SIMULATION STUDY OF SOIL WATER-SALT TRANSPORT AND IRRIGATION QUOTA FOR SUMMER MAIZE IN SALINIZED FARMLAND BASED ON THE SWAP MODEL

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基于 SWAP 模型的盐渍化农田夏玉米土壤水盐运移及灌溉定额模拟研究

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ABSTRACT

To determine the optimal water-saving irrigation quota for summer maize in the salinized farmland of the Lupotan area (near Shaanxi Province, Northwest China), the parameters of the SWAP (Soil-Water-Atmosphere-Plant) model were calibrated and validated using field experimental data from 2018 to 2019. The results showed that the simulated values of soil water content, soil salt content, and summer maize yield were in good agreement with the measured values. Under different irrigation scenarios, soil water flux, cumulative soil water flux, soil salt flux, and cumulative soil salt flux at the lower boundary of the crop root zone and storage zone decreased with decreasing irrigation quota. When the irrigation quota was reduced to 70% IQ and 60% IQ, the changes in cumulative soil water flux and cumulative soil salt flux were small. Soil water could be stably stored in the 0–100 cm soil layer to meet the growth requirements of summer maize. When the irrigation quota was 3500 $m^3 \cdot ha^{-1}$ (70% IQ), the yield reduction of summer maize was less than 10%. Therefore, 3500 $m^3 \cdot ha^{-1}$ was identified as the optimal irrigation quota for summer maize from the perspective of soil water-salt flux and crop yield. The SWAP model can effectively simulate and predict soil water-salt transport and water-saving irrigation quotas for summer maize in salinized farmland. This study provides technical support for the efficient utilization of water resources and guidance for agricultural production practices in Northwest China.

摘要

为了寻求中国西北陕西省卤泊滩地区盐渍化农田夏玉米最优的节水灌溉定额，本研究基于 2018 年和 2019 年的田间野外试验资料，对 SWAP（土壤-水-大气-植物）模型的参数进行了率定和验证。结果表明，土壤含水量、土壤含盐量和夏玉米产量的模型模拟值与实测值吻合较好。不同灌溉模拟情景下，作物根区和储水区下边界的土壤水分通量、土壤水分累计通量、土壤盐分通量和土壤盐分累计通量均随灌溉定额的减小而减小。当灌溉定额降低至 70％IQ 和 60％IQ 时，土壤水分累计通量和土壤盐分累计通量变化较小。土壤水分能够稳定储存在 0~100 cm 土层，以满足夏玉米生长的需求。当夏玉米灌溉定额为 3500 $m^3 \cdot ha^{-1}$ (70％IQ)时，夏玉米减产幅度小于 10％。综合考虑土壤水盐通量和作物产量的变化，3500 $m^3 \cdot ha^{-1}$ 为夏玉米最优的灌溉定额。SWAP 模型能够较好地模拟和预测盐渍化农田夏玉米土壤水盐运移和节水灌溉定额。本研究旨在为中国西北地区水资源高效利用提供技术支撑，同时为中国西北地区农业生产实践提供指导。

INTRODUCTION

Soil salinization is a significant global challenge and a main factor affecting agricultural productivity and the ecological health of farmlands in the world. According to statistical analysis, the salinization area of cultivated land has reached 9.21×10^6 ha, accounting for 6.62% of the total cultivated area in China *(Li et al., 2024)*. The rational utilization of salinization land is of great significance to the development of comprehensive agriculture in China.

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Lupotan was a closed structural depression, which located at the junction of Fuping County and Pucheng County in Shaanxi Province, Northwest China. Soil salt had accumulated in Lupotan for a long time, which was affected by natural and human activities. Although Lupotan was reclaimed as farmland in modern times, its low-lying topography resulted in poor farmland drainage, rising groundwater levels, and the gradual aggravation of soil salinization. Most farmland suffered from soil salinization to varying degrees, which seriously restricted local agriculture proceeding development *(Li et al., 2023).* The local relevant departments carried out large-scale development and renovation of the Lupotan through land levelling, drainage and alkali control measures at the end of the 20 century. The cultivated land was not salinized in large areas, and the crops planted were less affected by salt and alkali. However, the flood irrigation method was widely used in this area, which not only caused the waste of water resources, but also led to the current rise in groundwater levels and soil secondary salinization *(Li et al., 2021)*. In order to reduce soil secondary salinization and save water resources, water-saving irrigation measures should be adopted for summer maize in the study area. After the implementation of water-saving irrigation measures for summer maize, soil water-salt transport and water-salt balance would change. The relationship between soil water-salt flux change and irrigation quota was still not clear, and the optimal irrigation quota for summer maize was also not clear in the study area. Therefore, it was necessary to study the change of soil water-salt flux and the optimal irrigation quota of summer maize in Lupotan of Northwest China.

Field experiment was used to study soil water-salt transport and crop irrigation quota, but there were many factors affecting field experiment, which required a long cycle and high cost *(Jing et al., 2021; Dewedar et al., 2020)*. Mathematical models were widely used to simulate soil water-salt transport and crop irrigation quota based on field experiments *(Huang et al., 2024)*. In these mathematical models, the SWAP model was extensively utilized to simulate soil water-salt transport and crop irrigation quota in the world *(Ravensbergen et al., 2024)*. The theoretical basis of the SWAP model was mature and reliable and the model was relatively easy to operate and use. It had been widely accepted and recognized in arid or semi-arid areas around the world *(Heinen et al., 2024; Yuan et al., 2025)*. The SWAP model provided an effective method for the formulation and evaluation of crop irrigation system, the prediction of groundwater depth change, the prediction of soil water-salt transport, and the prediction of crop growth and yield *(Alibi et al., 2022; Yang et al., 2025)*. Shafiei et al. used SWAP model to simulate soil water distribution and water flow flux of two different types of fields in the arid area of Iran. It showed that the water flow flux of farmland soil deep layer downward leakage changed greatly and was more sensitive to the influence of soil hydraulic conductivity *(Shafiei et al., 2014)*. Jiang et al. used the SWAP model to simulate the soil water-salt transport of spring wheat in Shiyang River Basin of Gansu Province of Northwest China. It showed that soil salt could remain stable after five years of continuous saline water irrigation, and the SWAP model could predict soil water-salt dynamic changes over extended periods *(Jiang et al., 2016)*. Chen et al. used SWAP model to simulate soil water movement in paddy fields under four water-saving irrigation modes. It showed that the controlled irrigation and drainage modes under different hydrological years had obvious water-saving and labour-saving effects, and did not cause a reduction in rice yields, which was conducive to guiding the practice of rice water-saving irrigation *(Chen et al., 2019)*. *Babukani et al., (2024),* used SWAP model to simulate *evapotranspiration, yield, and water productivity of potato under six irrigation scenarios* in Fariman, Ghoochan, and Golmakan in the northeast Iran. It showed that the SWAP model well-simulated potato yield and water productivity. The model slightly overestimates the potato yield and underestimates the water productivity. The researchers used the SWAP model to simulate the changes of soil water-salt transport, crop irrigation management, which provided a theoretical basis and scientific basis for controlling soil salinization *(Li and Ren, 2020; Kramer and Mau, 2023)*. These publications show that the SWAP model could be used to deeply study soil water-salt transport and crop irrigation management under crop growth conditions in salinized regions. However, the relationship between soil water-salt fluxes, soil water-salt cumulative fluxes and irrigation quota for summer maize had been reported rarely under water-saving irrigation in Northwest China.

The SWAP model parameters were calibrated and validated based on field experiments and measured data in 2018 and 2019. The SWAP model was used to simulate the soil water-salt fluxes, soil water-salt cumulative fluxes and summer maize yield under different irrigation scenarios. The optimal irrigation quota for summer maize was found in the study area. This research explicitly stated that the water-saving irrigation quota has an important relationship with the change of soil water-salt flux at the lower boundary of crop root zone and storage zone in salinized farmland through the SWAP model simulation compared to previous studies. This research enriched the simulation and prediction of soil water-salt transport and crop irrigation quota in salinized farmland in semi-arid areas with SWAP model. The purpose of this study was to provide technical support for the efficient utilization of water resources and to guide agricultural production practice in Northwest China. The objectives were: (1) to calibrate and validate the SWAP model parameters based on field experiments and measured data in 2018 and 2019; (2) to simulate soil water-salt flux, soil water-salt cumulative flux and summer maize yield under different irrigation scenarios; (3) to find the optimal water-saving irrigation quota for summer maize in salinized farmland of Lupotan area.

MATERIAL AND METHODS

Design of field experiments

Field experiments were carried out from June 2018 to September 2019 in Lupotan area (109°22′E, 34°48′N, and altitude 490 m) of Northwest China. A standardized farmland was selected as the experimental field in Lupotan, with an area of 4.0×10^4 m^2 (Fig.1). The farming system was mainly winter wheat and summer maize rotation. There were a large number of saline alkali lands. The soil was characterized as typical sulphate saline-alkali soil, with a pH ranging from 8.3 to 8.6 in experiment region. The soil particle size composition was measured by laser particle size analyser (Master sizer 2000, UK). According to the international classification standard of soil texture, soil texture of the experimental area was determined. Soil physical properties for different soil layers in experiment region are shown in Table 1.

The experiment crop was summer maize with 25 cm plant spacing and 35 cm row spacing in 2018 and 2019. Summer maize was sown in early June and harvested at the end of September with whole growth period of about 120 days. Summer maize was irrigated with border irrigation method and was irrigated four times during the growth period, consistent with the actual conditions of local summer maize cultivation. The actual evapotranspiration (ET_c) of summer maize during the growth period was 500 mm *(Pan et al., 2020)*. The irrigation water quotas during the summer maize growth period were: 1200 $m^3\cdot ha^{-1}$ (June 25), 1300 $m^3\cdot ha^{-1}$ (July 15), 1300 $m^3\cdot ha^{-1}$ (August 22) and 1200 $m^3\cdot ha^{-1}$ (September 10). The total irrigation quota was 5000 $m^3\cdot ha^{-1}$ during the summer maize growth period. The salinity of the irrigation water was approximately 0.4 $g\cdot L^{-1}$. Due to the current irrigation conditions of summer maize, three summer maize fields were set up as three experimental plots in a standardized farmland. Three experimental plots had the same irrigation quota and irrigation data during the summer maize growth period in 2018 and 2019. Summer maize needed to be fertilized before sowing. The amount of fertilization was 600 $kg\cdot ha^{-1}$ for diammonium phosphate, 300 $kg\cdot ha^{-1}$ for urea, and 225 $kg\cdot ha^{-1}$ for potassium. Herbicides were sprayed before sowing summer maize. Other agronomic measures were consistent with the local actual situation.

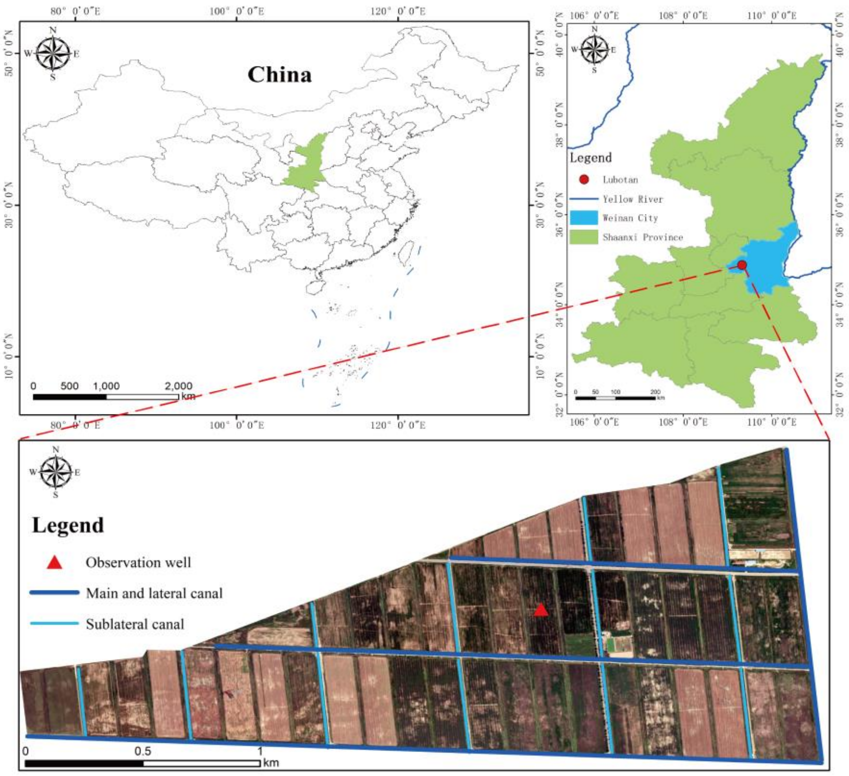

Fig. 1 - Location map of the study area and a standardized farmland within the study area

Table 1

Soil physical properties of different soil layers in the experimental region

Soil depth (cm)	Clay (< 0.002mm, %)	Silt (0.002~0.02mm, %)	Sand (0.02~2.00mm, %)	Soil bulk density ($g \cdot cm^{-3}$)	Soil texture
0-20	4.58	49.43	46.00	1.46	Silty sandy loam
20-40	3.23	46.81	44.05	1.48	
40-60	4.51	45.26	43.24	1.49	
60-100	4.26	45.74	45.27	1.50	

Experimental observation items and methods

The observation section was located in the centre of the standardized experimental field. The observation period was from June 2018 to September 2019. Soil samples were obtained before seeding, before and after every irrigation by soil auger during the summer maize growth period with the depth of 0-20, 20-40, 40-60, 60-80 and 80-100 cm, respectively. Gravimetric water content was determined by drying the soil sample. Volume water content was calculated by multiplying the gravimetric water content by the soil bulk density. Soil water content refers to volume water content in this paper. Electrical conductivity, $EC_{1:5}$ ($mS \cdot cm^{-1}$) was measured by conductivity meter and translated into soil salinity ($g \cdot kg^{-1}$) using the calculation equation ($S=0.2813EC_{1:5}-0.0056$, where S refers to soil salinity) (*Pan et al., 2020)*. There was a 3 metre deep groundwater observation well in the middle of the standardized experiment farmland, which was observed the change of groundwater table depth. The groundwater table depth was between 1.85 and 2.25 meters in experiment region. The initial soil water content, soil salt content and hydraulic characteristic parameters for different soil layers were obtained before sowing summer maize. The parameters of soil water characteristic curve were measured using a centrifuge, and the hydraulic characteristic parameters of VG (van Genuchten) model were fitted using RETC software (RETention Curve). The initial soil hydraulic characteristic parameters for different soil layers are shown in Table 2. The initial measured molecular diffusion coefficient was 3.5 $cm^2 \cdot d^{-1}$, and the dispersion length was 19.0 cm.

Table 2

Soil hydraulic parameters of different soil layers in the experimental region

Soil depths (cm)	θ_r ($cm^3 \cdot cm^{-3}$)	θ_s ($cm^3 \cdot cm^{-3}$)	K_s ($cm \cdot d^{-1}$)	α	n	γ
0-20	0.025	0.441	120.00	0.094	1.541	0.5
20-40	0.028	0.422	79.46	0.089	1.722	0.5
40-60	0.026	0.394	100.20	0.089	1.714	0.5
60-100	0.029	0.412	89.56	0.089	1.717	0.5

Note: θ_r is residual water content; θ_s is saturated water content; K_s is saturated hydraulic conductivity; α, n, γ are shape factor. The same applies below.

After the emergence of summer maize, the plant height (H), leaf length (L) and width (B) of summer maize under different growth stages were measured every 7-10 days using a steel tape. The leaf area index (LAI) was calculated using the equation ($LAI = (k \times L \times B) \cdot A^{-1}$, where k is the fitting coefficient (0.75 for summer maize), A is the area covered by summer maize leaves) *(Korzukhin and Grabovsky, 2020)*. A root auger with a diameter of 8 cm was used for sampling following the cross method. Five cores were taken from each maize plant, and each core was divided into five layers at 20 cm intervals, reaching a depth of 100 cm, to remove most of the maize roots and obtain root length data. The root length and root density distribution data of summer maize were obtained by scanning with a root scanner and analysed using a root analysis software (WinRHIZO PRO 2007). Summer maize yield was measured by the weight method after harvest, and yield was expressed as the dry grain yield ($kg \cdot ha^{-1}$). Meteorological data were obtained from an automatic weather station (Weather Hark, Campbell Scientific, Logan, UT, USA) located in the experimental area. The annual rainfall in 2018 and 2019 was 442.2 mm and 454.0 mm, respectively. Both years were considered normal years in the study area. The monthly average meteorological data are presented in Table 3.

Table 3

Monthly average meteorological data in 2018 and 2019

Month	Maximum temperature (°C)	Minimum temperature (°C)	Average temperature (°C)	Average humidity (%)	Average wind speed ($m \cdot s^{-1}$)	Average air pressure (kPa)	Rainfall (mm)
1	-0.51	-10.75	-2.54	56.34	1.17	90.82	2.40
2	1.56	-9.70	-1.67	48.46	1.27	90.33	4.40

Month	Maximum temperature (°C)	Minimum temperature (°C)	Average temperature (°C)	Average humidity (%)	Average wind speed ($m \cdot s^{-1}$)	Average air pressure (kPa)	Rainfall (mm)
3	11.61	-1.89	6.68	46.54	1.40	90.15	2.30
4	20.58	4.18	14.68	46.98	1.63	89.68	26.70
5	23.11	9.09	18.41	44.61	2.25	89.50	93.20
6	32.42	15.50	26.82	56.24	1.26	89.48	17.40
7	36.45	15.18	28.01	73.58	0.38	89.35	147.30
8	35.30	16.35	28.30	78.72	0.66	89.45	63.20
9	28.20	12.59	19.40	68.69	0.56	90.24	50.70
10	20.24	6.19	12.42	56.72	1.17	90.32	15.40
11	9.96	-2.01	3.19	58.83	1.26	90.69	31.00
12	0.77	-12.71	-3.17	62.84	1.37	90.59	0.00

SWAP Model

The SWAP (Soil-Water-Atmosphere-Plant) model was a comprehensive model that simulated soil water movement, solute transport, heat transfer, and crop growth processes at the field scale by integrating the theoretical research results of the current SPAC (Soil-Plant-Atmosphere Continuum) system *(Heinen et al., 2024)*. The SWAP model employed the classical Richards' equation to simulate the movement of unsaturated soil water, utilizes the convection-dispersion equation to model the transport of soil solute, and incorporated the WOFOST crop growth model to replicate the development of crops *(Hu et al., 2019)*. For a detailed introduction to the SWAP model, reference can be made to the SWAP model theory book by *van Dam et al. (1997)*.

The meteorological data used in the model were obtained from an automatic weather station installed in the experimental area in 2018 and 2019. Based on the soil texture and the depth of the active root zone of summer maize during the growth period, the simulated soil profile depth was set to 0-100 cm. The 0-100 cm soil profile was divided into 34 soil layers. The measured initial soil water content and soil salt content were used as input data for the SWAP model. The upper boundary conditions of the model included rainfall, evaporation, crop transpiration, and irrigation determined by meteorological factors. The lower boundary condition was defined as a prescribed head boundary based on the measured daily groundwater table depth in the study area. The actual irrigation quota was used for summer maize irrigation in the SWAP model. The simple crop growth module was used to simulate summer maize growth and yield. Summer maize growth was described using leaf area index (LAI), plant height (H), and rooting length (RL) as functions of the development stage (DVS). The DVS was assumed to vary linearly with growth time from emergence to harvest (0 < DVS < 2). Other input data required for the model were obtained from experimental measurements.

The RMSE (Root Mean Square Error) and MRE (Mean Relative Error) were utilized to quantify the deviation of the simulated results from the measured results. The RMSE and MRE were calculated using the following equations:

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

$$MRE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{S_i - M_i}{M_i}\right| \times 100\% \tag{2}$$

where N is the total number of measurements in the experiments, S_i and M_i are the i-th model simulated and measured values ($i=1, 2, \ldots, N$), respectively.

RESULTS AND ANALYSIS

Calibration and validation of SWAP model parameters

Soil water content

The comparison between the simulated and measured soil water content for different soil layers are shown in Fig. 2 and Fig. 3. The simulated values were in good agreement with the measured values in each soil layer during the summer maize growth period. The RMSE values were < 0.05 $cm^3 \cdot cm^{-3}$, and the MRE values were < 15%. These results indicate that the simulation of soil water content was feasible. The calibrated and validated parameters of the soil water characteristic curve are presented in Table 4.

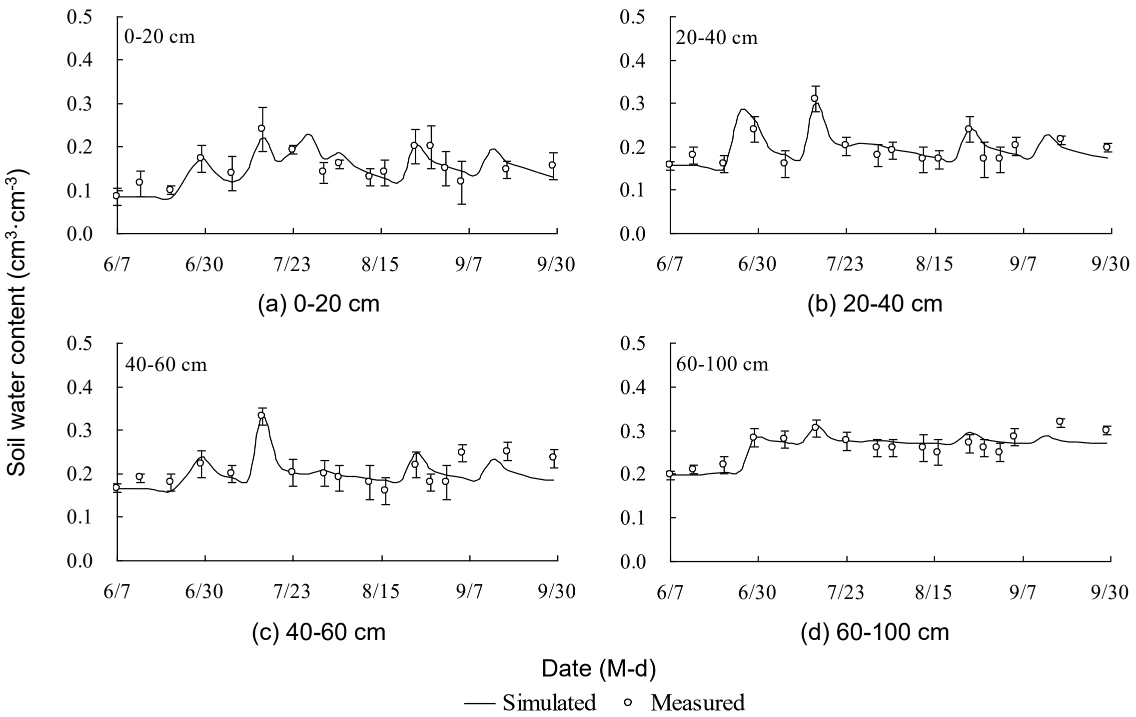

Fig. 2 - Comparison of simulated and measured soil water content for different soil layers during model calibration (2018)

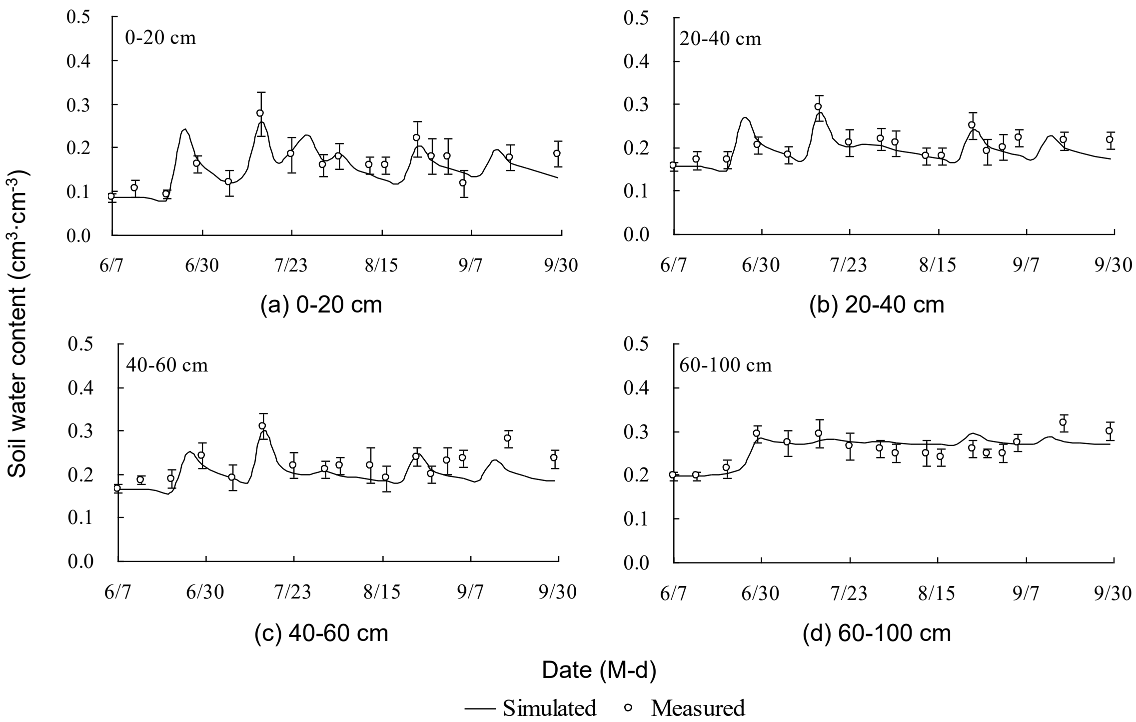

Fig. 3 - Comparison of simulated and measured soil water content for different soil layers during model validation (2019)

Table 4

Soil hydraulic parameters of different soil layers after calibration and validation

Soil depth (cm)	θ_r (cm^3·cm^{-3})	θ_s (cm^3·cm^{-3})	K_s (cm·d^{-1})	α	n	γ
0-20	0.020	0.446	140.00	0.074	1.941	0.5
20-40	0.028	0.393	99.86	0.045	1.823	0.5
40-60	0.024	0.383	120.00	0.044	1.814	0.5
60-100	0.028	0.384	99.86	0.043	1.715	0.5

Soil salt content

Soil salt content was defined as the percentage of salt mass relative to the dry soil mass. The comparison between simulated and measured soil salt content for different soil layers is shown in Fig. 4 and Fig. 5. The simulated values were in good agreement with the measured values in each soil layer during the summer maize growth period, although the agreement was slightly poorer than that obtained during the soil water content calibration. The RMSE values were < 0.10 mg·cm^{-3}, and the MRE values were < 20%. These results indicate that the simulation of soil salt content was feasible. After model calibration and validation, the molecular diffusion coefficient was 0.85 cm^2·d^{-1}, and the dispersion length was 10.0 cm.

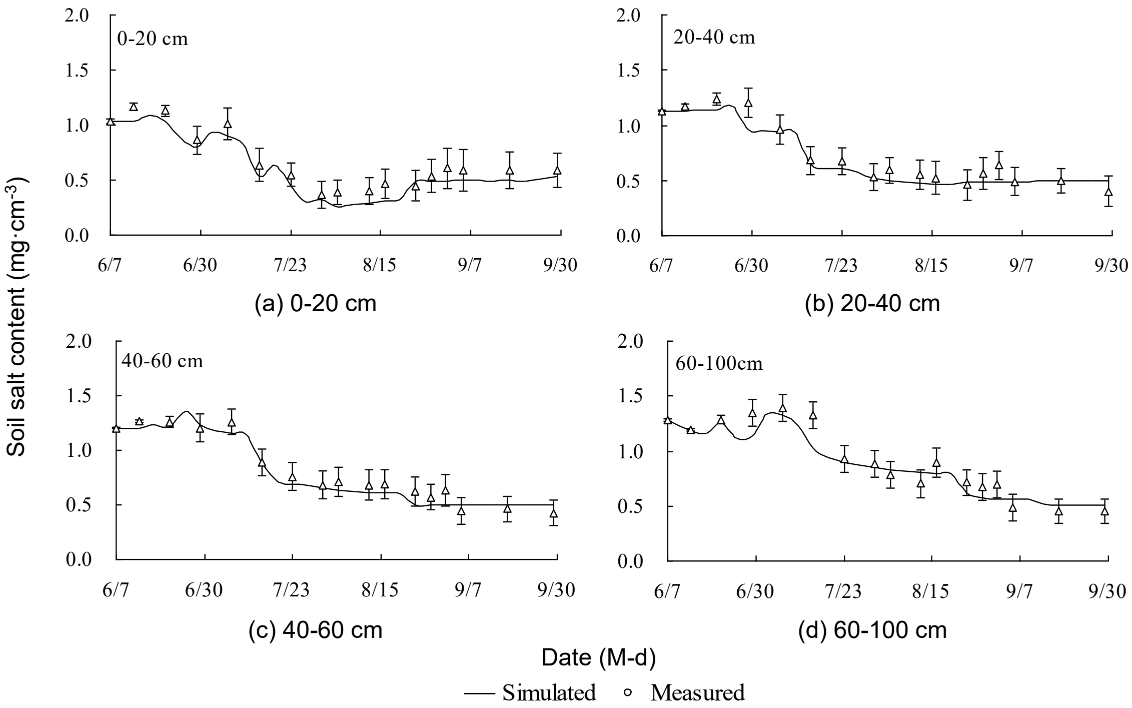

Fig. 4 - Comparison of simulated and measured soil salt content for different soil layers during model calibration (2018)

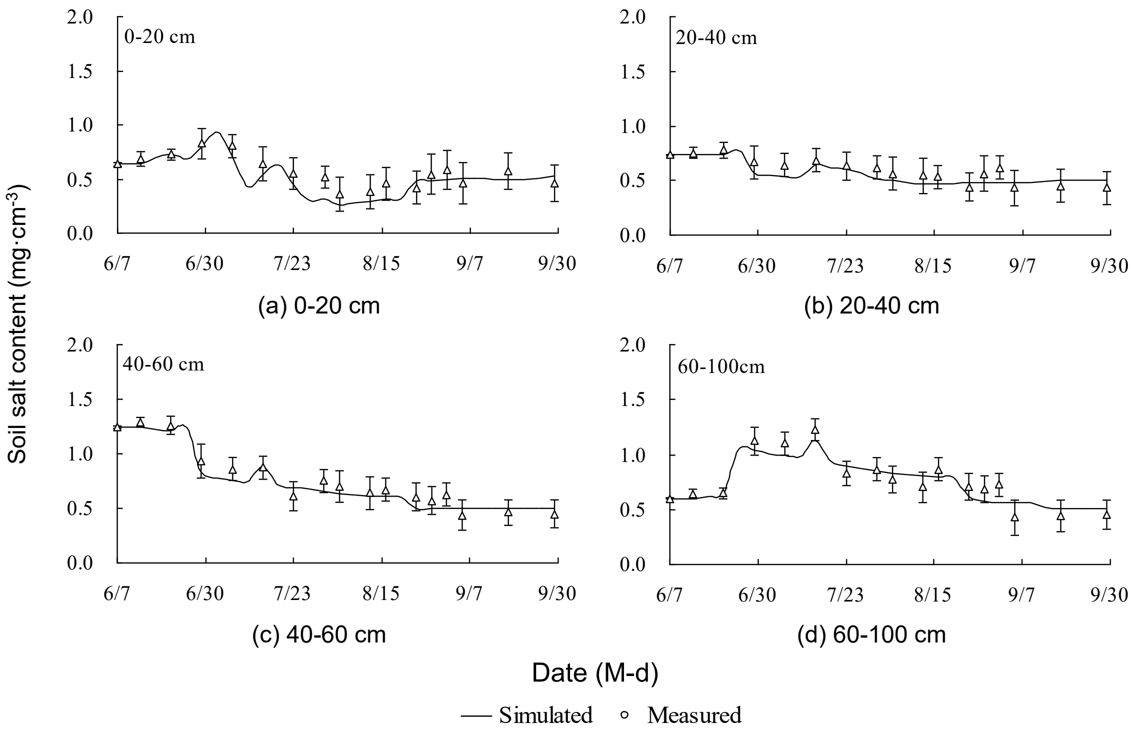

Fig. 5 - Comparison of simulated and measured soil salt content for different soil layers during model validation (2019)

Summer maize growth and yield

The comparison between simulated and measured plant height of summer maize is shown in Fig. 6. The simulated values were in good agreement with the measured values. The RMSE values were < 10 cm, and the MRE values were < 15%. The comparison between simulated and measured LAI of summer maize is shown in Fig. 7. The simulated values were also in good agreement with the measured values. The RMSE values of LAI were < 1.0 $cm^2 \cdot cm^{-2}$, and the MRE values were < 15%. These results indicate that the simulation of plant height and LAI was feasible.

The simulated yields of summer maize were 7902.4 and 7803.6 $kg \cdot ha^{-1}$ in 2018 and 2019, respectively. The measured yields from the field experiments were 8516.4 and 8507.0 $kg \cdot ha^{-1}$ in 2018 and 2019, respectively. The simulated values were in good agreement with the measured values (Fig. 8). The RMSE values for summer maize yield were < 800.0 $kg \cdot ha^{-1}$, and the MRE values were < 8.0 %. These results indicate that the simulation of summer maize yield was feasible. After model calibration and validation, the minimum canopy resistance, the critical salinity threshold (EC_{max}), and the decline rate of root water uptake per unit salinity (EC_{slope}) for summer maize were 70 $s \cdot m^{-1}$, 1.7 $dS \cdot m^{-1}$, and 12%, respectively.

The above results demonstrate that the SWAP model can accurately simulate soil water content, soil salt content, summer maize growth, and yield under the crop growth conditions in the study area after calibration and validation.

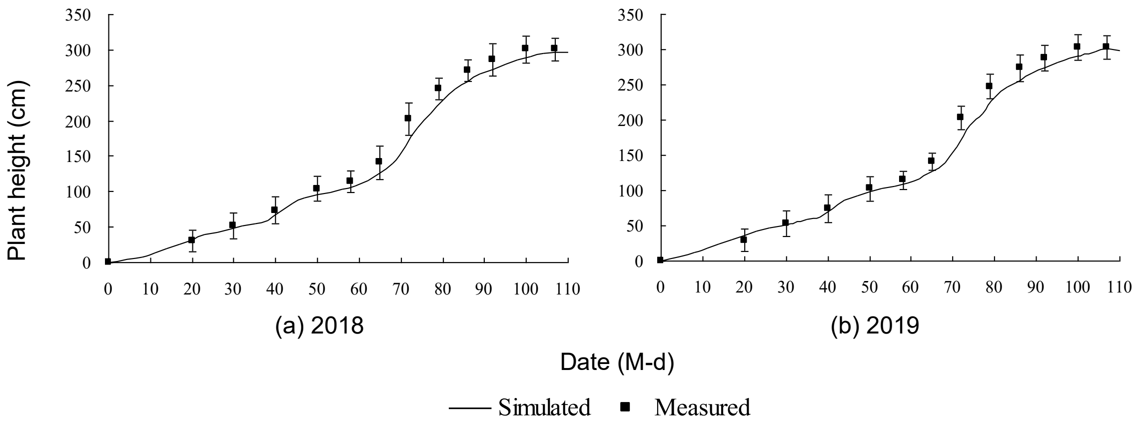

Fig. 6 - Comparison of simulated and measured plant height of summer maize during model calibration (a) and validation (b)

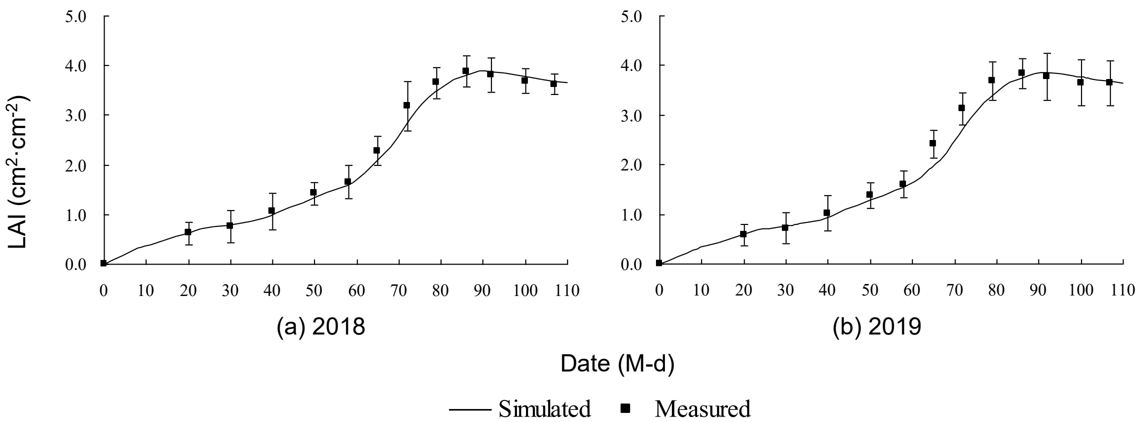

Fig. 7 - Comparison of simulated and measured LAI of summer maize during model calibration (a) and validation (b)

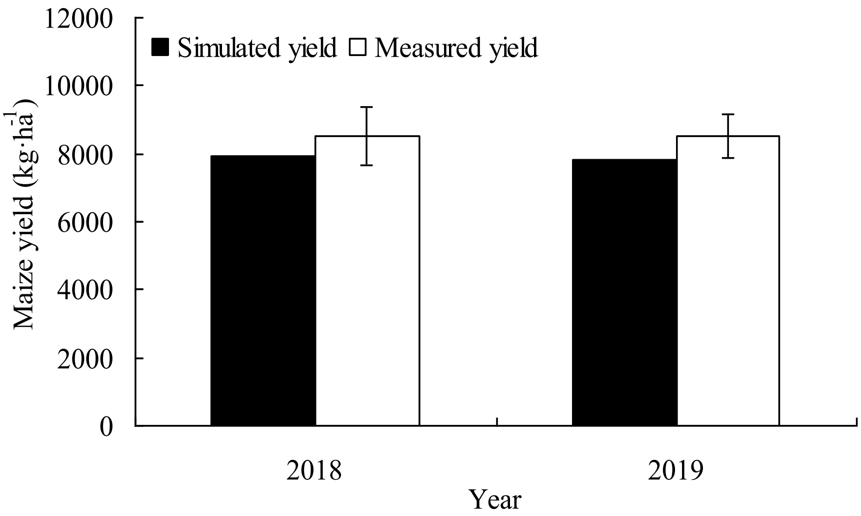

Fig. 8 - Comparison of simulated and measured summer maize yield during model calibration (2018) and validation (2019)

Simulation of soil water flux and cumulative soil water flux under different irrigation scenarios

Flood irrigation with canal water for summer maize is an extensive irrigation method in the Lupotan area of Northwest China, which easily leads to water resource waste and secondary soil salinization *(Xu et al., 2019)*. Proper adjustment and optimization of crop irrigation quotas can promote the efficient utilization of water resources. Based on meteorological data from 1961 to 2023, the rainfall corresponding to 25%, 50%, and 75% hydrologic years was 521, 454, and 405 mm, respectively. The differences among the different hydrologic year levels were small; therefore, only the 50% hydrologic year was used for model simulation. Under the actual planting conditions in Lupotan, the irrigation quota (IQ) for summer maize was 5000 $m^3 \cdot ha^{-1}$. In this study, three irrigation scenarios were simulated: 80% IQ (4000 $m^3 \cdot ha^{-1}$), 70% IQ (3500 $m^3 \cdot ha^{-1}$), and 60% IQ (3000 $m^3 \cdot ha^{-1}$). Meanwhile, the irrigation quota at each growth stage of summer maize was adjusted according to the corresponding proportion. The initial soil water and salt contents and summer maize growth parameters were consistent with the measured field experimental data from 2018. The upper boundary conditions included rainfall, evaporation, crop transpiration, and irrigation determined by meteorological factors. The lower boundary condition was defined as a prescribed groundwater table depth based on observations from a groundwater monitoring well in 2018. The simulated soil profile depth was set to 0-100 cm. Soil water flux and soil salt flux for different soil layers were simulated using the SWAP model. On this basis, the optimal irrigation quota for summer maize in the Lupotan area was determined.

Soil water flux simulation results of different soil profiles under different scenarios are shown in Fig. 9. The 60 cm profile was the soil profile of summer maize main root system layer, which was expressed as the water flux of the lower boundary of the root zone. The 100 cm profile was the soil profile of the largest root depth of summer maize, which was expressed as the water flux of the lower boundary of the storage zone. Soil water flux was negative downward and positive upward (the same as below). Soil water flux change was closely related to irrigation and rainfall at the lower boundary of root zone. Soil water leakage in root zone mainly occurred after four times irrigation, and decreased with the decrease in irrigation quota. Soil water flux was below -7.0 $mm \cdot d^{-1}$ under 80% IQ, and below -2.0 $mm \cdot d^{-1}$ under 70% IQ and 60% IQ scenarios. It was shown that the reduction of irrigation quota could reduce the amount of soil water leakage. It could reduce soil water loss, allowing most of the water introduced by irrigation and rainfall to be retained in the root zone of summer maize for crop use. Variation law of soil water flux at the lower boundary of the storage zone was similar to that of the root zone. Soil water flux was below -2.0 $mm \cdot d^{-1}$ under the 80% IQ scenario, and below -1.0 $mm \cdot d^{-1}$ under the 70% IQ and 60% IQ scenarios. All three scenarios reduced soil water flux at the lower boundary of the storage zone, decreased downward soil water leakage losses, and promoted soil water storage within the storage zone. Obvious soil water exchange occurred between the crop root zone and the storage zone.

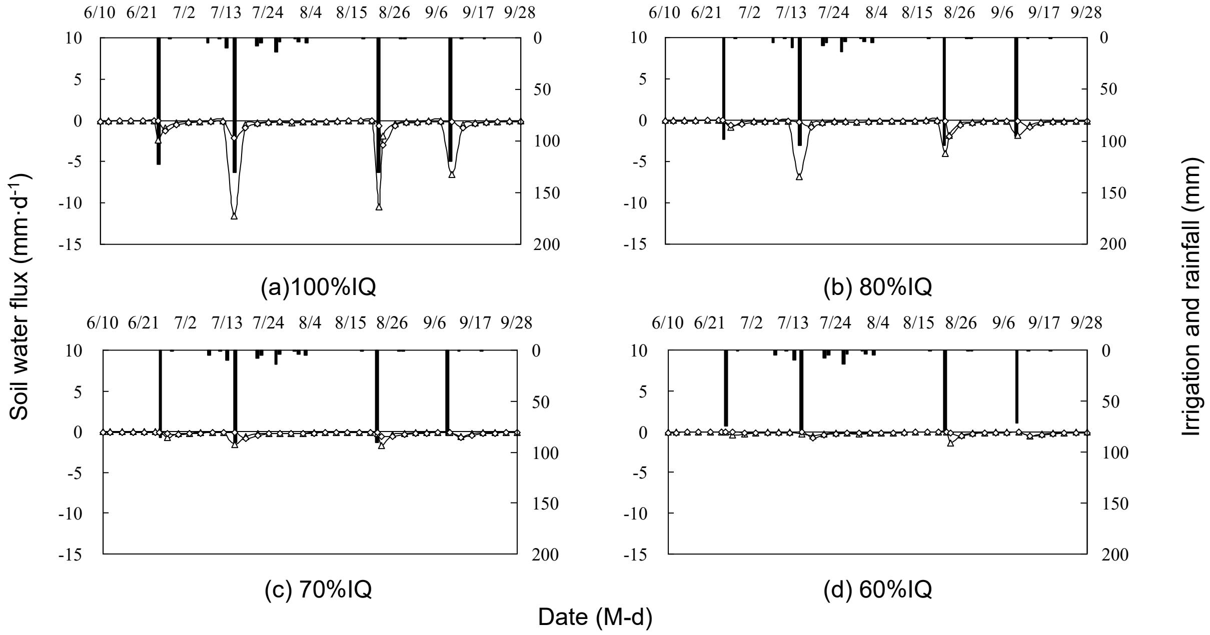

Fig. 9 - Simulated soil water flux under different irrigation scenarios: (a)100%IQ; (b)80%IQ; (c)70%IQ and (d) 60%IQ

Table 5 shows the soil water cumulative flux in different soil profiles under different irrigation scenarios. A negative soil water cumulative flux indicates downward soil water leakage. The soil water cumulative flux at the lower boundaries of the root zone and the storage zone decreased with decreasing irrigation quota. Compared with the 100% IQ scenario, the soil water cumulative flux at the lower boundary of the root zone decreased by 47.21%, 75.93%, and 81.31% under the 80% IQ, 70% IQ, and 60% IQ scenarios, respectively. Reducing the irrigation quota decreased soil water leakage from the root zone and improved crop water use efficiency. Similarly, the soil water cumulative flux at the lower boundary of the storage zone decreased by 27.23%, 42.20%, and 50.10% compared with the 100% IQ scenario under the 80% IQ, 70% IQ, and 60% IQ scenarios, respectively. Reducing the irrigation quota promoted soil water storage in the storage zone. Moreover, when the irrigation quota was reduced to 70% IQ and 60% IQ, the soil water cumulative flux at the lower boundaries of both the root zone and the storage zone was small, indicating that water supplied by irrigation and rainfall could be stably stored in the 0-100 cm soil layer to meet the growth requirements of summer maize.

Table 5

Soil water cumulative flux of 60 cm and 100 cm soil profiles under different irrigation scenarios

Soil profile (cm)	Soil water cumulative flux (mm)			
	100%IQ	**80%IQ**	**70%IQ**	**60%IQ**
60	-38.89	-20.53	-9.36	-7.27
100	-15.57	-11.33	-9.00	-7.77

Simulation of soil salt flux and cumulative soil salt flux under different irrigation scenarios

The simulation results of soil salt flux in different soil profiles under different irrigation scenarios are shown in Fig. 10. Soil salt flux exhibited a variation pattern similar to that of soil water flux, and soil salt flux at the lower boundary of the root zone decreased with decreasing irrigation quota. At the lower boundary of the root zone, soil salt flux was below -9.5 mg·(cm^2·d)$^{-1}$ under the 80% IQ scenario, below -3.0 mg·(cm^2·d)$^{-1}$ under the 70% IQ scenario, and below -1.5 mg·(cm^2·d)$^{-1}$ under the 60% IQ scenario. At the lower boundary of the storage zone, soil salt flux was below -1.8 mg·(cm^2·d)$^{-1}$ under the 80% IQ, 70% IQ, and 60% IQ scenarios. Soil salt flux decreased with decreasing soil water flux, which clearly reflects the water–salt transport characteristic that “salt comes with water and salt goes with water” *(Wang et al., 2019)*.

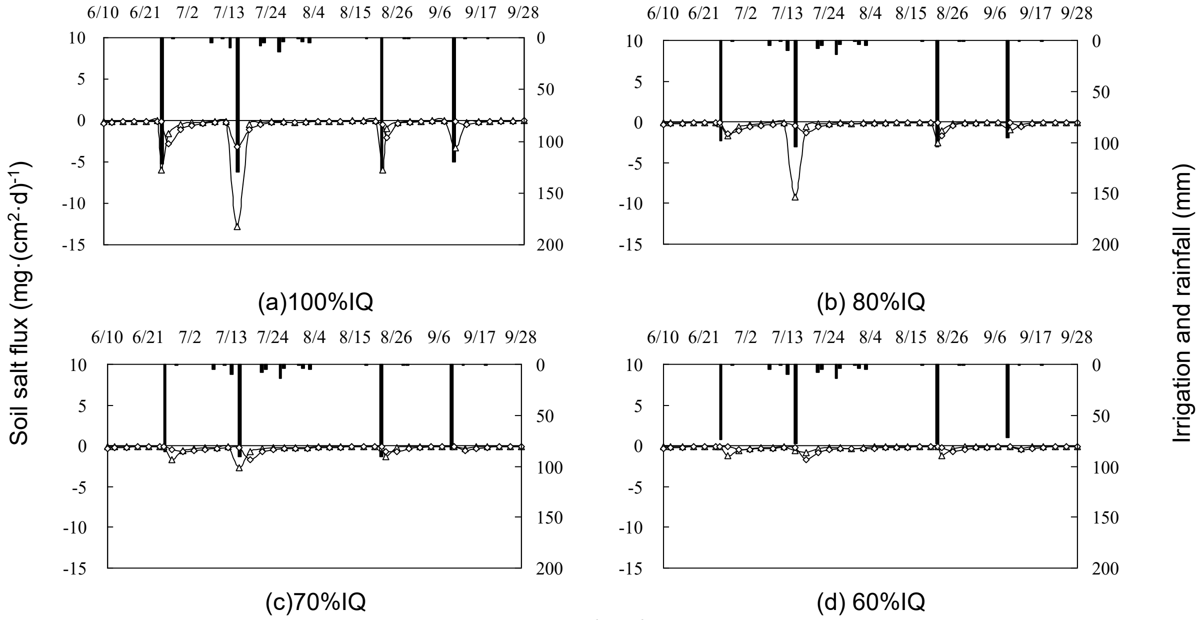

Fig. 10 - Simulated soil salt flux under different irrigation scenarios: (a)100%IQ; (b)80%IQ; (c)70%IQ and (d)60%IQ

The soil salt cumulative flux in different soil profiles under different irrigation scenarios was shown in Table 6. If soil salt cumulative flux was negative, it meant that soil salt was leached downward. The soil salt cumulative flux at the lower boundary of root zone and the lower boundary of water storage zone decreased with the decrease in irrigation quota. The soil salt cumulative flux at the boundary under the root zone decreased by 40.66%, 66.73% and 72.87 % compared with 100% IQ under 80% IQ, 70% IQ and 60% IQ scenarios, respectively.

The soil salt cumulative flux at the lower boundary of storage zone decreased by 21.36%, 26.91% and 29.58% compared with 100% IQ under 80% IQ, 70% IQ and 60% IQ scenarios, respectively. When irrigation quota was reduced to 70% IQ and 60% IQ, the change of soil salt cumulative flux at the lower boundary of root zone and the lower boundary of storage zone was small, and less soil salt brought by irrigation was accumulated in the 0-100 cm soil layer.

In addition, the simulated summer maize yield were 7408.50, 7182.16 and 6914.60 kg·ha^{-1} under 80% IQ, 70% IQ and 60% IQ scenarios, respectively, which were 6.25%, 9.11% and 12.5% lower than 100% IQ (7902.4 kg·ha^{-1}) scenarios. Through comprehensive analysis, the irrigation quota was optimized according to the standard that soil water-salt flux and soil water-salt cumulative flux at the lower boundary of root zone and storage zone were small and the yield reduction of summer maize was less than 10%. Therefore, 3500 m^3·ha^{-1} (70% IQ) could be used as the optimal irrigation quota for summer maize from the perspective of soil water-salt flux and crop yield in the study area.

Table 6

Soil salt cumulative flux of 60 cm and 100 cm soil profiles under different irrigation scenarios

Soil profile (cm)	Soil salt cumulative flux (mg·cm^{-2})			
	100%IQ	80%IQ	70%IQ	60%IQ
60	-35.05	-20.80	-11.66	-9.51
100	-17.65	-13.88	-12.90	-12.43

DISCUSSION

The SWAP model simulates soil water and solute transport in a one-dimensional vertical soil profile and does not consider the flow interactions between soil water and groundwater across different regions *(Hu et al., 2019)*. Although the study area was selected as a standardized farmland experimental field with a large area and potential exchange between soil water and groundwater, the SWAP model simulation did not account for soil water–groundwater interactions. Under these conditions, soil hydraulic characteristic parameters were relatively easier to calibrate accurately, resulting in higher model accuracy for soil hydraulic properties and solute transport parameters. The accuracy of solute transport parameters was relatively lower, mainly because parameters such as the molecular diffusion coefficient, dispersion, and the solute exchange rate between free water and adsorbed water are difficult to adjust to optimal values *(Zhang et al., 2021)*. In addition, solute transport occurs not only with soil water movement but also under the influence of solute concentration gradients *(Lei et al., 2023)*. During SWAP model calibration, parameter estimation was conducted using a trial-and-error approach *(Fattori and Marin, 2023; Wang et al., 2024)*. This method has limitations, including high computational demand, long processing time, and strong subjectivity. Moreover, the SWAP model lacks an embedded parameter sensitivity analysis module, making it difficult to accurately identify parameters with a greater influence on simulation results *(Zhao et al., 2020; Huang et al., 2024)*.

Although there were some limitations between the SWAP model and the actual situation in simulating soil water and salt transport and crop growth, the theoretical basis of the SWAP model was mature and reliable (*Yu et al., 2020*). Data of model simulation was easy to obtain through field experimental determination, and the model was relatively easy to operate and use. It had been widely accepted and recognized in practice. The SWAP model was widely used to simulate soil water and salt transport in arid or semi-arid areas around the world (*Ravensbergen et al., 2024*). Soil water and salt transport was complex and changeable. SWAP model simulation was an effective method to study the change of soil water-salt transport, crop growth and irrigation management (*Alavi et al., 2022*). The SWAP model can also be coupled with other soil physical models and crop growth models, which can improve the accuracy of the model simulation and improve the applicability of the model (*Zhang et al., 2025*).

CONCLUSIONS

To determine the optimal water-saving irrigation quota for summer maize in salinized farmland of Northwest China, the SWAP model parameters were calibrated and validated using field experimental data from 2018 and 2019. The simulated soil water content, soil salt content, and summer maize yield showed good agreement with the measured values. During calibration and validation, the RMSE and MRE values of soil water content were less than 0.05 $cm^3·cm^{-3}$ and 15%, respectively, while those of soil salt content were less than 0.10 $mg·cm^{-3}$ and 20%, respectively. The RMSE values of summer maize yield were below 800.0 $kg·ha^{-1}$, and the MRE values were below 8.0%. After calibration and validation, reliable model parameters were obtained, and the simulation of soil water content, soil salt content, summer maize growth, and yield was feasible. Using the calibrated and validated SWAP model, soil water–salt fluxes, cumulative soil water–salt fluxes, and summer maize yield were simulated under different irrigation scenarios (100% IQ, 80% IQ, 70% IQ, and 60% IQ) in the study area. Soil water flux, soil water cumulative flux, soil salt flux, and soil salt cumulative flux at the lower boundaries of the crop root zone and storage zone decreased with decreasing irrigation quota. When the irrigation quota was reduced to 70% IQ and 60% IQ, the changes in soil water cumulative flux and soil salt cumulative flux were small. Soil water introduced by irrigation and rainfall could be stably stored in the 0-100 cm soil layer to meet the growth requirements of summer maize. When the irrigation quota was 3500 $m^3·ha^{-1}$ (70% IQ), the yield reduction of summer maize was less than 10%. Therefore, 3500 $m^3·ha^{-1}$ (70% IQ) was identified as the optimal irrigation quota for summer maize from the perspective of soil water–salt flux and crop yield in the study area. This study provides technical support for the efficient utilization of water resources and guidance for agricultural production practices in Northwest China.

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