

THRESHOLD OPTIMIZATION OF CULTIVATED-WASTELAND PATTERNS UNDER SOIL SALINITY DYNAMICS BY INTEGRATING SALTMOD AND CLUE-S

OPTIMISATION DU SEUIL DES MODÈLES DE TERRES CULTIVÉES-TERRES EN FRICHE SOUS LA DYNAMIQUE DE LA SALINITÉ DU SOL EN INTÉGRANT SALTMOD ET CLUE-S

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ABSTRACT

Soil salinization threatens sustainable agriculture, and treating salt wastelands is crucial for maintaining soil productivity and ecological balance. However, excessive reclamation of these wastelands through land consolidation may exacerbate salinization, highlighting the need for optimized allocation. Although previous studies have mainly focused on field-scale water-salt transport, the integration of land-use spatial configuration with soil salinity redistribution remains insufficiently explored. To address this gap, this study developed a coupled SaltMod-CLUE-S framework to quantify interactions between land-use change and soil salinity in the Jiefangzha Irrigation Scheme of the Hetao Irrigation District. Remote-sensing data from 1996 to 2016 were integrated with the SaltMod water-salt balance model and the CLUE-S land-use simulation model to investigate cultivated-wasteland dynamics, spatiotemporal transfer patterns, and soil salinity responses under natural development, current irrigation, and water-saving scenarios.

The critical cultivation-to-salt wasteland ratio threshold (CSWR-T) was defined as the maximum cultivated land-to-salt wasteland ratio that can be sustained without persistent long-term root-zone salinity accumulation. Higher CSWR-T values indicate greater capacity for cultivated-land expansion while maintaining long-term salinity stability, whereas lower values reflect more restrictive salinity constraints. The optimal CSWR-T range of 7.5–8.5 balances food production with ecological safety, while excessive values above 9.0 reduce salt drainage capacity. Soil salinity showed threshold-dependent and nonlinear responses to irrigation management. Autumn irrigation promoted leaching, growing-season irrigation secured crop water supply, and total diversion determined the overall water-salt balance. Increased water-saving intensity reduced the CSWR-T, requiring larger salt wastelands to maintain ecological functions. These findings provide a quantitative basis for targeted, period-specific irrigation management and spatial optimization of salt wastelands, supporting sustainable land use, salinity control, and ecological security in arid and semi-arid irrigation districts.

Keyword: Sustainable; Soil salinity; Irrigation District; crop water supply; ecological security.

RESUME

La salinisation des sols menace l'agriculture durable, et le traitement des terres en friche salines est crucial pour maintenir la productivité des sols et l'équilibre écologique. Cependant, la mise en valeur excessive de ces terres en friche par le remembrement peut aggraver la salinisation, soulignant la nécessité d'une allocation optimisée. Bien que les études précédentes se soient principalement concentrées sur le

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transport du sel d'eau à l'échelle de terrain, l'intégration de la configuration spatiale de l'usage des sols avec la redistribution de la salinité des sols reste insuffisamment explorée. Pour combler cette lacune, cette étude a développé un cadre couplant les modèles SaltMod et CLUE-S afin de quantifier les interactions entre le changement d'usage des sols et la salinité du sol dans le projet d'irrigation de Jiefangzha du périmètre irrigué de Hetao. Les données de télédétection recueillies de 1996 à 2016 ont été intégrées au modèle d'équilibre eau-sel SaltMod et au modèle de simulation d'usage des terres CLUE-S afin d'étudier la dynamique des terres cultivées et les terres en friche, les schémas de transfert spatiotemporel et les réponses de la salinité des sols dans le cadre du développement naturel, l'irrigation actuelle et les scénarios d'économie d'eau.

Le seuil critique du rapport terre cultivée/terre en friche saline (CSWR-T) a été défini comme le rapport terre cultivée/terre en friche saline maximal qui peut être maintenu sans accumulation persistante à long terme de la salinité dans la zone racinaire. Des valeurs plus élevées de CSWR-T indiquent une plus grande capacité d'expansion des terres cultivées tout en maintenant la stabilité de la salinité à long terme, tandis que des valeurs plus faibles reflètent des contraintes de salinité plus restrictives. L'éventail optimal CSWR-T de 7,5–8,5 équilibre la production alimentaire avec la sécurité écologique, tandis que des valeurs supérieures à 9,0 réduisent la capacité de drainage du sel. La salinité du sol a montré des réponses dépendantes du seuil et non linéaires à la gestion de l'irrigation. L'irrigation d'automne a favorisé le lessivage, l'irrigation de la saison de croissance a assuré l'approvisionnement en eau des cultures et la dérivation totale a déterminé l'équilibre global eau-sel. L'augmentation de l'intensité des économies d'eau a réduit le CSWR-T, nécessitant de plus grandes terres en friche salines pour maintenir les fonctions écologiques. Ces résultats fournissent une base quantitative pour la gestion ciblée de l'irrigation sur des périodes spécifiques et l'optimisation spatiale des terres en friche salines, soutenant ainsi l'usage durable des sols, le contrôle de la salinité et la sécurité écologique dans les périmètres irrigués arides et semi-arides.

Mots-clés : Durable; Salinité des sols; Périmètre irrigué; Approvisionnement en eau des cultures; Sécurité écologique.

1. Introduction

Soil salinization is a major constraint on sustainable land use and food security in arid and semi-arid irrigation districts. In the Hetao Irrigation District (HID), especially the Jiefangzha Irrigation Scheme (JFIS), limited water resources, shallow groundwater, and strong evaporation make the region highly prone to salinization. Conventional measures such as artificial drainage and leaching can alleviate salinity but are often restricted by high water demand and infrastructure costs. In contrast, salt wastelands can act as temporary salt reservoirs by receiving water and salt fluxes from adjacent cultivated land through lateral groundwater movement, thereby providing an ecological or dry drainage function. With accelerated land-use change, especially land consolidation and cultivated-land expansion, the spatial distribution of salt wastelands has been substantially altered. Cultivated land supports food production, whereas salt wastelands contribute to ecological salt storage and drainage. Excessive reclamation of low-lying salt wastelands without sufficient alternative salt-discharge pathways may intensify salinity accumulation in cultivated land. Although previous studies have recognized the salt-storage role of wastelands, quantitative thresholds for balancing cultivated-land expansion and ecological salt-storage functions remain insufficiently incorporated into regional land-use planning. Existing studies in the HID have applied agro-hydrological models, soil water-heat-salt simulations, remote-sensing-based salinity mapping, and spatial analyses of salt-affected land. However, most have focused on hydrological processes, salinity assessment, or individual simulations. The integration of land-use spatial configuration, salinity-constrained optimization, ecological salt-storage functions, and salt-wasteland allocation remains limited, particularly under different irrigation and drainage regimes. Consequently, the regional-scale interactions among cultivated-land expansion, salt-wasteland retention, and soil salinity redistribution remain insufficiently quantified.

To address this gap, this study developed an integrated SaltMod–CLUE-S framework for the JFIS. SaltMod was used to simulate long-term water-salt balance and soil salinity dynamics under different

irrigation and drainage practices, while CLUE-S was used to allocate land-use changes spatially according to land demand, driving factors, and conversion rules. This coupling links salinity-constrained land demand with spatial land-use allocation, enabling evaluation of cultivated land-to-salt wasteland ratio thresholds and their spatial implications under alternative irrigation-management scenarios. Specifically, this study aims to: (1) reveal the spatiotemporal transfer mechanisms between cultivated land and salt wasteland; (2) quantify soil salinity evolution under different cultivated land-to-salt wasteland ratios (CSWRs) and water-saving irrigation conditions; and (3) identify critical CSWR thresholds (CSWR-Ts) for maintaining long-term root-zone salinity stability. The results provide quantitative support for salinity mitigation, land-use planning, ecological restoration, and sustainable agricultural development in arid and semi-arid irrigation districts.

2. Materials and methods

2.1 Study area

The Hetao Irrigation District (HID), located in the upper Yellow River Basin, is one of China's three largest irrigation districts and is characterized by arid climate, shallow groundwater, and widespread salinization (Figure 1).

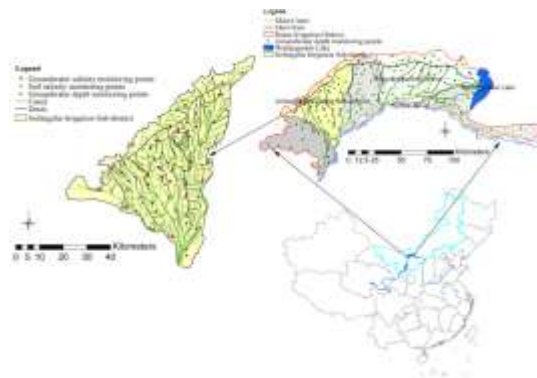


Figure 1. Study area location

The Jiefangzha Irrigation Scheme (JFIS) was selected as the study area. It covers 2.16×10^5 ha, including 1.42×10^5 ha of irrigated land and 7.36×10^4 ha of non-irrigated land, with salt wasteland accounting for about 47% of the latter. Annual precipitation is approximately 140 mm, whereas evaporation reaches about 2000 mm. Cultivated land is mainly distributed along canals and terraces, while salt wastelands occur in low-lying areas with poor drainage.

2.2 Overall methodological framework

To evaluate the relationship between land-use dynamics and soil salinity in the JFIS, this study developed a sequentially coupled SaltMod–CLUE-S framework (Figure. 2). SaltMod was first used to simulate long-term root-zone salinity responses under different cultivated land-to-salt wasteland ratios (CSWRs) and irrigation-management scenarios. Based on the simulated salinity trends, critical CSWR thresholds (CSWR-Ts) and salinity-constrained land-demand trajectories for cultivated land and salt wasteland were identified.

The SaltMod-derived land demand was then transferred to CLUE-S for spatial allocation. In CLUE-S, land-use changes were allocated across grid cells according to environmental, hydrological, locational, and socio-economic driving factors, together with conversion rules and elasticity settings. Thus, SaltMod provided quantitative salinity constraints, while CLUE-S generated spatially explicit land-use patterns. The coupling was implemented as a one-way sequential linkage from SaltMod to CLUE-S, ensuring consistency between land-use allocation and salinity-regulation requirements.

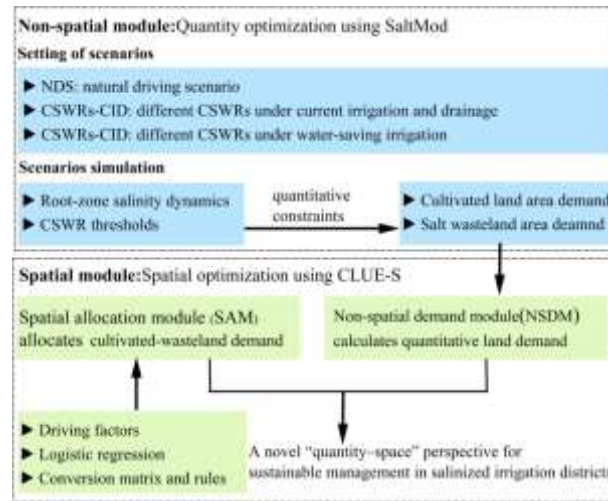


Figure 2. Framework of the integrated SaltMod-CLUE-S

2.3 Data sources and preprocessing

Datasets covering land use, topography, climate, vegetation, irrigation and drainage infrastructure, socio-economic conditions, soil salinity, groundwater, and water management were collected for 1996–2016 to support the coupled SaltMod–CLUE-S framework. Land-use data for 1996, 2001, 2006, 2011, and 2016 were obtained from the Resources and Environmental Sciences Data Center, Chinese Academy of Sciences, and reclassified into seven categories: cultivated land, woodland, grassland, water area, construction land, unused land, and salt wasteland. Topographic variables were derived from DEMs, while precipitation, temperature, population density, GDP, and NDVI were obtained from remote-sensing and statistical datasets. Euclidean distance rasters were generated for canals, drainage ditches, roads, and township centers. Groundwater-depth data from 57 monitoring wells were interpolated to represent multiyear average groundwater conditions. Soil EC, groundwater salinity, irrigation, rainfall, and evapotranspiration data were compiled from monitoring records and Chang et al. (2019). All spatial data were projected, resampled to 100 m × 100 m, and integrated into a unified raster database.

2.4 SaltMod-CLUE-S model configuration

The coupled SaltMod–CLUE-S framework was used to link salinity-constrained land demand with spatially explicit land-use allocation. SaltMod simulates long-term root-zone salinity dynamics based on seasonal water and salt balances among the surface layer, root zone, transition zone, and aquifer. In this study, SaltMod was used to identify the critical cultivated land-to-salt wasteland ratio threshold (CSWR-T), defined as the maximum CSWR under which cultivated-land root-zone salinity does not show persistent long-term accumulation relative to the baseline condition. SaltMod parameterization, calibration, and validation followed Chang et al. (2019), who calibrated the model for the JFIS using observed root-zone salinity, groundwater depth, and irrigation-drainage data. The model showed satisfactory performance, with $R^2 > 0.88$ and RMSE values of 0.09–0.13 dS m⁻¹. Soil salinity was expressed as root-zone saturated paste extract electrical conductivity (EC_e). Measured EC_{1:5} values were converted to EC_e using $EC_e = 8.6 \times EC_{1:5}$, and then converted to SaltMod input salinity using $EC = 2 \times EC_e$. Irrigation water salinity was expressed as EC, with 1 g L⁻¹ approximately equivalent to 1.7 dS m⁻¹ when conversion was required. CLUE-S was then used to spatially allocate the SaltMod-derived land demand. The model includes a non-spatial demand module and a spatial allocation module. In this study, the demand for cultivated land and salt wasteland was provided by SaltMod, while CLUE-S allocated land-use changes across 100 m × 100 m grid cells according to spatial suitability, conversion rules, and elasticity settings. CLUE-S was used to allocate the SaltMod-derived land demand across 100 m × 100 m grid cells. Spatial suitability was estimated using binary logistic regression based on

twelve driving factors: elevation, slope, NDVI, precipitation, temperature, distance to township centers, roads, canals, and drains, groundwater depth, GDP, and population density (Fig. 3).

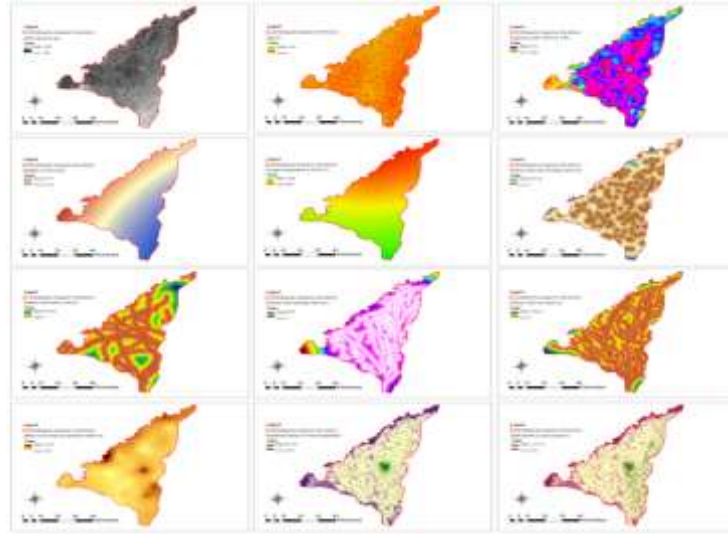


Figure 3. Grid map of the influencing factors

The logistic regression model was expressed as:

$$\text{Log}\left(\frac{P_{iu}}{1-P_{iu}}\right) = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} + \dots + \beta_n X_{n,i} \quad (1)$$

where $P_{i,u}$ is the probability that grid cell u is assigned to land-use type i ; $X_{1,i}, X_{2,i}, \dots, X_{n,i}$ are the explanatory variables; $\beta_0, \beta_1, \dots, \beta_n$ are the corresponding regression coefficients.

The suitability probabilities were incorporated into the spatial allocation module to calculate the total allocation probability:

$$TPROP_{i,u} = P_{i,u} + ELAS_u + ITER_u \quad (2)$$

where $TPROP_{i,u}$ is the total allocation probability of land-use type u to grid cell i ; $P_{i,u}$ is the logistic regression-derived suitability probability; $ELAS_u$ is the elasticity coefficient for land-use type u ; and $ITER_u$ is the iteration variable. Through iterative allocation, CLUE-S generates the final spatial distribution of each land-use type.

Land-use transitions were controlled by a conversion matrix and elasticity coefficients. All land-use categories were allowed to convert, while different elasticity values represented conversion resistance. Cultivated and construction land were assigned high resistance, woodland, grassland, water area, and unused land moderate resistance, and salt wasteland low resistance. Model performance was evaluated by simulating land-use patterns for 2006 and 2016 using the 1996 map as the baseline and comparing simulated and observed maps using overall accuracy and the Kappa coefficient.

2.5 Scenarios design

Scenario simulations were conducted for 2017–2036 to assess the combined effects of land-use adjustment and irrigation management on soil salinity. Spatial simulations were performed on a 100 m × 100 m grid, with 246,465 valid cells retained within the JFIS boundary. Three scenario groups were designed. The natural development scenario (NDS) projected cultivated land and salt wasteland changes based on historical land-use trends. The CSWR-CID scenarios tested preset cultivated land-to-salt wasteland ratios (CSWRs) under current irrigation and drainage (CID) conditions to identify the

baseline critical threshold (CSWR-T). The CSWR-WSI scenarios combined the same CSWR levels with water-saving irrigation strategies, including total water diversion reduction (TWD), growth-period irrigation reduction (GPI), and autumn-period irrigation reduction (API), each at 5% and 10% relative to CID. CSWR was calculated as cultivated land area divided by salt wasteland area. CSWR-T was defined as the maximum CSWR at which cultivated-land root-zone salinity showed no persistent long-term accumulation under a given irrigation-drainage scenario. Scenario settings are summarized in Table 1.

Table 1. Scenario groups, assumptions, and parameter settings used in the SaltMod-CLUE-S simulations.

Scenario group	Purpose	Assumptions / constraints	Parameter settings
the natural development scenario (NDS)	Baseline for land-use evolution under natural and socio-economic trends	No extreme events or new policy interventions; land-use dynamics follow historical trends	Land-use areas of cultivated land and salt wasteland predicted using linear interpolation from 1996, 2001, 2006, 2011, and 2016 land-use maps
cultivated land-to-salt wasteland ratio under current irrigation and drainage conditions (CSWR-CID)	Assess the effects of land conversion between cultivated land and salt wasteland under the current irrigation and drainage (CID) scenario	Other land-use categories remain fixed; irrigation and drainage conditions remain unchanged	Eleven cultivated land-to-salt wasteland ratios (CSWRs): 5.5, 5.8, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, and 10.0
cultivated land-to-salt wasteland ratio scenarios under water-saving irrigation conditions (CSWR-WSI)	Examine the combined effects of water-saving irrigation (WSI) and land-use adjustment on soil salinity	Other land-use categories remain fixed; bidirectional conversion is allowed between cultivated land and salt wasteland	The same eleven CSWR levels used in the CSWRs-CID scenarios were combined with six irrigation schemes: (i) total water diversion (TWD) reduced by 5% and 10%, (ii) growth-period irrigation (GPI) reduced by 5% and 10%, (iii) autumn-period irrigation (API) reduced by 5% and 10%; resulting in 66 coupled scenarios

3.1 Model validation and land-use suitability drivers

The simulated land-use patterns were generally consistent with the observed maps. Using the 1996 land-use map as the baseline, the model achieved overall accuracies of 76% and 74% for 2006 and 2016, respectively, with Kappa coefficients of 0.72 and 0.70, indicating satisfactory performance for subsequent scenario simulations. Logistic regression results showed that land-use suitability was jointly influenced by environmental, hydrological, locational, and socio-economic factors. Cultivated land was positively associated with NDVI and GDP, but negatively associated with groundwater depth and temperature, suggesting a preference for areas with better vegetation conditions and socio-economic support. In contrast, salt wasteland was mainly associated with low elevation, sparse vegetation, shallow groundwater, and low population density, reflecting typical salt-accumulation conditions in arid irrigation districts. These suitability relationships provided the spatial allocation basis for CLUE-S and supported the salinity-constrained scenario analysis.

3.2 Spatial and temporal changes in land-use

Over the past two decades, land use in the JFIS changed markedly in response to agricultural expansion, urbanization, and marginal-land reclamation. The landscape was dominated by cultivated land and unused land, followed by salt wasteland, grassland, construction land, woodland, and water area. From 1996 to 2016, cultivated land, woodland, and construction land expanded, whereas water area, unused land, and salt wasteland declined. Construction land showed the fastest increase, followed by woodland and cultivated land, while water area and unused land showed the strongest decreases.

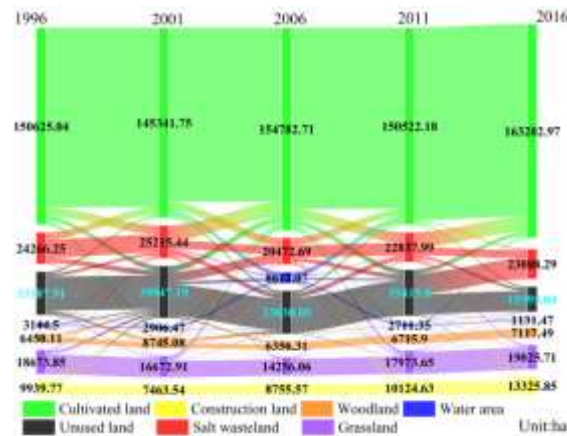


Figure 4. Sankey diagram of land-use conversion from 1996–2016

The comprehensive land-use dynamic degree increased after 2006, indicating accelerated land-use change, although the overall land-use system remained moderately stable. The dynamic degree analysis further confirmed the temporal heterogeneity of land-use change. Construction land had the highest positive dynamic degree, whereas water area, unused land, and salt wasteland showed negative dynamics. These results indicate that land-use change in the JFIS was mainly driven by cultivated-land expansion, construction-land growth, and the transformation of marginal lands.

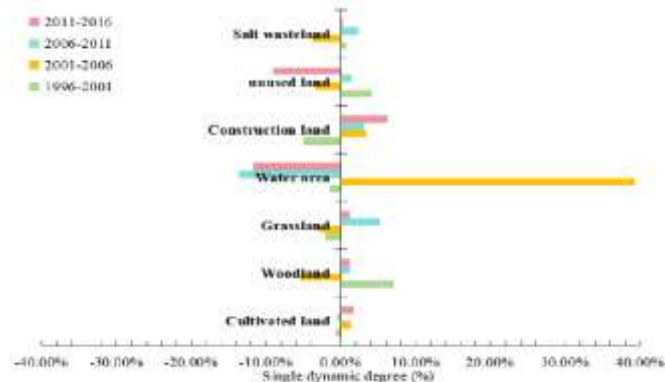


Figure 5. Single land-use dynamic degree in the JFZ region from 1996–2016

The land-use conversion results showed that salt wasteland experienced strong bidirectional transitions rather than a simple decline. From 1996 to 2016, only 25.3% of the original salt wasteland remained unchanged, while 74.7% was converted to other land-use types. Conversion to cultivated land was the dominant loss pathway, accounting for 13,007 ha, or 71.8% of total salt-wasteland loss. Meanwhile, 16,948 ha of other land-use types were converted into salt wasteland, mainly from unused land. This indicates a dynamic replacement process in which salt wasteland was reclaimed into cultivated land, while new salt wasteland continued to emerge from marginal unused land. Overall, the dominant transition pathway can be summarized as unused land → salt wasteland → cultivated land.

3.3 Scenario simulation and analysis

Long-term soil salinity simulations were conducted using the calibrated SaltMod model under current irrigation and drainage conditions and different water-saving irrigation schemes. The analysis focused on the cultivated land-to-salt wasteland ratio (CSWR), which reflects the balance between cultivated-land expansion and the ecological salt-regulation function of salt wastelands. From 1996 to 2016, CSWR increased from 6.201 to 7.065, indicating intensified cultivated-land use and reduced relative salt-

wasteland buffering capacity. Scenario simulations from 2017 to 2036 were then used to identify the critical CSWR threshold (CSWR-T) under different irrigation-management conditions.

3.3.1 NDS and CSWR-CID scenarios

Under the natural development scenario (NDS), CSWR increased steadily during 1996–2016 and was projected to reach 7.929 by 2036. Under different irrigation-management scenarios, moderate growth-period irrigation reduction maintained relatively stable root-zone salinity, whereas reductions in total water diversion and autumn-period irrigation promoted salinity accumulation, especially under 10% reduction levels. These results indicate that autumn irrigation plays a key role in salt leaching and in suppressing spring salt return. Under the CSWR-CID scenarios, root-zone salinity responses varied systematically with increasing CSWR. When CSWR remained below the threshold, root-zone salinity declined slightly or remained stable. However, excessive increases in CSWR weakened the salt-discharge function of residual salt wastelands and led to persistent long-term salinity accumulation. The critical threshold under current irrigation and drainage conditions was identified as CSWR-T = 8.5, suggesting that maintaining CSWR below this threshold is essential for balancing cultivated-land expansion with regional salinity regulation.

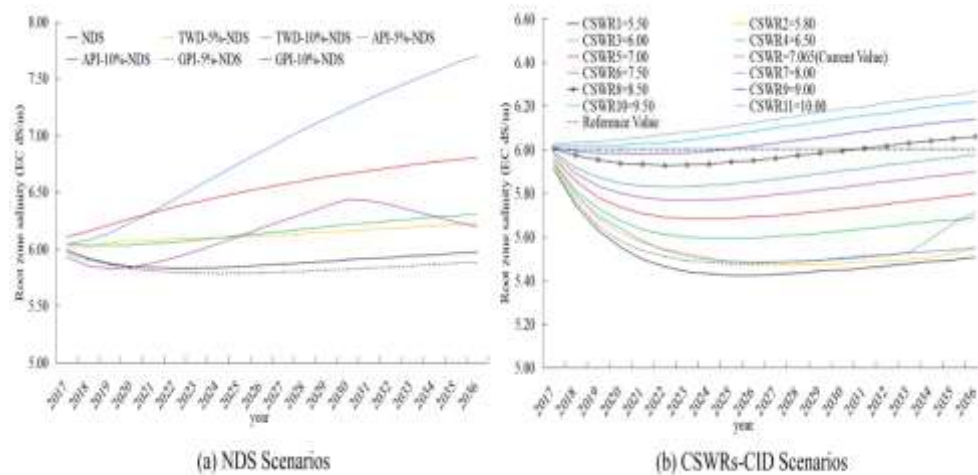


Figure 7. Soil salinity dynamics under NDS and CSWRs-CID scenario

3.3.2 CSWR-WSI scenarios

The CSWR-WSI scenarios further revealed the coupled effects of irrigation reduction and land-use structure on soil salinity. Across all water-saving irrigation scenarios, higher CSWR values increased the risk of root-zone salinity accumulation, particularly when CSWR exceeded the corresponding CSWR-T. The threshold declined as water-saving intensity increased, indicating that reduced irrigation water supply weakened the system's salt-leaching capacity. Different irrigation-reduction strategies showed distinct effects (Figure. 8).

Under total water diversion reduction, CSWR-T decreased to 7.5 under a 5% reduction and to 5.5 under a 10% reduction. Growth-period irrigation reduction showed a more moderate effect: a 5% reduction increased CSWR-T to 9.0, whereas a 10% reduction lowered it to 7.065. In contrast, autumn-period irrigation reduction had the strongest negative effect, with CSWR-T declining to 6.5 under a 5% reduction and 5.5 under a 10% reduction. These results highlight the critical role of autumn irrigation in maintaining long-term salt balance. Overall, CSWR-T was not fixed but varied with irrigation timing, reduction intensity, and land-use structure. Autumn irrigation should therefore be protected, growth-period irrigation can be moderately optimized, and sufficient salt wasteland should be retained to maintain ecological salt-discharge functions.

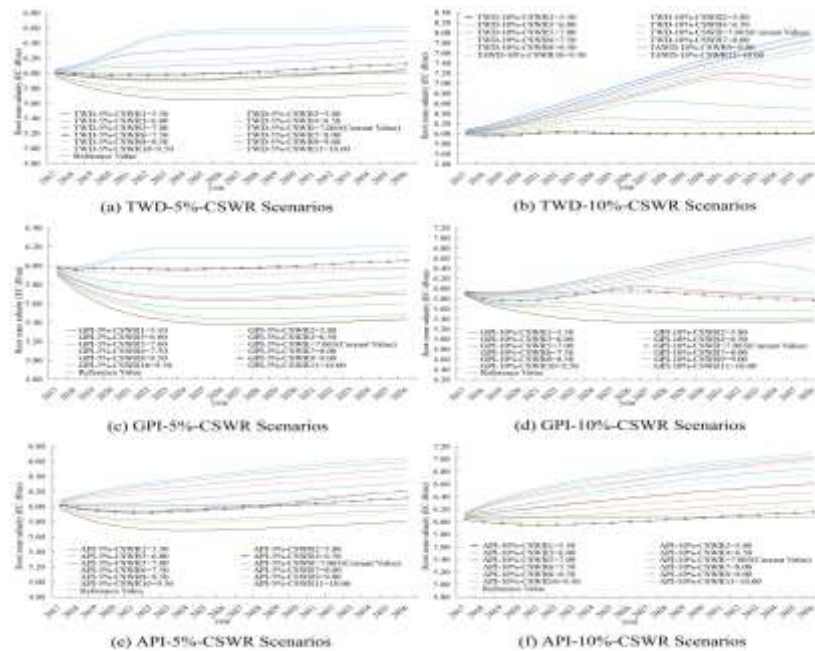


Figure 8. Soil salinity dynamics under CSWRs-WSI scenario

3.3.3 CSWR-T synthesis

The comparison of CSWR-Ts under different scenarios shows that irrigation timing and water-saving intensity strongly regulate the tolerable cultivated land-to-salt wasteland ratio. Under current irrigation and drainage conditions, CSWR-T was 8.5. Water-saving measures reduced this threshold when they weakened salt leaching, especially under autumn-period irrigation reduction and total water diversion reduction. The lowest CSWR-T of 5.5 occurred under 10% reductions in total water diversion and autumn-period irrigation, indicating strong salinity-control constraints under severe water-saving pressure. In contrast, moderate growth-period irrigation reduction increased CSWR-T to 9.0, suggesting that limited water saving during the crop-growing season may improve irrigation efficiency without compromising salinity control.

Overall, autumn irrigation had the strongest influence on CSWR-T, followed by total water diversion, while growth-period irrigation showed greater resilience. These findings indicate that maintaining an appropriate CSWR-T requires coordinated regulation of land-use structure and irrigation scheduling.

Table 2. Critical cultivated land-to-salt wasteland ratio thresholds under different irrigation-management scenarios.

Scenarios	Summer irrigation water volume (m ³ · ha ⁻¹)	Autumn irrigation water volume (m ³ · ha ⁻¹)	CSWR-T
NDS	2900–3220	2200–2440	7.929
CSWR-CID	3190	2420	8.50
TWD-5%	3080	2340	7.50
TWD-10%	3090	2340	5.50
GPI-5%	3000	2400	9.00
GPI-10%	2950	2480	7.065 (Current value)
API-5%	3320	2390	6.50
API-10%	3430	2340	5.50

3.4 Simulation of spatial pattern of salt wasteland

Using the 2016 land-use map as the baseline, the calibrated CLUE-S model simulated the spatial patterns of cultivated land and salt wasteland under different CSWR-T scenarios from 2016 to 2036 (Figure. 9).

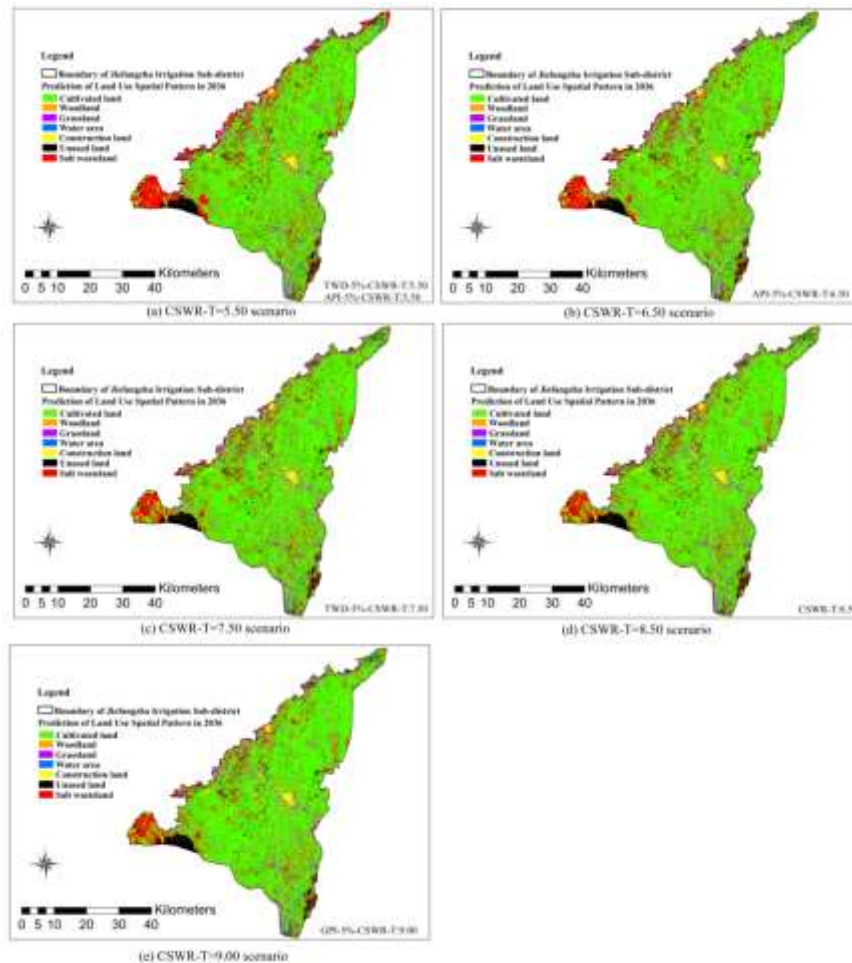


Figure 9. Land-use spatial optimization maps under the CSWR-T constraint scenarios in 2036

The results show that CSWR-T strongly regulated the balance between cultivated-land expansion and salt-wasteland retention. At low thresholds, especially CSWR-T = 5.5, cultivated land increased only slightly, whereas salt wasteland expanded markedly, indicating that stronger salinity constraints required more salt wasteland to maintain ecological salt-regulation functions. At CSWR-T = 6.5, cultivated-land stability improved and salt-wasteland expansion slowed, suggesting partial alleviation of salinization pressure. At CSWR-T = 7.5, cultivated land expanded steadily, while salt wasteland shifted from net expansion to net reduction. This indicates a key transition point at which reclamation began to exceed new salinization, reflecting a balance between agricultural production and ecological salt regulation. Under higher thresholds, especially CSWR-T = 8.5–9.0, cultivated-land expansion further increased and salt wasteland declined substantially. However, excessive salt-wasteland loss may weaken its ecological salt-storage and drainage function, increasing long-term salinization risk. Overall, the spatial simulation confirms that CSWR-T functions as a safety threshold linking cultivated-land expansion with regional salt-discharge capacity. A CSWR-T of approximately 7.5 represents a sustainable balance point, whereas values above 8.5–9.0 require caution because excessive reclamation may reduce the ecological buffering capacity of salt wastelands.

Conclusions

This study developed a coupled SaltMod-CLUE-S framework to investigate interactions among cultivated land, saline wasteland, and soil salinity in the JFIS of the HID. The non-spatial module (SaltMod) quantified the CSWR-Ts, which were found to range between 5.5 and 9.0 across different WSI regimes. An optimal value of 8.5 was determined under current irrigation-drainage conditions. Water-saving measures shifted the CSWR-Ts based on disturbance type: API produced the lowest (5.5–6.5), TWD intermediate (5.5–7.5), and GPI the highest (7.0–9.0). A 5% water decrease reduced the threshold by ~2.0 (TWD), ~1.9 (GPI), and ~1.0 (API), highlighting the system's sensitivity to seasonal irrigation strategies. Soil salinity exhibited nonlinear, threshold-dependent dynamics across 33 scenarios, with excessive CSWR-Ts accelerating salinity accumulation, particularly under API cuts that weakened leaching. The spatial CLUE-S module further demonstrated how cultivated and salt wasteland reallocation shapes soil salinity dynamics, thereby providing a coordinated quantity–space allocation mechanism.

By integrating salinity dynamics with land use allocation, this framework advances a novel quantity–space perspective for sustainable management in salinized irrigation districts. The findings highlight the irreplaceable role of API and the ecological buffering function of saline wasteland, offering actionable thresholds for adaptive land and water management under water scarcity.

Beyond current applications, future research should extend this coupled modelling to larger spatial scales, incorporate climate change projections and groundwater interactions, and explore socio-economic drivers of land reallocation. Such integrative approaches will strengthen the capacity to manage land–water–salt systems in arid and semi-arid regions under accelerating environmental and policy pressures.

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