OPTIMIZATION AND APPLICATION OF IRRIGATION SCHEDULING BASED ON HYDRUS-2D AND STEWART MODEL IN A SEMI-ARID AREA OF CHINA
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基于Hdyrus-2D 和Stewart 模型的半干旱区灌溉制度优化及其应用

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ABSTRACT
Water scarcity has been a critical constraint to economic development in semi-arid areas of China, so optimizing irrigation scheduling has become essential. This study obtained quantitative relationships between crop yield, crop water consumption, and irrigation quantity based on the Hydrus-2D and Stewart models. Different irrigation scheduling scenarios were evaluated to obtain the best irrigation scheduling based on the principle of simultaneous water conservation and crop productivity improvement with the evaluation indicators of crop yield, water use efficiency (WUE), irrigation water use efficiency (IWUE), and Critic-Topsis method. Taking drip irrigation under mulch as an example, the problem of optimizing the irrigation scheduling for different typical years was calculated. The optimization results showed that in the wet, normal, dry, and very dry years the annual irrigation quantity should be 49.68 mm, 49.68 mm, 85.38 mm, and 123.72 mm, when the WUE as well as IWUE, increases significantly, which had less impact on the crop yield and can save irrigation quantity by 30.00%, 30.00%, 35.00%, 27.00%. This study used Hydrus-2D to make a new attempt in irrigation scheduling optimization, giving full play to the model's high accuracy in soil water transport simulation and flexibility in boundary condition simulation. The optimization results can provide a reference for achieving accurate control of irrigation quantity during the crop growth period and reasonable irrigation scheduling formulation for regional crops.

摘要
在中国半干旱农灌区水资源短缺一直是制约经济发展的关键因素，因此对灌溉制度进行优化变的十分重要。本文基于 Hydrus-2D 和 Stewart 模型，得到作物产量-耗水量-灌溉量的定量关系，利用 Critic-Topsis 法，以水资源节约和作物生产力同步提高为原则，将作物产量、水分生产率、灌溉水利用效率作为评价指标对不同情景方案下的灌溉制度进行评价，优选得到最佳灌溉制度。以膜下滴灌为例，求解了不同水平年的灌溉制度优化问题，优化结果表明，在丰水年、平水年、枯水年、干旱年的年灌水量应为 49.68mm，49.68mm，85.38mm，123.72mm，水分利用效率以及灌溉水利用效率增加显著，对作物产量的影响较小的情况下，节约灌溉用水 30.00%，30.00%，35.00%，27.00%。本文利用 Hydrus-2D 在灌溉制度优化方面进行了新的尝试，充分发挥模型对土壤水运移模拟的高精度性及对边界条件模拟的灵活性，优化结果可为实现作物生育期内灌水量的精准控制，地区作物的合理的灌水方案制定提供参考。

INTRODUCTION
Agriculture water accounts for approximately 70% of global water resources and is the number one water user. China's arid and semi-arid areas, mainly located in the water-scarce north, account for an even higher proportion of agricultural water, making water scarcity even more of a problem for these areas, which are highly dependent on irrigation and also bear the brunt of agricultural production (*Soltani L. et al., 2022; Li M. et al., 2019*). Irrigation scheduling is the key and scientific basis for rational water use. Regulated deficit irrigation can reduce irrigation quantity and improve water use efficiency (WUE) while ensuring crop yields (*Cui J. et al., 2019; Ors S. et al., 2015*). Therefore, optimizing the existing irrigation scheduling and formulating a more reasonable irrigation scheduling to improve the water resources management level is necessary.

Irrigation scheduling optimization is an essential tool for regional water management and has been the subject of much research by scholars. There are currently two main ways of using models for irrigation scheduling optimization: (1) Use the model of crop response to water (Jensen model, Stewart model, etc.) to describe the relationship between water deficit and yield at different periods of crop growth through the analysis and fitting of experimental data, and carry out irrigation scheduling optimization. (2) Crop growth models (DSSAT model, AquaCrop model, etc.) (*Mubeen M. et al., 2016; Zhao Y. et al., 2021; Han C. et al., 2020*) are used to describe the relationship between soil moisture changes and crop growth and development for irrigation scheduling optimization.

The core objectives of irrigation scheduling optimization are to maximize crop yield and minimize irrigation water, however, the current approach to irrigation scheduling optimization is basically to use models to establish a relationship between crop yield and crop water consumption, based on which irrigation decisions can be further optimized. If the relationship between crop yield and irrigation quantity are established directly, it would provide greater convenience to irrigation decision-makers. In addition, when models are used to optimize irrigation scheduling, the study's environment is often idealized to a certain extent (*Araya A. et al., 2010; Salemi H. et al., 2011*). For example, the DSSAT model simplified the soil water transport to a one-dimensional model, and cannot simulate well the boundary conditions and the resulting lateral transport of soil water under irrigation methods such as drip irrigation under mulch and furrow irrigation, which will have a certain impact on the optimization effect.

Effective rainfall is one of the sources of soil moisture and has positive implications for improving irrigation water use efficiency when optimizing irrigation scheduling, yet many models do not consider rainfall comprehensively (*Xie Y. L. et al., 2018*). In addition, in areas with shallow groundwater depths, crop roots can access a certain amount of water through groundwater under the influence of capillary-effect, thus reducing irrigation water, but it is difficult to quantify groundwater recharge to crops when existing crop models are optimized for irrigation scheduling (*Peng Z. et al., 2019*). All of the above hurt optimization results.

The Hydrus-2D model is a finite element computational model for simulating water, solute, and heat transport in saturated-unsaturated porous media. The model allows a better and more flexible description of various boundary conditions, enables two-dimensional simulation of soil hydrothermal transport with high accuracy and enables simulation of transport fluxes, quantifies deep percolation and groundwater recharge to crops, and is now widely used to simulate soil moisture movement (*Shan G. et al., 2019; Karandish F. et al., 2019*). Given the advantages of the Hydrus-2D model in the simulation of soil water transport, it is necessary to use Hydrus-2D to study the optimization of irrigation scheduling (*Er-Raki S. et al., 2021*).

When using Hydrus-2D to optimize irrigation scheduling, the selection of optimization objectives was often directed at the water and solute processes, such as seeking to reduce crop water consumption (*Er-Raki S. et al., 2021*), reduce deep percolation (*Egea G. et al., 2016*) or optimize solute transport processes (*Shekhar S. et al., 2021; Zeng W. et al., 2014*). Crop yield is often a priority when optimizing irrigation scheduling, but the Hydrus-2D model does not simulate crop yield, so we combined the Hydrus-2D model with the Stewart water production function to optimize irrigation scheduling (*Wang D. et al., 2017; Cheng W. et al., 2016*), which took advantage of the Hydrus-2D model's strengths in soil water transport simulation while taking crop yield into account.

This paper presented a new attempt at optimizing irrigation scheduling using the Hydrus-2D model, combining Hydrus-2D and Stewart models to establish a quantitative crop yield-crop water consumption-irrigation quantity relationship under different meteorological conditions (typical years). We proposed an irrigation scheduling optimization method using Hydrus-2D and Stewart models based on the principle of simultaneous improvement of water conservation and crop productivity and applied it in the experimental area.

MATERIALS AND METHODS

Hydrus-2D model

The Hydrus-2D model is a finite element computational model developed by the US Salinity Laboratory to simulate the two-dimensional movement of water, heat, and solutes in saturated-unsaturated porous media. Hydrus-2D has the advantage of high simulation accuracy and a wide range of algorithms for arbitrarily complex terrain conditions and is now widely used to simulate soil moisture movement processes in the field. The Hydrus-2D soil water movement model consists of the Richard equation, the Van Genuchten-Mualem hydraulic model, crop root uptake, and evapotranspiration modules, where evapotranspiration is calculated using the Penman-Monteith model recommended by FAO-56.

The irrigation scheduling should be optimized by using Hydrus-2D to establish an in-situ soil water transport model in the field so that the effects of meteorological factors, ineffective deep percolation, and groundwater recharge to the crop on the irrigation quantity can be fully taken into account and the irrigation quantity can be accurately controlled during the crop growth period.

Stewart model

The crop water production function is an effective method for determining the quantitative relationship between crop water consumption and yield, and numerous experiments have established the applicability of the Stewart model in semi-arid areas (*Wang D. et al., 2017; Cheng W. et al., 2016*). The Stewart model reflects the effect of water stress on crop growth at different growth stages, using the relative water deficit as the independent variable, multiplied by the corresponding stage sensitivity coefficient to represent the water production function in the form shown in Equation 1. The model weakens the influence of climate and crop variety on the relationship between crop yield and crop water consumption. Compared with the crop growth model, it has the advantage of being simpler to calculate, requires fewer types of data, and can reflect the response of crop yield to moisture factors more accurately in the same region.

$$1-\frac{Y_a}{Y_m}=\sum_{i=1}^{n} Bi\left[\frac{\left(ET_{m_i}-ET_{ai}\right)}{ET_{m_i}}\right] \tag{1}$$

where: Y_a is the measured yield of the crop (kg/hm^2);

Y_m - the maximum yield of the crop (kg/hm^2);

ET_{ai} - the measured water requirement of the crop at each growth period (mm);

ET_{mi} - the crop water requirement under full irrigation treatment (mm);

B_i is the sensitivity coefficient of water deficit on yield at different growth period of the crop;

i = 1, 2, …, n is the serial number of the crop at each period of growth.

As a statistical model, the Stewart water production function is based on a large amount of field experiment data. Therefore, crop deficit irrigation experiments are required for irrigation scheduling optimization. The experiment is carried out in the field of the experimental area using the comparative method and the experimental treatments are designed according to different combinations of water deficit levels at each period of growth. Considering the influence of rainfall on irrigation, a movable rain shelter should be set up in the experimental plot and used during rainfall.

Critic-Topsis method

The evaluation indicators of irrigation scheduling involve various factors such as resources, economy, and ecological environment. For the multi-attribute and multi-objective characteristics of irrigation scheduling evaluation, Critic-Topsis can be used to evaluate the irrigation scheduling and preferably select the optimal irrigation scheduling. The Topsis method eliminates the influence of different indicator scales, makes full use of the information in the raw data, reflects the gaps between scenarios, and is universally applicable. The Critic weighting method takes into account the differences and correlations of each indicator, resulting in more objective and accurate weights (*Liu, X. et al., 2018; Liu X. et al., 2021*).

This paper is based on the principle of simultaneous improvement of water conservation and crop productivity, taking into account a combination of indexes of economic yield size (crop yield Y) and effectiveness indexes of water resources utilization (water use efficiency WUE and irrigation water use efficiency $IWUE$). WUE and $IWUE$ are calculated using equations 2,3 respectively.

$$WUE=\frac{Y}{ET} \tag{2}$$

$$IWUE=\frac{Y}{I} \tag{3}$$

where: Y is the crop yield (kg·hm^{-2});

WUE - water use efficiency (kg/m^3); and

$IWUE$ - irrigation water use efficiency (kg/m^3);

ET - crop water consumption (mm);

I - irrigation quantity (mm).

The above three indicators (Y, WUE, $IWUE$) constitute the pool of factors for the comprehensive evaluation of irrigation scheduling optimization in this study, with higher scores on the index Ci for Topsis indicating that the subject is closer to the optimal level.

Optimization process

The optimization process is shown in Fig.1.

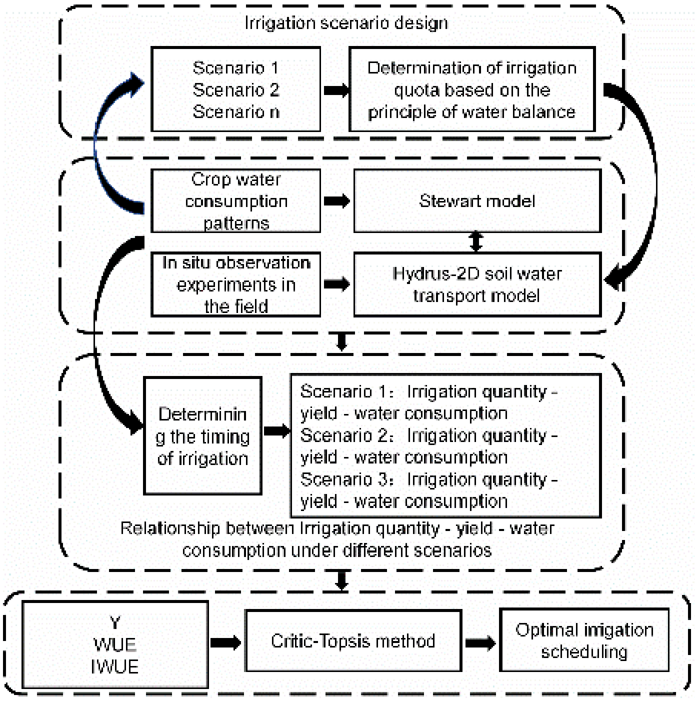

Fig. 1 - Optimization process

The first step is the establishment of the soil water model: Hdyrus-2D is used to establish the soil water transport model, the model parameters are calibrated and the simulation results are validated using in situ soil water transport monitoring experimental data in the field. The second step is the establishment of the crop water model: using the Stewart model, the yield-evapotranspiration (crop water consumption) relationship is fitted using the standardized and weakened dispersion of deficit irrigated crop data in the field. The third step is the design of scenarios for irrigation scheduling optimization: the design of scenarios for irrigation scheduling optimization at different combinations of water deficit levels for a growth period with a low water sensitivity coefficient. The fourth step is the simulation of the irrigation scheduling: the irrigation quota is determined according to the design scenario, based on the water balance method. Using the Subregions and Cumulative Fluxes modules in Hydrus-2D, iterative calculations are carried out to determine the irrigation time points and output the water consumption for different crop growth periods associated with irrigation quotas and meteorological data. Combined with the water production function, the relationship between crop yield - crop water consumption – irrigation quantity is obtained for different scenarios. The fifth step is irrigation scheduling optimal selection: considering crop yield, WUE, and $IWUE$, the Critic-Topsis method is used to evaluate the irrigation scheduling under different scenarios to obtain the optimal irrigation scheduling.

OPTIMIZATION OF DRIP IRRIGATION UNDER MULCH IRRIGATION SCHEDULING FOR MAIZE

Experimental design and data collection

The experiment was carried out at Jianping Irrigation Experimental Station in Chaoyang City, Liaoning Province, China, which is located at 119°18′ E, 41°47′ N, and 461 m above sea level. The average annual temperature is 5-6°C, the average annual precipitation is 440 mm and the average annual evapotranspiration is 1800-2100 mm. It has a typical semi-arid monsoon climate with low rainfall and high evaporation. The local irrigation method is drip irrigation under mulch, and the main crop is maize. The experiment started in April 2019 - ended in October 2019 and started in April 2021 - ended in October 2021. The average depth of groundwater in the study area during the test was 300 cm.

In-situ soil water transport monitoring experimental

Two monitoring sections were set up in the middle of the furrow (MFD) and the middle of the mulch (MMD). Three sets of 1 m deep trim tubes were set up at each monitoring section to monitor soil water content using TDR. The maximum monitoring depth was 80 cm. The monitoring section settings are shown in Fig.2.

Meteorological data on rainfall, temperature, humidity and wind speed were obtained from nearby weather station during the experiment (http://data.cma.cn, Station No. 54326).

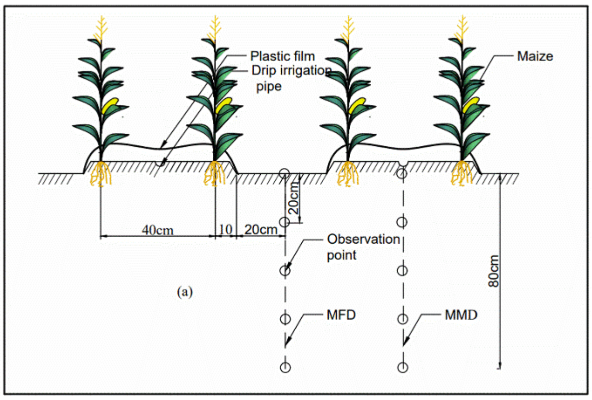

Fig. 2 - Settings of monitoring sections.

Deficit irrigation experiment

Considering the depth of groundwater in the study area, the experiment was carried out in a bottomed soil pit (2 m x 3.3 m). The experiment was set up according to the lower limit of irrigation for each growth stage of maize, dividing the entire growth period into seedling, jointing, tasseling, and filling stages. The experiment used 60% and 50% of the soil field capacity (θ_{fc}) as the lower limit of irrigation, eight experimental treatments, and one control group (the lower limit of irrigation was 70% θ_{fc}), the upper limit of irrigation was all soil field capacity, and three replications were set up for each treatment. The monitoring sections were set up in the same way as the in-situ soil water transport monitoring experimental data in the field. Five crops were selected for each treatment and the number of plants and spikes were counted for each treatment before harvest and the yield of the plants was measured.

Hydrus-2D model calibration and validation

Hydraulic parameters were initially predicted from the proportion of the soil particle size and soil water retention curve using the Rosetta program. The inverse module and the experimental data from 2019 were used to optimize the hydraulic parameters. The optimized Soil hydraulic parameters are shown in table 1.

Table 1

Soil hydraulic parameters

Depth (cm)	θ_r ($cm^3 \cdot cm^{-3}$)	θ_s ($cm^3 \cdot cm^{-3}$)	α (cm^{-1})	*n* (-)	*Ks* ($cm^3 \cdot day^{-1}$)	*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
70-80	0.025	0.43	0.124	1.27	435.07	0.5

The model was validated using experimental data from 2021. The performance of the model was evaluated using the following three statistical indicators: mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination (R^2). The results are shown in Fig.3, and Table 2.

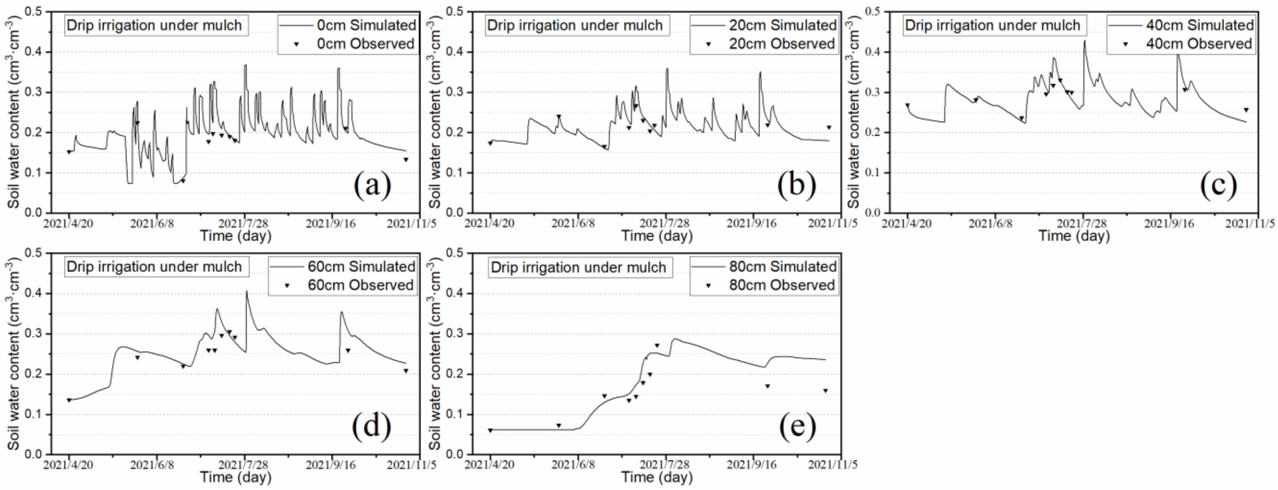

Fig. 3 - Simulated and measured soil water contents at different soil depths

(a), (b), (c), (d), and (e) are Simulated and measured soil water contents at 0, 20, 40, 60, and 80 cm soil depth respectively

Table 2

The error analysis of soil water contents

Depth (cm)	MAE (cm^3/cm^3)	R^2	RMSE (cm^3/cm^3)
0	0.017	0.87	0.025
20	0.015	0.79	0.021
40	0.015	0.78	0.024
60	0.023	0.85	0.028
80	0.033	0.79	0.040

The graphical and statistical results show that the trend of the simulated soil moisture content is consistent with the measured values, with R^2 of 0.78-0.87, RMSE of 0.021-0.040, and MAE of 0.015-0.033 at 0-80 cm. The model simulation accuracy is high and the simulated and measured soil moisture contents show a good agreement. Considering the complexity of the in situ field experiments, many disturbing factors (e.g., soil spatial variability, uneven distribution of rainfall and irrigation, the effects of uneven distribution of crop roots, etc.) might be encountered. Still, the model met the accuracy criteria and could simulate soil moisture movement better.

Stewart model calibration and validation

The Stewart water production function was fitted and optimized using the crop yield-crop water consumption relationship obtained from the deficit irrigation experiment, and the optimized parameters are shown in Table 3.

Water sensitivity coefficient Table 3

Water sensitivity coefficient	Seedling	Jointing	Tasseling	Filling
Bi	0.6854	0.1648	0.1002	0.2937

The simulation of the model was evaluated using three statistical indicators: mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination (R^2). The R^2 of the water production function is 0.99, the MAE is 66.543 and the RMSE is 75.199. The accuracy of the simulation of the Stewart model is high and met the accuracy criteria, which could better reflect the relationship between crop water consumption and crop yield.

Scenario design

To ensure maize yield, was selected the growth period that had a relatively low impact on the yield of the crop (filling and pulling stage) for deficit irrigation. Typical years were determined using the curve-fitting method, as shown in the table 4.

Typical year selection Table 4

Typical year	Rainfall (mm)	Frequency	Year
Wet year(W)	530.7	25%	1995
Normal year (N)	471.0	50%	2019
Dry year (D)	386.7	75%	1997
Very Dry year (VD)	333.9	90%	1992

Nine scenarios were designed using 70%θ_{fc}, 60%θ_{fc}, and 50%θ_{fc} as the lower limit of irrigation at the filling and pulling. The scenarios for the wet year are shown in table 5, where W1 is fully irrigated and W2-W9 is irrigated with varying degrees of deficit regulation. The scenario design for normal, dry, and very dry years is the same as for wet years.

Wet year scenario design Table 5

Wet year (W)	Seedling	Jointing	Tasseling	Filling
W1	70%θ_{fc}	70%θ_{fc}	70%θ_{fc}	70%θ_{fc}
W2	70%θ_{fc}	70%θ_{fc}	60%θ_{fc}	70%θ_{fc}
W3	70%θ_{fc}	70%θ_{fc}	50%θ_{fc}	70%θ_{fc}
W4	70%θ_{fc}	60%θ_{fc}	70%θ_{fc}	70%θ_{fc}
W5	70%θ_{fc}	60%θ_{fc}	60%θ_{fc}	70%θ_{fc}
W6	70%θ_{fc}	60%θ_{fc}	50%θ_{fc}	70%θ_{fc}
W7	70%θ_{fc}	50%θ_{fc}	70%θ_{fc}	70%θ_{fc}
W8	70%θ_{fc}	50%θ_{fc}	60%θ_{fc}	70%θ_{fc}
W9	70%θ_{fc}	50%θ_{fc}	50%θ_{fc}	70%θ_{fc}

Irrigation scheduling simulation

The Hydrus-2D model was used to simulate irrigation regimes for nine irrigation scenarios at different typical years. The results obtained are shown in Fig. 4 below.

As can be seen from Fig. 4, there is little change in irrigation scheduling for some scenarios, such as W1, W2, and W3 versus N1, N2, and N3. The reason for this might be related to the interannual distribution of rainfall in the year. In the case of W1, W2, and W3, all three scenarios are irrigated for deficits during the tasseling period, when rainfall is more frequently distributed to meet the normal water requirements of the crop, resulting in no need for irrigation during this period, thus resulting in little difference between the irrigation scheduling of the three scenarios. As the typical annual rainfall decreased, the irrigation scheduling varied increasingly across the typical years.

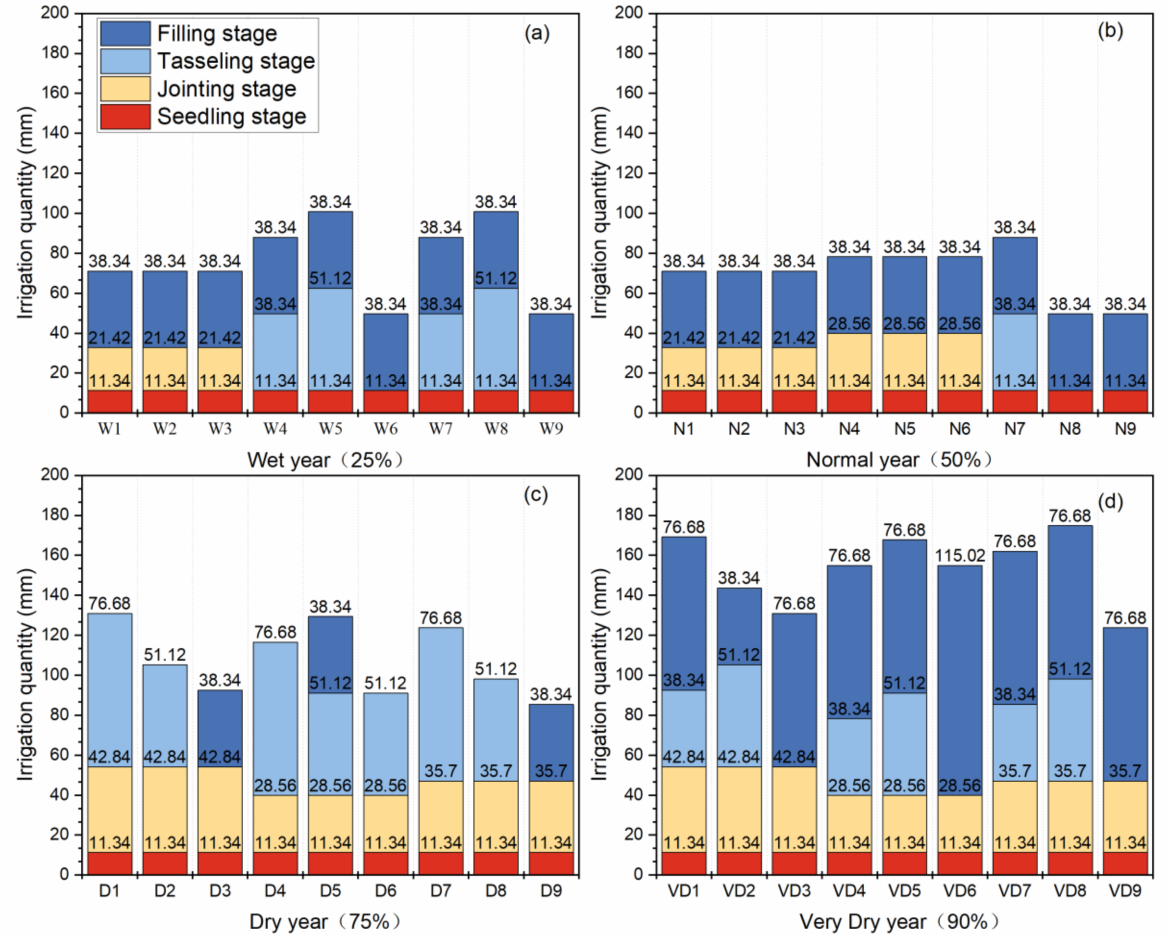

Fig. 4 - Irrigation scheduling simulation

(a) is wet year, (b) is normal year, (c) is dry year, and (d) is very dry year.

Optimal irrigation scheduling

The Hydrus-2D and Stewart models were used jointly to output the crop yield-crop water consumption-irrigation quantity relationship for different scenarios and to calculate WUE and IWUE. The Critic weighting method was used to calculate the weight values for the three indicators (yield, WUE, IWUE) for the years of wet (0.4458, 0.3234, 0.2308), normal (0.4799, 0.2995, 0.2207), dry (0.4409, 0.2792, 0.2800) and very dry (0.4021, 0.3428, 0.2551). The data was standardized and orthogonalized using the Topsis method to calculate Ci values. The results are shown in Fig.5.

As can be seen in Fig.5, W9, N9, D9, and VD9 are the optimal irrigation scheduling for the corresponding typical years, with Ci values of 0.5658, 0.5299, 0.5100, and 0.5515 respectively. The lower limit of irrigation for W9, N9, D9, and VD9 is 50% of θ_{fc} at the time of jointing and tasseling, which means that irrigation with 50% of θ_{fc} at the time of jointing and tasseling will result in better performance in terms for yield, WUE, and IWUE. The Ci values for W6 and W9 are the same in the wet year, which is related to the inter-annual distribution of rainfall for the reasons explained in section 3.5. The choice of W6 or W9 does not affect crop yield, WUE, and IWUE. For the sake of simplicity and practicality of the conclusions, W9 is chosen as the optimal irrigation scheduling in the wet year, and the same applies to N8 and N9 in the normal year.

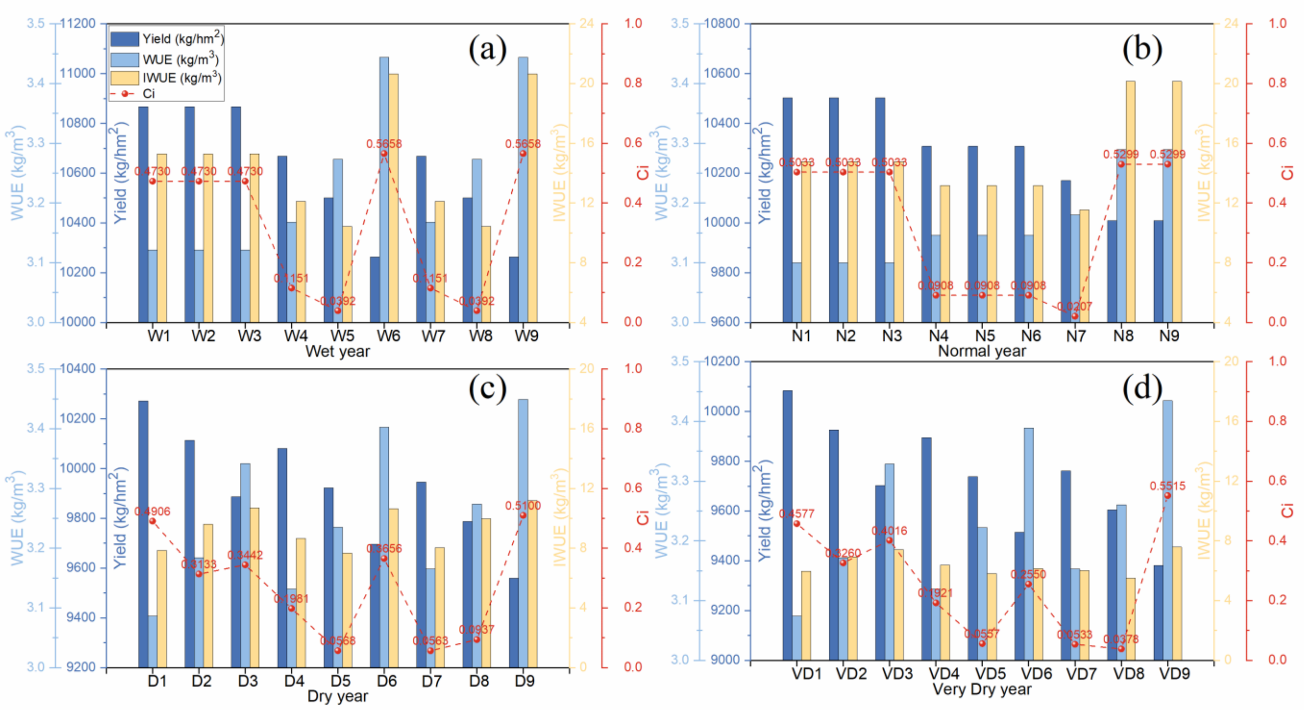

Fig. 5 - Irrigation scheduling simulation

(a) is wet year, (b) is normal year, (c) is dry year, and (d) is very dry year.

RESULTS

The semi-arid areas are located on a plain, with gentle topography, few rivers, active infiltration of precipitation, and almost no surface runoff. The hydrological cycle is characterized by predominantly groundwater recharge-discharge, with the main processes of the hydrological cycle being: precipitation-evaporation-infiltration to recharge groundwater-transpiration (*Wang Y. et al., 2021*). The Hydrus-2D model can simulate soil evaporation, crop transpiration, deep seepage, and groundwater recharge to crops in agricultural fields, and the entire hydrological element of semi-arid agricultural fields can be simulated using this model alone. The model is suitable for complex subsurface conditions and can better and more flexibly describe various boundary conditions. The boundary conditions under irrigation methods such as drip irrigation under mulch and furrow irrigation and the resulting lateral migration of soil water can be well simulated, the simulation accuracy is high, and the simulated and measured soil water content shows good agreement.

The combined use of Hydrus-2D and Stewart models enables the quantitative relationship between crop yield - crop water consumption - irrigation quantity to be obtained, bringing greater convenience to the multi-objective optimization of irrigation scheduling and the decision-making of irrigation strategies.

By optimizing the irrigation scheduling for maize drip irrigation under mulch, the optimum irrigation system was obtained for wet years, normal years, dry years, and very dry years. The irrigation scheduling is shown in Table 6 below. Compared to the initial irrigation scheduling with full irrigation, the yield of optimized irrigation scheduling decreased 603.88, 493.77, 712.51, and 702.08 kg/hm^2, accounting for 5.55%, 4.67%, 6.86%, and 6.86% of the yield of initial irrigation system, whereas the WUE increased by 10.33%, 6.13%, 11.84%, and 11.84%, respectively, and the IWUE increased by 35.16%, 36.43%, 42.76%, and 27.38%, respectively. It can be seen that the optimized irrigation scheduling has a significant increase in WUE as well as IWUE with less impact on crop yield, saving irrigation water by 30.00%, 30.00%, 35.00%, and 27.00%, respectively.

Table 6

Optimal irrigation scheduling

Typical year	Seedling(mm)	Jointing(mm)	Tasseling(mm)	Filling(mm)	Annual irrigation quantity(mm)
Wet year	11.34	0	0	38.34	49.68
Normal year	11.34	0	0	38.34	49.68
Dry year	11.34	35.7	0	38.34	85.38
Very Dry year	11.34	35.7	0	76.68	123.72

In this paper, the Stewart model was used to establish the crop water production function, but the choice of crop water production function is related to the irrigation method, crop type, location of the experimental area, etc. Therefore, the water sensitivity coefficient in Stewart also varies across areas (*Cheng W. et al., 2016; Saseendran S.A. et al., 2015*). To better optimize the irrigation scheduling and reduce the model error, an appropriate water production model should be chosen when establishing the water consumption-yield relationship (*Mukherjee D., 2021; Cheng W. et al., 2016*).

Maize water sensitivity coefficient values in the experimental area were seedling stage (0.6854) > filling stage (0.2937) > jointing stage (0.1648) > tasseling stage (0.1002). This suggested that rewatering after water deficits at the jointing stage and the tasseling stage could produce a compensation or overcompensation effect on plant growth and development (*Liu H. et al. 2017*). In addition, the experimental area receives sufficient rainfall at the jointing stage as well as at the tasseling stage, with about 70% of the annual rainfall falling between June and August, which provides a certain source of water for the crop.

The setting of the irrigation scenario may have an impact on the optimization results, as the lower limit of irrigation for the optimum irrigation scheduling may occur between70%θ_{fc} - 60%θ_{fc} or 60%θ_{fc} - 50%θ_{fc}, but the water sensitivity coefficient values are lower at the jointing stage and the tasseling stage, when deficit irrigation has less impact on yield and can increase WUE and $IWUE$ to a greater extent (*Yang X. et al., 2016*), so the conclusions are considered reliable. In the actual process of irrigation system optimization, irrigation scenarios should be designed to set more gradients and consider more growth periods to obtain better irrigation scheduling.

CONCLUSIONS

This paper proposed a method for optimizing irrigation scheduling in semi-arid areas based on the Hydrus-2D and Stewart models, with the principle of simultaneous water conservation and crop productivity improvement. The optimization process mainly included (1) the establishment of the soil water model; (2) the establishment of the crop water model; (3) the design of scenarios for irrigation scheduling optimization; (4) the simulation of the irrigation system; and (5) irrigation scheduling optimal selection.

The method is suitable for the characteristics of the hydrological cycle in semi-arid areas and takes full account of the influence of meteorological factors on the optimization of irrigation scheduling. The method allows for a better and more flexible description of the various boundary conditions and applies to irrigation scheduling optimization problems under various irrigation methods. Through the combined use of Hydrus-2D and Stewart models, a quantitative crop yield-crop water consumption-irrigation quantity relationship is obtained, bringing greater convenience to the multi-objective optimization of scheduling and the decision-making of irrigation strategies.

By optimizing the irrigation scheduling of maize drip irrigation under mulch in different typical years, the optimal annual irrigation quantity should be 49.68 mm, 49.68 mm, 85.38 mm, 123.72 mm for the wet year, normal year, dry year, and very dry year, and the lower limit of irrigation should be 50% θ_{fc} for jointing stage and tasseling stage. The WUE, as well as the $IWUE$, increased significantly at this time, saving 30.00%, 30.00%, 35.00%, and 27.00% of irrigation quantity respectively, with less impact on crop yield.

This paper used Hydrus-2D to optimize the irrigation system, the results of which could provide a reference for the precise control of irrigation water during the crop reproductive period and the development of a reasonable irrigation plan for regional crops. In practical application, attention should be paid to the choice of the water production function, the setting of irrigation scenarios, and the influence of the spatial and temporal distribution of rainfall on the optimization effect.

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