The effect of drip irrigation under mulch on groundwater infiltration and recharge in a semi-arid agricultural region in China

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ABSTRACT

The wide application of drip irrigation under mulch in semi-arid agricultural regions in China not only improves agricultural water efficiency, but also affects formation of groundwater and the mechanism of water infiltration to a certain extent. This paper takes the typical semi-arid agricultural region in China as the research object. The movement of soil water under the three types of underlying surface was simulated by the Hydrus-2D model for the quantitative analysis of groundwater recharge. The influence of drip irrigation under mulch on groundwater infiltration depth and cumulative infiltration amount under different level years was simulated. Taking a normal flow year as an example, the simulated results showed that the maximum infiltration depth of drip irrigation under mulch reached 250 cm, which was greater than that of border irrigation (138 cm) and bare area (158 cm). The cumulative infiltration amounts of drip irrigation under mulch at 80, 120, 140 and 200 cm were respectively 1,484.8 m^3/hm^2, 686.3 m^3/hm^2, 554.1 m^3/hm^2 and 238.1 m^3/hm^2, which were greater than that of border irrigation and bare land at the same depth. The results proved that drip irrigation under mulch could increase the infiltration depth and cumulative infiltration amount, which is beneficial to groundwater recharge in semi-arid agricultural regions of China.

Key words: accumulation infiltration amount, drip irrigation under mulch, groundwater recharge, Hydrus-2D, infiltration depth, semi-arid agricultural region in China

HIGHLIGHTS

- The cumulative infiltration and the maximum infiltration depth under different underlying surfaces were simulated.
- The effect of drip irrigation under mulch on groundwater recharge under membrane was annualized.
- The technology of drip irrigation under mulch was evaluated from the perspective of water resources.
- A reference is provided for choosing water-saving irrigation in similar areas.

INTRODUCTION

Arid and semi-arid areas, which account for more than 53 percent of China's total area, have low rainfall and high evaporation. Since the 21st century, with the development of agriculture, industry and economy in the region, the lack of surface water in the typical semi-arid region represented by the West Liaohe Plain can hardly meet normal production and living needs, and the rich groundwater resources have become an important source of water supply (Zhong *et al.* 2018). Long-term sustainable utilization of groundwater is the basis of economic development and agricultural production in such regions. Therefore, identifying the characteristics of groundwater recharge and groundwater security issues in these areas is critical to efficient water management and the security of groundwater-dependent ecosystems (Han *et al.* 2017; Smerdon 2017; Das & Pal 2020).

One of the characteristics of semi-arid areas' hydrological cycle is that rainfall is the main source of groundwater recharge. The core of groundwater scientific management is to ensure the sustainable recharge of groundwater by rainfall infiltration. However, the process is affected by many human and natural factors, especially increasing human activities, which make obvious changes to the infiltration recharge conditions and lead to the decrease of groundwater level. These changes complicate the groundwater recharge process (Wakode *et al.* 2018; Zhang *et al.* 2018a, 2018b, 2018c; Tonkul *et al.* 2019).

With the increasing demands for water in irrigation areas and the development of irrigation technology, under the background of 'water-saving and grain-increasing', the stanza water irrigation technique represented by drip irrigation under film has been widely promoted in the West Liaohe Plain (Wang *et al.* 2014). For the West Liaohe Plain, which is generally dominated by border irrigation, the extension of drip irrigation under mulch has changed the original underlying surface structure, which has an important impact on the process of rainfall and irrigation recharge groundwater. Compared with traditional irrigation in the Xiliaohe River basin, surface mulching affects the path of rainfall recharge groundwater (Jin *et al.* 2018; Chen *et al.* 2019). Drip irrigation under mulch makes the limited water cycle between soil and mulching, optimizes the coupling of root water, fertilizer, salt, light, heat, and gas and reduces evaporation between plants, changing the original hydrological cycle (Yuan *et al.* 2019). Depending on the precision irrigation setting, drip irrigation under mulch can save water by 30%–50%, and the water-use efficiency can reach 90%–95% (Zhang *et al.* 2017, 2018a, 2018b, 2018c). It can reduce deep seepage, that is, reduce the potential recharge amount of groundwater by irrigation regression, all of which has an impact on groundwater recharge and the local hydrological cycle.

The large-scale replacement of the underlying surface will affect processes such as field water composition, rainfall distribution, evapotranspiration and water infiltration, and then affect the groundwater infiltration and recharge process, which will have a fundamental impact on regional water resources management. Unfortunately, previous studies have paid little attention to this aspect.

In recent years, the methods to estimate groundwater recharge have mainly used direct measurement methods, water balance methods and numerical modelling methods. However, the first two methods are expensive and there is a lack of technical expertise in many areas, often requiring intense datasets and expensive investigation (Liu *et al.* 2010). Numerical modelling methods have been widely used because of their convenience and efficiency. Hydrus-2D is a software package for simulating the movement of water and can realize different underlying surface patterns using different boundary condition settings (Karandish & Šimůnek 2019; Shan *et al.* 2019). We simulated the movement of soil water under three types of underlying surface during the entire growth period of maize with the consideration of rainfall, irrigation, and evapotranspiration. The main objectives of this study were to (1) compare the difference of infiltration depth and accumulation infiltration amount between bare area, border irrigation and drip irrigation under mulch, and (2) investigate the influence of drip irrigation under mulch on groundwater recharge.

MATERIALS AND METHODS

Experimental site

The experimental area is located at the Jianping Irrigation Experimental Station, Chaoyang City, Liaoning Province, China (E119°18′, N41°47′), on the east bank of LaoHa River and has an elevation of 461 m. It is located in the transitional zone of oceanographic monsoon climate to continental climate, and belongs to the semi-arid monsoon continental climate. The average annual temperature in this region is 5–6 °C, the sunshine duration is 2,868–3,111 h, the rainfall is low but the evaporation is high, the average annual rainfall is 440 mm, and 70% of the rainfall is concentrated in June to August. The average annual evapotranspiration is 1,800–2,100 mm, and evaporation is largest in April–June, accounting for 45%–50% of the total annual evaporation.

Field irrigation methods in the experimental area are mainly border irrigation and drip irrigation under film under the background of water-saving irrigation. Rainfall rarely forms surface runoff in this region, and infiltration is intense. Rainfall is the main source of groundwater recharge. It has the characteristics of a vertical hydrological cycle and climate in a semi-arid region, which can represent the semi-arid area.

Since the 21st century, with the development of the economy, surface water can hardly meet the region's basic water demands, and the amount of groundwater exploitation continues to rise. In recent years, the level of groundwater has been declining year by year due to the overexploitation of groundwater and the lack of effective recharge (Xiao *et al.* 2016). The groundwater level in the pilot area has been reduced from 320 to 400 cm between 2019 and 2021.

Design and measurement

According to the actual planting situation of farmers in the agricultural irrigation area, maize was selected as the reference crop (Liaodan 1211). In the planting area of the experimental station, two irrigation methods were set, one was drip irrigation under mulch and the other was border irrigation. At the same time, the bare area (non-planted crops) was set as blank control, and there were three kinds of underlying surface forms. Due to the impermeability of drip irrigation and mulching under plastic film and the rain-catching effect of furrows, water will move sideways (Zhang *et al.* 2018a, 2018b, 2018c). To monitor the difference of soil water in different positions, in the drip irrigation under mulch, two monitoring sections were set up, namely,

the middle position of the plastic film (MPF) and the middle position of the furrow (MF). Separate monitoring sections, called MBI, MBA, were set up in the border irrigation and bare areas, respectively, as shown in Figure 1.

The physical properties of the soil in the experimental area were obtained by in-situ experiments, as shown in Table 1. Soil samples at different depths were sampled with a soil sampler. Soil samples were collected every 10 cm in the range 0–300 cm. Soil water content was measured by the drying method. Soil volume water content is the product of the soil mass moisture content and bulk density. The maize growth period generally begins in April and ends in October, so simulation began on April 29, 2019, and ended on October 22, 2019.

Establishment of soil water flow model

Hydrus used the modified Richards equation to describe the soil water movement model under drip irrigation under mulch, border irrigation and bare area:

$$\frac{\alpha\theta}{\alpha t} = \frac{\alpha}{\alpha x}\left[k(h) \times \frac{\alpha h}{\alpha x}\right] + \frac{\alpha}{\alpha z}\left[k(h) \times \frac{\alpha h}{\alpha z}\right] + \frac{\alpha k(h)}{\alpha z} - s(h) \tag{1}$$

where θ is the soil volume water content ($cm^3 \cdot cm^{-3}$), h is the pressure head (cm), $k(h)$ is the unsaturated hydraulic conductivity function ($cm \cdot day^{-1}$) and t is the time parameter (day); $s(h)$ is the root water uptake parameter.

The Van Genuchten–Mualem model was selected for the soil hydraulic properties model. Its expression form is:

$$k(\theta) = k_s \Theta_e^{\frac{1}{2}}\left[1 - \left(1 - \Theta_e^{\frac{1}{m}}\right)^m\right]^2 \tag{2}$$

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha|\psi_m|)^n}\right]^m \tag{3}$$

where θ_s is the saturated water content ($cm^3 \cdot cm^{-3}$), θ_r is the residual water content ($cm^3 \cdot cm^{-3}$), k_s is the saturated hydraulic conductivity ($cm \cdot day^{-1}$), α and n are the shape parameters, and I is the pore connectivity parameter.
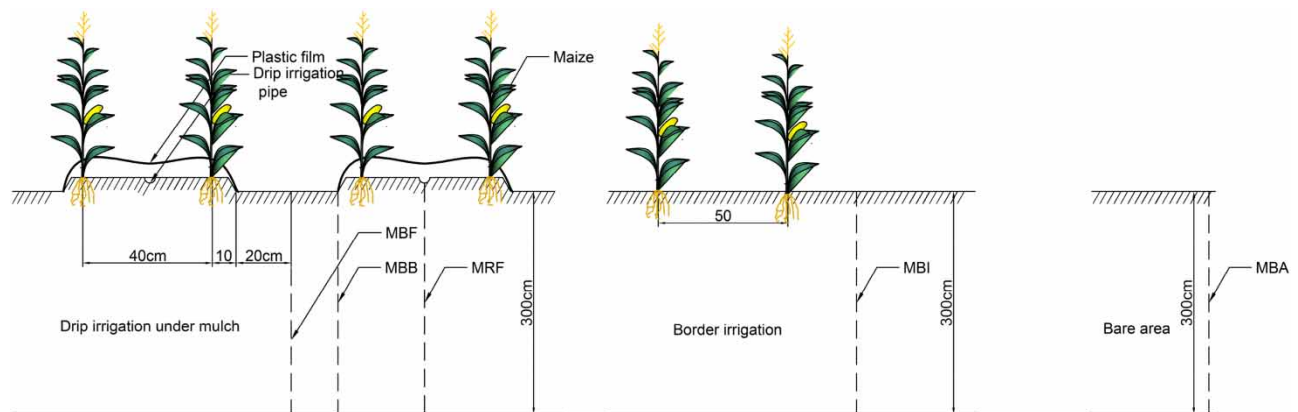

Figure 1 | Soil water content observation profile.

Table 1 | Physical properties of soil in experimental area

Soil depth/(cm)	Volume weight/(g·cm^{-3})	Field capacity/(cm^3·cm^{-3})	Saturated soil water content/(cm^3·cm^{-3})	Soil type
0–40	1.54	0.21	0.44	Loamy sand
40–70	1.65	0.35	0.44	Sandy loam
70–110	1.59	0.24	0.43	Sand
110–250	1.62	0.14	0.41	Sand
250–300	1.51	0.10	0.36	Sand

Crop root water uptake rate is the amount of water the crop takes up from the soil per unit volume per unit time. The Faddes model was selected to calculate crop water uptake:

$$S(x, z, t) = \alpha(h)S_P(x, z, t) = \alpha(h)b(x, z)L_t T_P \tag{4}$$

$$b(x, z) = \left(1 - \frac{z}{z_m}\right)\left(1 - \frac{x}{x_m}\right)e^{-\left(\frac{P_z}{z_m}|z^* - z| + \frac{P_x}{x_m}|x^* - x|\right)} \tag{5}$$

where $\alpha(h)$ is the soil water stress function (dimensionless); L_t is the length of the soil surface associated with transpiration (cm); T_P is the potential evapotranspiration (cm·day^{-1}); $b(x, z)$ is the normalized root water uptake distribution, where x_m and z_m are the maximum rooting lengths in the x- and z-directions (cm), respectively; x and z are the distances from the origin in the x- and z-directions (cm), respectively; and P_x, P_z, x^* (cm), and z^* (cm) are the empirical parameters.

Considering that there is a weather station near the experimental site, reliable meteorological data of the long time series can be obtained, and soil evaporation and crop transpiration can be calculated according to the double-crop coefficient method recommended in FAO29, which meets the application requirements of this paper. The Penman formula was used to calculate the potential evapotranspiration of reference crops (Allen *et al.* 2005):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T + 273}\mu_2(e_s - e_u)}{\Delta + \gamma(1 + 0.34\mu_2)} \tag{6}$$

where ET_0 is the reference evapotranspiration; R_n is the net radiation; G is the soil heat flux; γ is the psychrometric constant; T is the daily mean air temperature; μ_2 is the average wind speed at the height of 2 m; e_s is the saturation vapor pressure; e_a is the actual vapor pressure; and Δ is the slope of the saturation vapor pressure–temperature curve.

Generalization of the model boundary conditions

Assuming that the moist area on the vertical surface was symmetrical (Chen *et al.* 2014), the reference plants were set at the origin of the coordinates in drip irrigation under mulch, and the dropper was placed 20 cm to the right of the origin coordinate in drip irrigation under mulch. Due to the drip irrigation, a part of the top soil profile was set as a Variable Flux Boundary in drip irrigation under mulch. Due to the film mulching, the soil profile not in contact with the atmosphere was set as No Flux, and the soil wetting area during drip irrigation was calculated iteratively (Gärdenäs *et al.* 2005), and then the irrigation flux of drip irrigation under mulching was set. The soil profile in contact with the atmosphere was set as the Atmospheric Boundary. The lower boundary was adopted as a Free Drainage Boundary. Assuming no flow at the vertical boundary, a No Flux Boundary was adopted on both sides. The top soil of the border irrigation was set to Atmospheric Boundary, and the amount of irrigation water and rainfall were converted. Border irrigation and other boundary conditions of the bare area were set with reference to drip irrigation under mulch, as shown in Figure 2.

Criteria of model evaluation

The following three indexes were used to evaluate the simulation effect of the model, namely root mean square error, mean absolute error and correlation coefficient:

$$RMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - S_i)^2}}{\bar{M}} \tag{7}$$

$$MAE = \frac{\sum_{i=1}^{N}|M_i - S_i|}{N} \tag{8}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(S_i - \bar{S}_i)(M_i - \bar{M}_i)}{\sum_{i=1}^{n}(S_i - \bar{S}_i)\sum_{i=1}^{n}(M_i - \bar{M}_i)}\right]^2 \tag{9}$$
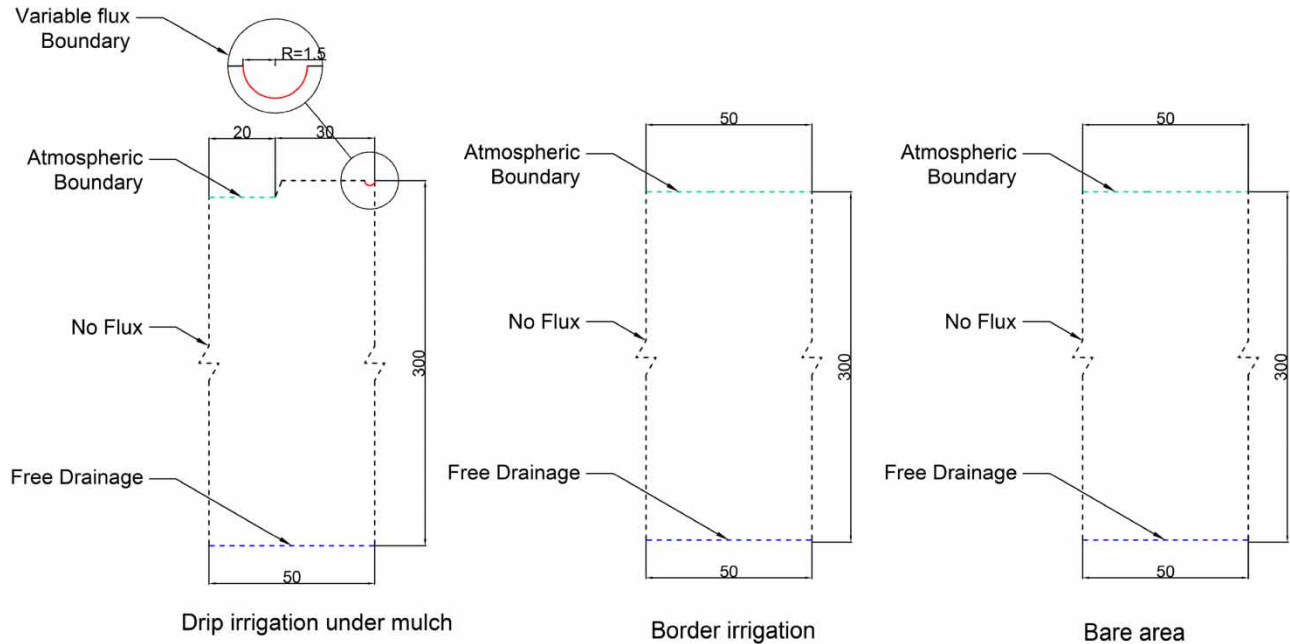
Figure 2 | Settings of boundary conditions.

where S_i is a simulated value; M_i is an observed value; N is the total number of observed values used in the calibration and validation processes; and $\bar{S}_i$ and $\bar{M}_i$ are the mean values of the simulated and observed data points, respectively.

RESULTS AND DISCUSSION

Soil hydraulic parameters and evaluation of model accuracy

Taking the results of the soil particle-size analysis experiment as a reference, the undisturbed soil in the test area was taken to obtain the soil water retention curves and saturated hydraulic conductivity (k_s) of the soil at different depths in the laboratory. The soil hydraulic parameters were optimized according to the measured and simulated data during the whole growth period of crops, and the optimized results are shown in Table 2. Due to the large number of soil observation points, the soil moisture change curves during the whole growth period with depths of 10, 40, 110 and 260 cm are selected for display, as shown in Figures 3–5. Among them, 10 cm represents the process of water changing the soil surface, 40 cm represents the water change process of shallow soil; 110 cm represents the water change process of middle soil, and 260 cm represents the water change process of deep soil; 40 and 110 cm also represent the water change process when soil properties change. The accuracy evaluation results of the model are shown in Table 3.

Considering the complexity of field experiments, there were many interference factors that might be encountered (such as spatial variability of soil, uneven distribution of rainfall irrigation water, and the influence of crop root distribution). It is believed that the model meets the accuracy standard and can better simulate the local soil water movement.

Table 2 | Soil hydraulic parameters

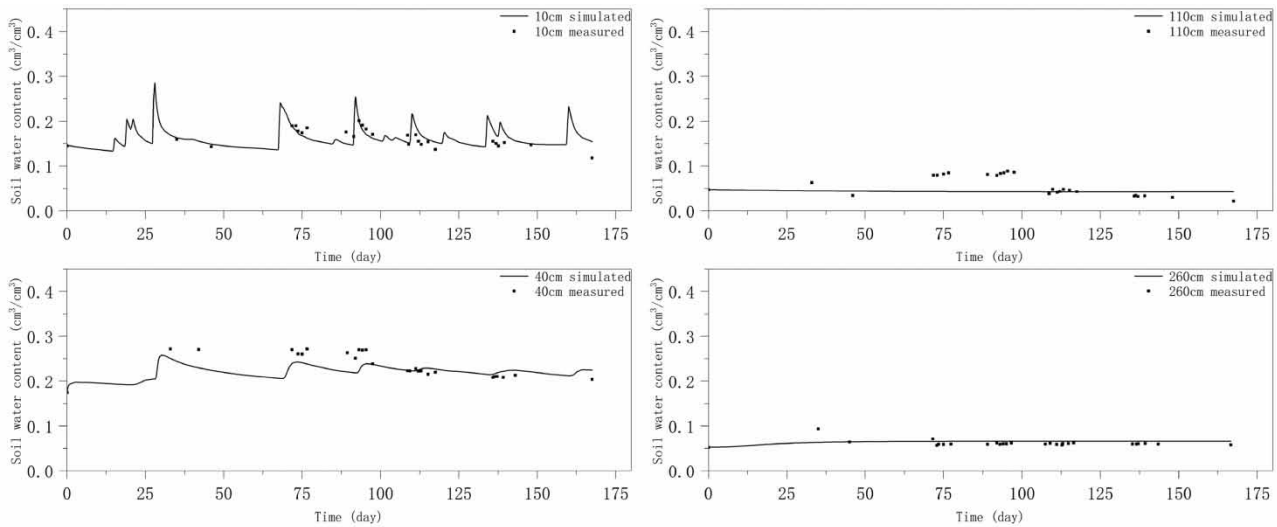| Soil depth/cm	θ_r/(cm³·cm⁻³)	θ_s/(cm³·cm⁻³)	α	N	K_s/(cm·day⁻¹)	I
0–40	0.065	0.44	0.114	1.53	348.00	0.5
40–70	0.057	0.44	0.106	1.38	41.10	0.5
70–110	0.025	0.43	0.124	1.27	435.07	0.5
110–250	0.026	0.41	0.129	1.70	450.00	0.5
250–300	0.027	0.36	0.145	2.00	500.00	0.5

Figure 3 | Comparison of measured and simulated soil moisture content in bare area.
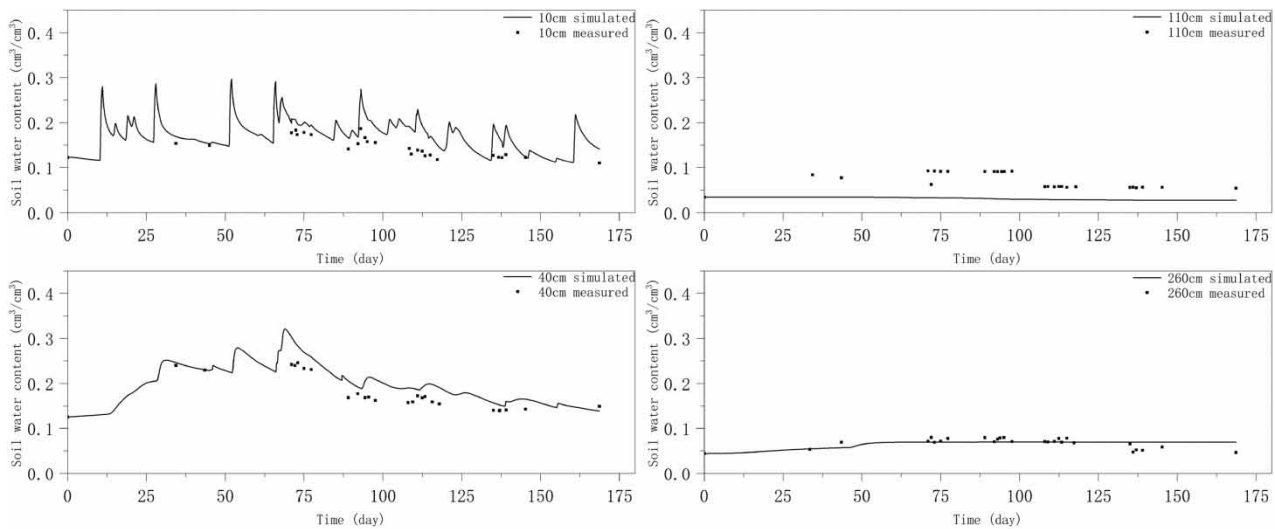

Figure 4 | Comparison of measured and simulated soil moisture content in border irrigation.

Selection of typical years and establishment of irrigation schedule

Selection of typical years

Based on the annual rainfall data of Jianping experimental station from 1970 to 2019, four level years (1978, 1979, 1997, 1992) were selected by the curve-fitting method, which were high-flow year (25%), normal-flow year (50%), low-flow year (75%), and dry year (90%). The annual cumulative rainfall was 510.6, 445.6, 386.7 and 332.6 mm, respectively. The irrigation system was made according to rainfall frequency in different typical years.

Calculation of irrigation schedule in typical years

Irrigation before sowing was set up according to the actual situation of the agricultural irrigation area. The irrigation quota was 600 m³/hm² for border irrigation and 300 m³/hm² for drip irrigation under mulch.

Irrigation quota was calculated according to the formula:
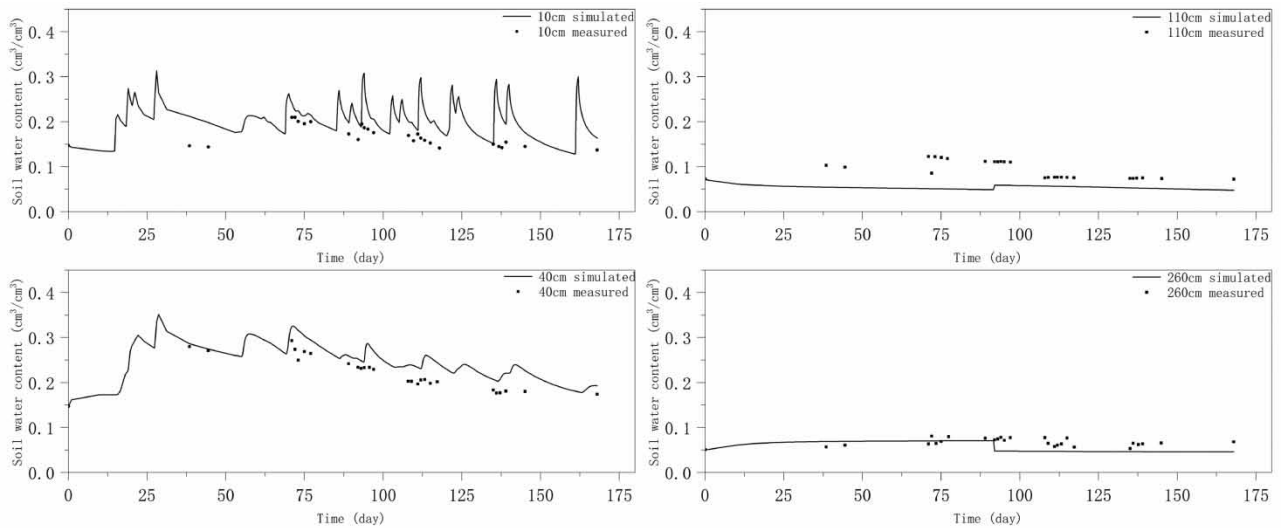
$$m = 0.1(\beta - \beta_0)Hpy \tag{10}$$

Figure 5 | Comparison of measured and simulated soil moisture content in drip irrigation under mulch.

Table 3 | The evaluation results of simulated and measured soil moisture values

Evaluation criterion	Bare area	Border irrigation	Drip irrigation under mulch
RMSE	0.06	0.06	0.07
MAE	0.02202	0.04003	0.13910
R^2	0.91	0.86	0.88

where m is the irrigation quota; β and β_0 are the field moisture capacity and the lower limit of allowable soil water content for crops, respectively, and the lower limit of soil moisture content is calculated as a percentage of field moisture capacity; y is the dry bulk density, and H is the depth of the planned wetting layer; p is the soil moisture ratio designed for micro-irrigation. The moisture ratio of drip irrigation under mulch is generally 60%–90%, and 60% is taken here. Parameters such as irrigation wetting layer and lower limit of soil moisture content are determined according to the actual situation of the local agricultural irrigation area, as shown in Table 4.

Hydrus-2D was used to calculate the average water content of the planned wetting layer at different time points. When it was less than the lower limit of soil allowable water content and could not receive effective rainfall in a short time, it was considered that irrigation was needed to determine the irrigation time point. Hydrus-2D was used to carry out iterative calculation and make irrigation plans for different typical years. The results are shown in Figure 6.

The maximum infiltration depth

Infiltration depth is an important index to reflect the state of infiltration and the potential of groundwater recharge. In this study, the measured water content at the early growth stage of crops was used as the initial water content to simulate

Table 4 | Irrigation quota parameters and irrigation quota of different growth periods

| Crop growth period	The depth of soil planned wetting layer/(cm)	The percentage of the lower limit of soil moisture content	Irrigation quota of border irrigation/(m³/hm²)	Irrigation quota of drip irrigation under film/(m³/hm²)
Early stage of crop growth	30	65%	220.05	132.00
Rapid growth stage of crop growth	50	75%	297.45	178.50
Middle and late stage of crop growth	80	80%	426.00	255.60
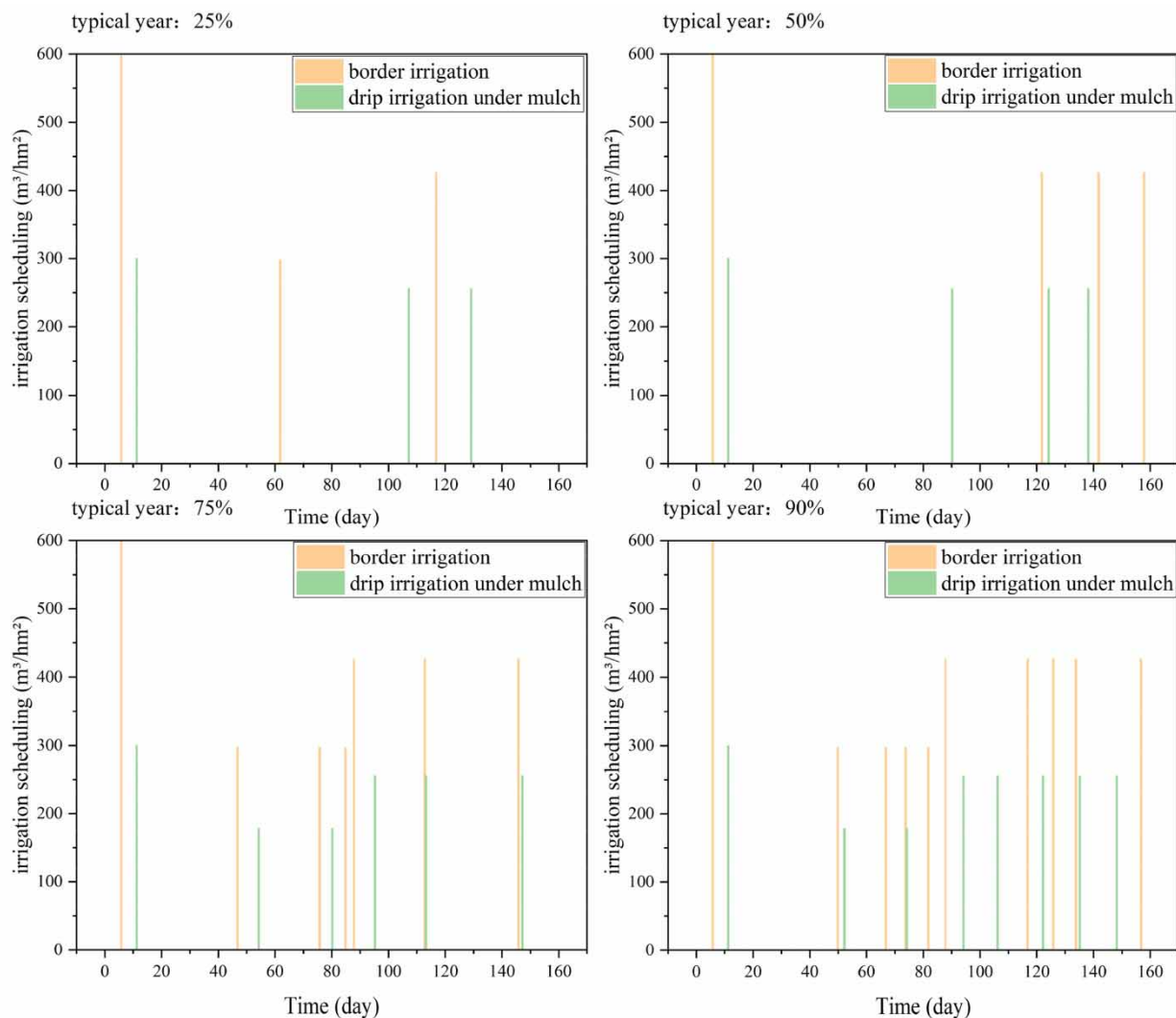
Figure 6 | Irrigation system under different typical years.

the maximum infiltration depth of crops in the whole growth period of selected typical years. The results are shown in Figure 7 below.

It can be seen from Figure 7 that the maximum infiltration depth of the bare area decreased with the decrease of rainfall in different typical years. Drip irrigation under mulch was less affected by rainfall in different typical years, and the average maximum infiltration depth was basically 270 cm, which was larger than the 158 cm of the bare area. According to the actual data in this area, many local rivers have been cut off. Rainfall is the main source of groundwater recharge, so the maximum infiltration depth of the bare area (natural state) would increase with the increase of rainfall in each typical year. Drip irrigation under mulch used less water for single irrigation, and the time arrangement between rainfall and irrigation was intensive. In the whole simulation period, the water content distribution of the soil planned wetting layer was uniform, and the maximum infiltration depth was less affected by typical annual rainfall and was larger than that of the bare area.

The maximum infiltration depth of border irrigation decreased from 180 to 80 cm, with an average of 138 cm, which was smaller than that of drip irrigation under mulch (270 cm). The difference between drip irrigation under mulch and border irrigation was mainly reflected in film mulching. Film mulching increased local temperature and reduced ineffective water loss. Because of the impermeability of film mulching, rainfall water had priority in confluence to furrows. Infiltration rainfall of drip irrigation under mulch in furrows was about twice that of border irrigation, which led to uneven distribution of rainfall in local areas and more water permeated from furrows. Because the hydrologic cycle in the experimental area was mainly vertical infiltration and the level of lateral infiltration was low, the infiltration depth of drip irrigation under mulch was greater
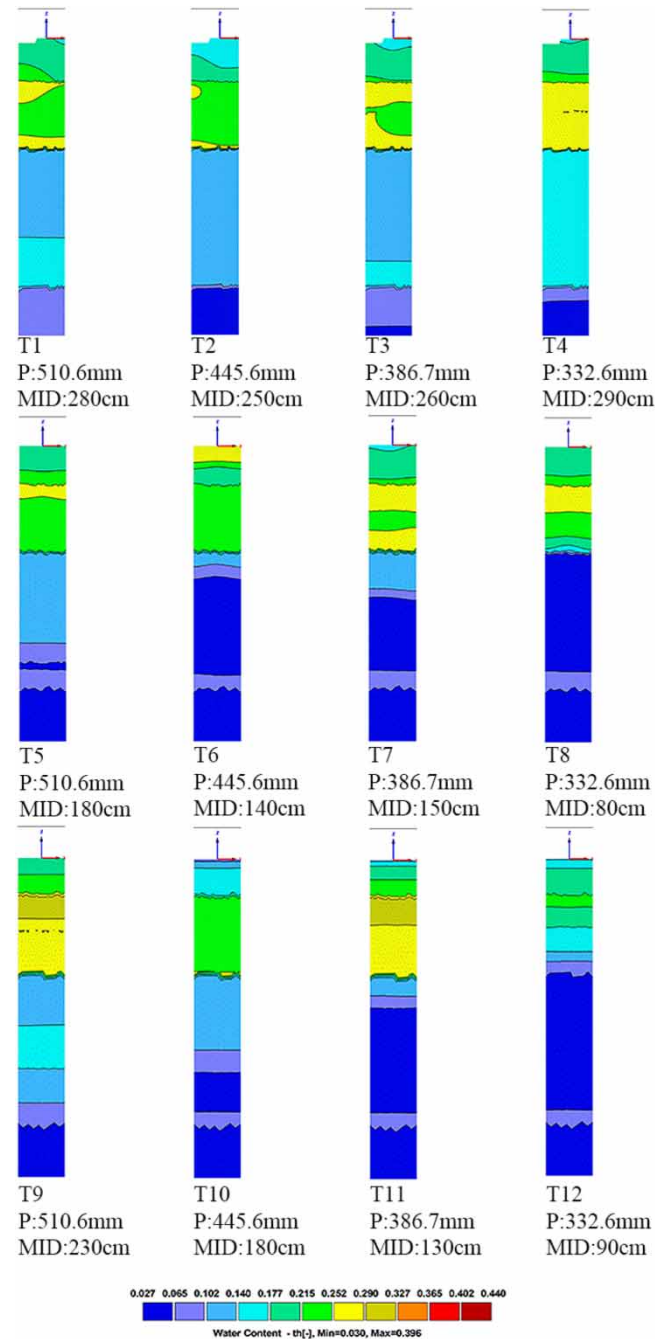
Figure 7 | Maximum irrigation depth for three underlying surface forms. (T1–T4 drip irrigation under mulch; T5–T8 border irrigation; T9–T12 bare area; MID means the maximum infiltration depth; P means precipitation.)

than that of border irrigation. The local soil had low clay content, good permeability and strong infiltration ability. The soil below 70 cm depth was mainly sandy soil. The special soil properties in the experimental area further increased the difference of infiltration depth. Considering the above factors, the infiltration depth of drip irrigation under mulch was greater than that of border irrigation in the same typical years.

Cumulative infiltration

Cumulative infiltration is an important index to reflect the state of infiltration and the potential of groundwater recharge. This study simulated and calculated the cumulative infiltration volume of three underlying surfaces in different typical years at 80,

120, 140 and 200 cm. Among these, sandy loam was dominant in the soil above 80 cm, in which clay and silt particles accounted for more than deep soil. In addition, the distribution depth of the main root layer and the planned wetting layer in the middle and late stage of crop growth was basically maintained at about 80 cm. Taking 80 cm as the boundary, the properties of the upper soil and the lower soil were quite different from the environment, so the cumulative infiltration at 80 cm was calculated. The soil at 120 and 140 cm was less affected by spatial variability and had a large infiltration coefficient. The depth at 120 and 140 cm was the depth at which the accumulated infiltration amount began to decay. The change of the accumulated infiltration amount at this depth can reflect the attenuation process of the accumulated infiltration amount. At 200 cm, border irrigation and bare area rarely form an infiltration process except under very special conditions (such as a high flow year), and can also reflect the attenuation process of drip irrigation under mulch. The simulation results are shown in Figure 8.

It can be seen from Figure 8 that the cumulative infiltration amount of bare area decreased with the decrease of rainfall in the typical year, while the cumulative infiltration of the same typical year decreased with the increase of depth. The cumulative infiltration amount of drip irrigation under mulch was greater than that of bare area. For example, in a normal flow year, the cumulative infiltration of drip irrigation under mulch at 80, 120, 140 and 200 cm was 1,484.8 m^3/hm^2, 686.3 m^3/hm^2, 554.1 m^3/hm^2 and 238.1 m^3/hm^2 respectively. The cumulative infiltration of bare area at different depths was 1,018.0 m^3/hm^2, 470.7 m^3/hm^2, 304.9 m^3/hm^2 and 9.8 m^3/hm^2, respectively. Since the rainfall in the experimental
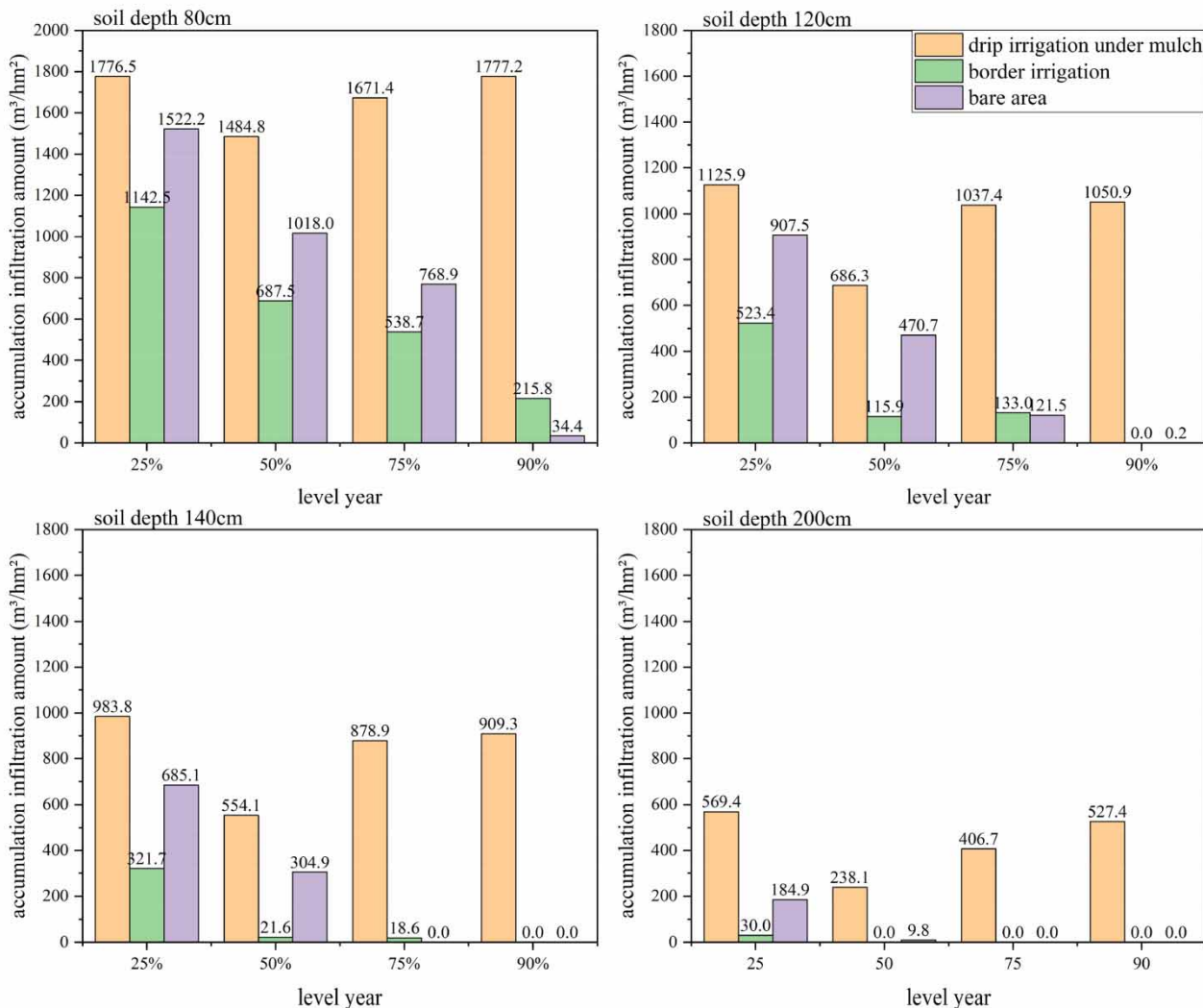

Figure 8 | Accumulated infiltration amount in the whole growth period of the three underlying surfaces at 80, 120, 140 and 200 cm.

area was mainly concentrated in June to August, the soil experienced winter and spring with few rainfalls after the last round of crop cultivation, so the surface soil was relatively dry, and the soil water content was lower than the field capacity. During the growth period, the infiltration process of water would first make the surface dry soil reach the soil field capacity, and then infiltrate into the deep soil. The maximum infiltration amount of drip irrigation under mulch was greater than that of bare area, indicating that drip irrigation under mulch caused more water to enter the deep soil, affecting the original hydrological cycle.

The cumulative infiltration amount of drip irrigation under mulch was the largest, and was less affected by the typical annual rainfall. By comparing the cumulative infiltration of drip irrigation under mulch with border irrigation, under the same typical years, the cumulative infiltration amount of drip irrigation under mulch at different depths was greater than that under border irrigation. For example, in the normal flow year, the cumulative infiltration of drip irrigation under mulch at 80, 120, 140 and 200 cm was 1,484.8 m^3/hm^2, 686.3 m^3/hm^2, 554.1 m^3/hm^2 and 238.1 m^3/hm^2 respectively. The cumulative infiltration of border irrigation at different depths was 687.5 m^3/hm^2, 115.9 m^3/hm^2, 21.6 m^3/hm^2 and 0.0 m^3/hm^2, respectively. The difference of cumulative infiltration between drip irrigation under mulch and border irrigation varied with typical years, and increased with the decrease of typical annual rainfall at the same depth. For example, at 80 cm, the difference from high-flow year to dry year was 634.0 m^3/hm^2, 797.3 m^3/hm^2, 1,132.7 m^3/hm^2, and 1,561.4 m^3/hm^2, respectively. The impermeability of drip irrigation under mulch greatly reduced soil moisture evaporation, which was about 60% less than that of border irrigation, according to field *in situ* observation experiment and Hydrus-2D simulations. At the same time, due to the rain-catching effect of ridging, more water was absorbed into the deep soil under the comprehensive effect of local soil.

With the increase of regional water pressure, drip irrigation under mulch, a water-saving measure, has been widely promoted. Compared with traditional irrigation, this new water-saving measure had a larger cumulative infiltration amount at the same depth, and a deeper infiltration depth. This showed that drip irrigation under mulch was conducive to groundwater infiltration and recharge, and had a mitigating effect on the continuous decline of local groundwater level.

CONCLUSION

In this paper, the Hydrus-2D model was used to simulate three types of underlying surfaces in four typical years, combining with field observation and the actual situation of the experimental area. The effect of drip irrigation under film on groundwater infiltration and recharge was analyzed. The results showed that the maximum infiltration depth of drip irrigation under mulch was basically maintained at 270 cm, which was larger than that of flat bare land (158 cm) and border irrigation (130 cm). The cumulative infiltration amount of drip irrigation under mulch with the same depth was significantly greater than that under border irrigation and bare area. For example, the cumulative infiltration of drip irrigation under mulch at 80, 120, 140 and 200 cm was 1,484.8 m^3/hm^2, 686.3 m^3/hm^2, 554.1 m^3/hm^2 and 238.1 m^3/hm^2 respectively. The cumulative infiltration of border irrigation at different depths was 687.5 m^3/hm^2, 115.9 m^3/hm^2, 21.6 m^3/hm^2 and 0.0 m^3/hm^2, respectively. The cumulative infiltration of bare area at different depths was 1,018.0 m^3/hm^2, 470.7 m^3/hm^2, 304.9 m^3/hm^2 and 9.8 m^3/hm^2, respectively.

The hydrological cycle in the experimental area has the characteristic of a vertical cycle. Due to the influence of drip irrigation under mulch on the underlying surface, the traditional hydrological cycle was affected, so that more water entered the deep soil. Under the comprehensive effect of local soil properties, drip irrigation under mulch is beneficial to groundwater recharge in a semi-arid agricultural region in China.

The maximum infiltration depth and cumulative infiltration amount of drip irrigation under mulch were greater than those of bare land and border irrigation, indicating that mulch drip irrigation could not only reduce irrigation water, but also be conducive to the recovery of local groundwater level. Drip irrigation under film could be continued to be promoted in semi-arid agricultural regions in China, which also provides a reference for other areas to choose water-saving irrigation.

DATA AVAILABILITY STATEMENT

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

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