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Simulation of Soil Water and Salt Balance in Three Water-Saving Irrigation Technologies with HYDRUS-2D

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Abstract: Mulch drip irrigation (MDI) technology can effectively solve the problem of insufficient temperature accumulation during the pre-fertility period and facilitate the efficient supplementation of water and fertilizer during the fertility period in spring corn planting. Moreover, this local MDI technology also has impacts on the farmland environment. To investigate the effect of drip irrigation technology on the water and salt environment of farmland, a field study on corn cultivation was carried out at West Liaohe Plain. In addition, the water and salt dynamics of the farmland were simulated using HYDRUS-2D for mulch drip irrigation (MDI), shallowly buried drip irrigation (SBDI), and sprinkler irrigation (SI), with variable rainfall and initial salt content. The results showed that the distribution of and variation in water and salt in the soil were similar under MDI and SBDI. The change near the drip tape was mainly affected by irrigation, while the water and salt in the soil between drip tapes were correlated with irrigation and rainfall. The amount of salt in the topsoil (5 cm) increased with a decrease in rainfall. With an initial EC = 480 µs/cm (soil salt content 0.1%), the salinity of the topsoil under MDI was significantly higher than that under SBDI and SI within two years. The topsoil salinity was similar for all three irrigation technologies with increasing operating life, reaching a relatively stable state, and much lower than the salinity determination threshold of 480 µs/cm. Given the current conditions of rainfall, soil, buried depth, and mineralization in the West Liaohe Plain, the risk of secondary salinization is minimal if irrigation management is reasonable. This study provides data to support the application of drip irrigation technology in the Western Liaohe Plain.

Keywords: mulch drip irrigation; shallowly buried drip irrigation; soil and water environment; water and salt transport; HYDRUS-2D

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1. Introduction

Located in the gold belt of corn production, the West Liaohe Plain is a substantial grain production base in China, with low rainfall and spring temperature. With the implementation of water-saving and grain-increasing initiatives and various technical promotion projects, the primary irrigation mode for corn has transitioned between ridged field flood irrigation, mulch drip irrigation (MDI), and shallowly buried drip irrigation (SBDI) with soil cover [1]. Applying water-saving irrigation technologies such as low-pressure pipe irrigation, MDI, and sprinkler irrigation (SI) results in water conservation and yield increase [2–4]. However, the promotion and application of a specific water-saving irrigation technology must consider the impact of the technology on the water and salt environment of the farmland, especially the increasing contradiction between water-saving irrigation and secondary soil salinization, to ensure sustainable development. Therefore, more attention should be paid to studies on improving soil water and salinity conditions to ensure sustainable agricultural development.

Since favorable results were obtained by the 8th Division of Xinjiang Production and Construction Corps in 1996, the practice of MDI in saline soil has been applied and promoted on a large scale in the Xinjiang region and throughout northern China [5]. In recent years, studies locally and abroad have shown that the MDI practice has many advantages compared with other irrigation technologies. It not only possesses the water-saving, fertilizer-saving, and salt control characteristics of drip irrigation, but it also has the temperature accumulation and soil water retention effect of mulching cultivation [6–9]. This method can provide a good water and soil environment for crop growth in saline soil and play a key role in crop growth and yield increase [10]. Studies have shown that the salt content of the topsoil layer (0–30 cm) of mulched drip irrigation can be reduced by up to 80% compared with un-mulched drip irrigation [11]. As drip irrigation is shallow and can form a leaching desalination zone below the drip head, the water is absorbed and used by the soil while the salt is confined to the bottom of the cultivated layer [12]. In addition, mulch can facilitate water storage in soil, reducing the amount of irrigation required, and thus reducing the accumulated salt brought into the field.

The mulch isolates soil water content from evaporation to the atmosphere and inhibits the accumulation of groundwater salt in the topsoil [13]. For conventional surface irrigation methods that lack plastic film covers, and with the increase in irrigation quotas, intense water evaporation in the soil leads to significant changes in the degree of soil leaching and the depth of soil desalination. The salt content rapidly rises, causing salt to accumulate in the topsoil. MDI technology has been shown to be effective in conserving water, controlling salinity, and ameliorating soil microenvironments, and it is widely used in arid and semi-arid regions worldwide [14–16]. Since the pilot test of under-mulch drip irrigation technology was carried out in 1996, it has been applied in China for 26 years, and its promotion has spread all over the arid and semi-arid areas of China. However, the conflict between increased yields and residual film contamination has become increasingly evident in MDI, which has seriously affected sustainable land use and caused environmental pollution [17].

An appropriate drip irrigation method should facilitate the normal photosynthesis of corn leaves, promote the accumulation and transport of dry matter, and increase yields [18]. Shallowly buried drip irrigation is an advanced water-saving irrigation and fertilization technology in which mulch is removed, and it has been studied and applied in recent years. The drip tape is directly buried in the topsoil (3–5 cm) [19]. This technology allows for better water and fertilizer transport to the crop root system, providing a more suitable water and nutrient environment for crop growth. Numerous studies have shown that SBDI significantly reduces ineffective evaporation and avoids the problem of residual film contamination. Moreover, like drip irrigation, it increases water and fertilizer use efficiency and crop yield [20,21]. Compared with traditional border irrigation, SBDI can significantly improve the dry matter accumulation, transport rate, and contribution rate of dry matter transport to the grain during the late fertility period of corn. It can also significantly improve the efficiency with which corn uses water and nitrogen, which is conducive to high and stable corn yields. In addition, under drip irrigation, the corn yield and water use efficiency increased by 35% and 33%, respectively, compared with the values under SI [22,23]. Up to now, drip irrigation has been widely used in agricultural production [24–26]. However, there is little knowledge about the effect of irrigation technology on the regulation of the water and salt environment in soil. Therefore, it is necessary to find a rational irrigation pattern for crops that can balance an increase in crop yield, water use efficiency, and agro-ecological sustainability.

Water scarcity and soil salinization are the primary factors threatening the environment and sustainable agricultural development in arid regions [27]. Most previous studies on drip irrigation under plastic mulch took the arid region of Xinjiang as their research object. They studied the long-term evolution of suitable irrigation strategies [28] and soil salinity [29,30]. The long-term evolution of soil water and salinity conditions in semi-arid areas such as the Liaohe Plain also needs attention, however. In this paper, the effects of long-term drip irrigation (MDI, SBDI) on water and salt distribution in the corn root zone in the West Liaohe Plain were studied. Furthermore, the HYDRUS-2D model was used to simulate the water and salt dynamics in the farmland under different irrigation methods, as HYDRUS-2D performs well in soil water and salt transport simulations [28]. Therefore, the paper provides data supporting the application of drip irrigation technology in the West Liaohe Plain.

2. Materials and Methods

2.1. Overview of the Study Area

The experiment was conducted from May to October 2016 in the Horqin Left Middle Banner (Figure 1, a central coordinate of 122°21′38″ E, 44°11′09″ N) on the southeastern edge of the Greater Khingan Range, a transition zone from the Songliao Plain to the Inner Mongolia Plateau. The ground elevation is between 120 m and 230 m. It has a north-temperate continental monsoon climate. The multi-year average temperature is 5.2–5.9 °C, with a maximum temperature of 40.9 °C and a minimum temperature of −33.9 °C. The accumulated temperature ranges from 3042.8 to 3152.4 °C. The multi-year average precipitation tends to increase from northwest to southeast, ranging from 342 mm to 392 mm, with uneven intra-annual distribution and significant interannual variations. The multi-year average maximum wind speed is 15.6 m/s, with a maximum instantaneous wind speed of 29 m/s and an average wind speed of less than 3.4 m/s during the irrigation season. Day-by-day rainfall and evapotranspiration data are shown in Figure 2.

The soil is light loam with a physical clay content (particle size < 0.01 mm) of >20%, a dry volumetric mass of 1.33 g/cm^3, an average porosity of 35.57%, a field water holding rate of 28.5% (volumetric water content), and an initial soil salinity of 1.21 g/kg (EC = 525 µs/cm). The shallow groundwater is buried at a depth of >10 m, with a total mineralization of <0.5 g/L. Irrigation can be guaranteed and the groundwater is suitable for crop growth.

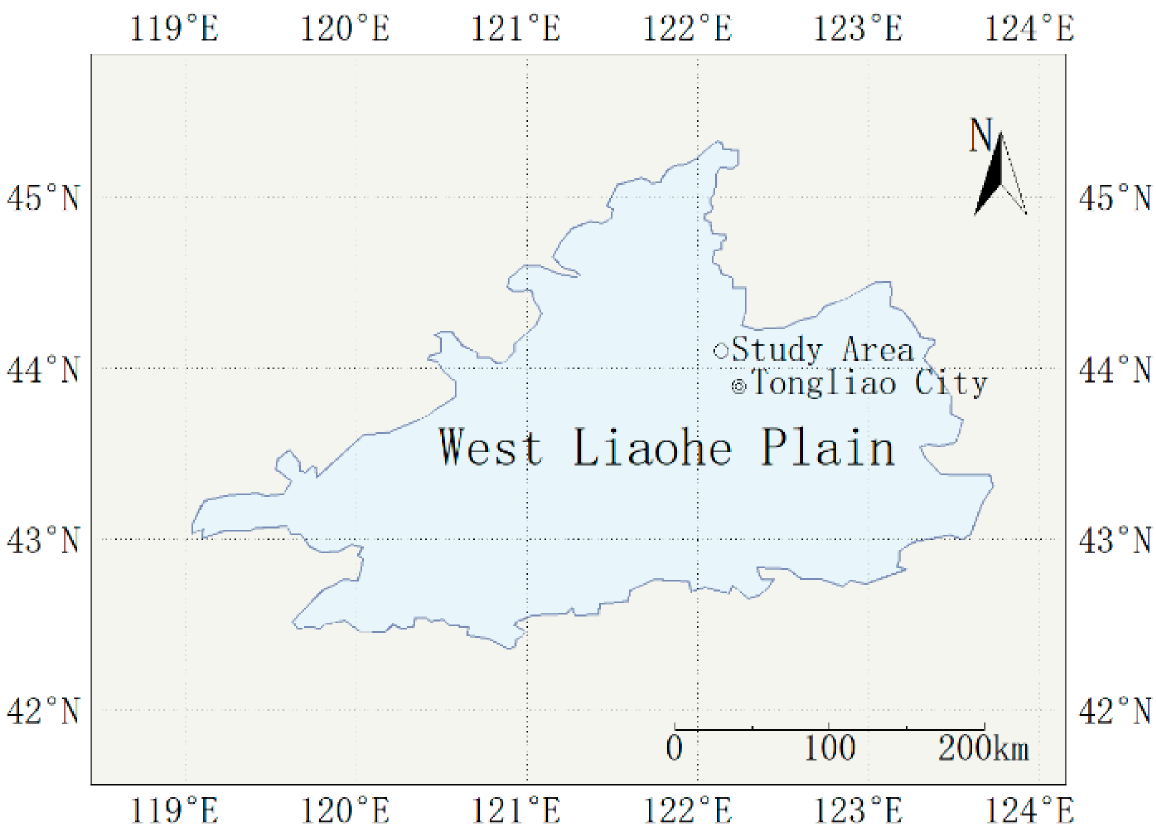

Figure 1. Location of study area.

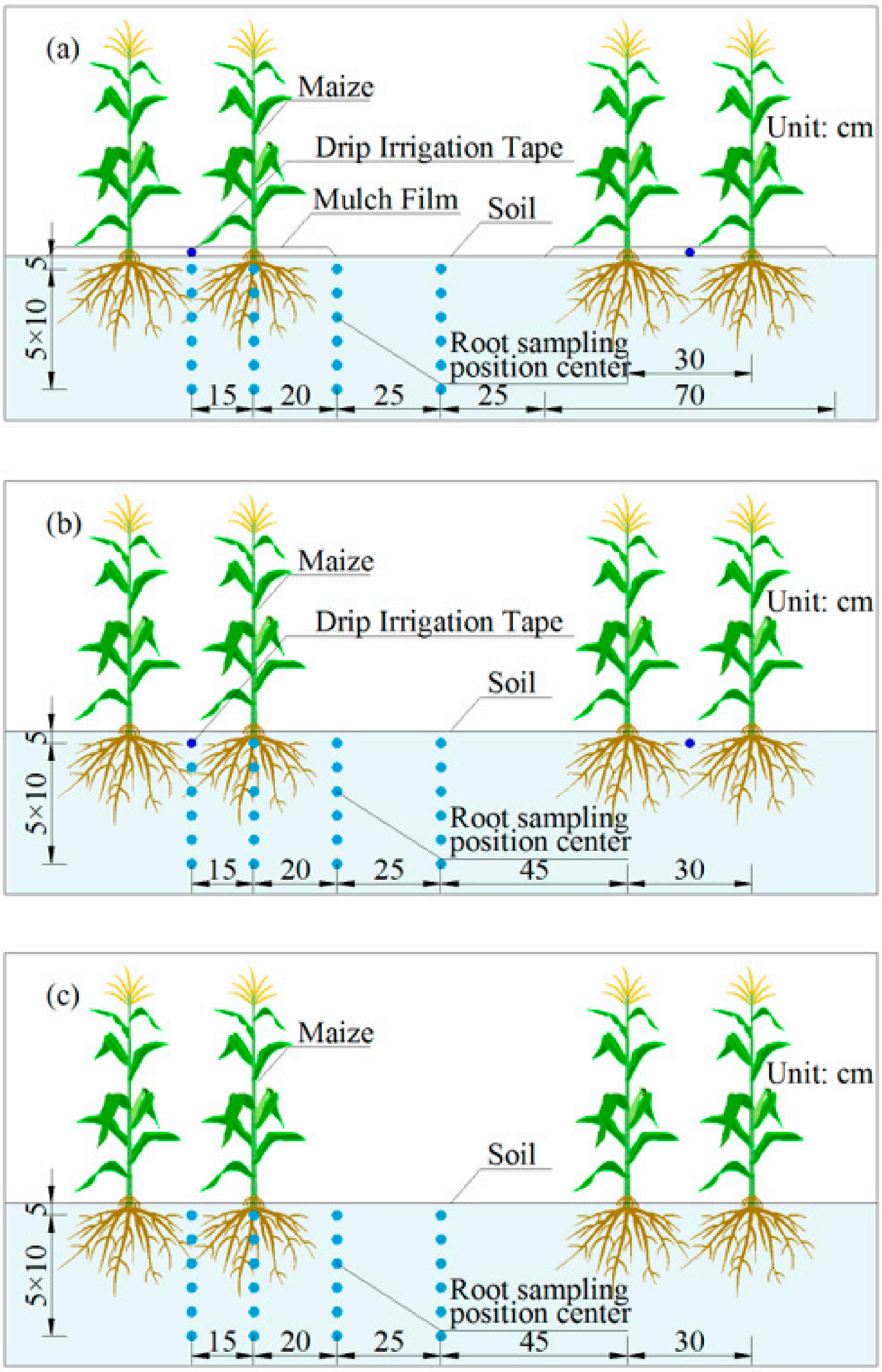

Figure 2. Schematic of Maize Planting and Irrigation. (**a**) Mulched drip irrigation; (**b**) shallow-buried drip irrigation; (**c**) sprinkler irrigation.

Corn is the main crop grown in the study area. Irrigation methods include mulch drip irrigation (MDI), shallowly buried drip irrigation (SBDI), and sprinkler irrigation (SI). In the mulch drip irrigation mode, the corn was planted in a 'one mulch and two rows' cropping system. The width of the mulch was 70 cm. The drip irrigation tapes were laid in the middle of the mulch with 120 cm between the center lines (Figure 3a). Under shallowly buried drip irrigation, the corn was planted in wide and narrow rows, with the drip tapes laid in the middle of the narrow rows. The drip tapes were laid in the center of two rows of corn, with the drip tapes spaced 120 cm apart (Figure 3b). The same drip irrigation tapes were used for cover drip irrigation and SBDI, with a dripper spacing of 25 cm, and the flow rate was 1.8 L/h. The depth of the SBDI belt was 3–5 cm, and the pipeline water supply pressure was 1 MPa. The corn treated with SI was planted in wide and narrow rows (Figure 3c). It was irrigated with a translation sprinkler, which had two spans, each 60 m, and water was supplied by pipeline. The fertilizer applied by SI had an effective N content of 270 kg/ha, a P content of 120 kg/ha, and a K content of 90 kg/ha. The drip irrigation (MDI and SBDI) was 1830 m^3/ha, and fertilizer was 397.5 kg/ha (N at 270 kg/ha, P at 63.75 kg/ha, and K at 63.75 kg/ha).

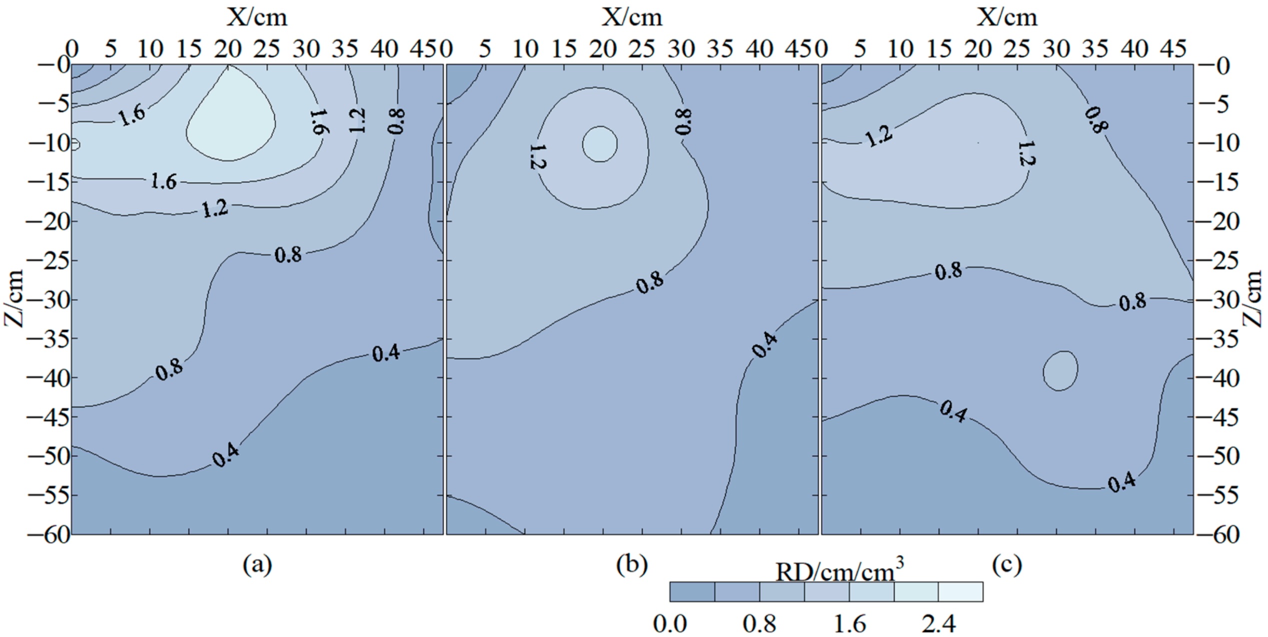

Figure 3. Root length density distribution map. (**a**) Mulched drip irrigation; (**b**) shallow-buried drip irrigation; (**c**) sprinkler irrigation.

2.2. Observation Indicators and Methods

The drying method was used to measure the soil water content. A typical location was selected for the three distinct irrigation technology test areas. The sampling depths were 10 cm, 30 cm, 50 cm, and 70 cm, and measurements were made every 14 days. The dry residue method was used to calibrate the relationship between soil salt content and conductivity. Soil samples were crushed and then passed through a 1 mm sieve. Twenty grams of soil were weighed and then placed into a triangular flask. A volume of 100 mL of distilled water was added, and the flask was shaken for 30 min using a shaker. Filtering was carried out after 10 min standing to obtain leachate with a water-to-soil ratio of 5:1. The standard curve and formula between soil salt content and electrical conductivity are shown in Figure 4. The conductivity of the leachate was determined using a conductivity meter (Shanghai Leici DDS-11A, Shanghai, China). After the end of the fertility period, undisturbed soil samples were taken from depths of 10 cm, 30 cm, 50 cm, and 70 cm. The soil hydraulic parameters were measured using a 1500 F1 pressure membrane instrument (Soilmoisture Equipment Corp., Goleta, CA, USA). Repeat sampling was carried out six times for each irrigation technology.

The corn roots were sampled using the root auger method at the time of jointing and tasseling in 2016 at a soil depth of 0–60 cm. The root sampling points for each irrigation method are shown in Figure 3a. Three replicates were collected each time. The extracted corn roots were soaked in water for 24 h and then picked out using a 0.5 mm sieve. The corn roots were dried at 65 °C to a constant weight. They were then spread on white paper with a 20 cm control line and photographed. The root length was calculated using R2v and

Photoshop software and divided by the volume of each soil sample at different layers to obtain the root length density.

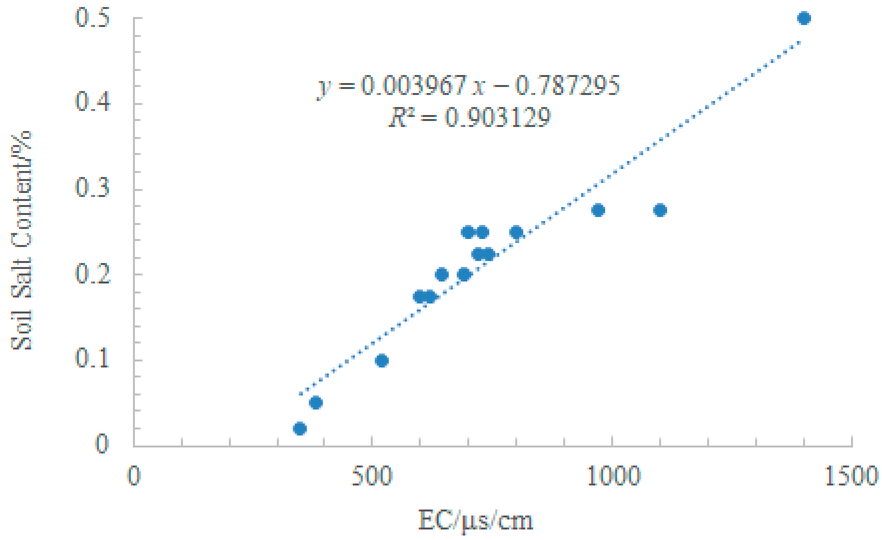

Figure 4. The relationship of soil salt content and conductivity.

2.3. Basic Equations of the HYDRUS-2D Model

The HYDRUS-2D software is a numerical model that can simulate the transport of water and solute in unsaturated porous media, and the general form of the basic equation for water and salt transport in unsaturated soils is as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K(K_{ij}^A\frac{\partial h}{\partial x_j} + K_{iz}^A)\right] - S \tag{1}$$

where θ is the volumetric water content of the soil $\left[\mathrm{L^3L^{-3}}\right]$, h is the negative soil pressure $[\mathrm{L}]$, S is the root water uptake term or other source sink term $\left[\mathrm{T^{-1}}\right]$, K_{ij}^A is the component [-] of the anisotropy tensor K^A, and K is the hydraulic conductivity of unsaturated soil $\left[\mathrm{LT^{-1}}\right]$.

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right) - \frac{\partial q_i c}{\partial x_i} \tag{2}$$

where c is the solute concentration in the soil solution $\left[\mathrm{ML^{-3}}\right]$, q_i is the Darcy flow rate at the direction of x_i $\left[\mathrm{LT^{-1}}\right]$, and D_{ij} is the saturated/unsaturated hydrodynamic dispersion coefficient $\left[\mathrm{L^2T^{-1}}\right]$.

HYDRUS-2D currently uses a modified model with the van Genuchten equation to represent the relationship between the volumetric water content of soil θ and the hydraulic conductivity K and negative pressure of soil h.

The root uptake term S in Equation (1), whose values are shown in Figure 5, represents the amount of water taken up by the plant roots from a unit volume of soil per unit of time. Feddes (1978) defined the expression S as:

$$S = \alpha(h)S_p \tag{3}$$

where $\alpha(h)$ represents the effect of negative soil water head (or soil water content) on root water uptake $[-]$ $(0 \leq a \leq 1)$.

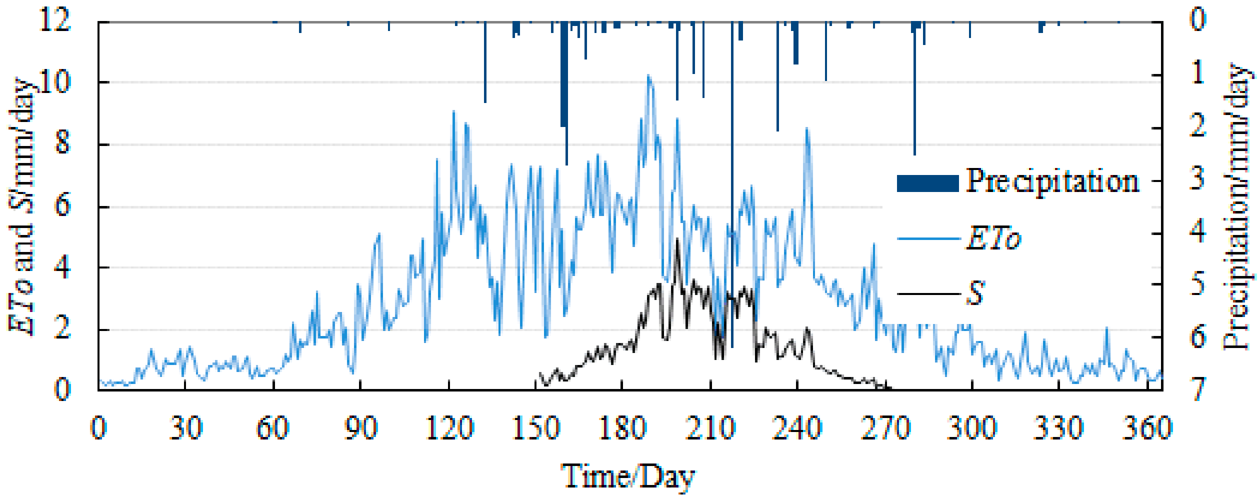

Figure 5. Rainfall, *ETo* and *S* calculation of Tongliao station.

2.4. Model Building and Parameters

The corn root zones under MDI, SBDI, and SI were abstracted into vertical 2D models according to current cropping patterns in the study area. The upper boundary was at ground level, and the lower boundary was at a depth of 80 cm. The left and right boundaries were the narrow and wide row centers, respectively.

Three different boundary conditions were set for the upper boundary of the MDI, i.e., the infiltration boundary, the flux-free boundary within the mulch, and the atmospheric boundary (infiltration, evaporation, etc.) of the inter-mulch open space (Figure 6a). The upper boundary of the SBDI was the atmospheric boundary, and the infiltration boundary of the drip tape was set on the left (Figure 6b). The upper boundary of the SI was also the atmospheric boundary, and irrigation was given through the atmospheric boundary. The lower boundary conditions for all three models were free drainage boundaries.

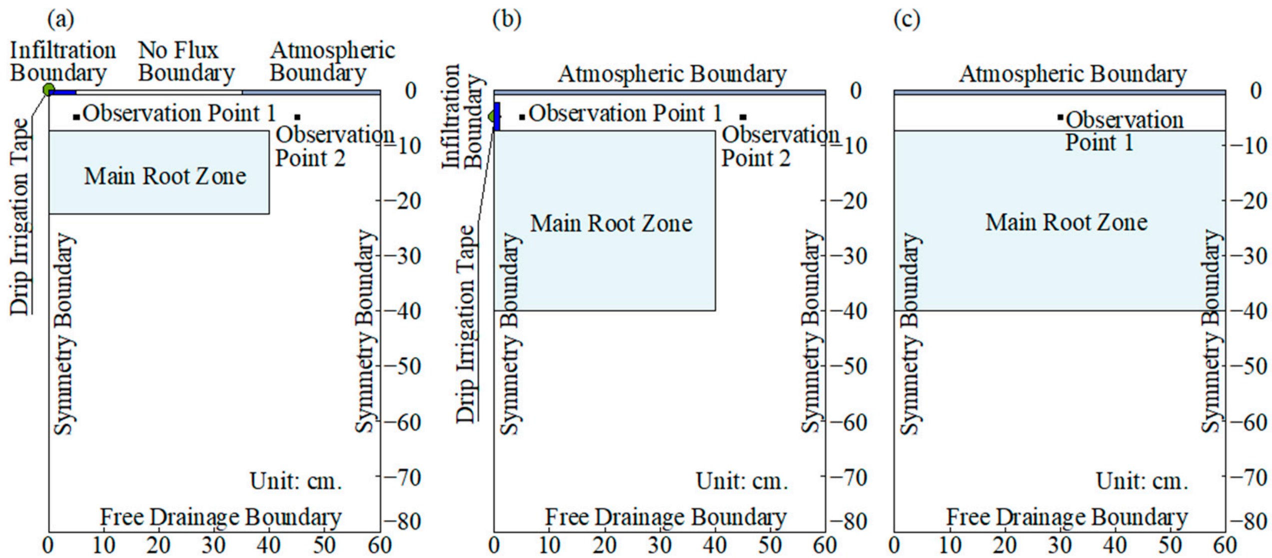

Figure 6. Schematic of soil water and salt transport simulation model. (**a**) Mulched drip irrigation; (**b**) shallow-buried drip irrigation; (**c**) sprinkler irrigation.

As is shown in Figure 6, the primary roots of the corn were at a depth of 10–60 cm, a finding similar to that of Zhang et al. [31]. The roots of cotton and corn with MDI were mainly concentrated at a depth of 20–50 cm, and the root density was significantly reduced below 50 cm. The physical water and salt transport model for the three irrigation techniques can be obtained by processing different root distribution, irrigation, and evaporation conditions (Figure 5).

In 2016, samples were taken at depths of 10 cm, 30 cm, 50 cm, and 70 cm for soil hydraulic parameters at a specific location for each irrigation technology test area. The measured values were averaged. The soil samples were then taken at depths of 10 cm, 30 cm, 50 cm, and 70 cm at 14-day intervals during the corn growing season to measure soil water content using the drying method and to measure the salinity using the conductivity method. The parameters of water and salt transport in the soil in the HYDRUS-2D model were calibrated and validated based on the measured data. The parameters after calibration and validation are shown in Tables 1 and 2. The coefficients of determination R^2 reached 0.75 (soil water movement) and 0.69 (soil solute transport). Our results showed that the calibrated and validated HYDRUS-2D model can accurately simulate the water and salt distribution in soil under different irrigation conditions in the test area.

Table 1. Soil parameters of each layer.

Soil layer depth (cm)	0~20	20~40	40~60	60~80
Buck density (g/cm^3)	1.39	1.38	1.23	1.32
Field water capacity (cm^3/cm^3)	25.08%	24.77%	30.05%	34.11%
soil texture	silty clay	clay loam	clay	clay
θ_r (cm^3/cm^3)	6.50%	6.50%	6.50%	6.50%
θ_s (cm^3/cm^3)	29.13%	28.64%	32.27%	37.23%
α (cm^{-1})	0.075	0.059	0.059	0.059
n (-)	1.89	1.48	1.48	1.48
Ks (cm/day)	56.01	31.44	3.80	5.20
l (-)	0.5	0.5	0.5	0.5

Table 2. Solute transport parameters.

DisperL.	**DisperT**	**Frac**	**ThImob**	**DifW**	**DifG**
cm	cm	[-]	[-]	cm^2/day	cm^2/day
4	0.1	1	0	0.018	0

The soil root system parameters are shown in Table 3, and the irrigation regime data are shown in Table 4.

Table 3. Root water uptake parameters.

P0	**P2H**	**P2L**	**P3**	**r2H**	**r2L**
cm	cm	cm	cm	cm/day	cm/day
−15	−325	−600	−5000	0.5	0.1

Table 4. Irrigation system.

Efficient Irrigation Technology	Sprinkler Irrigation				Mulched Drip Irrigation				Shallow-Buried Drip Irrigation			
Hydrological Year	**Dry Year**		**Normal Year**		**Dry Year**		**Normal Year**		**Dry Year**		**Normal Year**	
Irrigation System	n	W m^3/ha	n	W m^3/ha	n	W m^3/ha	n	W m^3/ha	n	W m^3/ha	n	W m^3/ha
Sowing~Seeding Stage	1	300~450	1	300~450	1	300	1	150	1	300	1	150
Seeding~Jointing Stage	2	375~450	1	375~450	1	300	1	300	1	375	1	375
Jointing~Tasseling Stage	2	375~525	2	375~525	3	375	2	300	3	375	2	300~375
Tasseling~Grain Filling Stage	2	375~450	1	375~450	1	375			1	375		
Grain Filling~Maturating Stage					2	200	3	240~300	3	300~375	3	270~375
Whole Growing Period	7	2550~3300	5	1800~2400	8	1700	7	1830	9	3150	7	2220

n is irrigation times; W (m^3/ha) is irrigation quota.

3. Results and Discussion

3.1. Simulation of the Soil and Water Environment in Corn Fields with Three Irrigation Techniques

With the soil data, corn growth data, and meteorological data from the experimental area, HYDRUS-2D was used to simulate the water and salt transport process in the soil and the salt accumulation in the topsoil under MDI, SBDI, and SI. The simulation period was 20 years. The water and salt changes in monitoring point 1 and 2 under different irrigation technologies were analyzed.

The simulation results showed similar distributions of water and salt in the soil under MDI and SBDI. The soil water content changes at point 1 under MDI and SBDI were primarily influenced by irrigation (Figures 7a and 8a). They were mainly due to the small distance between point 1 and the drip tape, which resulted in a sharp increase in soil water content after irrigation. In addition, the drip irrigation with a low flow rate and a high frequency had a greater water supply in the shallow area below the drip tape [32,33]. point 2 was located on the bare ground outside the mulch. The soil water content at point 2 was influenced by irrigation and closely correlated with rainfall. The trends in soil solution concentrations at monitoring points 1 and 2 were generally consistent. The soil solution concentration was mainly affected by fertilization and was higher in the fertility period but lower in the non-fertility period. This was mainly due to the drip irrigation and fertilization method, as it can directly deliver a precise water and fertilizer amount to the crop root zone according to the crop demands. In addition, it can infiltrate the most developed areas of the root system and maintain optimum water and nutrient content in the active root zone [34]. As a result, the soil solution concentration decreased significantly in the crops' non-fertility period without irrigation and fertilization. This result was consistent with the findings of Berrada et al. [35] and other scholars. The point source nature of drip irrigation is due to its shallow and frequent irrigation features and its small humid area. Salt is transported with the water to the edge of the wetted zone and then a desalination zone is formed near the center of the drip head [36,37]. Many studies have shown that drip irrigation is essential for improving saline soils. The findings that the soil water content increased with the increasing distance from the drip tape and that soil salinity became greater with the increasing distance from the drip tape were consistent [38,39]. Soil salt mainly accumulates at the edge of wet soil, resulting in the distribution of low soil salt inside the mulch and high soil salt between the mulches [36,40]. The relatively low soil salinity in the desalination area can provide a favorable environment for plant root growth and water absorption.

The effect of soil salinity regulation in the root zone under the mulch was assessed by selecting the intra- and interannual topsoil (5 cm) salinity. The simulation results showed that the salt content of the topsoil (5 cm) under the three irrigation technologies had the same variation pattern as that at the monitoring point (Figures 7c, 8c and 9c). In order to clarify the impact of the use of long-term irrigation technology on agricultural sustainability, the changes in soil salinity after 20 years of different irrigation technologies were simulated. The simulation results show that topsoil salinity increased with the operation years of the irrigation technology (Figures 7d, 8d and 9d). In contrast, the increases in soil salinity decreased, with the surface salinity gradually levelling off. The salt content of the topsoil (5 cm) was mainly affected by fertilization. The salt content of the topsoil was more extensive during the fertility period, with a maximum EC value of 327 μs/cm (soil salt content 252 kg/ha, 0.034%) for MDI, 330 μs/cm (soil salt content 254.25 kg/ha, 0.035%) for SBDI, and 307 μs/cm (soil salt content 185.7 kg/ha, 0.025%) for SI. Under the continuous action of leaching by irrigation, rainfall, and crop absorption, the respective EC values decreased to 252.3 μs/cm (soil salt content 7.5 kg/ha, 0.001%), 250.7 μs/cm (soil salt content 2.4 kg/ha, 0.0003%), and 251.9 μs/cm (soil salt content 5.85 kg/ha, 0.0008%) at the end of the fertility period, which was below than the threshold value for salinization (EC = 480 μs/cm, soil salt content 0.1% [41]). We found that irrigation technologies such as surface, sprinkler, and drip irrigation significantly affect water infiltration and salt leaching in soil, which is in line with the findings of Behera et al. [42]. In summary, MDI, SBDI, and

SI did not significantly impact the soil and water environment of the fields in the study area. They did not lead to soil salinity accumulation. Thus, they are irrigation methods suitable for this area.

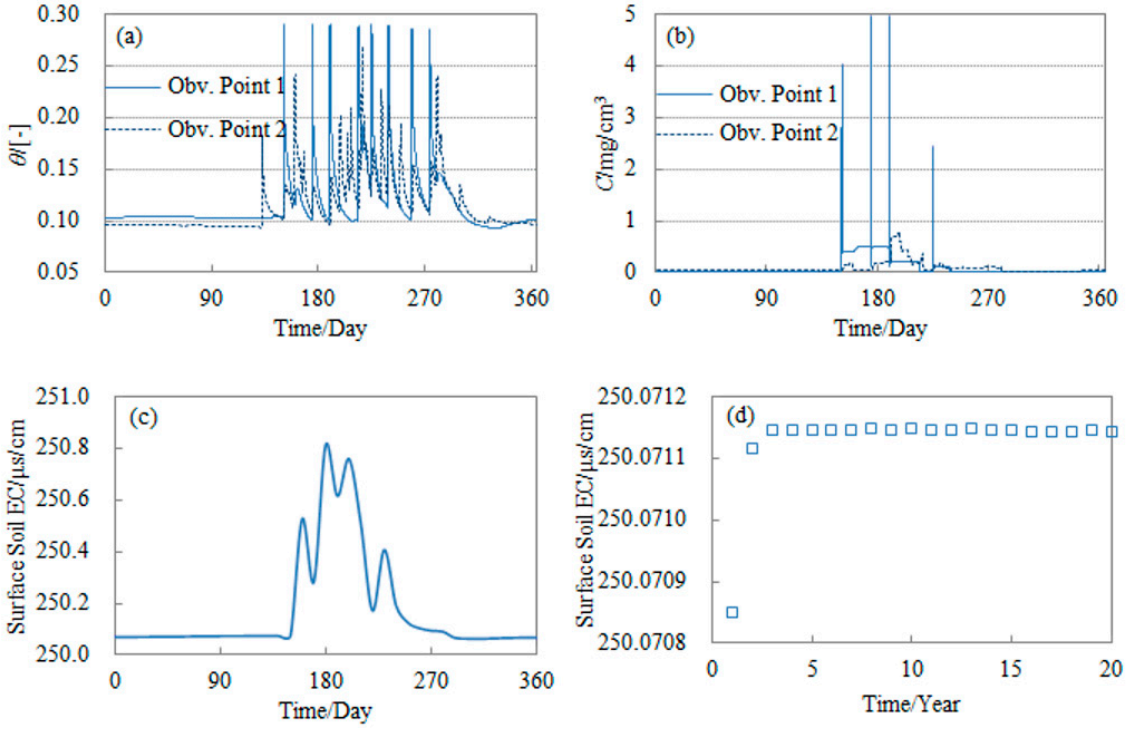

Figure 7. Annual and interannual changes in water and salt in mulched drip irrigation. (**a**) Water content at observation point; (**b**) concentration of soil solution at observation point; (**c**) annual variation in topsoil salinity; (**d**) interannual variation in topsoil salinity.

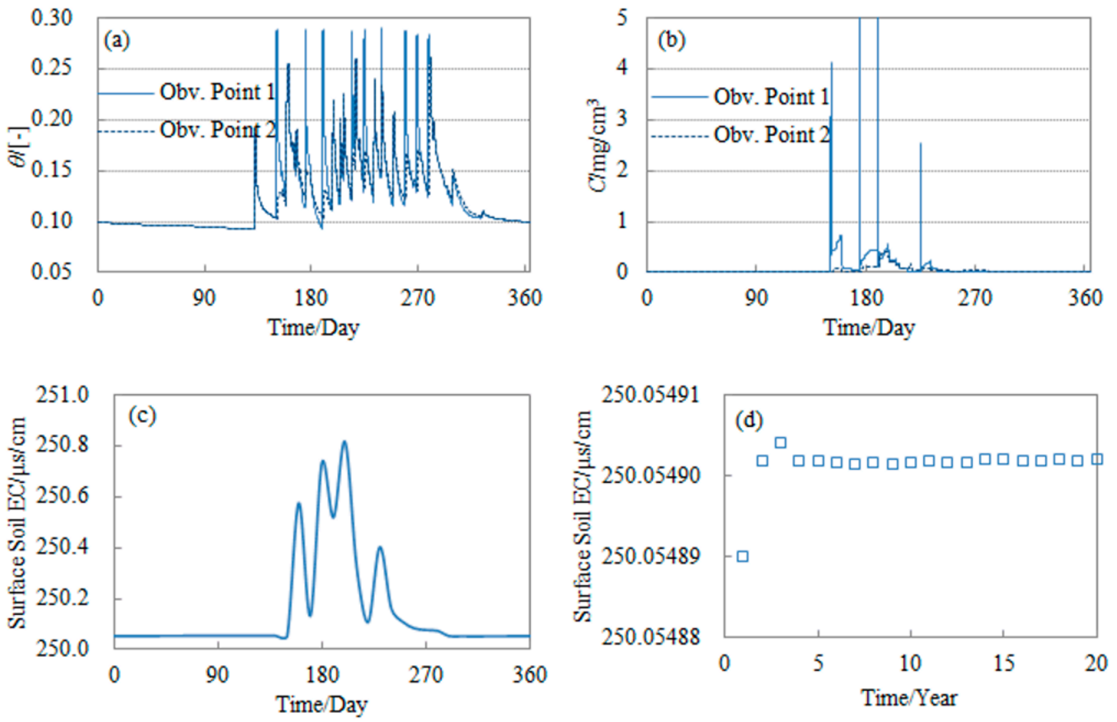

Figure 8. Annual and interannual changes in water and salt in shallow-buried drip irrigation. (**a**) Water content at observation point; (**b**) concentration of soil solution at observation point; (**c**) annual variation in topsoil salinity; (**d**): interannual variation in topsoil salinity.

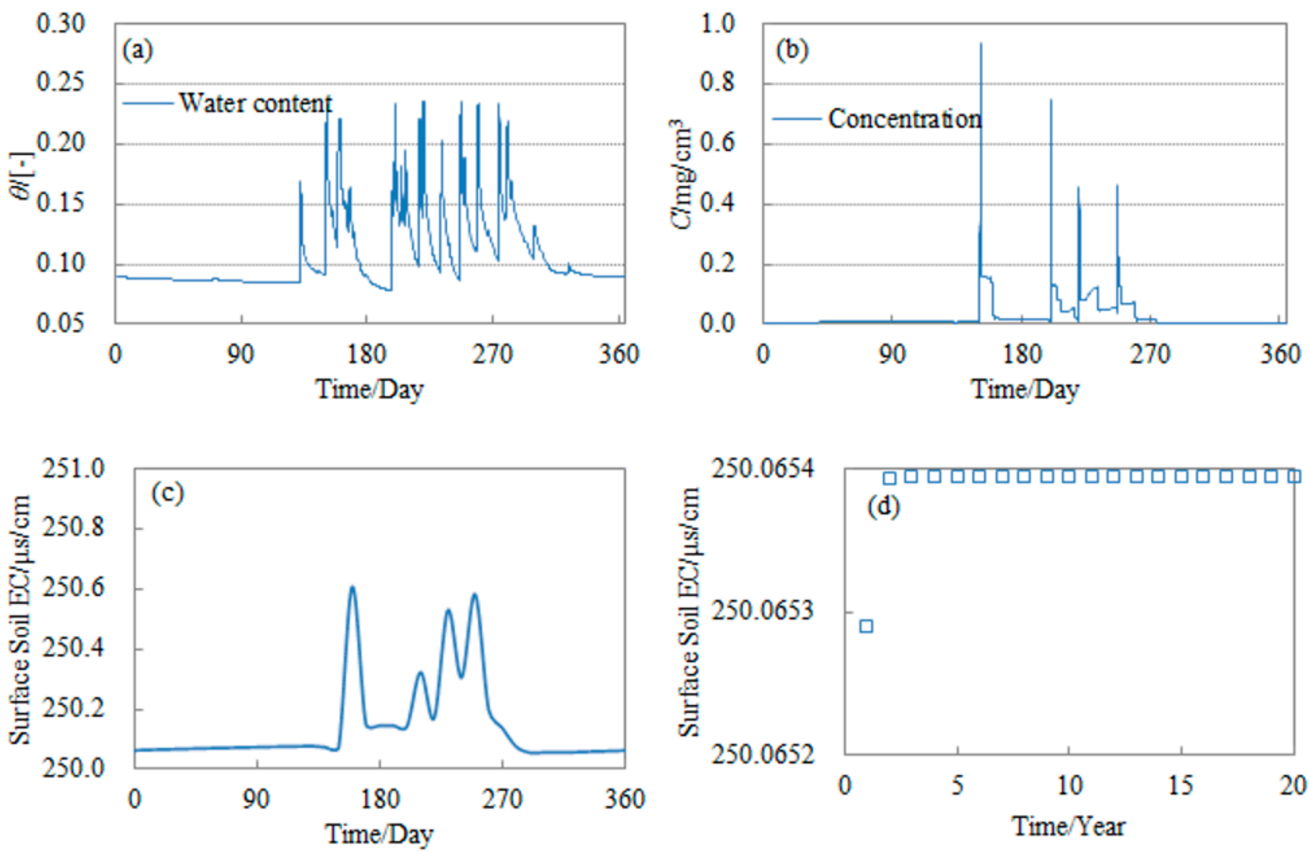

Figure 9. Annual and interannual changes in water and salt in sprinkler irrigation. (**a**) Water content at observation point; (**b**) concentration of soil solution at observation point; (**c**) annual variation in topsoil salinity; (**d**) interannual variation in topsoil salinity.

3.2. Results of Field Water and Soil Environment Simulations for Three Irrigation Techniques under Variable Rainfall Conditions

The results of the experiments and simulations in Figures 7–9 showed that the change patterns of soil solution concentration and salinity were influenced by irrigation and rainfall. To clarify the effect of meteorological changes on water and salt transport in soil, three different rainfall scenarios of P = 300 mm, P = 200 mm, and P = 100 mm were set. The effect of rainfall on the changes in salt content in the topsoil (5 cm) in the test area under MDI, SBDI, and SI was simulated for 20 years, and the simulation results are shown in Figure 10.

The simulation results showed that under all three irrigation technologies, the amount of salt accumulated in the topsoil (5 cm) tended to increase year by year as the amount of rainfall decreased. The salt content in the topsoil (5 cm) under MDI and SBDI when P = 100 mm was significantly higher than when P = 200 mm and when P = 300 mm. While the salt content in the topsoil under SI when P = 100 mm was also higher than that when P = 200 mm and when P = 300 mm, the difference was significantly smaller than that under MDI and SBDI. The maximum EC value was 275.8 µs/cm (soil salt content 84.61 kg/ha, 0.0113%) for the sub-membrane drip, 268.9 µs/cm (soil salt content 62.50 kg/ha, 0.0083%) for the shallowly buried drip, and 259.4 µs/cm (soil salt content 30.83 kg/ha, 0.0041%) for SI when the irrigation technique was applied for 20 years. They were all much lower than the salinity determination threshold of 480 µs/cm (soil salt content 0.1%). In a previous study on interannual changes in soil salinity, Zong et al. [29] found that long-term drip irrigation effectively reduced soil salinity through irrigation, a finding consistent with the results of Sun et al. [43]. The difference was that they conducted the analysis in different years.

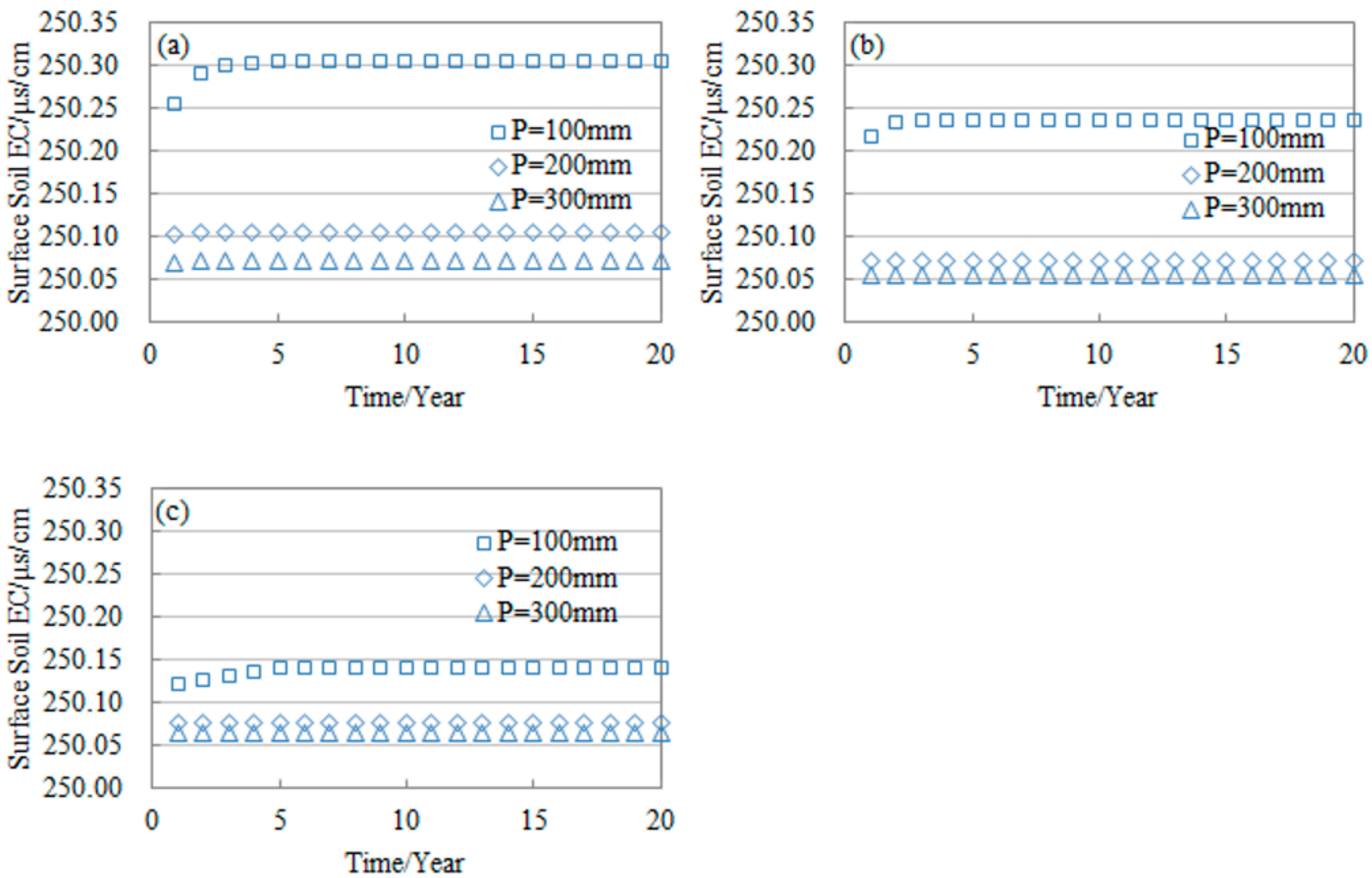

Figure 10. Annual variation in topsoil salinity under three irrigation methods and under different precipitation conditions. (**a**) Mulched drip irrigation; (**b**) shallow-buried drip irrigation; (**c**) sprinkler irrigation.

3.3. Simulation of the Soil and Water Environment in the Field for Three Irrigation Technologies at an Initial EC = 480 µs/cm (Soil Salt Content 0.1%)

Salt transport in the soil is influenced not only by irrigation technologies, irrigation volumes, and meteorological conditions, but also by soil conditions. To evaluate the effect of irrigation technology in saline soils, this study set the initial EC value as 480 µs/cm (soil salt content 0.1%). It simulated the water and salt distribution in soil with MDI, SBDI, and SI under real meteorological and field conditions in the test area. The simulation period was 20 years, and the results are shown in Figure 11.

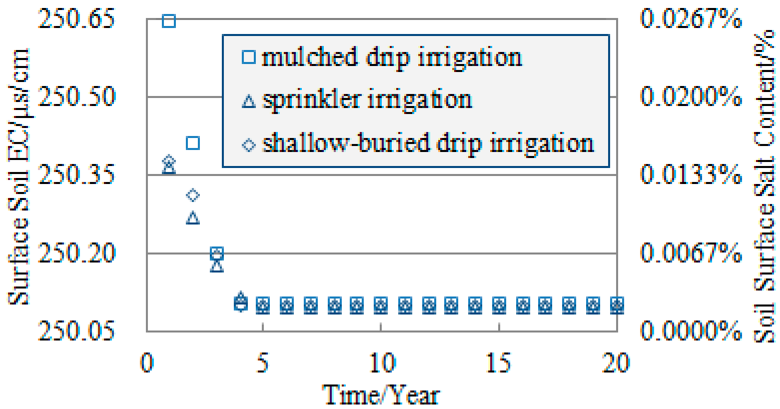

Figure 11. Annual variation in topsoil salinity under three irrigation methods with initial soil EC = 480 µs/cm (salt content of 0.1%).

The simulation results showed that under the leaching of the three irrigation technologies and of rainfall, the amount of accumulated salt in the topsoil (5 cm) presented a decreasing trend each year. It is worth noting that within two years of the operation of the irrigation technology, the salt content of the topsoil under MDI was significantly higher than that under SBDI and SI, i.e., by 44.76% and 46.60%, respectively. With the increase in the operation years of the irrigation technology, there was almost no difference in the salt content of the topsoil under the three irrigation technologies. By the fourth and fifth years, it had reached a relatively stable state. Kang et al. [44] used brackish water to drip-irrigate waxy maize under mulch film, finding that the salt content of the field soil layer increased in the early stage of the drip irrigation and that the soil salinity tended to stabilize in the later stage. These simulation results are in line with Kang's conclusion. The maximum EC value of the topsoil (5 cm) was 255.5 μs/cm (soil salt content 18.38 kg/ha, 0.0024%) under MDI, 255.3 μs/cm (soil salt content 17.34 kg/ha, 0.0023%) under SBDI, and 254.8 μs/cm (soil salt content 15.73 kg/ha, 0.0021%) under SI. All were well below the salinity threshold of 480 μs/cm (soil salt content 0.1%, Liu et al., 2001).

Given the current conditions of rainfall, soil, groundwater depth, and mineralization in the West Liaohe Plain, there is only a negligible risk of secondary salinization if irrigation is reasonable. It has been noted that soil salinity increases with drip irrigation if irrigation and drainage technologies are unsuitable or if irrigation water is highly mineralized [27,45]. Irrigation water mineralization affects soil water infiltration and salinity dynamics, and different mineralization levels increase the uncertainty of soil salinization [46–48]. However, the above conclusion was based on an arid area. Traditionally, secondary salinization is caused by flooding irrigation, that is, excessive irrigation water leading to a rise in the groundwater level, which in turn causes a loss of groundwater. Intense phreatic evaporation leads to salt moving upward and accumulating on the surface [49]. The rainfall in the experimental area was more significant than that in the arid region, and there was no need to leach the soil salt with a large amount of irrigation in the experimental area during the non-fertility period [29]. In addition, the salinity of the irrigation water source did not reach the level of brackish water.

4. Conclusions

To investigate the impact of drip irrigation on farmland soil and the water environment, this paper used field data from corn cultivation in the West Liaohe Plain and simulations with the HYDRUS-2D model. The water and salt change patterns of the farmland under mulch drip irrigation (MDI), shallowly buried drip irrigation (SBDI), and sprinkler irrigation (SI) with varying rainfall and initial salinity were simulated for 20 years. The following conclusions can be drawn:

(1) Different irrigation techniques significantly affected soil water infiltration and salt leaching, and the soil solution concentration was higher in the growth period and lower in the fallow period. Under MDI and SBDI conditions, soil water content and salinity were only affected by irrigation and closely related to rainfall. The long-term application of irrigation technology does not cause soil salinization.

(2) With decreasing rainfall, salt accumulation in the topsoil (5 cm) showed an increasing trend each year. After 20 years of applying the irrigation technology, the maximum EC value in the topsoil (5 cm) under MDI, SBDI, and SI was much lower than the salinity determination threshold of 480 μs/cm (soil salt content 0.1%).

(3) At an initial EC = 480 μs/cm, the topsoil salinity under MDI was significantly higher than that under SBDI and SI within two years of operation of the irrigation technology. As the operation years of the irrigation technologies increased, there was essentially no difference in the salt content in the topsoil with the three irrigation technologies. The salt content reached a relatively stable state and was well below the salinity threshold of 480 μs/cm. Given the current conditions of rainfall, soil, buried depth, and mineralization in the West Liaohe Plain, the risk of secondary salinization is minimal if irrigation is reasonable.

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