefore, sufficient drip irrigation facilitates salt leaching beyond the root zone, whereas inadequate water application results in salt accumulation within the root zone (Aragüés et al., 2014). In drip irrigation systems, this results in lower EC_e near the inlets and higher soil salinity in fields distant from the entrance (Figure 8). Lin et al. (2022) observed similar salinity distribution patterns through field experiments; furthermore, the spatial distribution of soil salinity under drip irrigation (lower irrigation depths) is mainly determined by the initial salinity variability, and the results was further confirmed by our simulation at the subunit scale (Table 6, Figure 8 g and h). Notwithstanding the nonsignificant ANOVA results ($p>0.32$) for drip hydraulic performance versus EC_e uniformity, improving hydraulic uniformity could nevertheless lead to reductions in EC_e and improvements in its uniformity to varying degrees. Notably, given inherent soil salinity variability, extreme scenarios inevitably exist (e.g., higher EC_e near inlets versus lower levels in distal fields). Such conditions may paradoxically diminish the salt leaching efficacy despite high hydraulic performance, as uniform water application cannot concentrate in high-salinity zones. Despite the presence of exceptional scenarios, improving hydraulic uniformity generally proves adaptable to drip subunits under diverse initial soil salinity conditions.

4.2 Cotton Yield response to initial soil salinity at drip subunit level

Cotton yield exhibited a spatial distribution pattern opposite to that of the initial soil salinity at subunit level (Fig 10). The effects of soil salinity are marked in cotton plants, which exhibit physiological changes including stomatal closure, osmotic stress, suppression of cell division, and photosynthetic impairment, ultimately leading to yield reduction, quality deterioration, or even plant mortality (Qadir and Shams, 1997; Ashraf and Ahmad, 2000; Aslam et al., 2011). The relationships between cotton yield and initial soil salinity at subunit level was further evaluated and shown in Figure 11. Generally, soil salinity in the root zone does not affect crops until reaches a certain level (Akca et al., 2020). The significant reductions in cotton yield (yield uniformity) of drip subunits occurred when the initial soil salinity exceeded 6.78 dS m^{-1} (Figure 11 a and c). An interesting finding is that increased initial salinity variability reduces the soil salinity at yield beginning decline, in which the EC_e values for H1, H3, and H5 were 6.82 (6.70), 6.52 (6.42), and 4.92 (5.95) $\text{dS} \cdot \text{m}^{-1}$, respectively (Figure 11 b and d). The threshold-slope response relationship (Maas and Hoffman, 1977) between cotton yield and soil salinity results in asymmetric yield responses to increases/decreases in salinity. Increased variability induces deviations in soil salinity within a subunit from the mean value (either increased or decreased), where increasing salinity causes linear yield reduction, whereas yield remains unaffected once salinity falls below the threshold. Consequently, increased salinity variability leads to reduced overall yield (yield uniformity) in subunits despite identical average salinity levels, as more extremely high-salinity zones are generated, ultimately lowering the soil salinity at yield (yield uniformity) beginning decline. For cotton production in high-salinity fields at the subunit level, particular attention should be given to soil salinity variability and localized high-salinity zones, as these factors may reduce overall yield and uniformity.

The relationship between cotton yield deviation (scenario simulation value without salinity variation – scenario simulation with salinity variation) and soil salinity variability under scenarios in which the soil salinity exceeds 6.78 dS m^{-1} are shown in Figure 11e. The results indicated that low soil salinity variability had no significant effect on the cotton yield of the subunit, and the yield deviation progressively increased with increasing salinity variability when the variability exceeded 33%. Similarly, a soil salinity variability that exceeded 35%, led to a significant reduction in yield uniformity (Figure 11f). In general, an initial soil salinity $> 6.8 \text{ dS m}^{-1}$ and salinity variability $> 35\%$ may constrain both yield potential and its uniformity under drip irrigation. These soil salinity control value could assist farmers in anticipating cotton salt injury and adopting precision management practices at the subunit level.

4.3 Adaptability of enhancing drip hydraulic performance in high-salinity subunits

The relationship between drip hydraulic performance and crop yield has been extensively explored, but current research generally overlooks the influence of inherent soil salinity in farmland (Stern and Bresler, 1983; Mateos et al., 1997; Pang et al., 1997; Bordovsky and Porter, 2008;). Salinity management relies predominantly on ensuring adequate salt leaching, making irrigation water management and irrigation equipment hydraulic performance the key research priority (Ayars et al., 2012; Chauhdary et al., 2020). However, given the complex overlapping effects of drip hydraulic performance and initial salinity conditions on the soil water/salt environment, whether hydraulic performance enhancement can benefit crop production in high-salinity farmlands remain debatable. Figure 12a shows the relationships between cotton yield deviation (scenario with uniform irrigation – scenario with nonuniform irrigation) and drip network design under scenarios with adverse salinity conditions (soil salinity and variability exceeding 6.79 dS m^{-1} and 35%, respectively). The simulation results demonstrated that even under adverse soil conditions, improved system uniformity could still improve both yield and uniformity (Figure 12 a and c). These findings suggest that the enhanced irrigation uniformity achieved through system optimization results in robust adaptability in drip systems operating in arid and high-salinity environments. The irrigation depths in this work were designed at a lower level (350 mm) under water saving management. It is foreseeable that enhanced drip hydraulic performance, which avoid local excessive/insufficient irrigation, could creating a more favorable water-salinity environment for increased crop yield at higher irrigation depths.

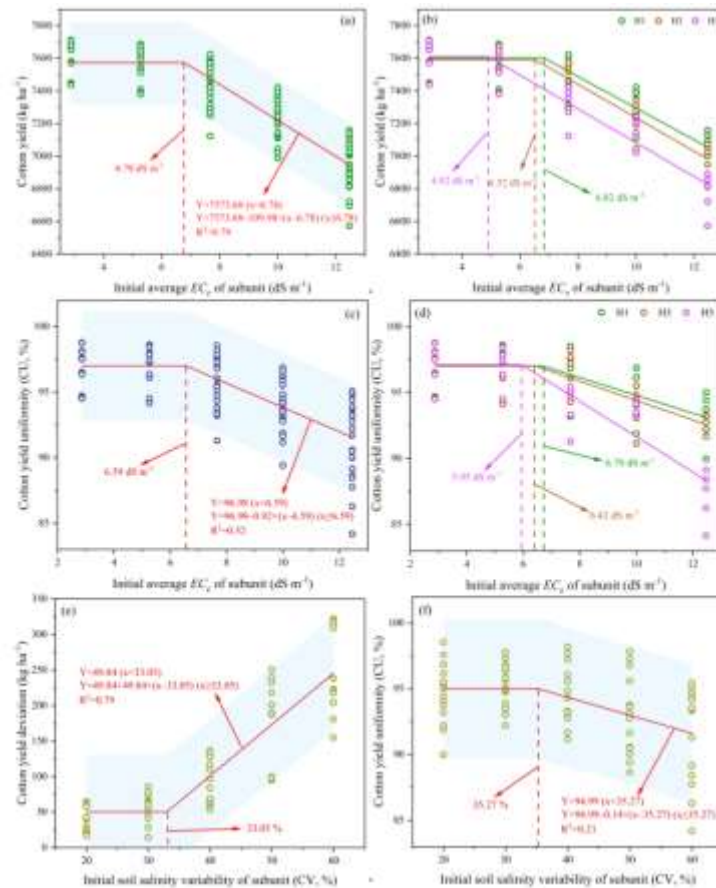


Figure 11. Effects of the initial average EC_e on the cotton yield of the subunit (a).

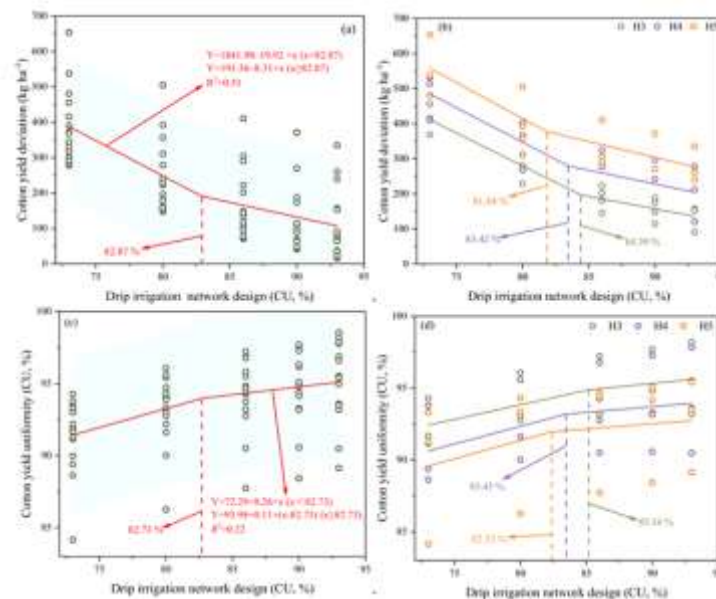


Figure 12. Effects of the drip irrigation network design (CU) on cotton yield deviation of subunit

A linear relationship with a globally positive correlation describes how enhanced drip system performance affects yield and uniformity at the subunit level, with this positive effect demonstrating attenuation when system uniformity (CU) exceeds 83% (Figure 12 a and c). The unlimited hydraulic performance enhancement does not yield proportional crop yield benefits, but the investment of materials and equipment with higher specifications will inevitably lead to increased installation cost and energy consumption (Chamba et al., 2019). We recommend 83% hydraulic uniformity as the optimal design standard for drip irrigation systems in arid regions with high-salinity farmland. Furthermore, with increasing initial salinity variability, the endpoints of the initial high-efficiency growth zone for the cotton yield-drip network design curves under H2, H3, and H5 were 84%, 83% and 82%, respectively, whereas those for the yield uniformity-drip network design curves were 85%, 83% and 82%, respectively (Figure 12 b and d). These phenomena indicate that increasing irrigation uniformity may have limited effectiveness in fields with high initial salt variability. In such scenarios, reducing hydraulic performance standards and reallocating resources toward increased irrigation depths for enhanced salt leaching represents a more effective management strategy.

5. CONCLUSION

This work systematically evaluated the impacts of drip hydraulic performance and initial soil salinity on irrigation distribution, the SWC/salinity environment, and cotton yield at the subunit scale through integrated modeling. When the initial soil salinity level was low, the SWC/salinity and crop yield within the subunit exhibited a regular spatial distribution pattern influenced by the drip hydraulic performance; as the soil salinity and its variability increased, the initial salinity distribution emerged as the predominant factor governing the spatial patterns of these three parameters. An increase in initial soil salinity and its variability exacerbates the non-uniformness of soil water-salt conditions under drip irrigation, leading to a reduced subunit yield and uniformity. The soil salinity caused a significant decline in both yield and uniformity at the subunit level when the initial average salinity exceeded 6.78 dS m⁻¹ and the variability was greater than 33%. For drip system design in arid regions with adverse initial salinity conditions, we recommend a hydraulic performance of 83% to ensure postirrigation uniformity of the SWC and EC_e , thereby increasing cotton productivity.

DECLARATION OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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