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Optimization of irrigation technical parameters of brackish water film hole furrow irrigation based on SRFR and Hydrus-3D model

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ABSTRACT

Through the combination of experimental observation and numerical simulation, the surface water flow advance process, soil water, and salt distribution characteristics, and irrigation quality influencing factors of brackish water film hole furrow irrigation were studied, and the technical parameters of brackish water film hole furrow irrigation were optimized. The results show that SRFR model is used to simulate the water flow advance process and Hydrus-3D model is used to simulate the water-salt distribution of film hole furrow irrigation with high reliability, which will greatly help the well-designed of film hole furrow irrigation system. The water flow advance process under the condition of film hole furrow irrigation is in accordance with the power function law, and the flow rate and the aperture ratio have a great influence on the advancing speed of water flow. The brackish water film hole furrow irrigation reduces the evaporation of water, inhibits the salt surface accumulation, effectively regulates the soil water and salt distribution, and has obvious leaching effect on the salt of 0–40 cm soil layer; in order to restrain salt content, the irrigation amount under the condition of film hole furrow irrigation should not be less than 300 m^3/hm^2. Under the condition of a certain furrow length, the flow rate and the aperture ratio have a significant influence on the irrigation efficiency, the uniformity of irrigation, and the desalination rate. By sorting the influencing factors of irrigation quality of brackish water film hole furrow irrigation, the reasonable combination of irrigation technical parameters of brackish water film hole furrow irrigation in the test area is proposed, and the optimal combination of irrigation technical parameters of brackish water film hole furrow irrigation is obtained. The aperture ratio is 3%, the furrow length is 70 m, the flow rate is 5 L/s, and the irrigation time is 11.9 min.

Keywords: SRFR model; Hydrus-3D model; Brackish water; Film hole furrow irrigation; Irrigation technical parameters; Optimization

1. Introduction

China is short of freshwater resources, rational utilization of brackish water is one of the effective ways to alleviate the contradiction between water supply and demand. The research and extension of brackish water irrigation technology have become a new idea to guarantee the sustainable development of agriculture in the arid area and saline-alkali land [1–3].

Research indicates that mulching irrigation technology can reduce soil moisture evaporation, increase soil temperature, adjust soil salt movement effectively, and ensure the normal growth of crops [4,5]. Film hole furrow irrigation has been applied in China for more than 10 y, and practice has proved that the effect of saving water and increasing yield of this technology was remarkable. Therefore, brackish water film hole furrow irrigation is a combination of the new water resource and water-saving technology, and it is of great practical significance to study the related theories and technologies. Now, many scholars have done research on the problems of water and salt of

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multiple irrigation methods. It has increased people's understanding of water and salt migration problems caused by irrigation technology. However, the above studies mainly focus on drip irrigation, furrow irrigation, and other aspects, and a study on the problems of water and salt of film hole furrow irrigation is relatively rare [6–19].

In this paper, experimental observation and numerical simulation were used to systematically study the process of surface water flow, distribution characteristics of soil water and salt, and the influencing factors of irrigation quality under the condition of brackish water film hole furrow irrigation. The comprehensive evaluation index system of irrigation quality was established by combining irrigation efficiency, irrigation uniformity and desalination ratio, and the optimized combination of irrigation technical parameters for the experimental area was obtained. It is expected to provide a favorable theoretical basis and technical guidance for the development and application of local water-saving irrigation technology.

2. Materials and methods

2.1. Field experiment

2.1.1. Overview of research area

The research area is located in Laizhou City, Shandong province (37°28′ N, 120°18′ E), the elevation of the area is around 10 m, with an average annual precipitation of 580 mm and average annual evaporation of 1,943.7 mm. The annual average sunshine hours 2,664.8 h, annual average temperature of 12.9°C. The surface slope of this area is 0.03%, the groundwater level is 2–4 m, and the mineralization degree of groundwater is 1.4 g/L, which is brackish water. The soil is sandy loam and a typical coastal beach saline-alkali soil. The physical and chemical properties of the soil are shown in Table 1.

2.1.2. Experimental design

The irrigation ditch used in the experiment is a trapezoidal section, with the ditch depth of 20 cm, the upper mouth width of 30 cm, the lower mouth width of 20 cm, and the ditch length of 35–37 m, arranged along the slope of the ground. Along the irrigation ditch, a layer of film with holes is laid, and the irrigation water flows over the film, infiltrates into the soil through the hole (Fig. 1). The ridge between furrows is exposed, and the width of the ridge is 70 cm. Treatments of field experiments are shown in Table 2, with a total of seven treatments. The experiment was done in a random permutation, with each treatment repeated three times. To avoid water lateral infiltration interference, a wide ridge is used to separate different treatments. Insert a ruler every 5 m along the length of the furrow, record the time of water advance with a stopwatch, and measure the water level in the furrow with a tape measure. The crop is peanut, and 600 m^3/hm^2 of water is irrigated in the flowering period and podding period, respectively. The water flow rate is measured by the water meter, and irrigation water is local groundwater.

Table 1
Soil properties of experiment fields

Soil depth (cm)	Salinity (mass ratio) (g/kg)	pH	Dry bulk density (g/cm^3)
Surface layer	5.7	8.2	1.05
0–20	5.4	7.6	1.20
20–40	3.8	7.2	1.37
40–60	3.6	7.0	1.40

2.1.3. Test items and methods

2.1.3.1. Soil moisture content and salinity

Peanut roots mainly distributed in the plough layer about 30 cm below the surface. Soil samples of 0, 20, 40, and 60 cm were collected after irrigation for 24 h, soil moisture content and salinity were measured, respectively. The soil samples were collected on the ridge at 5, 15, and 25 m along the length of a furrow. Soil moisture content was determined by dry method; when determining soil salinity, the soil samples were air-dried and ground through a 2 mm screen, and the conductivity of 5 mL: 1 g water to soil ratio extract was measured, then the conductivity was converted to soil salt content by the empirical formula.

2.1.3.2. Evaluation index of irrigation water quality

At present, the commonly used evaluation indexes of surface irrigation water quality are irrigation efficiency and irrigation uniformity. As brackish water irrigation involves salt migration, in addition to the above two commonly used irrigation evaluation indicators, this paper considered the introduction of desalination rate to comprehensively evaluate the irrigation quality of brackish water film hole furrow irrigation.

The calculative Eq. (1) of irrigation efficiency is:

$$E_a = \frac{W_1}{W} \tag{1}$$

In above formula, E_a = irrigation efficiency, dimensionless; W_1 = water amount stored in planned moisture layer in

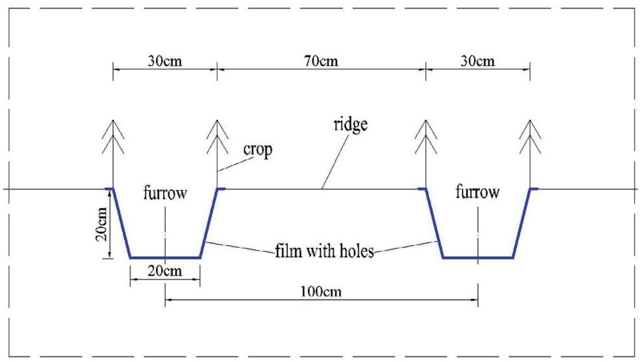

Fig. 1. Profile sketch of film hole furrow irrigation.

Table 2
Treatments of field experiment

Treatment number	Flow rate, Q (L/s)	Aperture ratio, ρ (%)
1	1.1	3
2	1.1	6
3	3.3	9
4	1.7	3
5	1.7	6
6	3.3	3
7	3.3	6

the soil after irrigation, m^3 or mm; W = total field irrigation water amount, m^3 or mm.

The calculative Eqs. (2) and (3) of irrigation uniformity is:

$$E_d = 1 - \frac{\Delta I}{\bar{I}} = 1 - \frac{\frac{1}{n}\sum_{j=1}^{n}\left|I_j - \bar{I}\right|}{\bar{I}} \quad (2)$$

$$\bar{I} = \frac{1}{n}\sum_{j=1}^{n} I_j \quad (3)$$

In above formula, E_d = irrigation uniformity, dimensionless; n = the number of the cross-section of infiltration depth measured along the length of a furrow; I_j = average infiltration depth at the jth cross-section, mm; $I(-)$ = average infiltration depth of the cross-sections along the length of a furrow, mm; ΔI = average deviation of the infiltration depth of the cross-sections along the length of a furrow, mm.

The calculative Eq. (4) of desalination rate is:

$$E_s = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{S_a - S_b}{S_a}\right)_i \quad (4)$$

In above formula, E_s = desalination rate, dimensionless; n = the number of cross-section of soil salinity measured along the length of a furrow; S_a, S_b = soil salinity in each layer before and after irrigation, g/kg.

2.2. Laboratory experiment

2.2.1. Experimental device and soil

According to the test requirement, we developed a device for film hole furrow irrigation. It was composed of soil box, film infiltration plate with holes, water chamber cover, Mariotte bottle, etc., as shown in Fig. 2.

The soil box was made of plexiglass with a thickness of 12 mm and the designed. The designed furrow distance was 60 cm, and the inner size of the soil box was (length) 24 cm × (width) 30 cm × (height) 60 cm. The cross-section of the designed furrow is trapezoidal, with an upper mouth width of 40 cm, a bottom width of 20 cm, a furrow depth of 20 cm, and a ridge width of 20 cm. Considering the symmetry

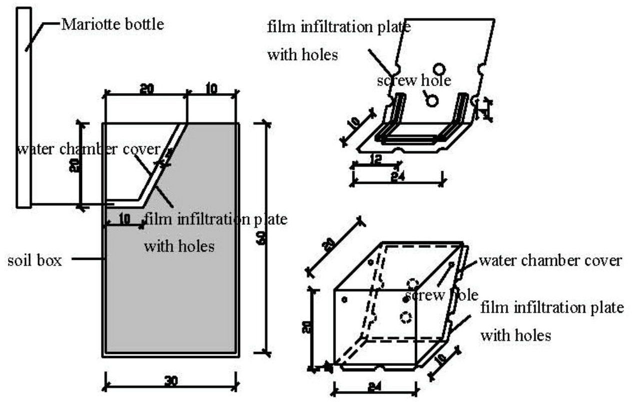

Fig. 2. Schematic of film hole furrow irrigation experimental device (unit: cm).

of the cross-section of the furrow, only half a section of furrow was used for the infiltration test [20–22].

The test soil was collected from the above experiment fields, and the physical and chemical properties of the soil are shown in Table 1.

2.2.2. Experimental design

The water supply device was a Mariotte bottle with a cross-sectional area of 64.4 cm^2. The water depth in furrow was controlled at 12 cm, and the observation sensitivity of per unit furrow length infiltration water was 0.2 cm^2. The salinity of irrigation water was controlled at about 1.4 g/L, which was closed to the actual salinity of irrigation water in the experiment fields. Different sizes of film infiltration plate with holes were selected according to different treatments, as shown in Table 3.

2.2.3. Test items and methods

The soil moisture, water potential, temperature, and salt monitoring system was used to observe the water and salinity during the irrigation process. Before irrigating, pre-embed FP/mts-field probe for moisture/temperature/salinity in furrow ridge (every 20 cm layer), using TDR/MUX/mpts with integrated data logger to collect test data.

2.3. Mathematical model

2.3.1. SRFR model

The SRFR model is a software developed by the US Department of Agriculture's Irrigation Research Center to simulate the hydraulic characteristics of the ground irrigation system, to perform irrigation system assessment, design, and operational management analysis based on the numerical solution of the zero inertia model [23–26]. The input parameters of the SRFR model are divided into three categories: (1) system geometric parameters: strip (furrow) length, strip width (furrow distance), and field topographical conditions; (2) soil parameters: surface water flow movement model, soil infiltration parameters, and field roughness coefficient; (3) management parameters:

Table 3
Treatments of laboratory experiment

Treatment number	Aperture ratio (%)	Irrigation amount (m^3)
1	3	0.00645
2	6	0.00645
3	9	0.00645

water price, designed moistening soil depth, irrigation water requirement, flow rate, and water supply time.

2.3.2. Hydrus-3D model

The Hydrus-3D model is a finite element computer model developed by Simunek et al. (2006) to simulate soil water movement, solute transport, heat transfer, and root water absorption in two and three dimensions [27,28]. The model water flow state is three-dimensional saturated-unsaturated Darcy flow, ignoring the influence of air on soil water movement. The water movement equation adopts the modified Richards equation, and the convection dispersion scheme is adopted for solute and thermal movement, a source term is embedded in the equation considering the root water absorption of the crop [29–35].

The numerical calculation model of film hole furrow irrigation infiltration was established (as shown in Fig. 3). The cross-section of the irrigation furrow is a symmetric trapezoidal section homogeneous soil. Considering the symmetry, only the left part of the plane CDKJ was studied. In the figure, plane ABCJIH is the cross-section of the irrigation furrow, plane OAHG is the furrow top, plane DKFE is the lower boundary of the soil; plane OEFG and plane CDKJ are symmetrical planes, and the horizontal flux is zero; plane OABCDE; and plane GHIJKF are zero flux.

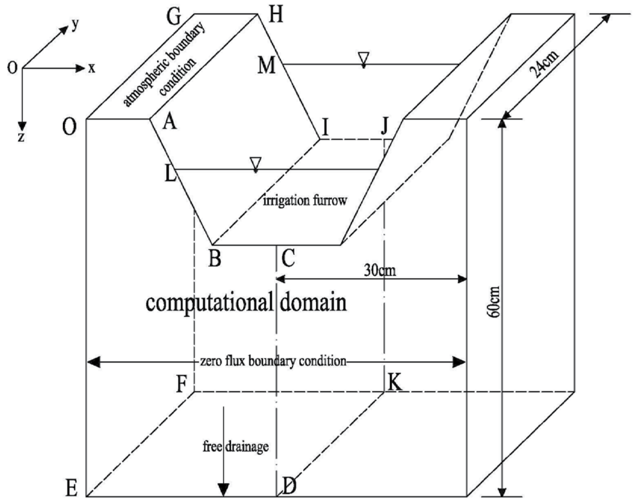

Fig. 3. Infiltration simulation model of film hole furrow irrigation.

Table 4
Fitting parameters and water flow advance speed

Treatment number	a	b	Correlation coefficient, R	Water flow advance speed (m/s)
1	3.15	1.80	0.979	0.070
2	2.55	1.87	0.993	0.033
3	5.58	1.18	0.999	0.089
4	0.73	2.02	0.990	0.104
5	18.73	0.86	0.998	0.081
6	4.82	0.98	0.999	0.225
7	5.02	1.04	0.999	0.172

3. Model simulation

3.1. Simulation and verification of water flow movement by SRFR model

3.1.1. Surface water flow advance process

The surface water flow advance process of film hole furrow irrigation is closely related to soil water and salt transport and irrigation quality. It is found by fitting that the water flow advance process under the condition of film hole furrow irrigation is in accordance with the power function law. The fitting Eq. (5) is:

$$t = ax^b \tag{5}$$

In above formula, t = water advance time, s; x = water advance distance, m; a, b = fitting parameters.

Table 4 shows the fitting parameters and water flow advance speed. It can be seen from the data in table that when the aperture ratio is the same, the water flow advance speed gradually increases with the increase of the flow rate into a furrow. This is because of the cross-sectional area of the cross-water increases as the flow rate into furrow increases. As the instantaneous water depth becomes larger, the force along the length of the groove increases, and the water flow advance speed increases. When the flow rate into furrow is the same, the water flow advance speed gradually decreases with the increase of the aperture ratio. This is because as the aperture ratio increases, the infiltration area increases, and the infiltration water volume also increases correspondingly, which slows down the water flow advance speed.

A representative time observation point was selected in each process, and the simulated and measured values of the SRFR model of the water advance time were compared and analyzed (Table 5).

According to the error analysis in Table 5, the relative error between the simulated and measured values of water flow advance distance is small, and there is no significant difference between the simulated and measured values of the advance time, and the simulation effect is better.

3.1.2. Irrigation efficiency and irrigation uniformity

The comparative analysis results of measured values and simulated values of film hole furrow irrigation efficiency and irrigation uniformity is shown in Table 6.

Table 5
Comparison of measured and simulated values of water flow advance time

Treatment number	Water advance distance (m)	Measured water advance time (min)	Simulated water advance time (min)	Relative error (%)
1	5	0.58	0.57	–2.3%
1	15	2.53	2.38	–6.1%
1	25	4.63	5.20	12.2%
1	35	10.93	10.70	–2.1%
1	37	13.35	13.20	–1.1%
2	5	0.46	0.45	–2.2%
2	15	2.75	2.13	–22.6%
2	25	6.32	4.80	–24.1%
2	35	10.94	10.10	–7.6%
2	37	11.97	12.10	1.1%
3	5	0.65	0.47	–27.7%
3	15	2.18	2.04	–6.6%
3	25	3.90	4.01	2.8%
3	35	6.45	6.45	0.0%
3	37	7.15	7.00	–2.1%
4	5	0.68	0.80	17.6%
4	15	3.90	3.41	–12.6%
4	25	6.87	6.88	0.2%
4	35	12.08	11.50	–4.8%
5	5	0.34	0.50	46.6%
5	15	1.98	2.20	10.9%
5	25	4.50	4.50	0.0%
5	35	7.72	7.57	–1.9%
6	5	0.42	0.25	–40.0%
6	15	0.97	0.99	2.4%
6	25	1.92	1.91	–0.3%
6	35	2.83	2.97	4.8%
7	5	0.45	0.30	–33.3%
7	15	1.40	1.19	–15.0%
7	25	2.27	2.27	0.1%
7	35	3.52	3.57	1.5%
Mean absolute error is 10.3%				

It can be seen from Table 6 that the absolute value of the error of irrigation efficiency is 6.0%, and the absolute value of the uniformity of irrigation uniformity is 13.9%. Combined with the actual situation of field engineering, it can be considered that the error is within a reasonable range. Therefore, the irrigation quality evaluation indicators obtained by SRFR model simulation can be considered reliable.

3.2. Simulation and verification of water and salt distribution of Hydrus-3D model

3.2.1. Infiltration wetting front

The simulated infiltration durations were the wetting fronts at 15, 60, and 150 min, respectively, and the simulated infiltration wet film values at the three aperture ratios were compared with the measured values (Fig. 4).

It can be seen from Fig. 4 that the simulation results of the shape of the wetting body at each moment are in good agreement with the measured results, and the simulated values of the wetting front are in good agreement with the measured values. Compared the three kinds of aperture ratio, the simulation results with the aperture ratio of 3% agree well with the measured results, the aperture ratio 6% followed, and the aperture ratio 9% are relatively the lowest. This is because, on the one hand, the soil water movement control equation adopted in this paper ignores the influence of temperature and soil gas on water movement, the influence of temperature and solute on soil water potential, and some soil physical parameters are not easy to measure, can only be obtained by inverse solution parameter, which leads to errors in the calculation results. On the other hand, water leakage is easy to occur during the test, and the larger the aperture ratio, the harder it is to control, thus affecting the test results.

Table 6
Comparison of measured values and simulated values of irrigation efficiency and irrigation uniformity

Treatment number	Irrigation efficiency		Relative error (%)
	Measured value	Simulated value	
1	0.91	0.89	–2.0%
2	0.93	0.90	–3.4%
3	0.91	0.90	–1.2%
4	0.96	0.85	–11.6%
5	0.94	0.74	–20.9%
6	0.88	0.86	–1.9%
7	0.87	0.86	–0.9%
Mean absolute error is 6.0%			

Treatment number	Irrigation uniformity		Relative error (%)
	Measured value	Simulated value	
1	0.82	0.84	2.9%
2	0.86	0.92	6.6%
3	0.82	0.94	14.5%
4	0.92	0.90	–2.4%
5	0.87	0.95	9.1%
6	0.75	0.98	30.0%
7	0.74	0.97	31.8%
Mean absolute error is 13.9%			

Therefore, the accuracy of the film hole infiltration test process should be improved as much as possible to avoid water leakage, and the wetting front development process can be well simulated by the Hydrus-3D model.

3.2.2. Vertical distribution of soil water and salt

The simulated values of water and salt at aperture ratios of 3%, 6%, and 9% were compared with the measured values (Fig. 5).

It can be seen from Fig. 5 that under the condition of the same irrigation amount, after the irrigation (observed immediately after stopping the irrigation), the peak of soil moisture content appears in the soil layer of 20–40 cm and the water peak decreases with the increase of the aperture ratio. The salt content in the 20–40 cm soil layer showed a significant decrease trend, indicating that the salt migrated to the deep soil with the irrigation water.

There is a certain error between the simulated value of soil moisture content and salt content and the measured value. The first cause of the error is the error caused by the difficulty in measuring the unsaturated soil water movement parameters, and the second is due to the insufficient control accuracy of the test deviation. The mean absolute value of the error between the simulated and measured values of soil moisture content is 11.4%. The mean absolute value of the error between the simulated and measured values of soil salinity is 8.1%. There is good consistency between the simulated and measured values. Therefore, the model simulation

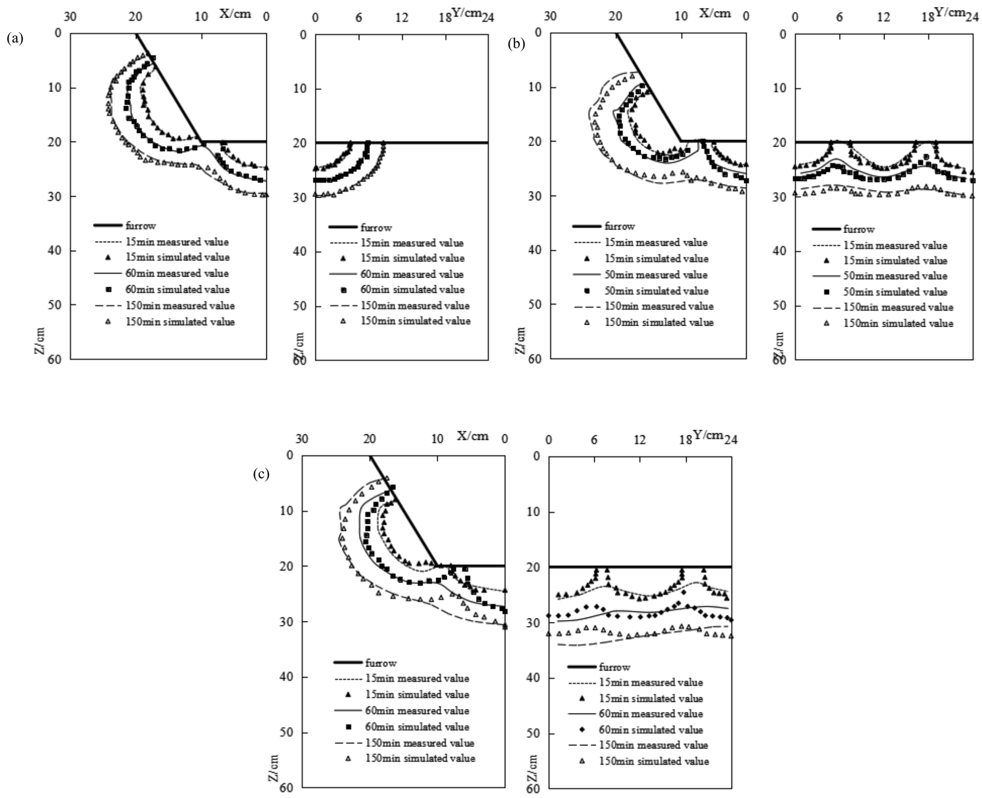

Fig. 4. Comparison of simulated wetting front with measured value at different moments. Aperture ratio (a) 3%, (b) 6%, and (c) 9%.

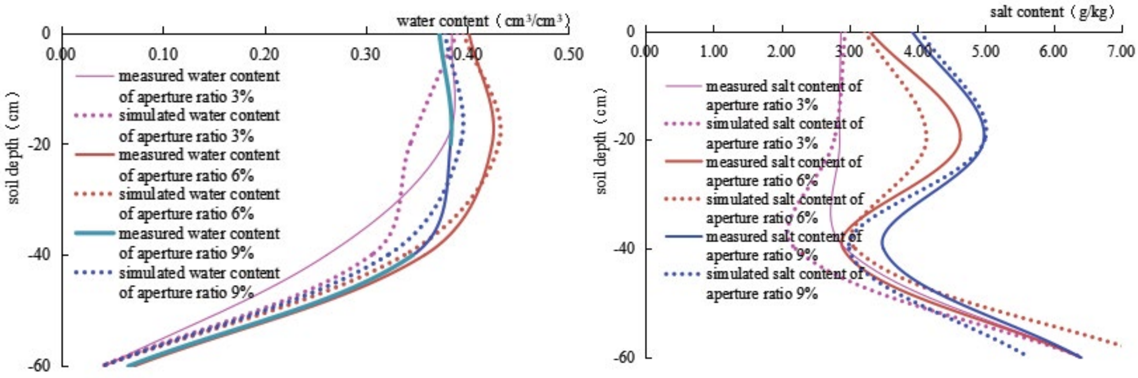

Fig. 5. Comparison of simulated and measured soil water contents and salt contents under film hole furrow irrigation with brackish water.

results can better reflect the distribution of water and salt after irrigation.

4. Model application

4.1. Simulation scheme

The combination of the Hydrus-3D model and the SRFR model was used to obtain the comprehensive evaluation index of irrigation quality and analyze it to determine the optimal irrigation technology combination of film hole furrow irrigation. The irrigation efficiency and irrigation uniformity were obtained by the SRFR model simulation method, and the desalination rate was obtained by the Hydrus-3D model simulation method.

4.1.1. SRFR model simulation scheme

The slope of the designed furrow bottom is the actual ground slope in the field test area (0.03%). The aperture ratio is designed to be three levels of 3%, 6%, and 9%. The flow rate is controlled at 1.0–5.0 L/s. The spacing of the irrigation furrow is 1 m; the trapezoidal section, the bottom of the furrow is 20 cm wide, the ditch depth is 20 cm, and the upper mouth width is 30 cm; the design ditch length is 5, 40, 50, 60, and 70 m (Table 7).

4.1.2. Hydrus-3D model simulation scheme

4.1.2.1. Irrigation amount simulation scheme

The aperture ratios were 3%, 6%, and 9%, respectively. The initial water content and salt content were the same as the initial soil moisture content of the indoor test, 0.012 cm^3/cm^3, and the initial soil salt content of the measured soil was 6.402 g/kg. The irrigation amount was set to five levels of 300, 450, 600, 750, and 900 m^3/hm^2 according to the irrigation practice experience (Table 8).

4.1.2.2. Desalination rate under different irrigation technology elements

The desalination rates under the combination of various irrigation technical parameters in Table 8 were simulated.

4.2. Analysis of simulation results

4.2.1. Irrigation efficiency and irrigation uniformity

The SRFR model was used to simulate the quality of film hole furrow irrigation in different experimental areas, and the irrigation efficiency and irrigation uniformity under different irrigation technology parameters were obtained (Table 9). Using SPSS statistical software, statistical analysis was carried out on the simulated data to determine the relationship between irrigation efficiency E_a and irrigation uniformity E_d and furrow length and flow rate under different aperture ratios (Table 10).

According to the relational expressions in the above table, the relationship diagram of irrigation efficiency E_a, irrigation uniformity E_d, and flow rate under different aperture ratios (3%, 6%, and 9%), different furrow lengths (30–70 m) are drawn. A partial result is shown by taking the furrow length of 30 m as an example (Fig. 6).

Table 7
Simulation irrigation technical parameters level of film hole furrow irrigation

Technical parameters level	Slope of furrow (%)	Aperture ratio (%)	Flow rate (L/s)	Furrow length (m)
1	0.03	3	1.0	30
2	/	6	2.0	40
3	/	9	3.0	50
4	/	/	4.0	60
5	/	/	5.0	70

Table 8
Simulation scheme with different amount of irrigation water

Aperture ratio (%)	Initial moisture content (cm^3/cm^3)	Initial salt content (g/kg)	Irrigation amount (m^3/hm^2)
			300
			450
3	0.012	6.402	600
			750
			900
			300
			450
6	0.012	6.402	600
			750
			900
			300
			450
9	0.012	6.402	600
			750
			900

Table 9
Simulation results of irrigation efficiency and uniformity of film hole furrow irrigation

Aperture ratio (%)	Furrow length (m)	Flow rate (L/s)	Irrigation time (min)	Irrigation efficiency (%)	Irrigation uniformity (%)
	30	1.0–4.0	11.5–3.4	87–90	73–96
	40	1.5–4.5	11.4–4.6	85–92	77–95
3	50	1.5–4.5	18.2–6.2	86–92	69–93
	60	2.0–5.0	16.8–7.4	85–91	74–93
	70	2.0–5.0	24.3–9.1	84–91	67–91
	30	1.0–4.0	9.13–2.32	83–92	69–95
	40	1.5–4.5	8.59–3.16	85–91	74–93
6	50	1.5–4.5	15.00–4.28	83–91	65–92
	60	2.0–5.0	13.00–5.12	84–91	70–92
	70	2.0–5.0	21.00–6.37	83–91	64–90
	30	1.0–3.5	18.80–5.04	84–91	66–92
	40	1.5–3.5	17.50–7.55	84–90	71–89
9	50	1.5–3.5	33.30–10.50	83–90	63–86
	60	2.0–3.5	27.50–13.80	85–88	67–83
	70	2.5–3.5	26.70–17.77	84–87	70–80

It can be seen from Fig. 6 that when furrow length is constant, the irrigation efficiency and irrigation uniformity increase first and then decreases with the increase of the flow rate. The lower limit is that the flow rate is small enough that the flow water just advancing to the end of the furrow, and the upper limit is that the flow rate is large enough that it just does not overflow the furrow. After SRFR simulation analysis for several times, the upper and lower limit theoretical values of flow rate were preliminarily determined (Table 11).

4.2.2. Desalination rate

4.2.2.1. Desalination rate under different irrigation amounts

Since the root system of peanut is mainly distributed around 30 cm, the irrigation efficiency and soil desalination rate in the 0–40 cm layer are used as evaluation indexes (Table 12). The higher the irrigation efficiency of 0–40 cm layer and the higher the soil desalination rate, the better the irrigation effect is. Through statistical analysis of soil desalination rate of 0–40 cm layer under different simulation

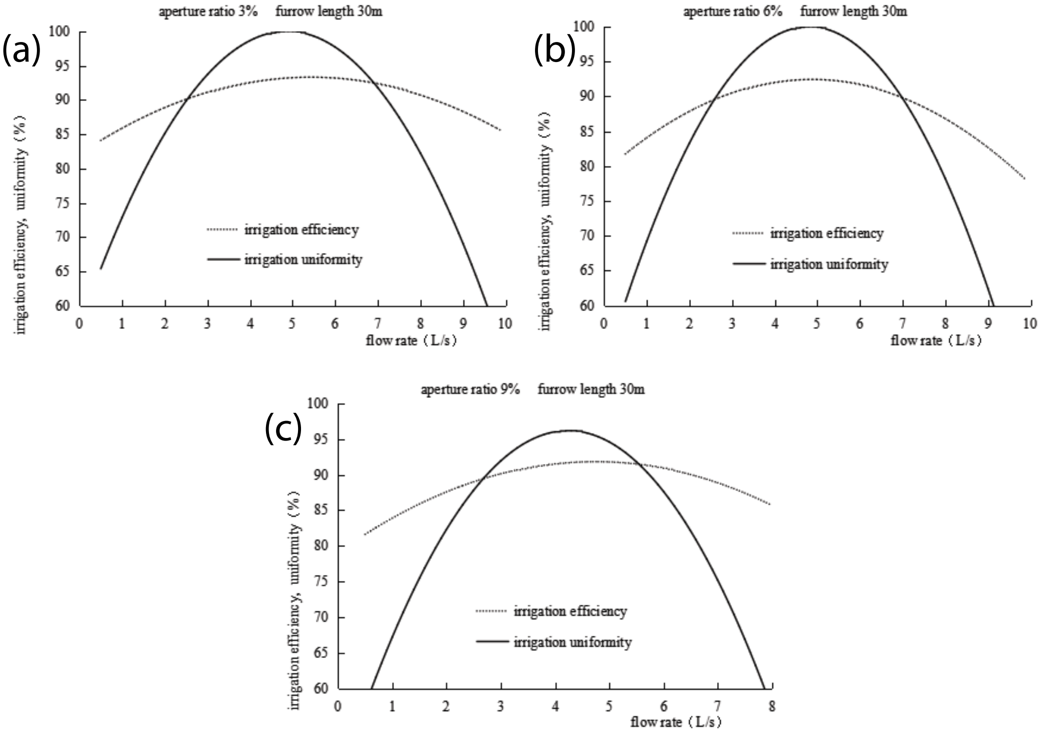

Fig. 6. Fitting relationship between irrigation efficiency, uniformity and flow rate under different aperture ratios.

Table 10
Relationship between water efficiency and uniformity of film hole furrow irrigation and furrow length, flow rate

Aperture ratio	Relation		Mean absolute value of relative error of measured value and simulated value
3%	E_a	$y = -0.270z_1 + 0.002z_1^2 + 4.155z_2 - 0.385z_2^2 + 88.414$	1.5%
	E_d	$\hat{y} = -0.547z_1 + 0.003z_1^2 + 17.677z_2 - 1.815z_2^2 + 71.062$	2.0%
6%	E_a	$y = -0.035z_1 + 0.0005z_1^2 + 5.476z_2 - 0.565z_2^2 + 80.643$	1.1%
	E_d	$\hat{y} = -0.488z_1 + 0.002z_1^2 + 20.447z_2 - 2.129z_2^2 + 63.732$	1.9%
9%	E_a	$y = -0.049z_1 + 0.0006z_1^2 + 5.395z_2 - 0.571z_2^2 + 81.079$	0.7%
	E_d	$\hat{y} = -0.634z_1 + 0.002z_1^2 + 23.384z_2 - 2.756z_2^2 + 63.790$	1.4%

y, irrigation efficiency, %; $\hat{y}$, irrigation uniformity, %; z_1, furrow length, m; z_2, flow rate, L/s.

schemes, it is found that with the same aperture ratio the irrigation effect decreases as the irrigation amount increases from 300 to 900 m^3/hm^2. This is because the soil desalination rate increases with the increase of irrigation water amount, but the corresponding increase of deep seepage decreases the irrigation efficiency, which leads to the decrease of irrigation effect.

Referring to the current research on the salt resistance of peanut, 3 g/kg is used as the measurement standard of soil salinity after irrigation. According to the data in Table 12, when the irrigation water amount is 300 m^3/hm^2, the soil salt content in the 0–40 cm layer is higher than the salt resistance of peanut, and the effect of restraining salt content is not obvious. When the irrigation amount is within 450–900 m^3/hm^2, the soil salinity in the 0–40 cm layer in each simulation scheme is lower than the salt resistance of peanut. The root system of peanut is mainly distributed around 30 cm below the surface. Irrigation water leaching soil salt into deeper soil layer, the desalination rates under 3%, 6%, and 9% aperture ratio are all above 46%, which has the effect of restraining salt content in the 0–40 cm layer in a short period of time, which provides a good environment for the

Table 11
The upper and lower limit theoretical values of flow rate under different furrow lengths

Furrow length (m)	Aperture ratio 3%		Aperture ratio 6%		Aperture ratio 9%	
	Flow rate lower limit (L/s)	Flow rate upper limit (L/s)	Flow rate lower limit (L/s)	Flow rate upper limit (L/s)	Flow rate lower limit (L/s)	Flow rate upper limit (L/s)
30	0.76	4.50	0.80	5.10	0.86	5.78
40	1.01	5.63	1.07	6.36	1.15	7.18
50	1.26	6.70	1.33	7.66	1.46	8.76
60	1.52	7.69	1.60	8.66	1.79	9.75
70	1.77	8.60	1.87	9.36	2.14	10.19

Table 12
Simulation results evaluation index

Aperture ratio (%)	Irrigation amount (m^3/hm^2)	Irrigation efficiency of 0–40 cm (%)	Desalination rate of 0–40 cm soil layer (%)
	300	85.89	45.28
	450	81.38	55.81
3	600	70.93	58.64
	750	47.84	57.48
	900	49.65	67.04
	300	90.30	45.37
	450	88.38	49.38
6	600	86.50	49.80
	750	70.28	49.97
	900	60.40	51.58
	300	89.73	44.29
	450	88.85	46.78
9	600	87.98	50.17
	750	72.97	52.41
	900	61.92	55.11

Table 13
Simulation results of desalination rate of film hole furrow irrigation

Aperture ratio (%)	Furrow length (m)	Flow rate (L/s)	Irrigation time (min)	Desalination rate of 0–40 cm soil layer (%)
	30	1.0–4.0	11.5–3.4	10.63–32.30
	40	1.5–4.5	11.4–4.6	25.81–44.45
3	50	1.5–4.5	18.2–6.2	38.26–51.52
	60	2.0–5.0	16.8–7.4	48.42–61.07
	70	2.0–5.0	24.3–9.1	56.72–73.02
	30	1.0–4.0	9.13–2.32	41.27–42.85
	40	1.5–4.5	8.59–3.16	42.69–44.08
6	50	1.5–4.5	15.00–4.28	43.87–46.10
	60	2.0–5.0	13.00–5.12	44.86–45.79
	70	2.0–5.0	21.00–6.37	45.70–48.15
	30	1.0–3.5	18.80–5.04	41.37–45.29
	40	1.5–3.5	17.50–7.55	44.64–46.26
9	50	1.5–3.5	33.30–10.50	47.48–54.57
	60	2.0–3.5	27.50–13.80	49.77–52.66
	70	2.5–3.5	26.70–17.77	52.00–53.51

Table 14
Multi-factor analysis of variance of irrigation quality of brackish water film hole furrow irrigation

Furrow length	Evaluation index of irrigation water quality	Influence factor	Sum of squares	Mean square error	Statistic value	Critical value
30 m	Irrigation efficiency	Flow rate	0.38	0.19	0.06	3.89
		Aperture ratio	71.33	11.89	3.66	3.00
		Error	38.95	3.25		
	Irrigation uniformity	Flow rate	93.43	46.71	6.53	3.89
		Aperture ratio	1,412.95	235.49	32.90	3.00
		Error	85.90	7.16		
	Desalination rate	Flow rate	2,248.20	1,124.10	62.38	3.89
		Aperture ratio	155.33	25.89	1.44	3.00
		Error	216.25	18.02		
40 m	Irrigation efficiency	Flow rate	2.95	1.48	0.96	3.89
		Aperture ratio	75.62	12.60	8.23	3.00
		Error	18.38	1.53		
	Irrigation uniformity	Flow rate	38.00	19.00	14.25	3.89
		Aperture ratio	944.57	157.43	118.07	3.00
		Error	16.00	1.33		
	Desalination rate	Flow rate	530.75	265.38	16.70	3.89
		Aperture ratio	118.59	19.77	1.24	3.00
		Error	190.65	15.89		
50 m	Irrigation efficiency	Flow rate	5.81	2.90	0.57	3.89
		Aperture ratio	130.48	21.75	4.24	3.00
		Error	61.52	5.13		
	Irrigation uniformity	Flow rate	56.00	28.00	15.27	3.89
		Aperture ratio	1,632.57	272.10	148.42	3.00
		Error	22.00	1.83		
	Desalination rate	Flow rate	84.42	42.21	4.92	3.89
		Aperture ratio	115.11	19.18	2.24	3.00
		Error	102.89	8.57		
60 m	Irrigation efficiency	Flow rate	2.38	1.19	1.23	3.89
		Aperture ratio	67.81	11.30	11.67	3.00
		Error	11.62	0.97		
	Irrigation uniformity	Flow rate	64.67	32.33	30.63	3.89
		Aperture ratio	1,029.62	171.60	162.57	3.00
		Error	12.67	1.06		
	Desalination rate	Flow rate	259.39	129.69	20.70	3.89
		Aperture ratio	62.00	10.33	1.65	3.00
		Error	75.17	6.26		
70 m	Irrigation efficiency	Flow rate	14.00	7.00	3.50	3.89
		Aperture ratio	128.57	21.43	10.71	3.00
		Error	24.00	2.00		
	Irrigation uniformity	Flow rate	196.29	98.14	8.23	3.89
		Aperture ratio	2,032.95	338.83	28.42	3.00
		Error	143.05	11.92		
	Desalination rate	Flow rate	968.81	484.41	50.48	3.89
		Aperture ratio	83.54	13.92	1.45	3.00
		Error	115.15	9.60		

growth of peanuts. Therefore, in order to restrain salt content, the irrigation amount under the condition of film hole furrow irrigation should not be less than 300 m^3/hm^2.

4.2.2.2. Desalination rate under different combination of irrigation technical parameters

The desalination rate under the combination of each irrigation technical parameter in Table 7 was simulated using the Hydrus-3D model (Table 13).

4.3. Optimization of irrigation technical parameters

4.3.1. Analysis of variance of factors affecting irrigation quality

The field irrigation technical parameters affecting the quality of film hole furrow irrigation mainly include the slope of furrow bottom, the aperture ratio, the flow rate, and the specifications of irrigation furrow. The slope of the furrow bottom has been determined to be 0.03% according to the actual conditions of the field test area. The effect of irrigation technical parameters on irrigation quality is mainly reflected in the difference between aperture ratio and flow rate under the condition of certain specifications and length of irrigation furrow (Table 14).

It can be seen from Table 14 that under the condition of a certain furrow length, the flow rate, and the aperture ratio have a significant influence on irrigation efficiency, irrigation uniformity, and the desalination rate. Among them, the aperture ratio has a significant effect on irrigation efficiency; both the influence of aperture ratio and flow rate on irrigation uniformity are significant, and the influence of the two on irrigation uniformity was ranked as the aperture ratio > the flow rate; the effect of the flow rate on the desalination rate is significant.

4.3.2. Optimization results of irrigation technical parameters

The irrigation quality evaluation introduces the index of desalination rate, comprehensively evaluates the irrigation quality of brackish water film hole furrow irrigation from two aspects of water and salt. And seeks the optimal combination of irrigation technical parameters on the basis of determining the reasonable combination range of furrow length and flow rate.

- Reasonable combination of irrigation technical parameters of brackish water film hole furrow irrigation

Based on the preliminary determination of the upper and lower limits of the flow rate under different furrow lengths, the relationship diagram of the irrigation efficiency E_a, the irrigation uniformity E_d and the flow rate under different aperture ratios (3%, 6%, and 9%) and different furrow lengths (30–70 m) are drawn according to the relational expressions in Table 10. Take the upper and lower limits of flow rate in Table 11 as the limit, the reasonable combination of furrow length and flow rate under different aperture ratios was determined according to the principle of irrigation efficiency $E_a \geq 85\%$, irrigation uniformity $E_d \geq 85\%$, and the sum of them is the largest (Table 15).

- Optimal combination of irrigation technical parameters of brackish water film hole furrow irrigation

By sorting the influencing factors of irrigation quality of brackish water film hole furrow irrigation, the optimal combination of irrigation technical parameters of brackish water film hole furrow irrigation is obtained by considering the influence of furrow length, flow rate, and aperture ratio on irrigation quality. The aperture ratio is 3%, the furrow length is 70 m, the flow rate is 5 L/s, and the irrigation time is 11.9 min. Under this combination, irrigation efficiency, irrigation uniformity, and desalination rate can reach 88%, 91%, and 66.63%, respectively.

5. Conclusions

- SRFR model is used to simulate the water flow advance process and Hydrus-3D model is used to simulate the water-salt distribution of film hole furrow irrigation with

Table 15
Reasonable combination of irrigation technical parameters of brackish water film hole furrow irrigation under different aperture ratios

Aperture ratio (%)	Furrow length (m)	Furrow distance (m)	Slope of furrow (%)	Irrigation amount (m^3/hm^2)	Flow rate (L/s)	Irrigation time (min)	The end of furrow
	30				2.00–4.50	5.7–12.7	
	40				2.30–5.63	6.0–14.8	
3	50	1	0.03	600	2.61–6.70	6.3–16.3	Closed
	60				2.90–6.85	7.4–17.6	
	70				3.12–6.61	9.0–19.1	
	30				2.15–5.10	5.0–11.9	
	40				2.48–6.36	5.3–13.7	
6	50	1	0.03	600	2.81–6.79	6.3–15.1	Closed
	60				3.16–6.44	7.9–16.1	
	70				3.52–6.08	9.8–16.9	
	30				2.23–6.26	4.1–11.4	
9	40	1	0.03	600	2.74–5.75	5.9–12.4	Closed
	50				3.47–5.02	8.5–12.2	

high reliability, which will greatly help the well-designed of film hole furrow irrigation system.

- The water flow advance process under the condition of film hole furrow irrigation is in accordance with the power function law, the flow rate, and the aperture ratio have a great influence on the advancing speed of water flow.
- Different flow rates and aperture ratios have significant effects on the vertical distribution of soil water content and salinity. The brackish water film hole furrow irrigation restrained salt content of the 0–40 cm soil layer while increasing the water content of the crop root layer, which provides a good environment for the growth of peanuts. In order to restrain salt content, the irrigation amount under the condition of film hole furrow irrigation should not be less than 300 m^3/hm^2.
- A comprehensive evaluation index system of irrigation quality combining irrigation efficiency, irrigation uniformity and desalination rate is established. The reasonable combination of irrigation technical parameters of brackish water film hole furrow irrigation in the test area is proposed, and the optimal combination of irrigation technical parameters of brackish water film hole furrow irrigation is obtained. The aperture ratio is 3%, the furrow length is 70 m, the flow rate is 5 L/s, and the irrigation time is 11.9 min. Under this combination, irrigation efficiency, irrigation uniformity, and desalination rate can reach 88%, 91%, and 66.63%, respectively.
- There are many factors affecting the salt distribution and irrigation quality of the brackish water film hole furrow irrigation. The results of this test are obtained under the meteorological conditions of sandy soil and coastal areas in the coastal saline-alkali area, and the salty conditions on the eastern coastal areas of China. It is of certain reference value to the application of film hole furrow irrigation in the east coastal area of China.

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