ENGINEERING Agriculture

Engineering Journals

RESEARCH ARTICLE

2027 / Volume 14 / Issue 3 / 27732

Optimization of cultivated-wasteland ratio and crop irrigation quota in the Hetao Irrigation District based on long-term soil salinity simulation

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KEYWORDS

China, Hetao Irrigation District, SaltMod model, branch canal scale

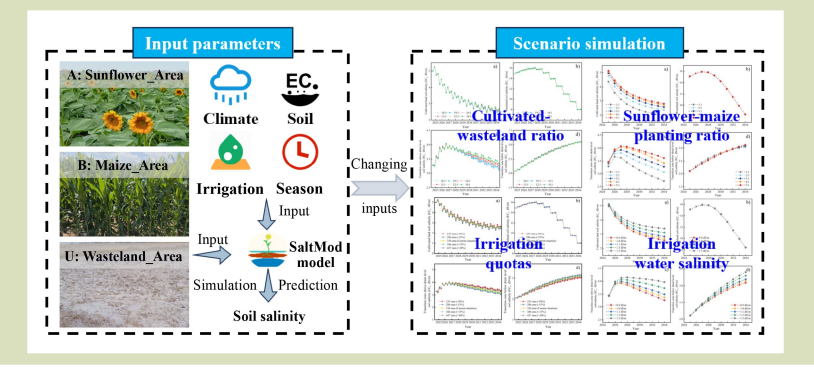
HIGHLIGHTS

- Simulate and predict soil salinity in the root zone and transition zone over the next 10 years.
- Obtain the optimal cultivated-wasteland ratio and sunflower-maize planting ratio.
- Determine the optimal irrigation quotas under the goals of water saving and salinity control.
- Determine the suitable threshold of irrigation water salinity.

Received May 5, 2026;
Accepted June 16, 2026.

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GRAPHICAL ABSTRACT



ABSTRACT

The Hetao Irrigation District serves as a vital grain production base in China. To enhance the allocation of water and soil resources within this district, this study conducted field experiments specifically in the Hetao Irrigation District. Utilizing long-term soil salinity simulations, various scenario schemes were established to optimize the cultivated-wasteland ratio and crop irrigation quotas in the area under investigation. The results indicate that over the next decade, soil salinity levels in wasteland, cultivated land, and the transition zone above the drain level are expected to decrease, whereas soil salinity in the transition zone below the drain level is projected to increase. The optimal cultivated-wasteland ratio identified for the study area is 12:1, with a suitable sunflower-maize planting ratio threshold of 4:1. The optimal irrigation quotas for maize and sunflower are determined to be 286 and 175 mm, respectively, which represent water savings of 15% and 5% compared to the existing

irrigation quotas, thereby effectively controlling soil salinization. Additionally, the suitable threshold for irrigation water salinity in this area is established at 1.0 dS·m^{-1}. This study provides a scientific foundation for the prevention and control of soil salinization, as well as the efficient utilization of water and soil resources within the irrigation district.

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1 Introduction

Soil salinization is a critical issue that restricts sustainable agricultural development and ecological stability in arid and semi-arid regions worldwide[1–3]. Statistically, approximately 1 billion hectares of land globally are affected by salinization[4]. With the increasing prominence of climate change and water scarcity[5,6], the risk of regional salt stress continues to intensify[7,8]. The Hetao Irrigation District, situated in the Yellow River Basin, serves as an important production base for grain and oil crops in China[9,10] and is recognized as a typical salinized irrigation district[11]. For an extended period, the diversion of the Yellow River for irrigation has supported agricultural development while altering the regional natural water-salt cycle[12]. Coupled with high evaporation rates and inappropriate irrigation and tillage practices, the risk of secondary soil salinization has been further exacerbated, thereby restricting the sustainable use of cultivated land[13]. Consequently, optimizing and maintaining a long-term balance of soil salts in the irrigation district has emerged as a core scientific issue that urgently requires resolution for the sustainable agricultural development of the Hetao Irrigation District.

Dynamic simulation of soil salinity serves as a crucial foundation for understanding the evolution of salinization and optimizing agricultural management strategies[14,15]. Currently, researchers both domestically and internationally have conducted extensive studies on soil salinity simulation using various models, including HYDRUS[16,17], SWAP[18,19], and UNSATCHEM[20]. However, there is a notable lack of studies focusing on the long-term evolution of soil salinity across different land types, such as cultivated land with multiple crops and wasteland, as well as the optimization of the cultivated-wasteland ratio and crop planting ratio[21,22]. Wasteland is a crucial component of the irrigation ecosystem and can receive salts leached and migrated from cultivated land through the "dry drainage" effect[23]. Studies have demonstrated that salts in cultivated soil are leached into groundwater following irrigation; driven by a hydraulic gradient, groundwater transports substantial amounts of salt to wasteland, where these salts ultimately accumulate with water due to evapotranspiration[24,25]. However, an excessively high proportion of wasteland occupies cultivated land resources and reduces grain yield, while an excessively low proportion diminishes salt discharge capacity and increases the risk of salinization in cultivated land. Meanwhile, optimizing the crop planting structure is also vital for the ecological health of irrigation districts[26]. In recent years, the planting area of sunflowers has continued to expand in the Yichang Irrigation Subdistrict of the Hetao Irrigation District, establishing it as the main crop for regional agricultural production[27]. Compared to maize, sunflowers require less irrigation water during the growing season, and their soil salt leaching effect is significantly weaker than that of maize fields. The continuous increase in the sunflower planting area tends to exacerbate salt accumulation in the soil profile and heightens the risk of secondary salinization. Therefore, determining a reasonable cultivated-wasteland ratio and an appropriate sunflower-maize planting ratio threshold is of great significance for achieving efficient land resource utilization and controlling salinization in the irrigation district.

Irrigation serves as a crucial measure for salt regulation in irrigation districts, with the irrigation quota directly influencing the input and output processes of regional salt dynamics[28,29]. Currently, most studies on irrigation quota optimization rely on short-term experiments and single-crop responses[30,31], neglecting the long-term soil salt accumulation processes associated with various crops. Given the significant disparities in water demand among different crops, it is essential to examine their optimal irrigation quotas separately to facilitate precise irrigation management and salt regulation at a regional scale. The SaltMod model has gained popularity in simulating regional salt dynamics due to its minimal parameter requirements, moderate input data needs, and suitability for

long-term simulations[32]. However, the majority of current applications of the SaltMod model concentrate on optimizing regional comprehensive irrigation quotas[33,34], with relatively few studies addressing irrigation quotas for crops with distinct water requirements. Moreover, selecting an appropriate scale can elucidate the essence of the research subject[35]. The branch canal scale, as an optimal scale bridging farmland and region, possesses relatively complete hydrological boundaries[36] and reflects the interactions within the cultivated-wasteland system, making it an appropriate scale for optimizing the cultivated-wasteland ratio and irrigation quota. Long-term simulations at the branch canal scale allow for the incorporation of various land type configurations and crop combinations into the analysis, thereby enhancing the practical significance of the optimization scheme.

In light of the aforementioned shortcomings, this study focuses on a typical branch canal within the Hetao Irrigation District as the research unit. It conducts a long-term simulation of soil salt dynamics using the SaltMod model, while systematically optimizing the cultivated-wasteland ratio and irrigation quota. The primary contributions of this research are as follows: (1) Extending the depth of soil simulation from the root zone to the transition zone, enabling the simulation and prediction of dynamic changes in soil salinity across different soil layers over the next decade at the branch canal scale. (2) Determining the optimal cultivated-wasteland ratio and threshold for sunflower-maize planting ratios based on long-term soil salinity simulations, achieved by establishing scenarios with varying cultivated-wasteland ratios and sunflower-maize planting ratios. (3) Taking into account the differences in irrigation requirements between sunflower and maize, the study optimizes irrigation quotas for each crop separately and explores coordinated regulation schemes under various irrigation water salinity scenarios. This research provides a scientific foundation and technical support for controlling soil salinization and for the efficient utilization of agricultural water resources in the Hetao Irrigation District.

2 Material and methods

2.1 Study area

The experiment was conducted from 2022 to 2024 in the Yichang Irrigation Subdistrict, located in the lower reaches of the Hetao Irrigation District in Inner Mongolia, China. The study area encompasses the irrigation and drainage unit controlled by the Zuo Er Branch Canal, measuring approximately 2.78 km in width from east to west and 5.24 km in length from north to south, with a total area of 1553 ha. Geographically, it is situated at a longitude of 108°19′7″ to 108°21′19″ E and a latitude of 41°6′41″ to 41°9′39″ N, with an altitude ranging from 1021.23 m to 1025.97 m. The region experiences a temperate continental monsoon climate, characterized by dry and windy conditions throughout the year, ample sunshine, significant evaporation, large diurnal temperature variations, and a brief frost-free period. The daily meteorological elements of the study area from 2022 to 2024 are shown in Fig. 1.

2.2 Experimental design

In 2022, 53 soil sampling sites were arranged using a grid method (600 m × 600 m). In 2023 and 2024, the soil sampling sites were adjusted to 48 locations. Soil sampling was conducted from April to October each year using an auger for layered sampling. Sampling was performed at an interval of 20 cm. Denser sampling was implemented for the topsoil due to its severe soil salinization. The final sampling depths were 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm. A portion of the collected soil samples was air-dried and passed through a 1 mm sieve to prepare a soil-water extract at a ratio of 1:5, and the electrical conductivity was measured using a conductivity meter (Leici DDS-307A, Shanghai, China). The soil data adopted in this study are the average values of each soil layer. A total of 11 groundwater observation wells were installed in the study area, with groundwater depth measured directly using a plumb bob. The field coordinates of soil sampling sites and groundwater wells were recorded utilizing GPS technology. The irrigation schedules for maize and sunflower in the study area from 2022 to 2024 are presented in Table 1.

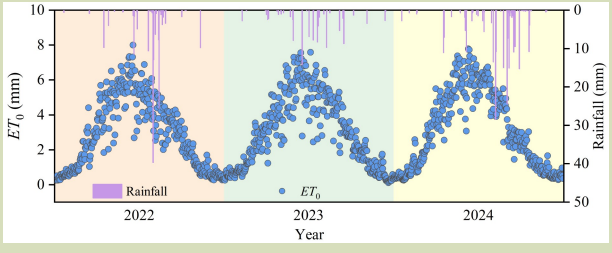


Fig. 1 Meteorological parameters in the study area.

Table 1 Irrigation schedule in the study area

Crop	Year	Irrigation date	Average irrigation depth per application (mm)	Coefficient of variation for irrigation depth per application (%)	Irrigation quota (mm)
Maize	2022	June 17	103	6.22	307
		July 15	109	9.71	
		August 24	95	6.47	
	2023	June 27	98	6.58	296
		July 15	103	11.54	
		August 4	95	5.35	
	2024	June 14	93	5.52	405
		July 9	90	4.71	
		July 24	106	12.21	
		August 6	116	8.68	
Sunflower	2022	April 18	190	11.12	190
	2023	April 29	171	10.72	171
	2024	April 2	190	11.63	190

2.3 SaltMod model

2.3.1 Model fundamental principles

The SaltMod model is predicated on the principles of water and salt balance, utilized for simulating and predicting soil salinity across various regions[37]. This model executes simulation calculations using a seasonal time step as input, allowing for the division of a year into one to four simulation seasons. Additionally, it categorizes each season into three distinct agricultural planting areas (A, B, U). The model further stratifies the study area into four balance zones: the surface layer, root zone, transition zone, and aquifer. Given that the study area is situated in an arid region characterized by low rainfall and high evaporation rates, surface runoff is assumed to be negligible. Furthermore, due to the considerable depth of the aquifer, its salinity is effectively constant and thus not analyzed in this study. Consequently, this research focuses exclusively on the root zone and transition zone as the two primary balance zones. The principles and equations governing the salt balance within the model are comprehensively referenced from the *SaltMod Model Manual*[37].

2.3.2 Principles of model simulation and prediction

The SaltMod model is designed to predict long-term water and salt dynamics by analyzing general trends and simulating future variations using long-term average input values. Initially, historical measured data from the study area are utilized to calibrate and validate the fundamental model parameters, ensuring that the model accurately reflects the laws governing water and salt movement in the region. Subsequently, the model's operational duration is established to facilitate dynamic simulation and prediction of water and salt conditions. During this predictive phase, the basic parameters and average values derived from historical measured data are employed as initial conditions. Finally, seasonal time steps are implemented, adhering to the recursive principle whereby the final conditions from the previous year (such as groundwater levels and salinity) are automatically adopted as the initial conditions for the subsequent period. The calculations continue year by year until the model's predetermined operational years are completed.

2.3.3 Determination of model input parameters

The main crops in the study area are sunflower and maize, so the study area is divided into Zone A (sunflower), Zone B (maize), and Zone U (wasteland). Groundwater depth, seasonal irrigation amount, precipitation and soil salinity adopt the measured data of the study area. Evapotranspiration can be calculated by the crop coefficient method and empirical formulas referenced from the Hetao Irrigation District[38–40]. The principal model parameters are established based on the measured data from the study area, model calibration, and

findings from prior research conducted in the Hetao Irrigation District (Table 2)[41,42].

The soil salinity data input into the SaltMod model is the salinity (*EC*) of field soil at saturated moisture content, while the salinity value calculated in this paper is $EC_{1:5}$. It is necessary to first convert it to EC_e and then to *EC*, with the specific conversion formulas as follows[43]:

$$EC = 2EC_e \quad (1)$$

$$EC_e = 5.88EC_{1:5}+1.33 \quad (2)$$

where *EC* is the salinity of field soil at saturated moisture content, dS·m^{-1}; EC_e is the electrical conductivity of saturated soil extract, dS·m^{-1}; $EC_{1:5}$ is the electrical conductivity of soil extract with a soil-to-water ratio of 1:5, dS·m^{-1}.

Table 2 Main input parameters of the model

Input parameter	Parameter value
Number of years for the model to run	10
Cultivated land area (ha)	1233
Wasteland area (ha)	78
Average area fraction of Zone A	0.71
Average area fraction of Zone B	0.23
Average area fraction of Zone U	0.06
Simulated seasons	4
Season 1	April–May
Season 2	June–September
Season 3	October–November
Season 4	December–March
Canal water utilization coefficient	0.8
Root zone thickness (m)	1
Transition zone thickness (m)	4
Aquifer thickness (m)	90
Root zone total porosity	0.48
Transition zone total porosity	0.48
Aquifer total porosity	0.4
Root zone drainable porosity	0.07
Transition zone drainable porosity	0.07
Aquifer total drainable porosity	0.1
Salinity irrigation water (dS·m^{-1})	0.9
Salinity rainfall (dS·m^{-1})	0
Initial groundwater depth (m)	1.8
Critical depth of the water table for capillary rise (m)	2.3

3 Results

3.1 Validation of the SaltMod Model

Natural drainage discharge (G_n) is challenging to measure experimentally; therefore, its value is determined through fitting analysis that compares simulated and measured values. G_n is defined as the difference between seasonal ground water outflow through the aquifer (G_o, m^3·m^{-2}·season^{-1}) and seasonal ground water inflow through the aquifer (G_i, m^3·m^{-2}·season^{-1}). The overall accuracy of natural drainage was verified using simulated and measured seasonal drainage volume from 2022 to 2024 (Fig. 2). Four sets of parameter combinations (0.01, –0.03, 0.01, 0), (0.03, –0.05, 0.02, 0), (0.05, –0.07, 0.03, 0) and (0.07, –0.09, 0.04, 0) were selected corresponding to Season 1 to Season 4 respectively. Positive values indicate G_i = 0 and G_o equal to the positive value; negative values indicate G_o = 0 and G_i equal to the absolute value of the negative number. When G_n was set to (0.05, –0.07, 0.03, 0), the coefficient of determination (R^2) between simulated and measured seasonal drainage volume reached 0.6964, which was 1.25% to 13.49% higher than the other combinations. By utilizing the three-year average data as model input, the fitted R^2 between simulated and measured seasonal drainage volumes was 0.8818, indicating high accuracy and strong representativeness (Fig. 2(e)). Thus, G_n = (0.05, –0.07, 0.03, 0) was determined for the study area.

3.2 Long-term soil salinity simulation

In this study, the input data for the SaltMod model were the average of observed data from 2022 to 2024. With 2025 as the starting year, the dynamic changes in soil salinity in the study area were predicted for the next ten years. In the model, the root zone was further categorized into cultivated land and wasteland. Consequently, the soil salinity of cultivated land in this study specifically refers to the root zone salinity of cultivated land, while the soil salinity of wasteland pertains to the root zone salinity of wasteland. As shown in Table 3, from 2025 to 2034, soil salinity in wasteland, cultivated land, and the transition zone above the drain level decreased by 6.725, 2.399, and 0.161 dS·m^{-1}, respectively, while soil salinity

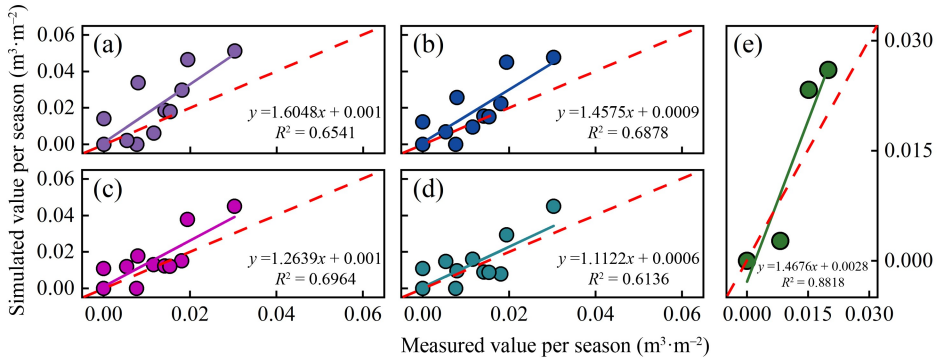


Fig. 2 Overall accuracy verification of natural drainage volume. (a) G_n = (0.01, –0.03, 0.01, 0); (b) G_n = (0.03, –0.05, 0.02, 0); (c) G_n = (0.05, –0.07, 0.03, 0); (d) G_n = (0.07, –0.09, 0.04, 0); (e) Verification of G_n with the 3-year average drainage volume.

Table 3 Simulated soil salinity values in the study area for the 10 years

Year	Wasteland soil salinity (dS·m^{-1})	Cultivated land soil salinity (dS·m^{-1})	Transition zone above drain level soil salinity (dS·m^{-1})	Transition zone below drain level soil salinity (dS·m^{-1})
2025	15.113	4.958	3.429	2.101
2026	15.613	4.255	3.880	2.259
2027	15.900	3.789	3.930	2.414
2028	15.825	3.453	3.858	2.555
2029	15.288	3.196	3.749	2.680
2030	14.250	3.001	3.650	2.788
2031	12.925	2.851	3.553	2.881
2032	11.438	2.733	3.458	2.964
2033	9.888	2.639	3.364	3.031
2034	8.388	2.559	3.268	3.089

in the transition zone below the drain level increased by 0.988 dS·m^{-1}. This is due to the annual implementation of autumn irrigation in the study area. Large volumes of irrigation water leach soil salts down to deeper layers, which are subsequently discharged through drainage ditches. As a result, the soil salt content above the drainage outlets in both cultivated land and transitional zones decreased in 2034 compared to 2025. During the irrigation of cultivated land, water laterally recharges adjacent wasteland and leaches its salts into deeper soil layers for subsequent drainage, leading to reduced salinity in the wasteland. In contrast, the soil beneath the drainage outlets in transitional zones retains residual salts that are not effectively drained, resulting in gradual salt accumulation and increasing salinity.

3.3 Optimization of cultivated-wasteland ratio

To investigate the optimal area ratio of cultivated land to wasteland in the study area, six scenarios with varying cultivated-wasteland ratios were established by modifying the wasteland area: 24:1, 19:1, 16:1 (current situation), 13:1, 12:1, and 10:1. Based on the average simulated soil salinity from 2025 to 2034, the soil salinity in the transition zone above the drain level was found to be sensitive to fluctuations in the cultivated-wasteland ratio (Fig. 3). As the ratio decreased from 24:1 to 12:1, the soil salinity in the transition zone above the drain level in 2034 was lower than that in 2025, with the reduction rate diminishing as the ratio declined. Specifically, at a ratio of 12:1, the soil salinity in the transition zone above the drain level in 2034 decreased by 1.47% compared to 2025.

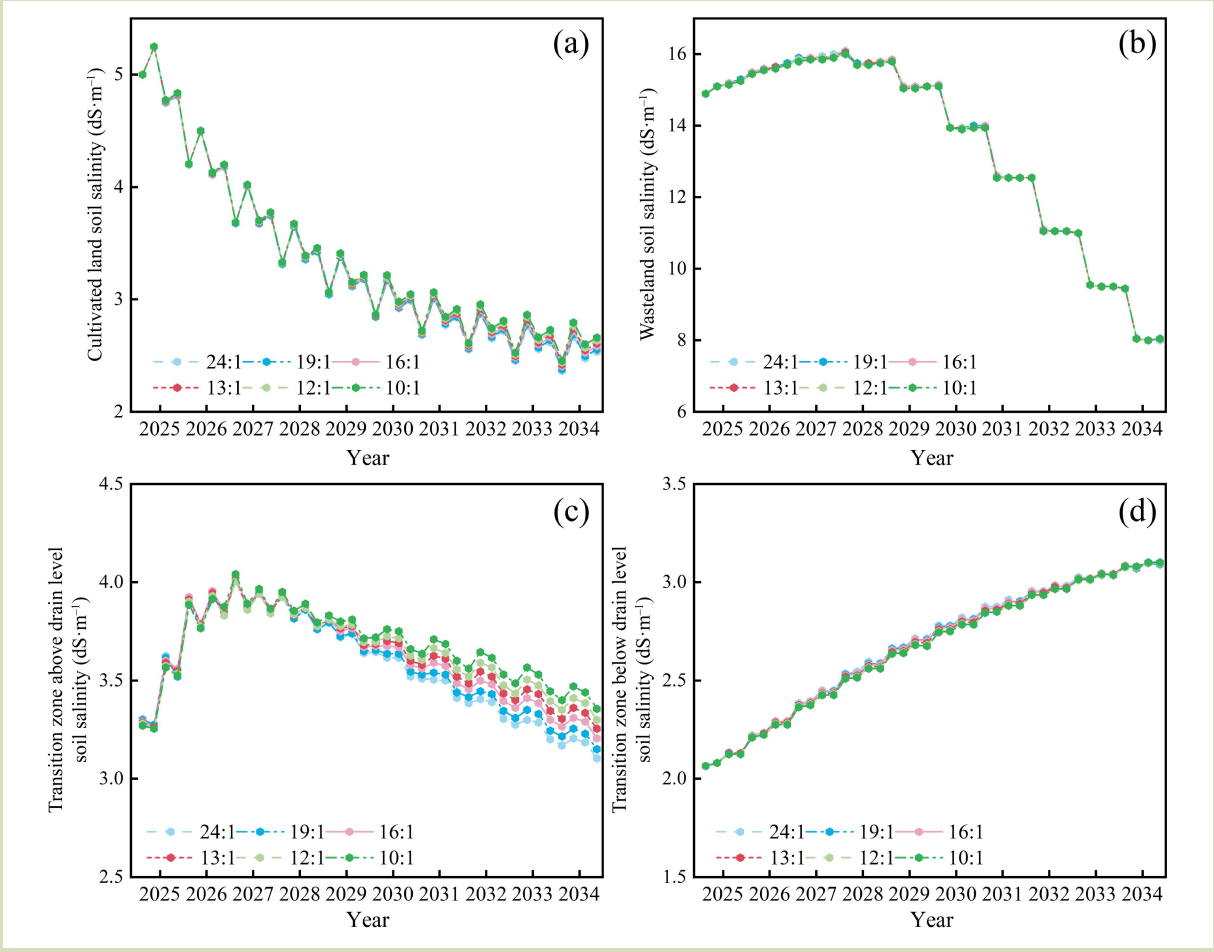


Fig. 3 Simulation and prediction of soil salinity under different cultivated-wasteland ratios.

However, when the ratio further decreased to 10:1, the soil salinity in this transition zone increased by 0.37% relative to 2025, indicating the onset of salt accumulation. Overall, soil salinity in both wasteland and cultivated land exhibited a continuous decreasing trend, while salinity in the transition zone below the drain level continued to rise and was less influenced by the cultivated-wasteland ratio. In conclusion, a cultivated-wasteland ratio of 12:1 effectively controls soil salinity in the transition zone above the drain level and maintains favorable salinity evolution in both cultivated land and wasteland, thus establishing it as the optimal area ratio for the study area.

3.4 Optimization of sunflower-maize planting ratio

To explore the optimal cropping structure ratio in the study area, this study simulated soil salinity changes over the next ten years under various cropping patterns by adjusting the planting area ratio of the main crops. Five scenarios were designed for the sunflower-maize planting area ratio: 1:1, 2:1, 3:1 (current situation), 4:1, and 5:1, to determine the appropriate threshold ratio. As the sunflower-maize planting ratio increased, the reduction rate of soil salinity in wasteland remained relatively stable, while that in cultivated land gradually decreased. This indicates that a larger sunflower planting area resulted in higher soil salinity in cultivated land (Fig. 4). Soil salinity in both wasteland and cultivated land showed a decreasing trend over the ten years. Compared with 2025, soil salinity in 2034 decreased by 44.36%–44.50% in wasteland and by 45.24%–53.82% in cultivated land under all scenarios. In terms of the change rate of transition zone salinity in 2034 relative to 2025, soil salinity in the transition zone above the drain level

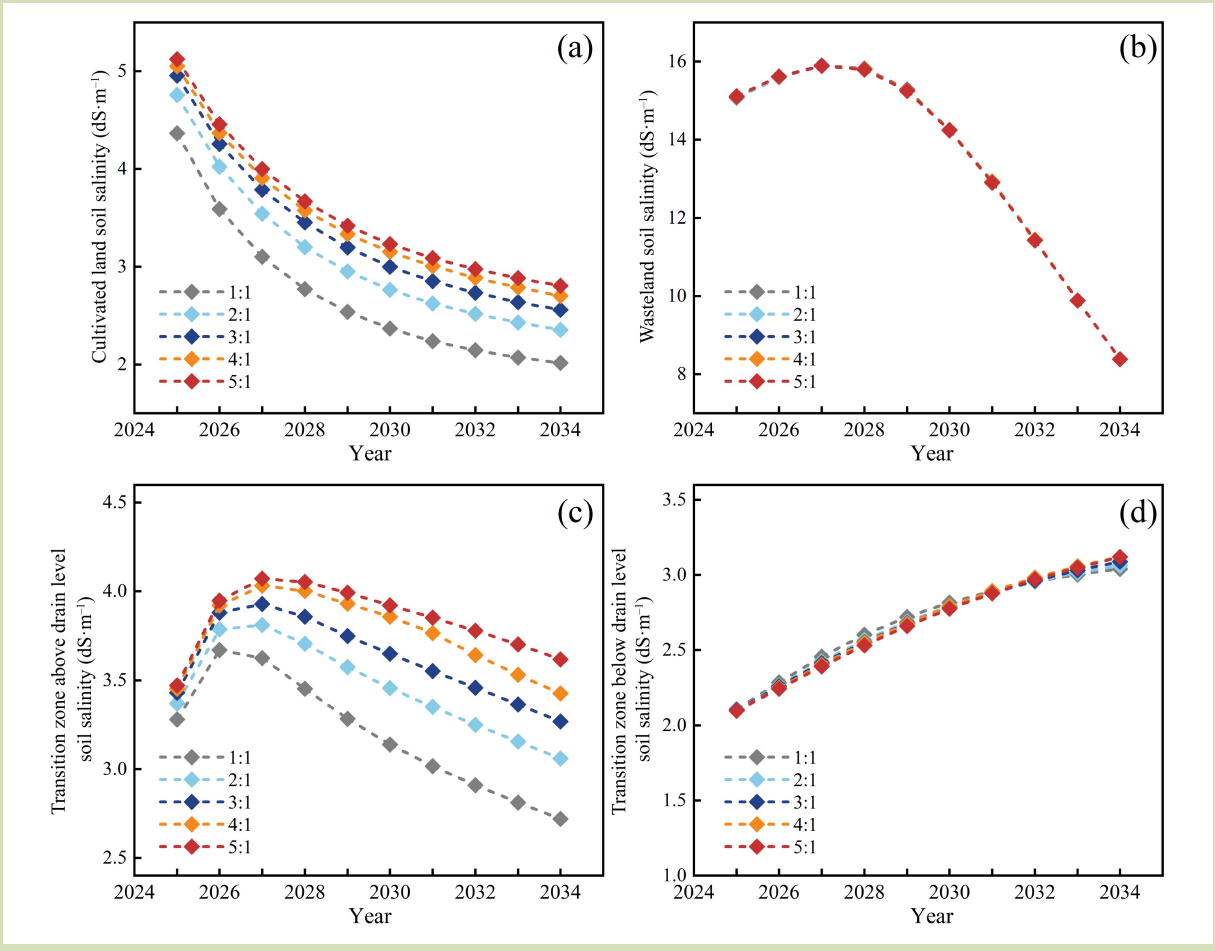


Fig. 4 Simulation and prediction of soil salinity under different sunflower-maize planting ratio.

shifted from desalination to salt accumulation as the sunflower proportion increased. Under ratios of 1:1 to 4:1, salinity in this layer continued to decline, with the desalination rate decreasing from 17.04% to 0.80% as the sunflower ratio rose. When the ratio reached 5:1, the transition zone above the drain level began to accumulate salt, with a salt accumulation rate of 4.21%, indicating that this ratio exceeded the safe threshold for regional soil salinity regulation. Soil salinity in the transition zone below the drain level increased under all scenarios, with an increasing range of 44.31%–48.75%, and the increment gradually enlarged with a higher sunflower proportion. Based on the salinity variation characteristics of each soil layer, the suitable threshold of the sunflower-maize planting ratio for the study area was determined to be 4:1. This ratio can maintain significant desalination in both cultivated land and wasteland, while avoiding secondary salinization caused by salt accumulation in the transition zone.

3.5 Optimization of irrigation quota for different crops

To investigate the optimal irrigation quotas for maize and sunflower in the study area, soil salinity was simulated using the SaltMod model. Five irrigation quota scenarios were established for maize: 235 mm (−30%), 286 mm (−15%), 336 mm (current situation), 386 mm (+15%), and 437 mm (+30%). Similarly, five scenarios for sunflower were set: 166 mm (−10%), 175 mm (−5%), 184 mm (current situation), 193 mm (+5%), and 202 mm (+10%). Based on the change rate of simulated soil salinity in 2034 compared to 2025, the responses of soil salinity in different soil layers to adjustments in irrigation quotas varied significantly. Notably, the soil salinity in the transition zone above the drain level exhibited the highest sensitivity (Fig. 5, Fig. 6). The change rate of soil salinity in 2034 compared to 2025 indicates that soil salinity in

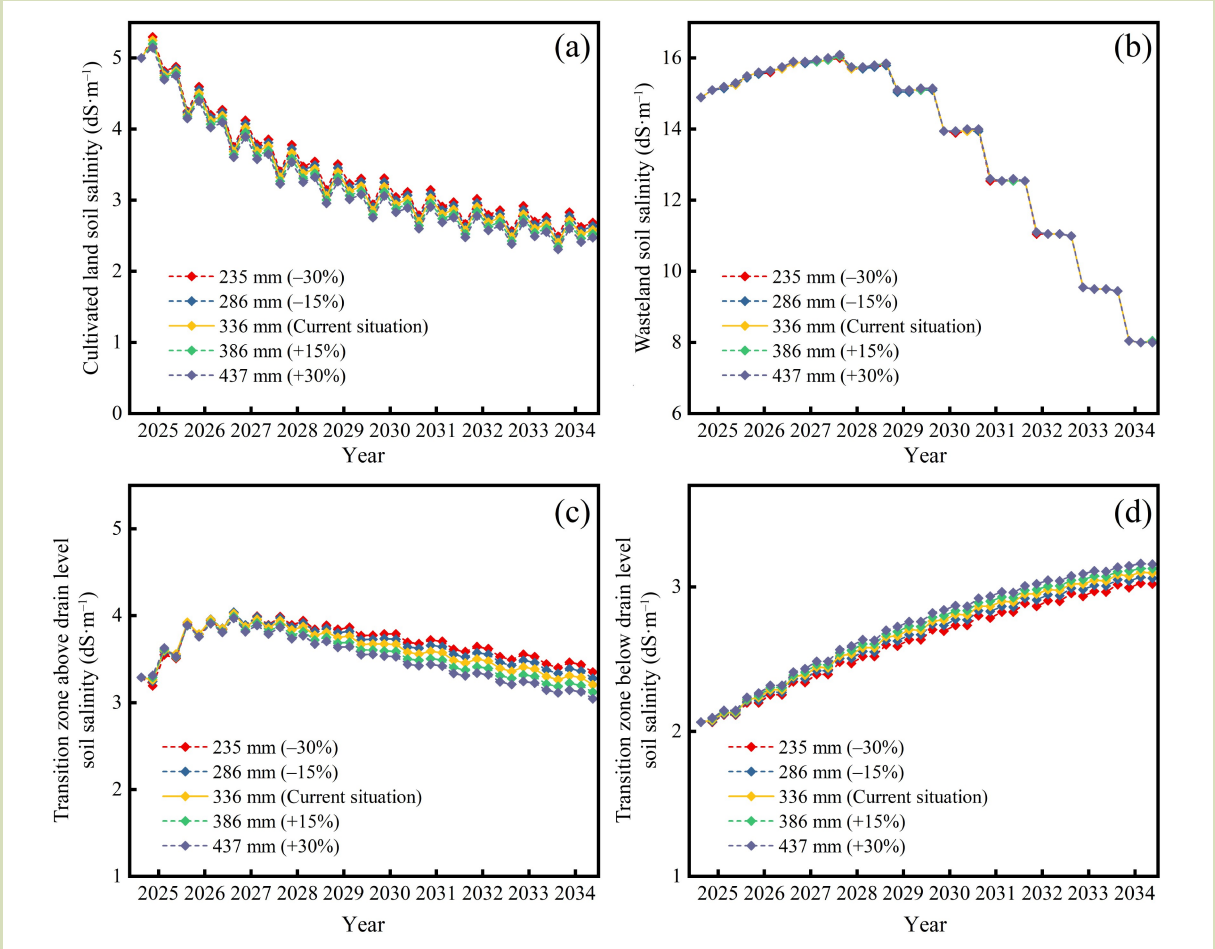


Fig. 5 Simulation and prediction of soil salinity under different maize irrigation quota scenarios.

both wasteland and cultivated land exhibited a decreasing trend under various irrigation scenarios, with the reduction rate increasing alongside the irrigation quota. Under different maize irrigation quota scenarios, soil salinity in wasteland and cultivated land decreased by 44.45%–44.63% and 46.83%–50.00%, respectively. In the case of sunflower irrigation quota scenarios, soil salinity in wasteland and cultivated land decreased by 44.41%–44.67% and 44.91%–51.52%, respectively. When the maize irrigation quota was set at 235 mm (–30%), soil salinity in the transition zone above drain level increased by 0.78%, failing to meet the salinity control target. However, at 286 mm (–15%), soil salinity in the transition zone above drain level decreased by 2.16%, effectively controlling salt accumulation and achieving the salinity control target. This scenario also resulted in a 15% water savings compared to the current quota, demonstrating significant water-saving benefits, while the increase in soil salinity in the transition zone below drain level remained within a manageable range. When the sunflower irrigation quota was 166 mm (–10%), soil salinity in the transition zone above drain level increased by 3.65%, again failing to meet the salinity control target. At 175 mm (–5%), soil salinity in the transition zone above drain level decreased by 0.63%, meeting the salinity control target. This scenario also achieved a 5% water savings compared to the current quota, with notable water-saving benefits, while the increase in soil salinity in the transition zone below drain level remained within a controllable range. Based on the dual optimization goals of water saving and salinity control, 286 mm was identified as the optimal maize irrigation quota (15% water saving), and 175 mm was determined as the optimal sunflower irrigation quota (5% water saving) for the study area.

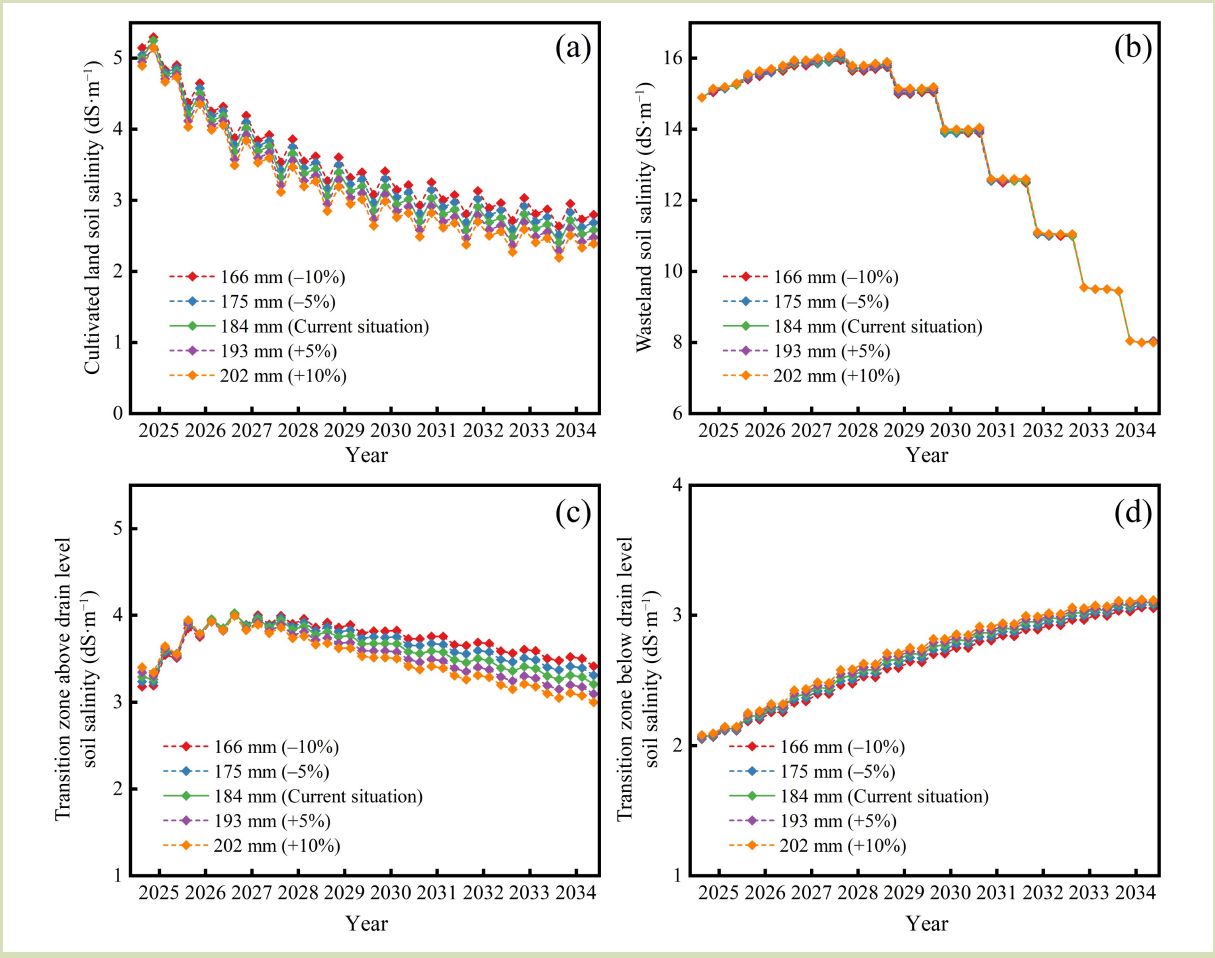


Fig. 6 Simulation and prediction of soil salinity under different sunflower irrigation quota scenarios.

3.6 Optimization of irrigation water salinity

To explore the suitable irrigation water salinity for the study area, this study simulated changes in soil salinity over the next ten years under various irrigation conditions by establishing different levels of irrigation water salinity. Five scenarios were designed, with irrigation water salinity levels of 0.9 (current situation), 1.0, 1.1, 1.3, and 1.5 dS·m^{-1}, to determine the appropriate threshold value. As illustrated in Fig. 7, with the increase in irrigation water salinity, soil salinity in both wasteland and cultivated land exhibited a decreasing trend over the next ten years. The reduction rate of soil salinity in wasteland was relatively stable, while that in cultivated land gradually decreased, indicating that soil salinity in cultivated land increased with rising irrigation water salinity. From the change rate of soil salinity in 2034 relative to 2025, salinity in wasteland decreased by 44.46%–44.50%, whereas in cultivated land it decreased by 33.26%–48.39% under different scenarios. Soil salinity in the transition zone above the drain level shifted from desalination to salt accumulation as irrigation water salinity increased. Under salinity levels of 0.9–1.0 dS·m^{-1}, salinity in this layer maintained a decreasing trend, with the desalination rate dropping from 4.70% to 1.53% as salinity increased. When irrigation water salinity rose to 1.1 dS·m^{-1}, the transition zone above the drain level began to accumulate salt at an accumulation rate of 1.75%, indicating that this salinity exceeded the safe threshold for regional soil salinity regulation. Soil salinity in the transition zone below the drain level increased under all scenarios, with an increase ranging from 47.00% to 61.18%, and the increment gradually enlarged with higher irrigation water salinity. Based on the salinity variation characteristics of each soil layer, the suitable threshold for irrigation water salinity in the study area was determined to be

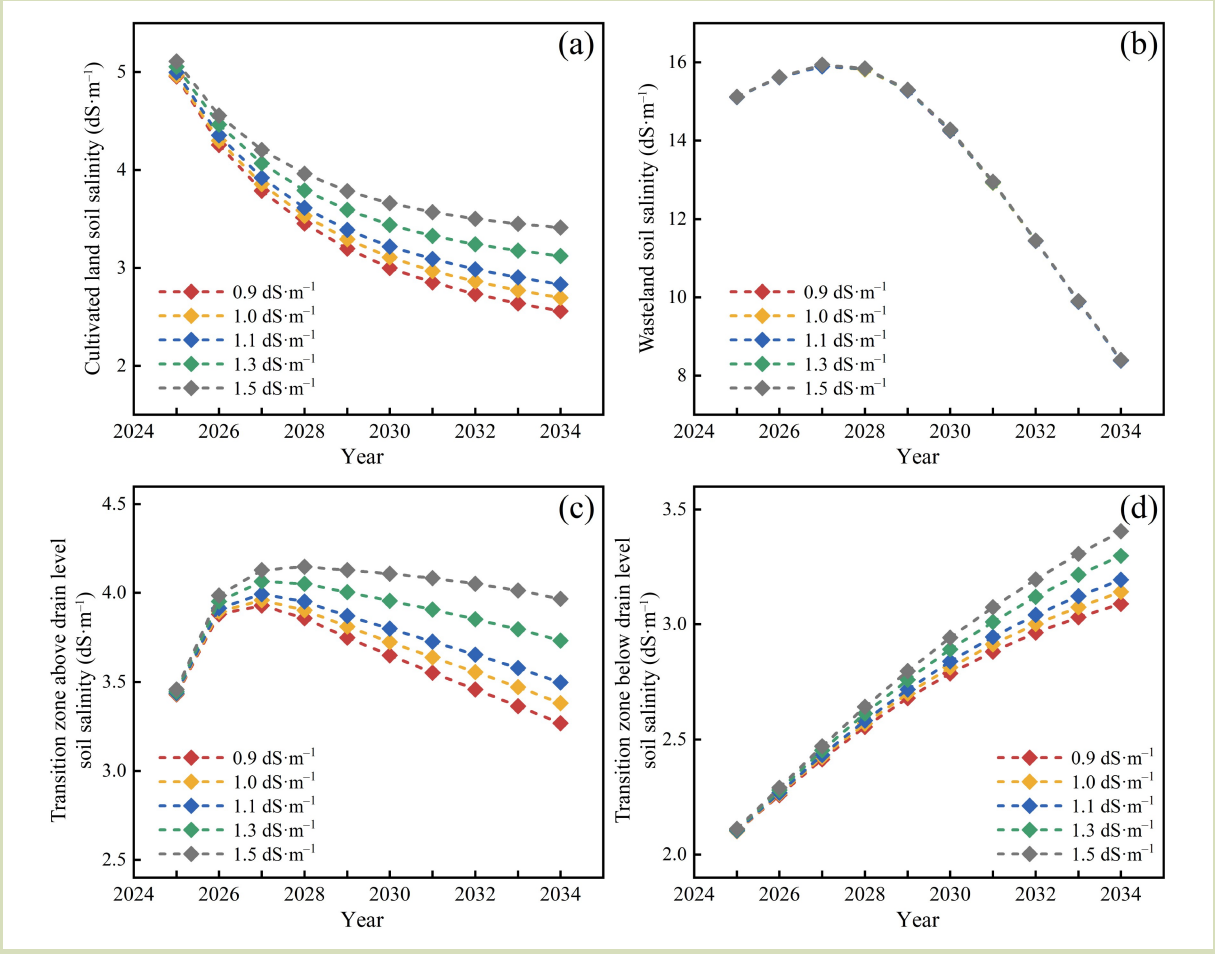


Fig. 7 Simulation and prediction of soil salinity under different irrigation water salinity scenarios.

1.0 dS·m^{-1}. This level can maintain significant desalination in both cultivated land and wasteland while avoiding the risk of secondary salinization caused by salt accumulation in the transition zone above the drain level.

4 Discussion

4.1 Optimization of cultivated-wasteland ratio

The spatial ratio of cultivated land to wasteland serves as a crucial regulatory measure for maintaining regional salt balance in arid irrigation districts[44]. Wasteland receives salts leached from cultivated land through the "dry drainage" mechanism, which effectively mitigates the risk of regional soil salinization[45,46]. Studies indicate that dry drainage not only regulates soil moisture in irrigated areas but also facilitates the transfer of significant amounts of salt from cultivated land to fallow areas[47]. A numerical simulation of groundwater migration between cultivated and wasteland in the Hetao Irrigation District demonstrated that approximately 14.22% of groundwater and 38.68% of salt from cultivated land migrated to wasteland via dry drainage during the crop growing season[23]. This study explores the optimal ratio of cultivated land to wasteland at the branch canal scale in the Hetao Irrigation District using the SaltMod model. Researchers analyzed the influencing factors of "dry drainage" salt control using numerical simulations and found a critical ratio at which cultivated land begins to desalinate[44]. In contrast to previous studies, this research extends the soil investigation depth from the root zone to the transitional layer and comprehensively evaluates the long-term effects of varying cultivated land-

wasteland ratios on salt evolution within the cultivated land-wasteland system. Some scholars have proposed optimization schemes at the landscape scale for the Hetao Irrigation District, reducing the cultivated land-wasteland ratio from 14.41 to 12.97, effectively improving the distribution of soil salinity[48]. Unlike prior research, this study expands the research scale to the branch canal level and analyzes the influence of the spatial layout of cultivated land and wasteland on soil salinity at this scale. The results indicate that a ratio of 12:1 effectively controls salt accumulation in the transition zone above the drain level while maintaining favorable salt evolution in both cultivated land and wasteland. Studies have shown that sunflower cultivation in the Hetao Irrigation District has rapidly expanded due to its salt tolerance and relatively high economic benefits[43]. Building on the optimization of the cultivated land to wasteland ratio, this study further explores the long-term impacts of sunflower-maize planting ratios on soil salt evolution. Sunflowers consume less water and exhibit a weak salt leaching effect, whereas maize requires more water and leaches salts more effectively. An excessively high proportion of maize can leach substantial salts into the transitional layer, causing salt accumulation there. Conversely, an excessively high proportion of sunflower area reduces salt leaching efficiency. Intense evaporation results in salt accumulation in the root zone, further exacerbating soil salinization in cultivated land. This study concludes that the appropriate threshold ratio of sunflowers to maize in the study area is 4:1. At this ratio, a balance is achieved between the leaching effects of the two crops: the salt-leaching function of maize maintains a downward salt flux in cultivated land, while excessive leaching and subsequent salt accumulation in the transition zone are avoided, thus forming a beneficial cycle of salt migration within the cultivated-wasteland system.

4.2 Optimization of irrigation quota

Agricultural irrigation is a fundamental measure for regulating soil salinization in irrigation districts. It must not only meet crop water requirements but also account for soil salinity control[49]. Therefore, the reasonable optimization of irrigation quotas is crucial for maintaining long-term soil health[50]. Some studies have determined the economic irrigation quota for summer maize under varying precipitation conditions based on maize growth functions[51]. Unlike approaches that formulate irrigation quotas based solely on crop growth rules, this study predicts future soil salinity using measured data and optimizes crop irrigation quotas specifically for salt control. Other studies have aimed to achieve stable yields and maximize irrigation water use efficiency to determine the optimal field-scale crop irrigation volumes, thereby conserving water while ensuring yield[52]. In contrast, this study shifts the focus to the branch canal scale, which is more applicable to regional water resource management, and optimizes crop irrigation quotas at this scale. Some researchers have utilized the SaltMod model to explore the effects of various irrigation regimes on soil salinity within the root zone, resulting in the identification of an overall optimal regional irrigation quota[34]. However, their work does not address the optimal irrigation quota for individual crops. Consequently, this study conducts scenario simulations using the SaltMod model, considering the impacts of sunflower and maize on long-term soil salt dynamics, and optimizes the irrigation quota for each crop respectively. The optimal irrigation quota for maize in the study area was determined as 286 mm (15% water saving), and the optimal irrigation quota for sunflower was 175 mm (5% water saving). Maize necessitates a higher irrigation quota due to its significant water demand during the growth period, while effective water leaching facilitates the downward movement of salts from the root zone, thereby maintaining a low-salinity environment. In contrast, the lower irrigation quota for sunflower aligns with its shorter growth period and robust salt tolerance. The optimized irrigation quotas for both crops effectively satisfy their respective water requirements and mitigate soil salinization. Building on the optimized irrigation quota, this study further investigated the long-term response of soil salinity under various irrigation water salinity scenarios. The suitable threshold for irrigation water salinity in the study area was established at 1.0 $dS \cdot m^{-1}$.

Based on the SaltMod model, this study systematically conducted a collaborative optimization of the cultivated-wasteland ratio, sunflower-maize planting ratio, crop irrigation quota, and irrigation water salinity at the branch canal scale. The results provide a scientific basis for preventing and controlling soil salinization, efficiently utilizing agricultural water resources, and managing cultivated land sustainably in arid and semi-arid irrigation districts. However, the current study focuses solely on the branch canal scale, neglecting the spatial heterogeneity within the irrigation district. Furthermore, it does not account for variations in climatic, soil, and hydrological conditions across different arid and semi-arid regions, which limits the generalizability of its conclusions to other areas. Additionally, the parameter optimization primarily emphasizes water-salt regulation, with insufficient integration

of economic and ecological benefits. Future research should conduct multi-scale studies and integrate remote sensing data with ground monitoring to enhance simulation accuracy. By addressing the typical characteristics of diverse arid and semi-arid regions worldwide, a classified multi-objective collaborative optimization system can be established to propose differentiated regulation strategies, thereby creating a more applicable framework for the sustainable management of irrigation districts.

5 Conclusions

This study optimizes the cultivated land-wasteland ratio, sunflower-maize planting ratio, crop irrigation quota, and irrigation water salinity at the typical branch canal scale of the Hetao Irrigation District based on long-term soil salinity simulation. The main conclusions of this study are as follows: (1) Over the next decade, soil salinity in wasteland, cultivated land, and the transition zone above the drain level will decrease, while soil salinity in the transition zone below the drain level will increase. Annual autumn irrigation leaches salts, and drainage ditches remove salts from the soil. As a result, desalination occurs in wasteland, cultivated land and the transitional layer above drainage outlets, while salt accumulates in the transitional layer below outlets due to trapped residual salts. (2) The optimal cultivated-wasteland ratio is 12:1, and the suitable threshold for the sunflower-maize planting ratio is 4:1, which can effectively control soil salinity in the transition zone above the drain level and maintain a favorable salinity evolution in cultivated land and wasteland. (3) From the dual goals of water saving and salinity control, the optimal irrigation quota is 286 mm for maize (15% water saving) and 175 mm for sunflower (5% water saving). (4) The suitable threshold of irrigation water salinity is determined as 1.0 $dS \cdot m^{-1}$. This study provides a scientific foundation for the control of soil salinization and the efficient utilization of water resources within the Hetao Irrigation District.

Acknowledgements

This research was funded by the National Natural Science Foundation of China (U2443210, U24A20179), the Natural Science Foundation of Inner Mongolia Autonomous Region of China (2025MS05046), the First-class Discipline Research Special Project of Inner Mongolia Autonomous Region, China (YLXKZX-NND-052, YLXKZX-NND-022).

Compliance with ethics guidelines

Yi Zhao, Shuya Yang, Haibin Shi, Xianyue Li, Qingfeng Miao, Jianwen Yan, Cong Hou, Badarifu, and Lixia Wang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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