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Water-Quality-Integrated Optimal Allocation of Agricultural Water Resources in Arid Irrigation Districts: A Case Study of Yingjisha County, Xinjiang

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Abstract

We developed a comprehensive water-quality-integrated model for allocating agricultural water resources in Yingjisha County, a hyper-arid county in Xinjiang, China. Groundwater was classified into four salinity levels, and brackish water was incorporated into the irrigation water supply system according to crop salt tolerance. The objective was to maximize agricultural net profit, while accounting for the Maas–Hoffman yield reduction coefficient, a graded salt damage penalty, and soft-constraint penalties, subject to constraints on water quantity, water quality, land area, food security, and freshwater conservation. Under the graded penalty framework, low-salinity brackish water remained economically viable for irrigation: freshwater dependency was governed by the freshwater-conservation ratio, gross agricultural profit increased by 13.6–17.0%, and the time to onset of mild soil salinization reached 5.7–6.0 years under the corrected per-class constraints. These results demonstrate the feasibility of classified regulation for brackish water irrigation in arid irrigation districts.

Keywords: agricultural water resources; optimal allocation; brackish water irrigation; water quality; salt tolerance; salinization; Xinjiang

1. Introduction

1.1. Research Background

Freshwater is fundamental to human survival and social development [1]. China's per capita freshwater resources are only one quarter of the global average, and Xinjiang, in the northwest, faces the most acute shortage; 80% of its water resources are used for agricultural irrigation [2,3]. Irrigation supply in the region remains insufficient. Rapid social and economic development has raised domestic (2%) and industrial (1.8%) water demand, intensifying the imbalance between supply and demand [4,5] and constraining sustainable growth [6]. The problem is especially acute in the extremely arid Tarim Basin, where mean annual precipitation is 69.8 mm, potential evaporation reaches 2170.7 mm, and the aridity index exceeds 30. Agricultural production there depends almost entirely on irrigation, making groundwater an increasingly important supplementary source.

Groundwater in arid regions commonly has high mineralization because evaporation is intense and recharge is limited. In Yingjisha County, only 26.3% of available groundwater has a mineralization degree (MD) ≤ 1 g/L (freshwater); the remaining 73.7% is



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brackish water with MD between 1 and 4 g/L. This brackish groundwater has traditionally been excluded from irrigation because of salinity concerns, leaving abundant low-quality water unused while freshwater is heavily overexploited. The resulting scarcity is driven less by total volume than by water quality, a pattern that can be described as quality-induced water scarcity and which coexists with conventional resource-based scarcity in arid irrigation districts.

Many arid irrigation districts now use brackish water to ease supply pressure [7,8], although brackish irrigation can aggravate soil salinization [9] and affect crop growth. Recent studies address different parts of this challenge. Biochar application improves saline-alkali soil properties and water movement and provides a basis for the safe use of slightly saline water [10]. In a pot experiment, short-term irrigation with mixed saline and reclaimed water did not pose a clear risk of secondary soil salinization, although long-term effects remain uncertain [11]. In a typical cotton-growing area of Yingjisha County, slightly saline water of medium-to-high salinity produced cotton quality and yields comparable to, or better than, freshwater under high soil sand content [12]. Other work has examined how irrigation methods affect soil salinity distribution, maize yield, and water consumption [13]. These findings highlight the need for the rational allocation and use of brackish water in the water-saving agriculture of northwest China.

Nevertheless, most brackish-water studies focus on field-scale agronomic experiments, and few integrate brackish water into regional water-resource allocation models. The economic effect of yield loss under saline irrigation, quantified by the Maas–Hoffman model [14], is also rarely included in optimization frameworks. When the yield–salinity relationship is omitted, models can overstate the benefits of brackish water and recommend allocations that are not economically defensible.

1.2. Literature Review

1.2.1. Optimal Allocation of Water Resources

Optimal water allocation is widely used to address supply–demand imbalances [2], and allocation of limited water has received increasing attention [15]. Early studies combined surface water and groundwater, using nonlinear optimization [16] or queueing theory to distribute canal water under uncertain groundwater availability [17]. Later work introduced diverse algorithmic strategies. Particle swarm optimization and genetic algorithms have been applied to a dual-objective socioeconomic model in arid regions [18], and cooperative particle swarm optimization (CPSO) has been proposed to overcome the limitations of linear and dynamic programming [19]. Multi-objective evolutionary approaches have also been used; a self-improved NSGA-II-S algorithm minimized total allocation while maximizing economic benefits [20]. At the irrigation-district scale, two-level canal systems have been optimized on the basis of actual supply volumes [21]. Hierarchical optimization has jointly adjusted crop structures and irrigation regimes through large-system decomposition and non-domination sorting [22]. More recently, irrigation return-flow reuse has been incorporated into an uncertain optimization model, improving efficiency and reducing cost [3].

1.2.2. Coupled Water Quantity and Quality Optimization

Since the 1990s, the traditional objective of maximizing water supply volume and economic benefits has become inadequate as pollution and water crises have intensified [6]. Water quality and ecological factors have therefore been progressively incorporated into allocation frameworks. The pioneering work on allocating water of different qualities was conducted in Pakistan using a nonlinear programming model [23], and an early joint quantity–quality optimization study laid the groundwork [24]. Subsequent studies simu-

lated interactions among groundwater levels, quality, and pumping costs [25]; used linear objective programming to allocate water of different qualities according to demand [26]; and demonstrated efficiency gains under dual-control constraints [27]. To address resource- and engineering-based scarcity in northern China, a dual-control model raised GDP and reclaimed-water use [28]. More advanced tools, such as coupling FloPy with Pymoo, have reduced groundwater fluctuations and pollution diffusion in multi-objective settings [29]. At the system level, a connection-number model has evaluated coordinated development of water resources, social economy, and ecological environment [30].

1.2.3. Brackish Water Irrigation and Crop Salt Tolerance

Safe brackish-water irrigation depends critically on crop salt tolerance. The Maas–Hoffman model [14] holds that yield is unaffected until salinity exceeds a crop-specific threshold T_j and then declines linearly beyond it; the relationship has been widely validated and documented in FAO Irrigation and Drainage Paper 29 [31]. Crop-specific evidence spans several fronts. Most fruit-tree species are salt-sensitive and have low tolerance thresholds [32]. For wheat, dose–response data link irrigation-water mineralization to relative yield [33], and alternate saline irrigation at different growth stages can sustain yield under controlled salinity [34]. Soil salt dynamics and stress regulation in winter wheat under brackish irrigation have also been examined [35]. Maize has received considerable attention, including mineralization effects on growth and water-use efficiency [36], mitigation of salt and water stress by *Bacillus aryabhattai* [37], time-lapse electrical resistivity tomography of brackish wastewater irrigation [38], and CO₂ and N₂O emissions under alternate saline and groundwater irrigation [39]. For cotton, a key crop in Xinjiang, responses to salinity [40] and salt accumulation in drip-irrigated, film-mulched fields [41] have been studied. Regional syntheses from China [42] and macro-level evidence from Israel [43] complement these results, while brackish-water desalination and rice growth have been assessed under different irrigation modes [44]. Agricultural water-use efficiency and irrigation development in arid and semi-arid regions have also been analyzed [45,46].

These studies show that different crops have distinct salt-tolerance thresholds, that short-term brackish irrigation can sustain yields of salt-tolerant crops such as cotton, and that long-term use requires leaching and monitoring to control salinization. The quantitative Maas–Hoffman relationship, however, has rarely been built into regional optimization models. Without that relationship, models cannot distinguish economically viable from unviable brackish-water uses and may produce inflated benefit estimates and suboptimal allocations.

1.3. Research Gaps and Innovations

1.3.1. Research Gaps

Extensive research has addressed optimal water allocation, and work coupling water quantity and quality is growing. Several issues, however, remain unaddressed:

- Quality as supply, not just constraint. Coupled quantity–quality optimization has concentrated on pollution and reclaimed water, which are mainly affected by human activities. In this study, different water qualities arise chiefly from natural mineralization. Most existing models also treat water quality as an objective, namely avoiding environmental pollution during use. Here, water of different quality is instead part of the supply system, allowing fuller utilization.
- Yield–salinity response in optimization. Earlier allocation models that include brackish water usually assume constant yield as long as salinity remains within crop tolerance. This assumption neglects the Maas–Hoffman yield reduction effect [14], which lowers yield progressively once the crop-specific threshold is exceeded. Models without this

term can overestimate the benefits of brackish irrigation and recommend substitutions that are not economically rational, such as replacing freshwater with high-salinity water for marginally salt-tolerant crops.

- **Constraint integrity.** Conflicting constraints are common when multiple water quality levels are introduced. Some approaches delete conflicting constraints selectively, which compromises model integrity. Soft constraints with penalty functions preserve the full constraint structure while allowing controlled flexibility.
- **Regional specificity.** Quantity–quality optimization has been studied in many regions, including Pakistan [23] and Iran [18], but remains comparatively uncommon for Xinjiang. The Yingjisha case can therefore clarify how such models perform at a smaller scale in hyper-arid settings.
- **Salt accumulation under optimized allocation.** Few reviewed studies assess long-term salinization risk under optimized allocation. More importantly, most salt-accumulation models are used after optimization and are not connected to the decision process. Without internalizing long-term soil damage, an optimization model can maximize short-term economic benefit while leaving an unresolved economic–ecological tradeoff.

1.3.2. Innovations

To address these gaps, this study makes the following contributions:

- **Application innovation.** Brackish groundwater (MD 1–4 g/L) enters the irrigation supply system according to crop salt tolerance instead of being excluded or treated only as a quality constraint. The water-quality-integrated supply concept allows freshwater substitution for salt-tolerant crops.
- **Methodological improvement.** The Maas–Hoffman yield reduction coefficient [14,31] is included in the objective function and prices the yield loss from saline irrigation. Brackish water is therefore recommended only when the savings from freshwater substitution exceed the yield reduction cost.
- **Constraint system optimization.** Quadratic-penalty soft constraints replace selective deletion of conflicting constraints, preserving model integrity. A surface-water allocation variable maintains spatial feasibility.
- **Salt accumulation model improvement.** Crop-specific leaching efficiency coefficients are incorporated, and soil bulk density is set to 1326 kg/m³, giving more realistic long-term salinization estimates.
- **Graded salt damage penalty with freshwater conservation.** A quality-graded penalty enters the objective. Unlike a uniform penalty that treats all brackish grades alike, the graded structure favors MD 1–2 water and still permits MD > 2 water for salt-tolerant crops when economically viable. A freshwater conservation constraint prevents excessive replacement of freshwater, while the full quality constraint system, including the per-class quality constraints, is preserved. The salt accumulation model is thus linked to the optimization objective through a penalty term rather than used only after optimization.

The optimization uses a convex quadratic objective with linear constraints. Its contribution lies mainly in the domain application and model formulation, not in a new algorithmic method.

1.4. Research Objectives and Organization

This study uses Yingjisha County in Xinjiang, China, as a case study. It proposes a water-quality-integrated supply concept, treats different-quality water as both a supply source and a quality constraint, and constructs an optimal allocation model for irrigation water quality. The specific objectives are as follows:

- To quantify the quality-differentiated water supply and demand in the study area, identifying the extent of quality-induced water scarcity.
- To develop an optimization model with a convex quadratic objective and linear constraints that maximizes agricultural net profit while satisfying water quantity, water quality, land area, and food security constraints, incorporating the Maas–Hoffman yield reduction coefficient.
- To evaluate the optimization results across three dimensions: economic benefits, crop planting structure (the area allocated to each crop in each town under each water-quality class), and water resource allocation, with town-level resolution.
- To assess the long-term soil salt accumulation risk under the optimal allocation scheme using an improved salt balance model with leaching efficiency coefficients.
- To propose classified regulation measures for sustainable brackish water irrigation management.

The optimization results are evaluated through economic benefits, crop planting structure, and water allocation. An improved salt accumulation model is then used to assess long-term salinization risk, and classified regulation measures are proposed. The framework is intended to support rational use of different-quality water in arid and semi-arid irrigation districts and to ease the imbalance between supply and demand.

The rest of the paper is organized as follows. Section 2 describes the study area and the optimization method, including model formulation and parameter calibration. Section 3 presents supply–demand analysis, economic benefits, crop structure, water allocation, and salt accumulation. Section 4 gives conclusions and classified regulation measures.

2. Materials and Methods

2.1. Study Area

2.1.1. Geographic and Climatic Conditions

Yingjisha County is located in the southwestern part of the Tarim Basin, Xinjiang Uygur Autonomous Region, China (38°47′–39°02′ N, 75°53′–76°04′ E). The county covers a total area of approximately 3425 km², bordering the Taklamakan Desert to the east and the Kunlun Mountains to the south. The terrain slopes from southwest to northeast, with elevations ranging from 1200 to 2000 m above sea level [47].

The study area has a hyper-arid continental climate. Mean annual precipitation is 69.8 mm, mean annual potential evaporation is 2170.7 mm, and the aridity index exceeds 30. Mean annual temperature is 11.4 °C and the frost-free period is about 220 days. More than 90% of agricultural land is cultivated under drip irrigation with full plastic-film mulching, which reduces evaporation but also limits use of scarce rainfall. Figure 1 shows the location of the study area [47]. The geographic and climatic data are drawn from the county water-resources yearbook and meteorological station records.

2.1.2. Population and Crop Overview

The county has a total population of 276,641 [47], of which approximately 75% are engaged in agriculture. The total arable land area was 29,953.26 ha in 2021–2022 and increased to 34,085.39 ha in 2022–2023 due to land reclamation [48]. The county comprises 14 towns (Table 1); Wucha, Sahan, and Sugaiti are the largest agricultural towns by arable land.

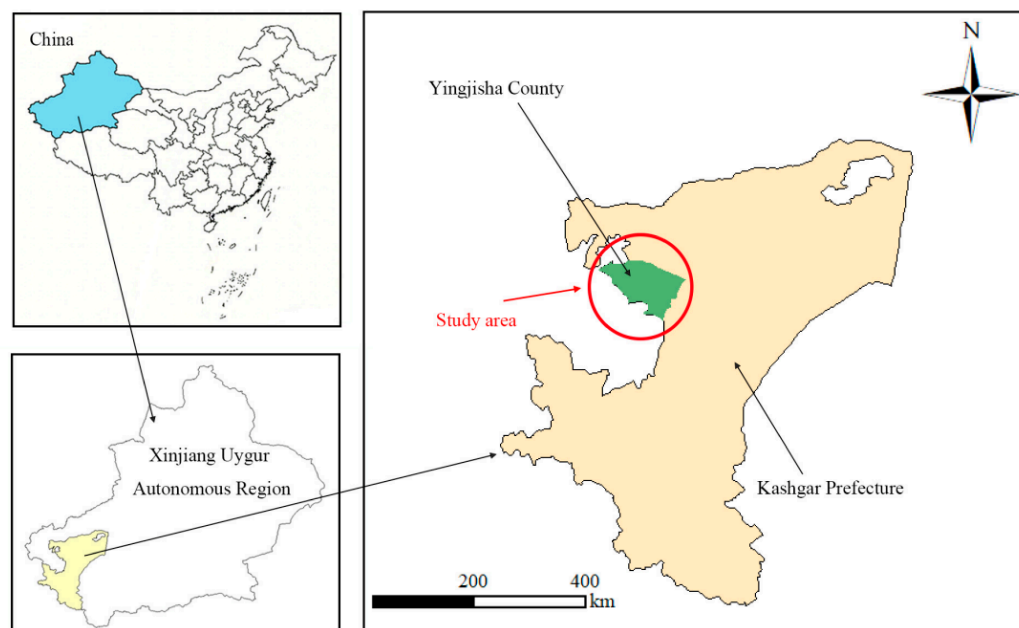


Figure 1. Location of Yingjisha County in Xinjiang Uygur Autonomous Region, China.

Table 1. Available arable land area in each town.

Town	Code	Available Arable Land (ha)
Wucha	i = 1	4466.81
Mangsin	i = 2	1608.38
Sahan	i = 3	3847.45
Chengguan	i = 4	880.85
Qiaolepan	i = 5	2075.84
Longpu	i = 6	1735.54
Saitili	i = 7	2818.12
Yingyer	i = 8	2261.30
Kezile	i = 9	2485.27
Topruk	i = 10	2444.62
Sugaiti	i = 11	3786.88
Aigus	i = 12	854.38
Yingjisha	i = 13	145.04
Yigezayer	i = 14	542.79

Five major crops are cultivated: winter wheat (*Triticum aestivum*), cotton (*Gossypium hirsutum*), corn (*Zea mays*), fruit (primarily apricot, *Prunus armeniaca*), and vegetables (primarily potato, *Solanum tuberosum*). Wheat and corn serve as staple food crops, cotton and fruit as cash crops, and vegetables for both food security and income generation. The crop planting structure has remained relatively stable over the past two decades, with historical planting area bounds summarized in Table 2.

Table 2. Maximum and minimum planting areas of five crops.

Crop	Code	Max Area $j_{\max}^A$ (ha)	Min Area $j_{\min}^A$ (ha)
Wheat	j = 1	18,730	10,400
Cotton	j = 2	19,750	7310
Corn	j = 3	18,060	30
Fruit	j = 4	4490	610
Vegetable	j = 5	5260	870

2.1.3. Water Resources Overview

Agricultural irrigation accounts for about 80% of total water consumption in the county. The water supply system has two components:

- **Surface water:** Derived from reservoir storage with a total capacity of $253.690 \times 10^6 \text{ m}^3$. With an irrigation utilization coefficient of 0.80 [45,46], the available surface water for irrigation is $253.690 \times 10^6 \text{ m}^3 \times 0.8 = 202.952 \times 10^6 \text{ m}^3$. Because the reservoir is recharged by snowmelt and seasonal runoff from the Kunlun Mountains, surface-water availability is subject to interannual variability; the freshwater-conservation constraint (θ) therefore reserves a buffer against drought years.
- **Groundwater.** Groundwater is available in 14 towns at four mineralization levels. Total availability is $97.160 \times 10^6 \text{ m}^3$, of which $25.560 \times 10^6 \text{ m}^3$ ($\text{MD} \leq 1 \text{ g/L}$) is freshwater; the remaining $71.600 \times 10^6 \text{ m}^3$ is brackish ($\text{MD} 1\text{--}4 \text{ g/L}$) and has traditionally been unused because of salinity. Combined freshwater supply (surface water plus $\text{MD} \leq 1$ groundwater) is $228.512 \times 10^6 \text{ m}^3$, while total supply across all quality levels is $300.112 \times 10^6 \text{ m}^3$.

Groundwater quality varies among towns (Figure 2). Wucha, Sahan, and Sugaiti have relatively abundant MD 1–2 groundwater, whereas Yingjisha and Yigezayer have the smallest resources. This heterogeneity creates the basis for quality-differentiated allocation.

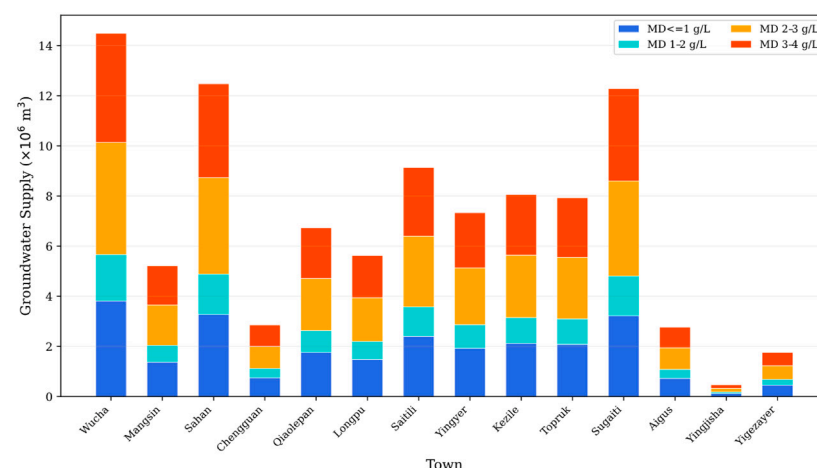


Figure 2. Spatial distribution of groundwater supply across 14 towns in Yingjisha County by mineralization level.

2.2. Optimization Allocation Method for Agricultural Water Resources Considering Water Quality

2.2.1. Overall Approach

Figure 3 outlines the technical roadmap. The optimization framework follows a seven-step logic:

- **Problem identification:** Quantify the dual challenge of freshwater scarcity and under-utilized brackish groundwater.
- **Concept formulation:** Propose “water-quality-integrated supply,” classifying groundwater into four MD levels (≤ 1 , 1–2, 2–3, 3–4 g/L) and matching irrigation sources to crop salt tolerance.
- **Supply–demand analysis:** Calculate quality-differentiated water supply and demand, with effective rainfall estimated for reporting under film-mulched drip irrigation.
- **Model construction:** Build an original optimization model with linear constraints and quadratic soft-constraint penalties, with three-dimensional decision variables $x_{i,j,k}$, a Maas–Hoffman-based yield reduction coefficient $\alpha_{j,k}$ in the objective function, a

graded salt penalty function $\gamma_k \cdot \sigma_{j,k}$, and a freshwater conservation constraint with theta as a scenario variable (0.60–0.90, base 0.75).

- Three-dimensional evaluation: Assess outcomes in terms of economic benefits, planting structure, and water resource allocation.
- Salt accumulation assessment: Evaluate long-term soil salinization risk using an improved salt balance model incorporating leaching efficiency coefficients λ_j .
- Classified regulation measures: Propose crop-specific and town-specific water quality management strategies.

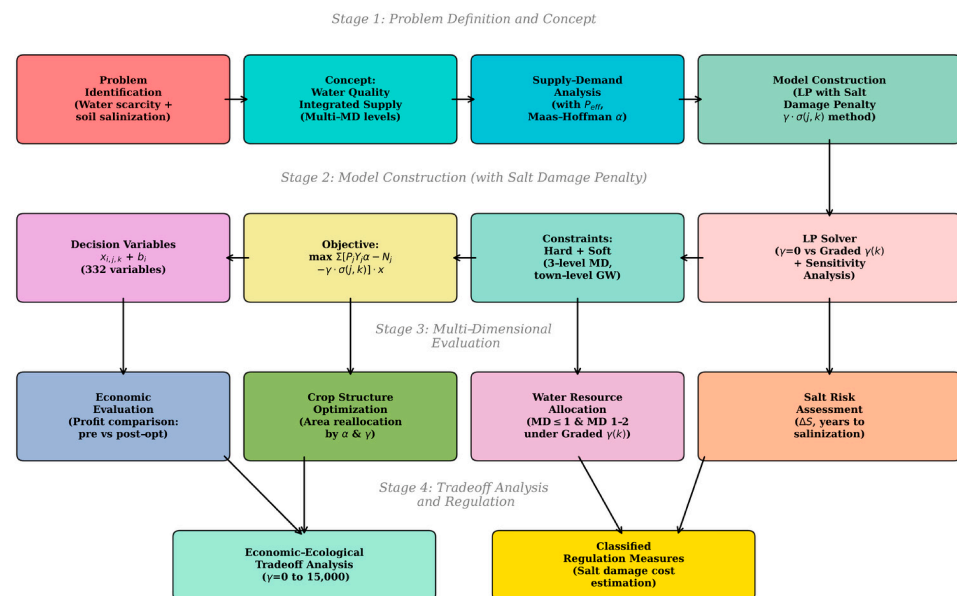


Figure 3. Technical roadmap of the water-quality-integrated optimization framework.

2.2.2. Calculation Methods for Water Supply and Demand Considering Water Quality

1. Water Supply Calculation

Total irrigation supply consists of surface water and groundwater at four quality levels:

$$W_{\text{total}} = B + W \quad (1)$$

where $B = 202.952 \times 10^6 \text{ m}^3$ is the available surface water (all classified as $\text{MD} \leq 1 \text{ g/L}$), and W is the total groundwater volume; W_k ($k = 1, \dots, 4$) denotes the incremental groundwater volume of quality class k . The quality-differentiated water supply is shown in Table 3.

Table 3. Quality-differentiated water supply summary.

Quality Level	MD Range (g/L)	Representative MD (g/L)	Groundwater W_k (Incremental, $\times 10^6 \text{ m}^3$)	Total Supply Incl. Surface Water ($\times 10^6 \text{ m}^3$)
$k = 1$	$\text{MD} \leq 1$	0.5	25.560	228.512
$k = 2$	$1 < \text{MD} \leq 2$	1.5	23.000	—
$k = 3$	$2 < \text{MD} \leq 3$	2.5	24.000	—
$k = 4$	$3 < \text{MD} \leq 4$	3.5	24.600	300.112

Note: W_k denotes the incremental groundwater volume of quality class k , i.e., 25.560, 23.000, 24.000, and $24.600 \times 10^6 \text{ m}^3$ for $\text{MD} \leq 1$, MD 1–2, MD 2–3, and MD 3–4, respectively, derived by differencing the measured cumulative volumes (25.560, 48.560, 72.560, and $97.160 \times 10^6 \text{ m}^3$). In the reported runs, the allocation is limited primarily by the freshwater conservation constraint (θ) and crop salt tolerance (α).

Figure 2 shows the spatial distribution of groundwater supply, and Figure 4 shows overall supply composition. For the model, town-level volumes $W_{i,k}$ were allocated proportionally to arable land within each quality class.

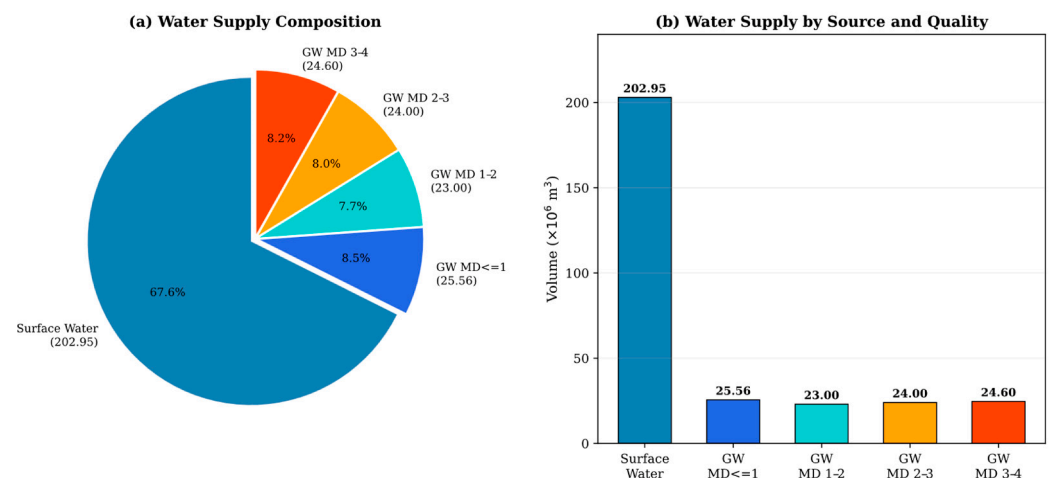


Figure 4. Overall (a) water supply composition and (b) surface water vs. groundwater by quality level.

2. Water Demand Calculation

The total irrigation source demand is calculated as follows:

$$RW = \sum_{i=1}^{14} \sum_{j=1}^5 \sum_{k=1}^{K_j} x_{i,j,k} \cdot D_{j,k} \quad (2)$$

where $D_{j,k}$ is the effective irrigation quota for crop j under water-quality class k (Table 4).

Table 4. Crop-specific technical and economic parameters.

Crop	Irrigation Quota D_j (m ³ /ha)	Baseline Yield Y_j (kg/ha)	Unit Price P_j (CNY/kg)	Planting Cost C_j (CNY/ha)
Wheat	7800	6000	3.0	16,000
Cotton	8100	2250	17.5	33,000
Corn	7500	9000	2.6	18,000
Fruit	6000	8000	8.0	20,000
Vegetable	7800	30,000	3.0	35,000

For brackish water ($k \geq 2$), irrigation requires an additional leaching fraction to control salt accumulation. Following the standard leaching-requirement model, $LR_{j,k} = EC_{w,k} / (5 \cdot EC_{e,j} - EC_{w,k})$, where $EC_{w,k}$ is the electrical conductivity of the irrigation water of quality class k and $EC_{e,j}$ is the soil saturation-extract electrical conductivity corresponding to the salt-tolerance threshold of crop j . The effective irrigation quota is therefore $D_{j,k} = D_j \cdot (1 + LR_{j,k})$, with $LR = 0$ for freshwater ($k = 1$). The additional leaching water is supplied to flush salts out of the root zone, and its salinity is assumed to leave with drainage rather than accumulate in the soil; the net salt-removal effect is therefore captured by the leaching-efficiency coefficient λ_j in the salt-balance model (Section 2.2.3).

Effective rainfall estimation. Under drip irrigation with >90% plastic-film coverage, most rainfall is intercepted by the film and lost to evaporation or runoff. Given the arid

climate (69.8 mm rainfall vs. 2170.7 mm evaporation), the rainfall utilization coefficient β is set to 0.10, following Kang and Cai [48] for similar conditions in northwest China:

$$P_{\text{eff}} = 10 \times P \times A \times \beta \quad (3)$$

where $P = 69.8$ mm is annual rainfall, A is the total arable land (ha), and $\beta = 0.10$. P_{eff} is 2.09×10^6 m³ in 2021–2022 and 2.38×10^6 m³ in 2022–2023. Because this amount is small, it is reported separately and conservatively not deducted from irrigation source demand; reported totals are therefore based on crop irrigation quotas.

2.2.3. Water Resources Optimization Allocation Model Considering Water Quality

1. Decision Variables

The model has three sets of decision variables:

- $x_{i,j,k}$ is the planting area of crop j in town i irrigated with water quality level k (ha), with $i = 1, \dots, 14$, $j = 1, \dots, 5$, and $k = 1, \dots, K_j$. K_j is the number of applicable quality levels, which depends on crop salt tolerance, giving 168 x-variables.
- b_i is the surface water volume allocated to town i (m³), $i = 1, \dots, 14$, where the notation b is used for the town-level surface-water distribution to each town. This variable ensures that total surface water allocation does not exceed B and, at the town level, is capped by each town's own freshwater demand (Section 2.2.3). A third set, the soft-constraint slack variables δ , is defined in the soft-constraint section below.

The crop–quality matching scheme is defined by salt tolerance thresholds (Figure 5, Tables 5 and 6):

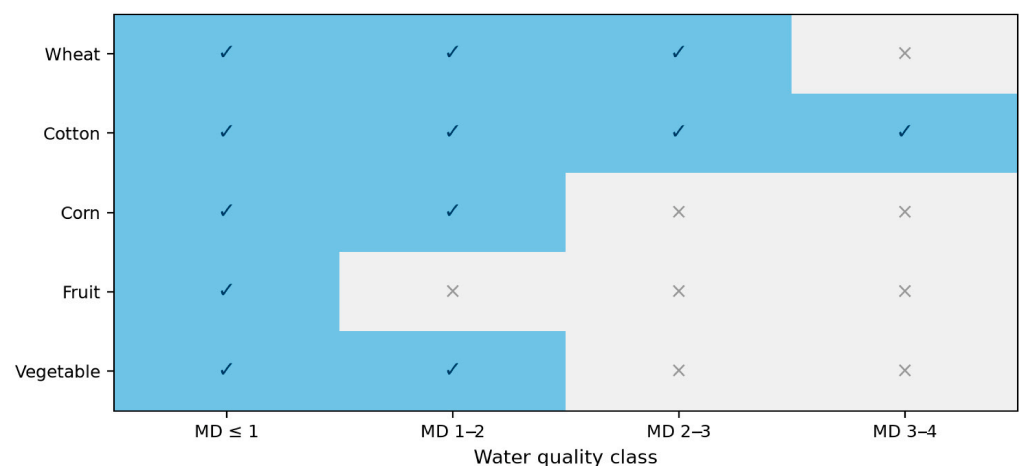


Figure 5. Crop salt tolerance classification and applicable irrigation water quality levels for five crops (✓ indicates that the crop can tolerate irrigation water with this mineralization level; × indicates that the crop cannot tolerate irrigation water with this mineralization level).

Table 5. Crop salt tolerance parameters, yield reduction coefficients, and minimum yield demand.

Crop	T_j (g/L)	s_j (%/g/L)	K_j	α (MD ≤ 1)	α (MD 1–2)	α (MD 2–3)	α (MD 3–4)	Per Capita Demand (kg/yr)	Min Yield ($\times 10^6$ kg)
Wheat	2.5	4.6	3	1.000	1.000	1.000	—	150	41.5
Cotton	3.3	3.3	4	1.000	1.000	1.000	0.9934	—	—
Corn	0.7	7.7	2	1.000	0.9384	—	—	20	5.53
Fruit	0.7	15.4	1	1.000	—	—	—	—	—
Vegetable	1.1	6.3	2	1.000	0.9748	—	—	100	27.66

Table 6. Crop salt tolerance thresholds and applicable water quality levels.

Crop (j)	Salt Tolerance Threshold T_j (g/L)	Applicable Quality Levels	K_j
Wheat (j = 1)	2.5	k = 1, k = 2, k = 3	3
Cotton (j = 2)	3.3	k = 1, k = 2, k = 3, k = 4	4
Corn (j = 3)	0.7	k = 1, k = 2	2
Fruit (j = 4)	0.7	k = 1	1
Vegetable (j = 5)	1.1	k = 1, k = 2	2

Notes: T_j = salt tolerance threshold (Maas–Hoffman model [14]); K_j = number of applicable quality levels; Minimum yield demand based on population of 276,641. Parameters calibrated from FAO Paper 29 [31] and regional field experiments in Xinjiang.

2. Objective Function

The objective maximizes annual net profit across the county, accounting for yield reduction under brackish irrigation, long-term soil salt damage, and penalties for soft-constraint violations:

$$\max f(x) = \sum_{i=1}^{14} \sum_{j=1}^5 \sum_{k=1}^{K_j} \left[P_j \cdot Y_j \cdot \alpha_{j,k} - C_j - \gamma_k \cdot \sigma_{j,k} \right] \cdot x_{i,j,k} - \sum_{m \in S} \lambda_m \cdot \delta_m^2 \quad (4)$$

where P_j is the unit price of crop j (Table 4), Y_j is the freshwater-irrigated baseline yield, C_j is the planting cost per hectare, $\alpha_{j,k}$ is the Maas–Hoffman yield reduction coefficient, γ_k is the quality-graded salt damage penalty coefficient, $\sigma_{j,k}$ is the unit-area annual soil salt increment (g/kg per ha) for crop j irrigated with water quality k , λ_m is the penalty coefficient for soft constraints, δ_m is the slack variable for the m -th soft constraint, and S is the set of soft constraints.

The graded salt penalty term $\gamma_k \cdot \sigma_{j,k}$ represents the monetized long-term soil damage cost per hectare, with γ_k differentiated by water quality level: $\gamma_1 = 0$ for freshwater ($MD \leq 1$), $\gamma_2 = 400$ for low-risk brackish (MD 1–2), $\gamma_3 = 800$ for medium-risk brackish (MD 2–3), and $\gamma_4 = 1200$ for high-risk brackish (MD 3–4). This graded structure incentivizes brackish water utilization while internalizing ecological costs proportionally to salinity risk.

Yield reduction coefficient $\alpha_{j,k}$: Based on the Maas–Hoffman model [14], the relative yield under saline irrigation is as follows:

$$\alpha_{j,k} = \begin{cases} 1 & \text{if } MD_k \leq T_j \\ 1 - \frac{s_j \cdot (MD_k - T_j)}{100} & \text{if } MD_k > T_j \end{cases} \quad (5)$$

where MD_k is the representative mineralization of quality level k , T_j is the salt tolerance threshold, and s_j is the yield decline slope (% per g/L beyond threshold). The Maas–Hoffman parameters and resulting α values are presented in Table 5.

The calibration of T_j and s_j follows two steps. Initial values are derived from FAO Paper 29 by converting soil saturation extract EC_e to irrigation-water mineralization using a concentration factor $f = 1.5$ and a TDS–EC conversion of 0.64. Values are then adjusted to match regional salt-tolerance evidence in Xinjiang [8,32–34,36,37,40–42], which reports that short-term brackish irrigation did not cause statistically significant yield loss. The calibrated α values are 1.000 for wheat at $MD = 2.5$, 0.9934 for cotton at $MD = 3.5$, and 0.9384 for corn at $MD = 1.5$.

3. Constraints

The constraints include 95 hard constraints and 150 soft constraints:

- Hard constraints (must be satisfied):

Total planting area constraint:

$$\sum_{i=1}^{14} \sum_{j=1}^5 \sum_{k=1}^{K_j} x_{ij,k} \leq S \quad (6)$$

where S is the total arable land area.

Town-level planting area constraint:

$$\sum_{j=1}^5 \sum_{k=1}^{K_j} x_{ij,k} \leq S_i, \quad i = 1, \dots, 14 \quad (7)$$

Total water volume constraint:

$$\sum_{i,j,k} x_{ij,k} \cdot D_{j,k} \leq W + B \quad (8)$$

Per-class water quality equilibrium constraints (incremental, non-cumulative): surface water B enters only the freshwater ($k = 1$) class; each brackish class $k \geq 2$ is balanced independently:

$$\begin{cases} \sum_{i=1}^{14} \sum_{j=1}^5 x_{ij,1} \cdot D_{j,1} \leq W_1 + B \\ \sum_{i=1}^{14} \sum_{j=1}^5 x_{ij,2} \cdot D_{j,2} \leq W_2 \\ \sum_{i=1}^{14} \sum_{j=1}^5 x_{ij,3} \cdot D_{j,3} \leq W_3 \\ \sum_{i=1}^{14} \sum_{j=1}^5 x_{ij,4} \cdot D_{j,4} \leq W_4 \end{cases} \quad (9)$$

Town-level per-class water quality constraints (same incremental structure as Equation (9)):

$$\begin{cases} \sum_{j=1}^5 x_{ij,1} \cdot D_{j,1} \leq W_{i,1} + b_i \\ \sum_{j=1}^5 x_{ij,2} \cdot D_{j,2} \leq W_{i,2} \\ \sum_{j=1}^5 x_{ij,3} \cdot D_{j,3} \leq W_{i,3} \\ \sum_{j=1}^5 x_{ij,4} \cdot D_{j,4} \leq W_{i,4} \end{cases} \quad (10)$$

Surface water allocation constraints:

$$\sum_{i=1}^{14} b_i \leq B \quad (11)$$

$$b_i \leq \sum_j x_{ij,1} \cdot D_{j,1}, \quad i = 1, \dots, 14 \quad (12)$$

This constraint ensures that the sum of surface water allocated to all towns does not exceed the total available amount. In addition, the surface water allocated to each town is capped by that town's own freshwater demand (Equation (12)). Combined with the town-level freshwater constraint (Equation (9)), this brackets b_i between the town's residual freshwater demand (its $MD \leq 1$ irrigation demand minus its own $MD \leq 1$ groundwater) and its total $MD \leq 1$ demand, so that no town receives more surface water than it can use. Because b enters no economic term of the objective, the optimum is otherwise

degenerate in b ; a negligible tie-breaking regularization (3×10^{-6} CNY/m³; total effect below $10^{-3} \times 10^6$ CNY, i.e., below the reporting precision) selects the local-groundwater-first allocation, in which each town uses its own $MD \leq 1$ groundwater before drawing surface water.

Freshwater conservation constraint. To reserve freshwater for high-value salt-sensitive crops (fruit, vegetable) and food-security crops, total demand from $MD \leq 1$ water is capped at fraction θ of total freshwater supply:

$$\sum_i \sum_j \sum_{k: MD_k \leq 1} x_{i,j,k} \cdot D_{j,1} \leq \theta \cdot (W_1 + B) \quad (13)$$

where $\theta \in [0.60, 0.90]$ (base 0.75); at most 75% of freshwater supply can be used directly for irrigation, leaving at least 25% unallocated for ecological flow and drought contingency.

Minimum yield constraints:

$$\begin{cases} \sum_i \sum_{k=1}^3 x_{i,1,k} \cdot Y_1 \cdot \alpha_{1,k} \geq I_1 \\ \sum_i \sum_{k=1}^3 x_{i,3,k} \cdot Y_3 \cdot \alpha_{3,k} \geq I_3 \\ \sum_i x_{i,5,1} \cdot Y_5 \geq I_5 \end{cases} \quad (14)$$

where I_j is minimum yield demand based on population and per capita consumption. α is included in yield calculations so that food-security constraints reflect realistic yield expectations.

- Soft constraints (handled through quadratic penalties in the objective function):

Town-level crop area change bounds:

$$\begin{cases} \sum_k x_{i,j,k} \leq 1.25 \cdot S_{i,j} + i, j_+^\delta \\ \sum_k x_{i,j,k} \geq 0.75 \cdot S_{i,j} - i, j_-^\delta \end{cases} \quad (15)$$

Historical area bounds:

$$\begin{cases} \sum_i \sum_k x_{i,j,k} \leq j_{\max}^A + M, j_+^\delta \\ \sum_i \sum_k x_{i,j,k} \geq j_{\min}^A - N, j_-^\delta \end{cases} \quad (16)$$

where $S_{i,j}$ is the pre-optimization planting area, $A_j^{\max}$ and $A_j^{\min}$ are historical maxima and minima, respectively, and δ are slack variables penalized at $\lambda m = 5 \times 10^5$ Chinese Yuan (CNY)/ha². The marginal penalty $2 \cdot \lambda m \cdot \delta$ at $\delta = 1$ ha equals 1.0×10^6 CNY/ha, about 18 times the highest realized per-hectare margin, so violations are strongly discouraged and slacks approach zero at the optimum.

The model contains 332 decision variables (168 $\times$, 14 b , 150 δ) and 577 constraints (95 hard, 150 soft, 332 non-negativity). It is a convex quadratic program with linear constraints and is solved with the Clarabel interior-point solver (v0.11) in Python 3.13. The soft-constraint penalty is large enough to discourage violations while preserving the full constraint structure.

4. Salt Accumulation Model

To assess long-term ecological risk, the soil salt balance model was revised in two ways: Annual salt input:

$$\Delta S_{in,j} = D_j \times C \times (1 - \lambda_j) \quad (17)$$

where C is irrigation-water mineralization (kg/m^3 , equal to representative MD), and λ_j is crop-specific leaching efficiency, which represents partial salt removal by leaching, crop uptake, and drainage during the growing season. λ_j (leaching efficiency, salt-removal side) is thus distinguished from the leaching-requirement fraction LR (water-volume side, Section 2.2.2): LR enlarges the irrigation quota to supply the additional leaching water, whose salinity leaves with drainage, so the salt balance uses the base quota D_j rather than the effective quota $D_{j,k}$.

Annual soil salt increment:

$$\Delta S_j = \frac{\Delta S_{in,j} \times 1000}{10,000 \times z \times \rho_b} \quad (18)$$

where $z = 1.0 \text{ m}$ is the soil depth, and $\rho_b = 1326 \text{ kg}/\text{m}^3$ is the soil bulk density.

Years to reach salinization grades:

$$n_j = \frac{S_c - S_0}{\Delta S_j} \quad (19)$$

where $S_0 = 0.6 \text{ g}/\text{kg}$ is the initial soil salt content and S_c is the salinization threshold: 3.0 g/kg (mild), 5.0 g/kg (moderate), 8.0 g/kg (severe).

2.2.4. Graded Salt Damage Penalty Function

The salt accumulation model assesses long-term salinization risk after optimization. Without a salt penalty, the objective function maximizes short-term economic profit and ignores long-term soil damage, creating an economic–ecological tradeoff. To address this issue, a monetized salt damage cost is incorporated directly into the objective function, enabling the model to explicitly account for soil sustainability. The penalty function was selected for the following reasons: (1) it preserves a convex objective and linear constraints; (2) it avoids additional hard constraints and solution infeasibility; (3) it yields a well-defined optimum for a given penalty scheme, although strict uniqueness of the optimum requires additional strict convexity conditions.

The initial uniform penalty assigns the same cost to all water quality levels, so low-salinity brackish water (MD 1–2) is penalized as heavily as high-salinity water (MD 3–4). This discourages brackish use and conflicts with the study objective. A graded coefficient γ_k avoids that problem:

$$\gamma_k = \begin{cases} 0 & k = 1(\text{MD} \leq 1 \text{ g/L, freshwater}) \\ 400 & k = 2(\text{MD } 1\text{--}2 \text{ g/L, low - risk brackish}) \\ 800 & k = 3(\text{MD } 2\text{--}3 \text{ g/L, medium - risk brackish}) \\ 1200 & k = 4(\text{MD } 3\text{--}4 \text{ g/L, high - risk brackish}) \end{cases} \quad (20)$$

Estimation rationale. The maximum penalty $\gamma_4 = 1200 \text{ CNY}/(\text{g}/\text{kg} \cdot \text{ha})$ is based on Xinjiang soil remediation cost data. Local saline–alkali land improvement projects cost 15,000–30,000 CNY/ha and reduce salt content by 2–3 g/kg. Midpoint values (22,500 CNY/ha, 2.5 g/kg) give the following:

$$\gamma_{\max} = \frac{22,500 \text{ CNY/ha}}{2.5 \text{ g/kg}} \times \frac{1}{n_{\text{remed}}} = \frac{9000}{7.5} \approx 1200 \text{ CNY}/(\text{g}/\text{kg} \cdot \text{ha}) \quad (21)$$

where $n_{\text{remed}} \approx 7.5$ years is an assumed remediation interval based on regional practice. The annualization factor ($1/n_{\text{remed}} \approx 0.133$) converts one-time remediation cost into an equivalent annual penalty rate.

The lower-tier penalties are proportional fractions of $\gamma_{\max}$: $\gamma_1 = 0$ because freshwater contributes little salt accumulation, $\gamma_2 = 400$ (one-third), and $\gamma_3 = 800$ (two-thirds). This approach creates a progressive cost structure that favors low-salinity brackish water while still permitting high-salinity water when economically justified.

Unit-area salt increment $\sigma_{j,k}$. The salt increment per hectare for each crop–quality combination is derived from the salt balance model:

$$\sigma_{j,k} = \frac{D_j \cdot C_k \cdot (1 - \lambda_j) \times 1000}{10,000 \times z \times \rho_b} \quad (22)$$

where C_k is representative mineralization of quality level k and λ_j is leaching efficiency. The unit-area salt increment a is shown in Table 7.

Table 7. Annual salt input and annual soil salt increment.

Crop	Parameter	MD ≤ 1 (0.5 g/L)	MD 1–2 (1.5 g/L)	MD 2–3 (2.5 g/L)	MD 3–4 (3.5 g/L)
Wheat	ΔS_{in} (kg/ha)	2340	7020	11,700	—
	σ (g/kg/ha)	0.1765	0.5294	0.8824	—
Cotton	ΔS_{in} (kg/ha)	3240	9720	16,200	22,680
	σ (g/kg/ha)	0.2443	0.7330	1.2217	1.7104
Corn	ΔS_{in} (kg/ha)	2437.5	7312.5	—	—
	σ (g/kg/ha)	0.1838	0.5515	—	—
Fruit	ΔS_{in} (kg/ha)	2250	—	—	—
	σ (g/kg/ha)	0.1697	—	—	—
Vegetable	ΔS_{in} (kg/ha)	2535	7605	—	—
	σ (g/kg/ha)	0.1912	0.5735	—	—

Effective profit matrix. With the graded penalty γ_k , the effective profit per hectare becomes the following:

$$\pi_{\text{eff}}(j, k) = [P_j \cdot Y_j \cdot \alpha_{j,k} - C_j] - \gamma_k \cdot \sigma_{j,k} \quad (23)$$

Figure 6 and Table 8 compare the effective profit matrix obtained under the graded γ_k scheme with that of the no-penalty case. Under the graded scheme, wheat and corn retain positive effective profits when irrigated with MD 1–2 water (1788.24 and 3737.97 CNY/ha, respectively), and cotton remains economically viable when irrigated with MD 2–3 water, because $\gamma_3 = 800$ is a moderate penalty. The graded structure therefore creates a viable pathway across multiple quality tiers, without imposing disproportionate penalties on low- or medium-salinity water.

Freshwater conservation constraint. To prevent all freshwater from being replaced by low-penalty brackish water, Equation (13) limits total MD ≤ 1 demand to 75% of available freshwater. A minimum freshwater buffer is thereby reserved for ecological needs and drought contingency; the reserved portion is not allocated to irrigation or treated as substitutable.

To examine the role of the graded penalty function γ_k under the freshwater-conservation ratio $\theta \in [0.60, 0.90]$ (base 0.75), a sensitivity analysis explores four penalty schemes ranging from aggressive brackish water promotion to a no-penalty benchmark, with details given in Table 9.

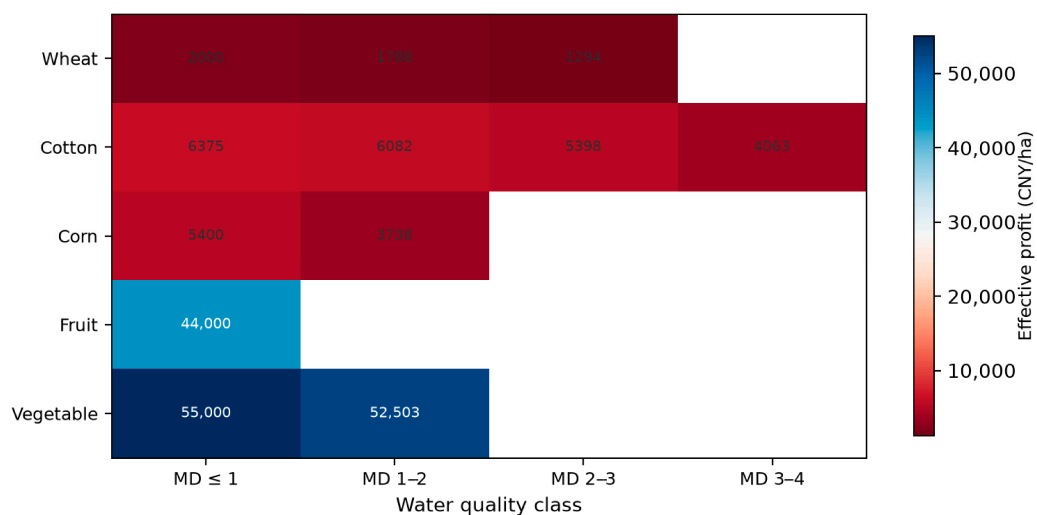


Figure 6. Effective profit matrix under graded salt penalty, showing net profit, salt penalty, and effective profit for each crop-quality combination.

Table 8. Effective profit matrix with graded salt penalty γ_k .

Crop	Item	MD ≤ 1 ($\gamma = 0$)	MD 1–2 ($\gamma = 400$)	MD 2–3 ($\gamma = 800$)	MD 3–4 ($\gamma = 1200$)
Wheat	Net profit (CNY/ha)	2000	2000	2000	—
	Effective profit (CNY/ha)	2000	1788.24	1294.12	—
Cotton	Net profit (CNY/ha)	6375	6375	6375	6375
	Effective profit (CNY/ha)	6375	6081.79	5397.62	4062.64
Corn	Net profit (CNY/ha)	5400	5400	—	—
	Effective profit (CNY/ha)	5400	3737.97	—	—
Fruit	Net profit (CNY/ha)	44,000	—	—	—
	Effective profit (CNY/ha)	44,000	—	—	—
Vegetable	Net profit (CNY/ha)	55,000	55,000	—	—
	Effective profit (CNY/ha)	55,000	52,502.59	—	—

Notes: Effective profit = net profit – $\gamma_k \cdot \sigma_{j,k}$. Graded $\gamma_k = [0, 400, 800, 1200]$ CNY/(g/kg·ha). Low effective profits (e.g., cotton with MD 3–4) indicate marginal economic viability.

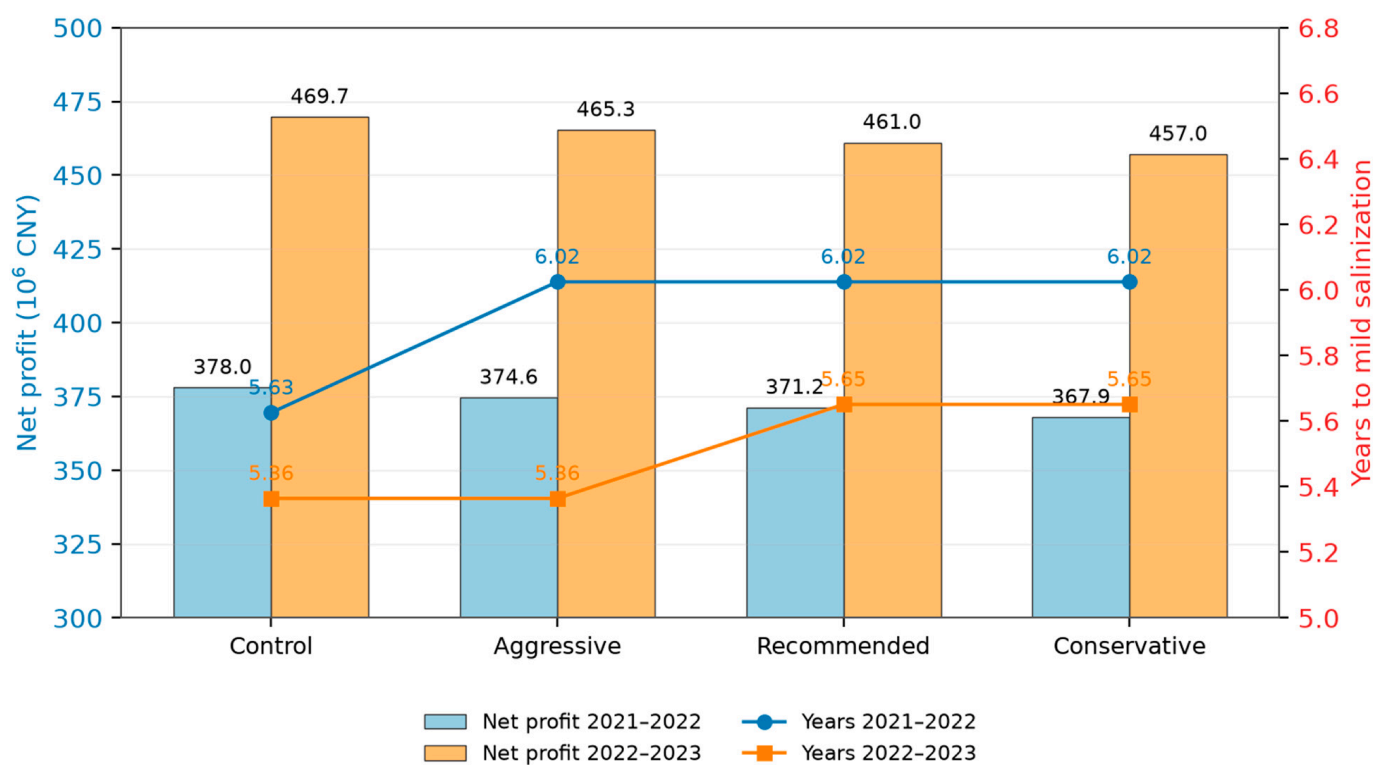
Table 9. Penalty schemes for sensitivity analysis.

Scheme	γ_1	γ_2	γ_3	γ_4	Description
Aggressive	0	200	400	600	Strongly incentivizes brackish use
Recommended	0	400	800	1200	Baseline graded scheme
Conservative	0	600	1200	1800	Moderately discourages brackish use
Control	0	0	0	0	No salt penalty (benchmark)

The recommended scheme ($\gamma_k = [0, 400, 800, 1200]$) is the primary case study. The choice does not depend on precise γ_k calibration: all graded schemes produce the same water allocation, and only the no-penalty control differs qualitatively. Table 10 and Figure 7 report the four schemes.

Table 10. Economic–Ecological Tradeoff.

γ_k Scheme	Profit (10^6 CNY)	Salt Penalty (10^6 CNY)	Water (10^6 m ³)	σ_{avg} (g/kg)	Mild (yr)	MD $\leq$ 1 Water (10^6 m ³)	MD 1–2 Water (10^6 m ³)	MD 2–3 Water (10^6 m ³)	MD 3–4 Water (10^6 m ³)
Aggressive $\gamma = [0, 200, 400, 600]$	377.97	3.36	237.99	0.3984	6.02	171.38	23.00	24.00	19.61
Recommended $\gamma = [0, 400, 800, 1200]$	377.97	6.72	237.99	0.3984	6.02	171.38	23.00	24.00	19.61
Conservative $\gamma = [0, 600, 1200, 1800]$	377.97	10.08	237.99	0.3984	6.02	171.38	23.00	24.00	19.61
Control $\gamma = [0, 0, 0, 0]$	378.01	0.00	236.57	0.4266	5.63	171.38	23.00	24.00	18.19

**Figure 7.** Economic–ecological tradeoff across four graded penalty schemes, showing profit, salt penalty, and years to mild salinization.

2.2.5. Model Parameters

Key parameters required for the optimal allocation model are given in Table 11.

Table 11. Summarizes key model parameters [8,14,31,44–46,48].

No.	Parameter	Symbol	Unit	Value
1	Irrigation quota	D_j	m^3/ha	7800, 8100, 7500, 6000, 7800
2	Baseline yield (freshwater)	Y_j	kg/ha	6000, 2250, 9000, 8000, 30,000
3	Unit price	P_j	CNY/kg	3.0, 17.5, 2.6, 8.0, 3.0
4	Planting cost	C_j	CNY/ha	16,000, 33,000, 18,000, 20,000, 35,000
5	Salt tolerance threshold	T_j	g/L	2.5, 3.3, 0.7, 0.7, 1.1
6	Yield reduction slope	s_j	%/(g/L)	4.6, 3.3, 7.7, 15.4, 6.3
7	Leaching fraction	λ_j	—	0.4, 0.2, 0.35, 0.25, 0.35
8	Root-zone depth	z	m	1
9	Freshwater conservation ratio	θ	—	0.75
10	Surface water supply	B	$\times 10^6 \text{ m}^3$	202.952
11	Effective rainfall	P_{eff}	$\times 10^6 \text{ m}^3$	2.09 (2021–2022), 2.38 (2022–2023)
12	Rainfall utilization coeff.	β	—	0.10
13	Penalty coefficient	λ_m	—	5×10^5
14	Graded salt penalty coeff.	γ_k	CNY/(g/kg·ha)	[0, 400, 800, 1200]
15	Unit-area salt increment	$\sigma_{j,k}$	g/kg/ha	0.170–1.710
16	Leaching requirement fraction	$LR_{j,k}$	—	0.065–0.400

3. Results and Discussion

First, we verify the reliability of the optimized configuration model. The pre-optimization crop areas and the quota-based demand derived from them (230.49 and $261.07 \times 10^6 \text{ m}^3$ for 2021–2022 and 2022–2023) are calibrated directly from county statistics, so their agreement with the reported planting structure is a consistency check by construction. As a comparison against county-reported withdrawals, the modeled pre-optimization consumption corresponds to gross withdrawals of 288.11 and $326.34 \times 10^6 \text{ m}^3$ at the irrigation utilization coefficient of 0.80 . County-reported total water use in 2022 was $707.60 \times 10^6 \text{ m}^3$, of which $80.89 \times 10^6 \text{ m}^3$ was ecological replenishment and approximately 80% was agricultural use [49]. The modeled gross withdrawals thus account for 51 – 58% of reported agricultural withdrawals, a share consistent with the model scope—the $29,953$ – $34,085$ ha of five major field crops—which excludes the county's $\approx 11,800$ ha of apricot orchards and ≈ 1430 ha of melons reported in the county statistical communiqué [50]. The magnitude and coverage of the modeled consumption therefore agree with the county-reported withdrawals.

3.1. Analysis of Supply–Demand Balance of Water Resources

The total irrigation water supply in the study area is $300.112 \times 10^6 \text{ m}^3$, comprising $202.952 \times 10^6 \text{ m}^3$ of surface water (67.6%) and $97.160 \times 10^6 \text{ m}^3$ of groundwater (32.4%). Among the groundwater extracted for irrigation, only $25.560 \times 10^6 \text{ m}^3$ (26.3%) is freshwater ($\text{MD} \leq 1 \text{ g/L}$), while $71.600 \times 10^6 \text{ m}^3$ (73.7%) is brackish water with MD ranging from 1 to 4 g/L .

Groundwater supply varies across the 14 towns (Figure 2). Wucha, Sahan, and Sugaiti have the largest groundwater resources, whereas Yingjisha and Yigezayer have the smallest. Groundwater with an MD of 1 – 2 g/L , the main brackish water resource used for irrigation, is concentrated in Wucha, Sahan, and Sugaiti.

Figures 8 and 9 present quality-differentiated irrigation demand by town for the two periods. The pre-optimization water source demand, calculated based on crop irrigation quotas, is $230.49 \times 10^6 \text{ m}^3$ in 2021–2022 and $261.07 \times 10^6 \text{ m}^3$ in 2022–2023.

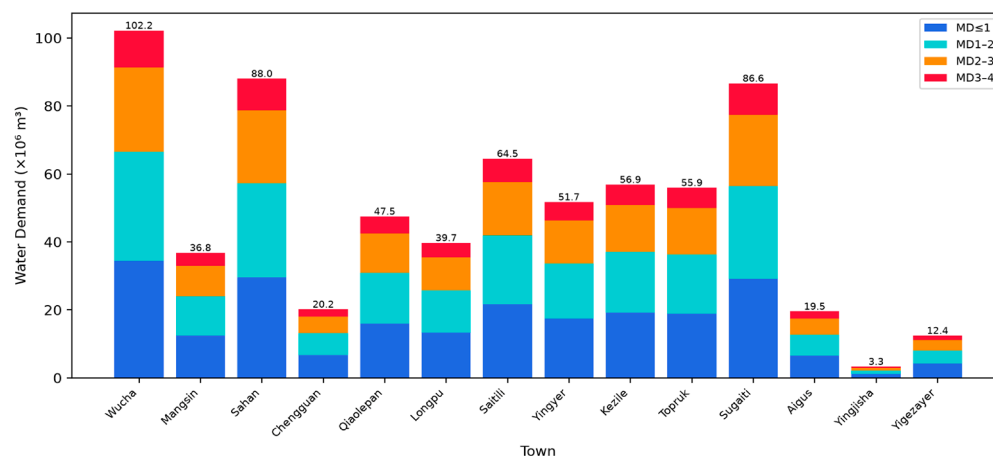


Figure 8. Quality-differentiated irrigation water demand by town for 2021–2022.

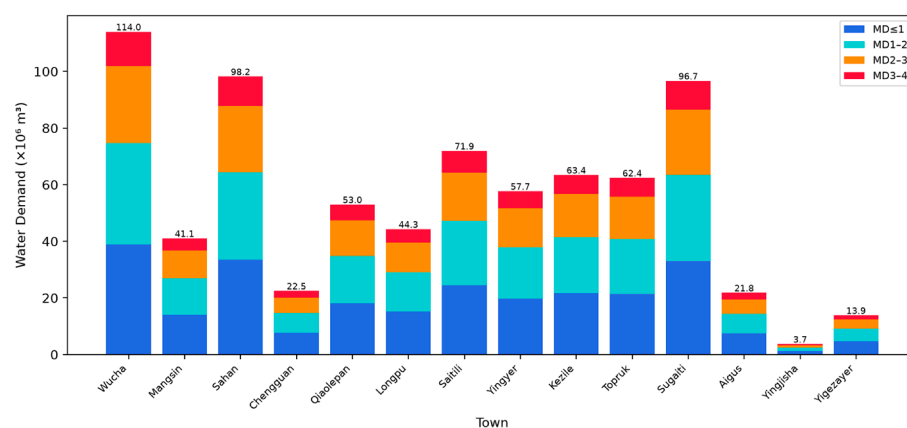


Figure 9. Quality-differentiated irrigation water demand by town for 2022–2023.

Under the current cropping pattern, the demand for $MD \leq 1$ water (required by fruits and vegetables and preferred by all crops) exceeds available freshwater supply.

Fruits and vegetables alone account for approximately $30.2 \times 10^6 \text{ m}^3$ and $41.2 \times 10^6 \text{ m}^3$ of gross $MD \leq 1$ water demand across the two study periods, all of which must be sourced from freshwater reserves. Wheat, cotton, and corn must compete for the remaining freshwater and, after water resource integration, brackish water resources.

Table 12 summarizes the supply–demand balance by water quality for 2021–2022 and provides the corresponding graded-scheme totals for 2022–2023. In both periods, total demand is lower than total supply, meaning the limiting factor is the availability of $MD \leq 1$ freshwater, rather than total water volume. Figures 8 and 9 show the quality-differentiated pre-optimization demand. This pattern supports the premise that integrating brackish water can alleviate freshwater scarcity without exceeding total water availability.

Table 12. Water supply–demand balance and crop-level allocation by quality.

Item	MD ≤ 1 (0.5 g/L)	MD 1–2 (1.5 g/L)	MD 2–3 (2.5 g/L)	MD 3–4 (3.5 g/L)
Supply ($\times 10^6 \text{ m}^3$)	228.512	23.000	24.000	24.600
Total demand γ_k 2021–2022 ($\times 10^6 \text{ m}^3$)	171.38	23.00	24.00	19.61
Total demand γ_k 2022–2023 ($\times 10^6 \text{ m}^3$)	171.38	23.00	24.00	24.60

3.2. Optimization Results of Economic Benefits

The model was solved to optimality for both periods under two scenarios: $\gamma = 0$ (no salt penalty) and graded $\gamma_k = [0, 400, 800, 1200]$. Tables 13 and 14 and Figures 10 and 11 report the results.

Table 13. County-level comparison of pre- and post-optimization results.

Item	2021–2022			2022–2023		
	Pre-Opt	Post-Opt	Δ	Pre-Opt	Post-Opt	Δ
Total profit ($\times 10^6$ CNY)	323.1	377.97	+16.98%	412.95	469.08	+13.59%
Net profit after penalty ($\times 10^6$ CNY)	323.1	371.22	+14.89%	412.95	461.03	+11.64%
Irrigation demand ($\times 10^6$ m ³)	230.49	237.99	+3.26%	261.07	242.98	−6.93%
Weighted salt increment (g/kg/yr)	—	0.3984	—	—	0.4247	—
Years to mild salinization	—	6.02	—	—	5.65	—
Wheat area (ha)	12,000	10,400.0	−13.3%	13,000	10,400.0	−20.0%
Cotton area (ha)	9000	10,610.5	+17.9%	10,000	9160.5	−8.4%
Corn area (ha)	4500	3375.0	−25.0%	5000	3750.0	−25.0%
Fruit area (ha)	2500	3125.5	+25.0%	3500	4375.5	+25.0%
Vegetable area (ha)	1953.26	2442.3	+25.0%	2585.39	3232.4	+25.0%

Table 14. Optimization results summary for both study periods.

Metric	2021–2022				2022–2023			
	Pre-Opt	Post-Opt $\gamma = 0$	Post-Opt $G\gamma_k$	Change	Pre-Opt	Post-Opt $\gamma = 0$	Post-Opt $G\gamma_k$	Change
Gross agricultural profit ($\times 10^6$ CNY)	323.1	378.01	377.97	+16.98%	412.95	469.69	469.08	+13.59%
Salt penalty ($\times 10^6$ CNY)	—	0.00	6.72	—	—	0.00	8.02	—
Net profit after penalty ($\times 10^6$ CNY)	323.1	377.99	371.22	+14.89%	412.95	469.66	461.03	+11.64%
Irrigation demand ($\times 10^6$ m ³)	230.49	236.57	237.99	+3.26%	261.07	242.98	242.98	−6.93%
Unit water profit (CNY/m ³)	1.4	1.60	1.56	+11.42%	1.58	1.93	1.90	+20.09%
Weighted salt increment (g/kg/yr)	—	0.4266	0.3984	−6.6%	—	0.4474	0.4247	−5.1%
Years to mild salinization	—	5.63	6.02	+7.1%	—	5.36	5.65	+5.3%

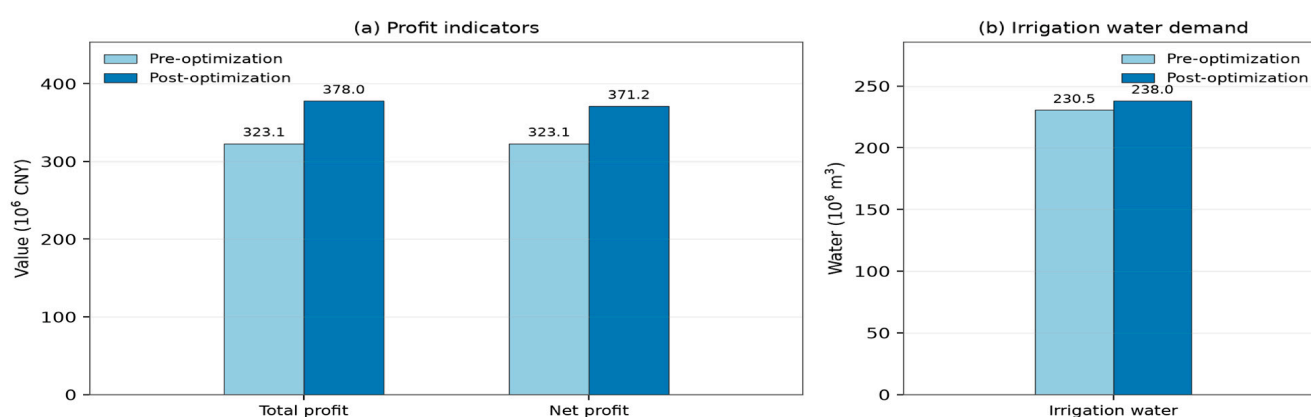


Figure 10. Comparison of economic indicators before and after optimization for 2021–2022: net profit, irrigation demand, and salt metrics under $\gamma = 0$ and graded γ_k scenarios.

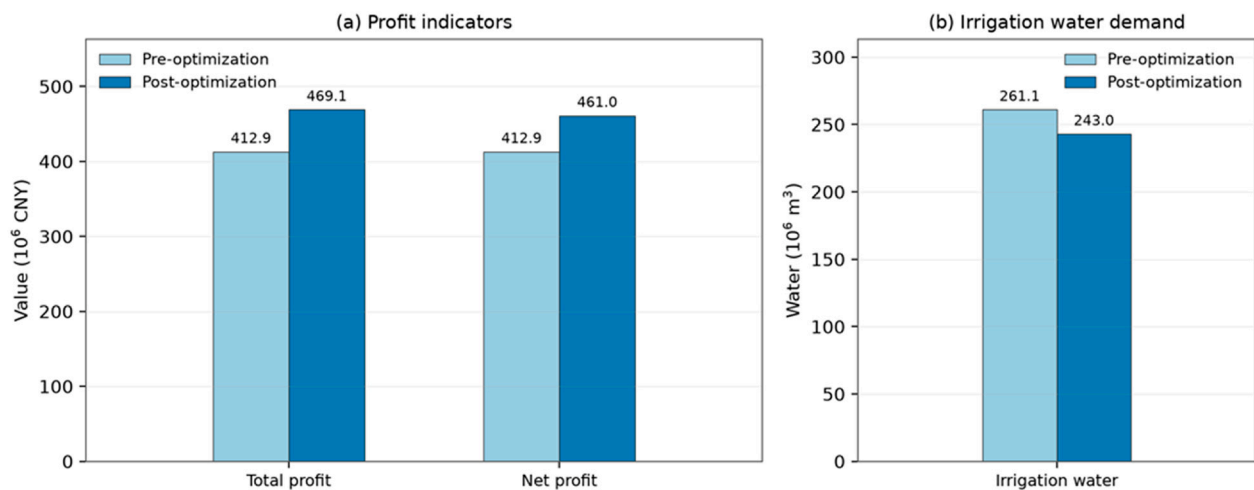


Figure 11. Comparison of economic indicators before and after optimization for 2022–2023: net profit, irrigation demand, and salt metrics under $\gamma = 0$ and graded γ_k scenarios.

Profit performance with internalized salt cost. Under graded γ_k , gross agricultural profit is 377.97×10^6 CNY in 2021–2022 and 469.08×10^6 CNY in 2022–2023, up 16.98% and 13.59% from pre-optimization levels. After subtracting the salt penalty, net profit (the objective value) is 371.22×10^6 CNY and 461.03×10^6 CNY, representing increases of 14.89% and 11.64% respectively.

By construction, $\gamma = 0$ does not include any internalized salt cost, but it yields higher physical salt accumulation, ranging from 0.4266 to 0.4474 g/kg/yr. A graded penalty internalizes salt damage at a cost of $6.72\text{--}8.02 \times 10^6$ CNY. With this penalty framework, $\gamma_2 = 400$ makes low-salinity brackish irrigation economically viable, while $\gamma_3 = 800$ and $\gamma_4 = 1200$ allow the use of high-salinity water when such use is economically justified.

Comparison with the no-penalty scenario. When $\gamma = 0$, the optimizer maximizes short-term profit without internalizing soil damage. Gross profit is nearly identical to that of the graded scheme (378.01 and 469.69×10^6 CNY), but salt accumulation is higher (0.4266 and 0.4474 g/kg/yr). The graded scheme reduces salt increment by 6.6% and 5.1% in the two periods, without sacrificing gross profitability.

Salt risk mitigation. The weighted average salt increment decreases from 0.4266–0.4474 g/kg/yr when $\gamma = 0$ to 0.3984–0.4247 g/kg/yr under the graded scheme. This extends the time to reach mild salinization from 5.63 to 6.02 years (+7.1%) and from 5.36 to 5.65 years (+5.3%).

Brackish water use is maintained: MD 1–2 water accounts for 23.00×10^6 m³, while MD 2–3 (24.00) and MD 3–4 (19.61–24.60) are also used under the corrected constraints.

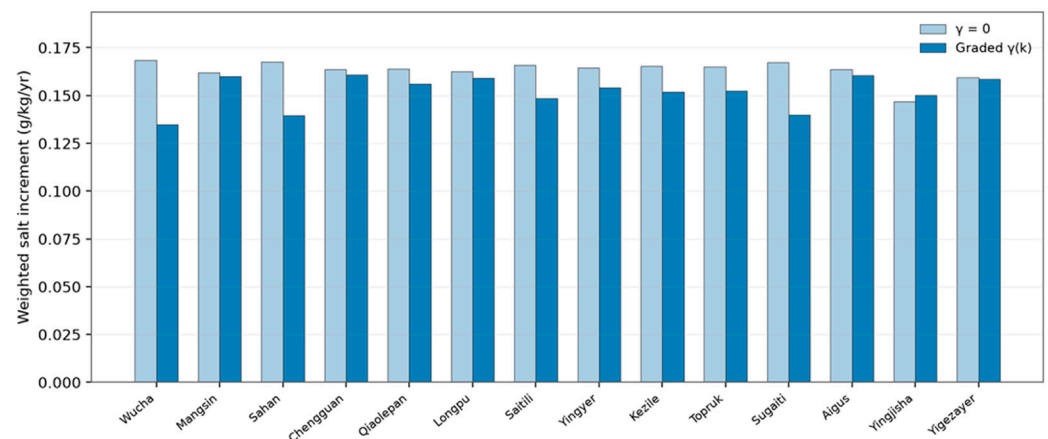
Compared with the no-penalty scenario, which allocates more high-salinity water, the graded penalty scheme shifts the system toward a more ecologically balanced water allocation without reducing gross economic performance.

Town-level analysis (Table 15, Figure 12). All 14 towns achieve 12–16% profit growth under the graded scheme. Because the graded penalty changes the crop–water–quality matching rather than the total planted area, the weighted salt increment is reduced in all 14 towns relative to $\gamma = 0$, while the absolute reduction is largest in the towns with the largest brackish-water use (Wucha, Sahan, and Sugaiti). This spatial differentiation allows towns with abundant brackish groundwater to exploit this resource without excessive ecological risk.

Table 15. Town-level water allocation: pre- vs. post-optimization (graded γ_k , 2021–2022).

Town	Pre-Opt Profit (10^6 CNY)	Post-Opt Profit (10^6 CNY)	Post-Opt Water (10^6 m ^{3})	MD ≤ 1 Water (10^6 m ^{3})	MD 1–2 Water (10^6 m ^{3})	Surface Water (10^6 m ^{3})	MD 2–3 Water (10^6 m ^{3})	MD 3–4 Water (10^6 m ^{3})
Wucha	48.18	55.75	35.45	25.97	3.43	22.16	3.58	2.47
Mangsin	17.35	19.79	12.79	9.07	1.24	7.70	1.29	1.20
Sahan	41.5	47.95	30.55	22.24	2.95	18.96	3.08	2.27
Chengguan	9.5	10.71	7.00	4.95	0.68	4.20	0.71	0.66
Qiaolepan	22.39	25.67	16.51	11.76	1.59	9.99	1.66	1.49
Longpu	18.72	21.39	13.81	9.80	1.33	8.32	1.39	1.29
Saitili	30.4	35.00	22.40	16.12	2.16	13.72	2.26	1.86
Yingyer	24.39	28.00	17.98	12.84	1.74	10.91	1.81	1.59
Kezile	26.81	30.82	19.76	14.16	1.91	12.04	1.99	1.70
Topruk	26.37	30.30	19.44	13.92	1.88	11.83	1.96	1.68
Sugaiti	40.85	47.19	30.07	21.88	2.91	18.65	3.03	2.25
Aigus	9.22	10.38	6.79	4.80	0.66	4.07	0.68	0.64
Yingjisha	1.56	1.75	1.15	0.82	0.11	0.70	0.12	0.10
Yigezayer	5.86	6.56	4.31	3.06	0.42	2.60	0.43	0.40

Note: Surface water covers each town's residual MD ≤ 1 demand after its own MD ≤ 1 groundwater ($W_{i,1}$, allocated in proportion to arable land; county total 25.56×10^6 m ^{3}) is fully used. The county total of $\approx 145.8 \times 10^6$ m ^{3} equals the MD ≤ 1 demand (171.38) minus the MD ≤ 1 groundwater (25.56); the remaining $\approx 57.1 \times 10^6$ m ^{3} of the 202.95×10^6 m ^{3} available surface water is retained in reservoir storage as part of the θ freshwater buffer. Values may not sum exactly due to rounding.

**Figure 12.** Town-level salt accumulation risk under $\gamma = 0$ and graded γ_k scenarios, showing salt increment and reduction across 14 towns.

Sources of the profit gain. Because every brackish class reaches its supply limit and the MD ≤ 1 share is capped by θ , the optimum is a corner solution, and the profit gain can be decomposed into a crop-restructuring component and a brackish-substitution component. A fresh-water-only counterfactual—identical land, food-security, freshwater-conservation ($\theta = 0.75$), and soft-bound constraints, but with every crop restricted to MD ≤ 1 water—shows that restructuring alone yields no gain under freshwater scarcity: in 2021–2022, the irrigated area contracts by 26.4% to 22,052 ha, below the 25% contraction floor of the soft bounds, and gross profit falls to 180.94×10^6 CNY (−44.0% versus the pre-optimization level), because the 171.38×10^6 m ^{3} freshwater cap cannot support the historical cropping pattern. The entire observed gain is therefore enabled by brackish-water substitution, which releases 66.61×10^6 m ^{3} of freshwater capacity for the +25% expansion of fruit and vegetables; without substitution, the same restructuring adjustment would reduce gross profit by 142.16×10^6 CNY. The 2022–2023 pattern is identical (fresh-water-only gross profit 193.67×10^6 CNY, −53.1%, versus a full-model gain of $+56.13 \times 10^6$ CNY, +13.6%).

The graded γ_k scheme addresses a key limitation of earlier penalty formulations. When $\gamma = 0$, high-salinity water is used without regard for soil damage; when an excessively high uniform penalty is applied, brackish water would be economically excluded. The graded scheme keeps both MD 1–2 and MD 2–3 water viable for salt-tolerant crops (cotton and wheat). With the reported parameters (T_j , s_j , α , λ_j , z) and the per-class quality constraints, water with salinity > 2 g/L can be included in the allocation.

3.3. Optimized Results of Crop Planting Structure

Figures 13–16 present the optimized crop planting structure. The optimization shifts the crop structure in the same direction across all scenarios, but the magnitude of this shift depends on the penalty structure.

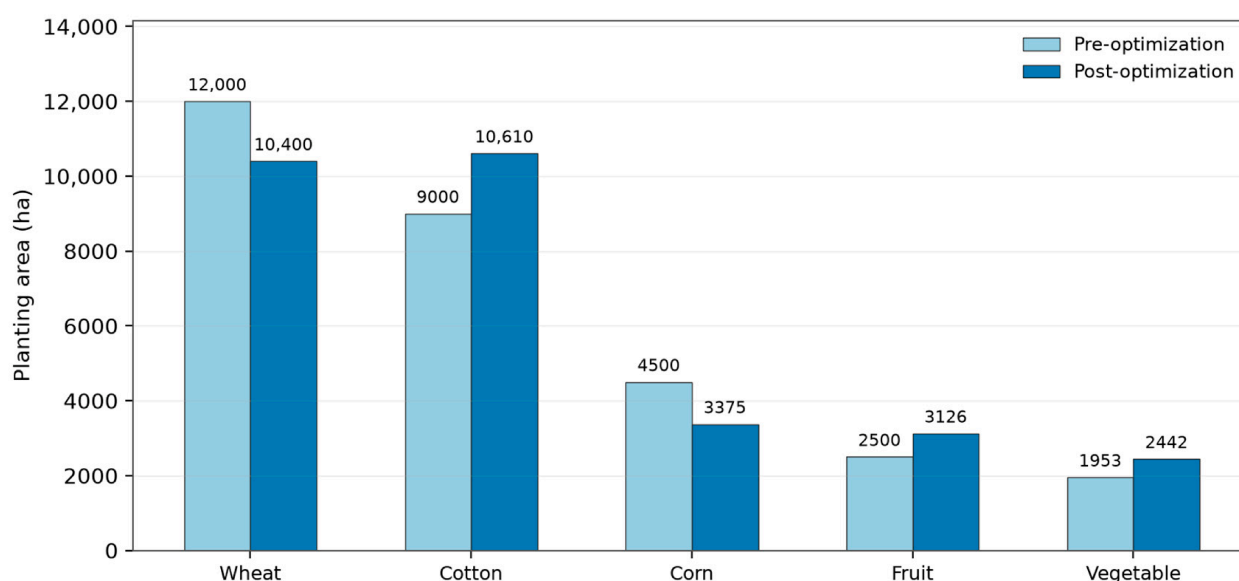


Figure 13. Crop planting area changes for 2021–2022: pre-optimization vs. post-optimization for five crops.

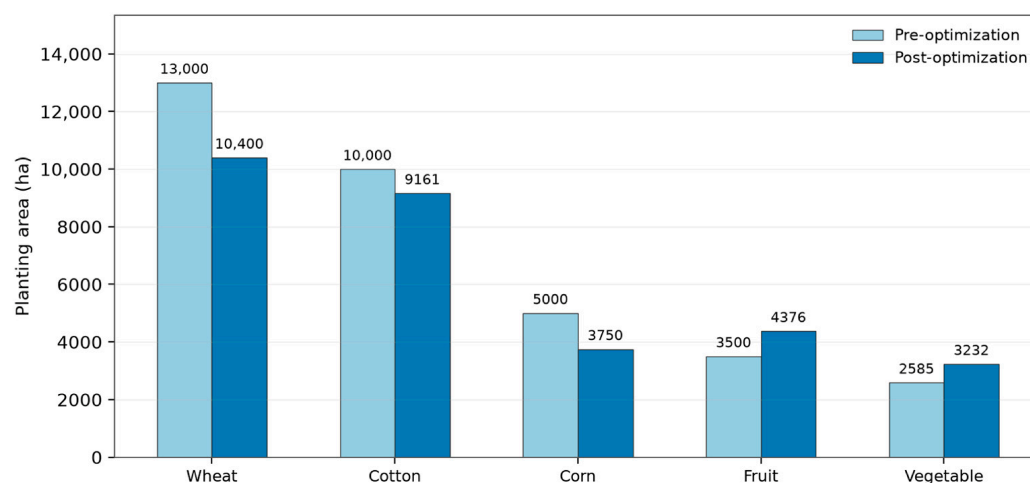


Figure 14. Crop planting area changes for 2022–2023: pre-optimization vs. post-optimization for five crops.

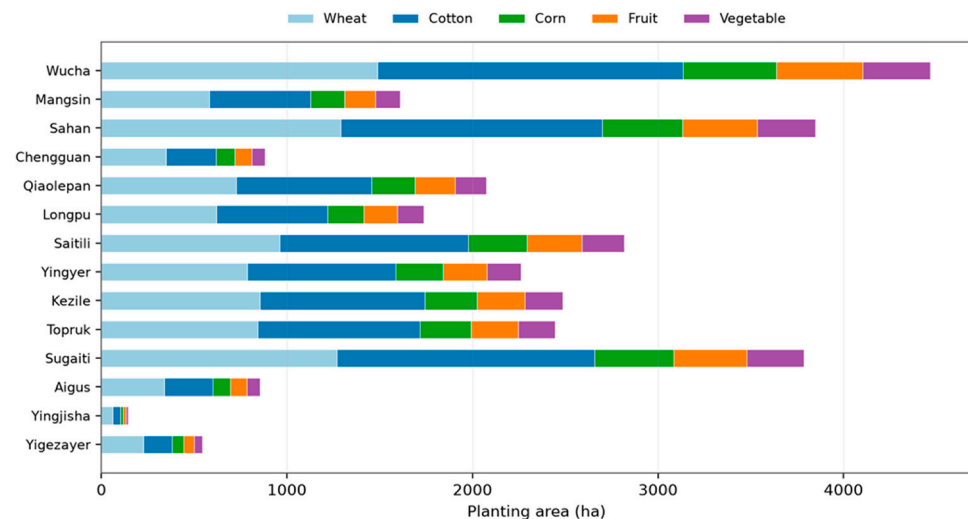


Figure 15. Town-level crop structure for 2021–2022: optimized planting area by crop and town under graded γ_k .

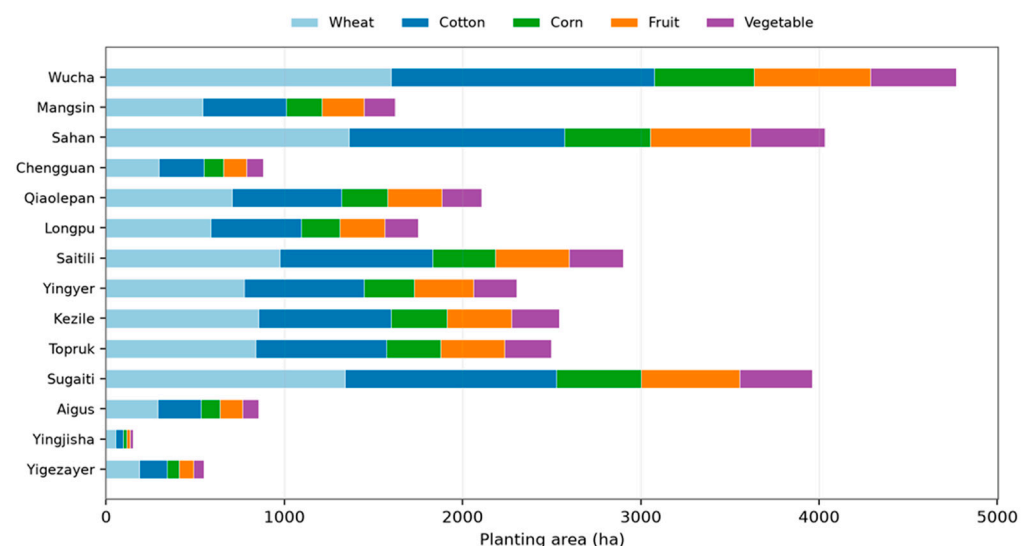


Figure 16. Town-level crop structure for 2022–2023: optimized planting area by crop and town under graded γ_k .

- Under $\gamma = 0$ (no salt penalty):

The planting area of low-salt-tolerance crops has decreased.

Corn area falls by 25.00% (−1125 ha) in 2021–2022 and 25.00% (−1250 ha) in 2022–2023, because corn has a low salt tolerance threshold ($T = 0.7$ g/L) and is restricted to water up to MD 1–2.

Wheat area decreases to a historical minimum of 10,400 ha (−13.3% and −20.0%), and cotton becomes the primary user of MD 1–2 brackish water in 2022–2023, whereas wheat is the primary user in 2021–2022.

Areas planted with high-profit crops have expanded. The acreage for fruit and vegetables has increased, due to their higher profitability (44,000 and 55,000 CNY/ha, respectively); cotton acreage also increased in 2021–2022, driven mainly by its high salt tolerance.

Cotton acreage increased by 17.9% (+1610 ha) in 2021–2022 but decreased by 8.4% (−839 ha) in 2022–2023. Cotton can adapt to all four water quality levels because of its high salt tolerance ($T = 3.3$ g/L, $K = 4$), which makes it the designated consumer of brackish water.

Acreage for fruit and vegetables increased by 25.00% to reach the soft-constraint maximum ($1.25 \times$ pre-optimization area).

- Under graded $\gamma_k = [0, 400, 800, 1200]$:

Wheat cultivation is at a historical minimum. Wheat planting area has decreased to 10,400 ha across both periods (−13.3% in 2021–2022 and −20.0% in 2022–2023), hitting the historical lower bound. When the lower penalty $\gamma_2 = 400$ is applied, wheat can use MD 1–2 water while still maintaining a positive effective profit of 1788 CNY/ha. As a result, wheat becomes the primary user of brackish water in 2021–2022.

Cotton area increased to 10,610 ha in 2021–2022 but decreased to 9160 ha in 2022–2023, both well above the historical minimum of 7310 ha. In 2021–2022, cotton uses $69.11 \times 10^6 \text{ m}^3$ of MD ≤ 1 water and $19.61 \times 10^6 \text{ m}^3$ of MD 3–4 water. In 2022–2023, cotton uses $31.47 \times 10^6 \text{ m}^3$ of MD ≤ 1 water, $23.00 \times 10^6 \text{ m}^3$ of MD 1–2 water, and $24.60 \times 10^6 \text{ m}^3$ of MD 3–4 water.

High-profit crops are planted at their upper bound limits. The area allocated to fruit and vegetables is kept at its maximum bound (+25.00%), and all production uses MD ≤ 1 water. The area planted with corn is reduced to the minimum (−25.00%) due to its low salt tolerance threshold ($T = 0.7 \text{ g/L}$).

Comparison with $\gamma = 0$. Under $\gamma = 0$, the cultivation areas of all crops remain essentially the same as under the graded scheme, and the per-class water allocation is identical for MD ≤ 1 , MD 1–2, and MD 2–3 (all binding). The difference appears only in the high-salinity MD 3–4 class (18.19 vs. $19.61 \times 10^6 \text{ m}^3$ in 2021–2022), where $\gamma = 0$ shows higher salt accumulation (0.4266 vs. 0.3984 g/kg/yr) because it does not internalize any ecological cost. The graded scheme preserves profits while reducing salt accumulation, which indicates that differentiated penalty pricing limits reliance on high-salinity water without excluding it entirely.

Town-level patterns are shown in Figures 15 and 16. The direction of structural change is consistent across all 14 towns. Sugaiti maintains the highest proportion of cotton, while Wucha and Kezile contribute a large share of the overall county-level change.

Under this graded allocation scheme, towns with abundant MD 1–2 groundwater (Wucha, Sahan, and Sugaiti) allocate most of their cotton-growing area to irrigation with brackish water, whereas towns with limited brackish water resources (Yingjisha, Yigezayer) rely mainly on freshwater for irrigation.

3.4. Optimized Results of Water Resource Allocation

Figure 17 presents the total water allocation. In the reported scenarios, each town uses its own MD ≤ 1 groundwater first and draws surface water only for its residual freshwater demand; total surface-water use is $\approx 145.8 \times 10^6 \text{ m}^3$ (71.8% of the available surface water), and the remaining $\approx 57.1 \times 10^6 \text{ m}^3$ is retained in reservoir storage as part of the θ freshwater buffer for ecological flow and drought contingency. Under the graded γ_k scenario, non-freshwater demand totals $66.61 \times 10^6 \text{ m}^3$ for 2021–2022 and $71.60 \times 10^6 \text{ m}^3$ for 2022–2023.

Table 12 and Figures 18 and 19 summarize quality-differentiated water allocation.

- Under $\gamma = 0$ (no salt penalty):

2021–2022: Water with MD ≤ 1 accounts for $171.38 \times 10^6 \text{ m}^3$ (72.4%), water with MD 1–2 accounts for $23.00 \times 10^6 \text{ m}^3$ (9.7%), and water with MD 2–3 accounts for $24.00 \times 10^6 \text{ m}^3$ (10.1%), and MD 3–4 for $18.19 \times 10^6 \text{ m}^3$ (7.7%).

2022–2023: Water with MD ≤ 1 accounts for $171.38 \times 10^6 \text{ m}^3$ (70.5%), water with MD 1–2 accounts for $23.00 \times 10^6 \text{ m}^3$ (9.5%), and water with MD 2–3 accounts for $24.00 \times 10^6 \text{ m}^3$ (9.9%), and MD 3–4 for $24.60 \times 10^6 \text{ m}^3$ (10.1%).

The $\alpha_{j,k}$ coefficient allows for the use of water with MD > 1. With the updated thresholds (T_j), cotton has $\alpha = 1.000$ at MD = 1.5 ($T_j = 3.3$ g/L) and $\alpha = 0.9934$ at MD = 3.5, corresponding to a 0.7% yield reduction. Wheat has $\alpha = 1.000$ at MD = 1.5 ($T_j = 2.5$ g/L). Corn has $\alpha = 0.9384$ at MD = 1.5 ($T_j = 0.7$ g/L), corresponding to a 6.2% yield reduction. Vegetables have $\alpha = 0.9748$ at MD = 1.5 ($T_j = 1.1$ g/L).

Therefore, water with an MD of 1–2 is viable for cotton and wheat, while corn experiences a notable yield penalty (6.2%) and vegetables a smaller penalty (2.5%) at MD 1–2.

- Under graded $\gamma_k = [0, 400, 800, 1200]$:

2021–2022: Water with MD ≤ 1 accounts for 171.38×10^6 m³ (72.0%), and water with MD 1–2 accounts for 23.00×10^6 m³ (9.7%), MD 2–3 for 24.00×10^6 m³ (10.1%), and MD 3–4 for 19.61×10^6 m³ (8.2%).

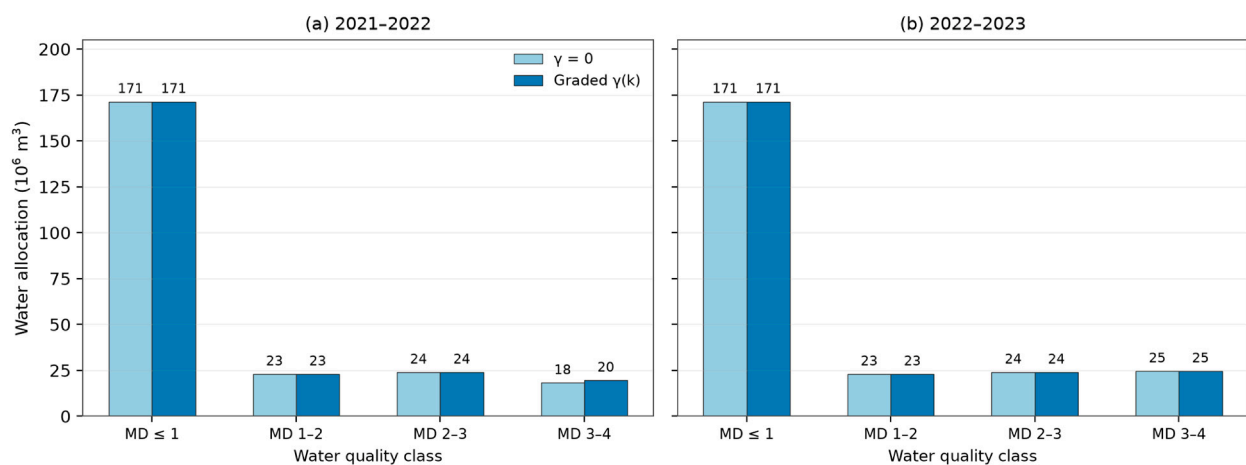


Figure 17. Water resource allocation by quality level for 2021–2022 and 2022–2023 under graded γ_k .

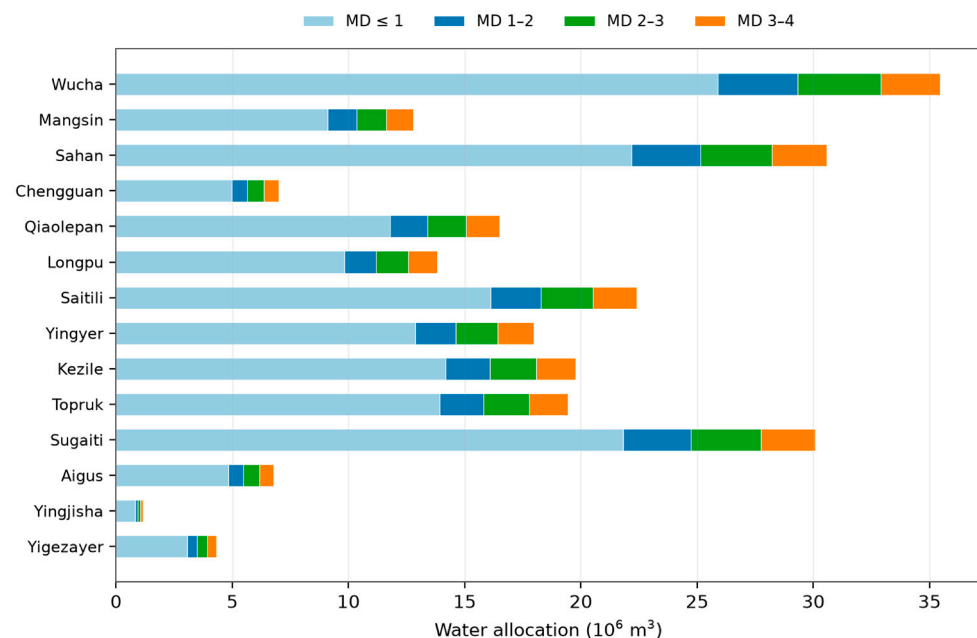


Figure 18. Water quality allocation by town for 2021–2022: MD ≤ 1 , MD 1–2, MD 2–3, MD 3–4 under $\gamma = 0$ and graded γ_k .

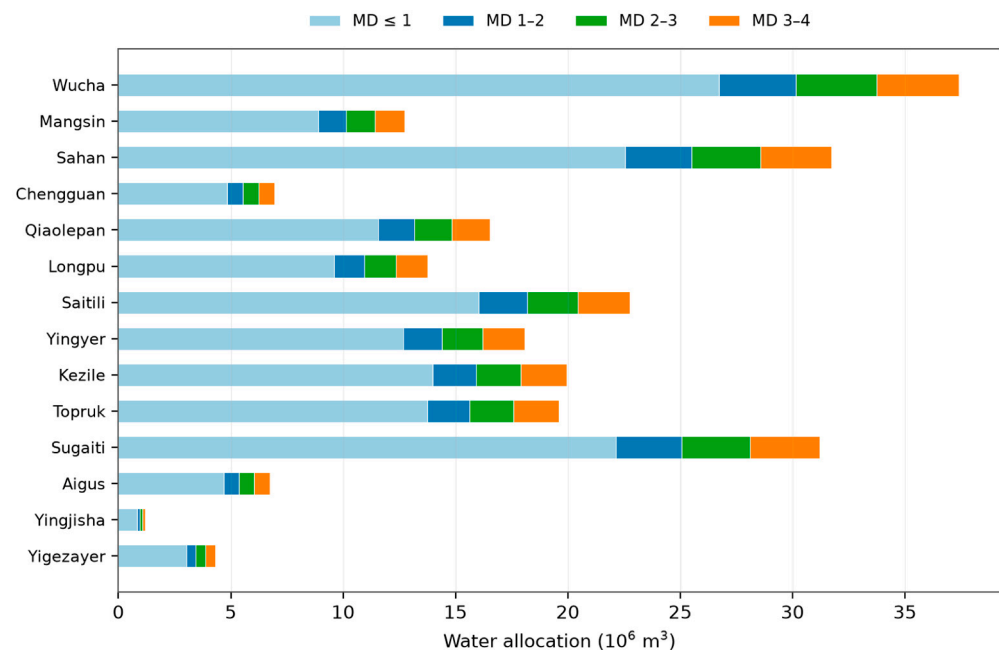


Figure 19. Water quality allocation by town for 2022–2023: MD ≤ 1, MD 1–2, MD 2–3, MD 3–4 under $\gamma = 0$ and graded γ_k .

2022–2023: Water with MD ≤ 1 accounts for $171.38 \times 10^6 \text{ m}^3$ (70.5%), water with MD 1–2 accounts for $23.00 \times 10^6 \text{ m}^3$ (9.5%), and water with MD 2–3 accounts for $24.00 \times 10^6 \text{ m}^3$ (9.9%), and MD 3–4 for $24.60 \times 10^6 \text{ m}^3$ (10.1%).

The main effect of the graded penalty is to moderate brackish water use relative to $\gamma = 0$. When $\gamma = 0$, MD 2–3 water accounts for 9.9–10.1% of total demand, because $\alpha = 1.000$ for wheat and cotton at MD = 2.5. Under the graded scheme, MD 1–2 water accounts for 9.5–9.7% of demand, MD 2–3 water remains at 9.9–10.1%, and the total salt damage cost ranges from $6.72\text{--}8.02 \times 10^6 \text{ CNY}$.

The freshwater conservation constraint is binding: MD ≤ 1 demand reaches $171.38 \times 10^6 \text{ m}^3$ in both periods, which is exactly 75% of total freshwater supply ($0.75 \times 228.512 = 171.38$). This result confirms that the constraint acts as the active limit on freshwater use, and reserves the intended 25% buffer.

Under the graded scheme, crop allocation follows water quality constraints: fruit, vegetables, and corn use only MD ≤ 1 water. In 2021–2022, wheat uses $39.16 \times 10^6 \text{ m}^3$ of MD ≤ 1 water, $23.00 \times 10^6 \text{ m}^3$ of MD 1–2 water, and $24.00 \times 10^6 \text{ m}^3$ of MD 2–3 water, while cotton uses $69.11 \times 10^6 \text{ m}^3$ of MD ≤ 1 water and $19.61 \times 10^6 \text{ m}^3$ of MD 3–4 water. In 2022–2023, wheat uses $60.32 \times 10^6 \text{ m}^3$ of MD ≤ 1 water and $24.00 \times 10^6 \text{ m}^3$ of MD 2–3 water, while cotton uses $31.47 \times 10^6 \text{ m}^3$ of MD ≤ 1 water, $23.00 \times 10^6 \text{ m}^3$ of MD 1–2 water, and $24.60 \times 10^6 \text{ m}^3$ of MD 3–4 water. Thus, wheat is the primary user of MD 1–2 water in 2021–2022, whereas cotton becomes the primary user of MD 1–2 water in 2022–2023.

Wucha, Sahan, and Sugaiti have the largest absolute brackish water use, while Yingjisha and Yigezayer rely mainly on freshwater. The allocation scheme reported in the study reduces spatial inequality in salt risk relative to $\gamma = 0$, because the freshwater conservation constraint limits over-reliance on brackish water, and the graded penalty structure makes salt costs proportional to salinity risk.

3.5. Long-Term Soil Salt Accumulation Effects

Brackish irrigation introduces salt into the soil profile even when it improves economic outcomes. Under film-mulched drip irrigation with negligible natural leaching (groundwater table > 10 m, rainfall 69.8 mm vs. evaporation 2170.7 mm), accumulated salt

can degrade soil over time. A salt accumulation model is used to assess this risk. Table 7 reports annual salt input and soil salt increment for each crop–quality combination. For example, for wheat irrigated with MD 1–2 water ($C = 1.5$ g/L), the annual salt input is $\Delta S_{in} = 7800 \times 1.5 \times (1 - 0.4) = 7020$ kg/ha, and the annual soil salt increment is $\Delta S = 7020 \times 1000 / (10,000 \times 1.0 \times 1326) = 0.5294$ g/kg per year.

Table 16 and Figure 20 show the number of years required to reach mild (3.0 g/kg), moderate (5.0 g/kg), and severe (8.0 g/kg) salinization. For wheat irrigated with water of MD ≤ 1 ($C = 0.5$ g/L, $\Delta S = 0.1765$ g/kg/yr), it takes 13.60 years to reach mild salinization and 41.93 years to reach severe salinization. For wheat irrigated with water of MD 1–2 ($C = 1.5$ g/L, $\Delta S = 0.5294$ g/kg/yr), these timeframes shorten to 4.53 years and 13.98 years, respectively. For cotton irrigated with water of MD ≤ 1 , the corresponding timeframes are 9.8 years (mild) and 30.3 years (severe). For cotton irrigated with water of MD 1–2, the timeframes are 3.3 years (mild) and 10.1 years (severe).

Table 16. Years to reach different salinization grades.

Crop	ΔS_{in} (kg/ha/yr)	σ (g/kg/ha)	Mild (3.0 g/kg)	Moderate (5.0 g/kg)	Severe (8.0 g/kg)
Wheat (MD ≤ 1)	2340	0.1765	13.6	24.93	41.93
Wheat (MD 1–2)	7020	0.5294	4.53	8.31	13.98
Wheat (MD 2–3)	11,700	0.8824	2.72	4.99	8.39
Cotton (MD ≤ 1)	3240	0.2443	9.82	18.01	30.29
Cotton (MD 1–2)	9720	0.7330	3.27	6.00	10.1
Cotton (MD 2–3)	16,200	1.2217	1.96	3.60	6.06
Cotton (MD 3–4)	22,680	1.7104	1.4	2.57	4.33
Corn (MD ≤ 1)	2437.5	0.1838	13.06	23.94	40.26
Corn (MD 1–2)	7312.5	0.5515	4.35	7.98	13.42
Fruit (MD ≤ 1)	2250	0.1697	14.14	25.93	43.61
Vegetable (MD ≤ 1)	2535	0.1912	12.55	23.02	38.71
Vegetable (MD 1–2)	7605	0.5735	4.18	7.67	12.9

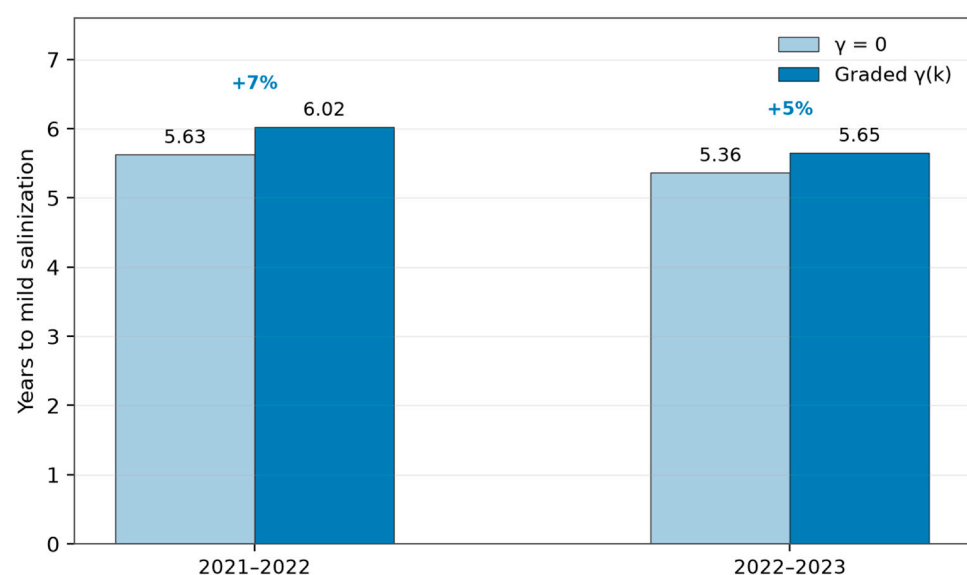


Figure 20. Salt accumulation timeline: years to reach mild, moderate, and severe salinization under $\gamma = 0$ and graded γ_k scenarios for both study periods.

Under $\gamma = 0$:

For the county-level weighted average under $\gamma = 0$, the time to reach mild salinization is 5.63 years for 2021–2022 and 5.36 years for 2022–2023.

Under graded $\gamma_k = [0, 400, 800, 1200]$, with the grading scheme, a mixture of water across all four quality classes yields weighted salt increments of 0.3984 g/kg/yr for 2021–2022 and 0.4247 g/kg/yr for 2022–2023. The time to mild salinization extends to 6.02 (+7.1%) and 5.65 (+5.3%) years.

Water with MD 2–3 accounts for $24.00 \times 10^6 \text{ m}^3$ (10.1%) in 2021–2022 and $24.00 \times 10^6 \text{ m}^3$ (9.9%), and MD 3–4 for $19.61 \times 10^6 \text{ m}^3$ (8.2%) in 2021–2022 and $24.60 \times 10^6 \text{ m}^3$ (10.1%) in 2022–2023.

Figure 20 compares salt accumulation trajectories: $\gamma = 0$ yields the fastest accumulation rate, with mild salinization occurring in 5.4–5.6 years. In contrast, the graded scheme delays the onset of mild salinization to 5.7–6.0 years, while achieving 28–30% brackish water substitution with only a small internalized salt cost.

Based on the salt risk assessment and optimization results, we propose the following classified regulation measures:

- (1) Water with MD ≤ 1 g/L: Suitable for all crops. Priority should be given to salt-sensitive crops (fruits, vegetables) and corn (which experiences a 6.2% yield reduction at MD 1–2 g/L; MD 2–3 g/L and MD 3–4 g/L are not applicable for this crop). Under the graded penalty scheme, the freshwater conservation constraint requires that at least 25% of freshwater remains unallocated to maintain an ecological buffer. For the daily irrigation of salt-sensitive crops (fruits and vegetables), the model restricts them to MD ≤ 1 freshwater throughout the growing season, so that daily irrigation carries no yield penalty and soil moisture remains stress-free; brackish water is allocated only to salt-tolerant crops (wheat, cotton) with periodic leaching, as recommended above.
- (2) Water with MD 1–2 g/L: Suitable for wheat and cotton ($\alpha = 1.000$, no yield loss when MD ≤ 2.5 g/L).
- (3) Water with MD 2–3 g/L: No yield loss for wheat and cotton ($\alpha = 1.000$, $T_j \geq 2.5$ g/L), and corn cannot use water with MD 2–3 g/L ($K_j = 2$). Under the graded penalty ($\gamma_3 = 800$), the salt penalty shifts water allocation toward lower-salinity sources, but water with MD 2–3 g/L remains economically viable for cotton, accounting for 9.9–10.1% of total demand under the graded scheme. This water should be used with periodic freshwater leaching every 2–3 years.

Town-specific recommendations (under graded γ_k):

- (1) Saitili: Saitili has a notable dependence on brackish water, where wheat and cotton are irrigated with brackish water. Establishment of town-level salt monitoring stations is recommended to track soil salt accumulation and schedule leaching cycles. Rotating crops with deep-rooted varieties may enhance natural salt leaching.
- (2) Wucha: This town has the largest absolute area under brackish water irrigation, primarily for wheat and cotton. An annual soil salt census and biennial freshwater leaching are recommended.
- (3) Yingjisha and Yigezayer: These towns rely mainly on freshwater, and the use of brackish water remains small. They serve as a baseline for comparing salt accumulation trajectories under different water quality regimes.

To examine the role of γ_k under the base freshwater-conservation ratio $\theta = 0.75$, the model was solved for four penalty schemes, with the following results:

- (1) The recommended scheme is robust to γ_k calibration. The aggressive, recommended, and conservative schemes all converge to the same optimal water allocation: MD $\leq 1 = 171.38 \times 10^6 \text{ m}^3$ (72.0% in 2021–2022, 70.5% in 2022–2023), MD 1–2 = $23.00\text{--}23.00 \times 10^6 \text{ m}^3$, and MD 2–3 = $24.00\text{--}24.00 \times 10^6 \text{ m}^3$. In the reported scenarios, MD ≤ 1 is binding, meaning θ limits freshwater allocation and α determines crop–water matching; the magnitude of γ_k does not change the optimal matching. Salt penalty

cost scales linearly with γ_k ($3.36, 6.72, 10.08 \times 10^6$ CNY for aggressive, recommended, and conservative, respectively), but it remains below 3% of total profit and therefore does not alter crop–water matching. This robustness is useful because the policy outcome does not depend on precise penalty parameterization.

- (2) The penalty function is the critical determinant of salt accumulation. In the control scenario ($\gamma = [0, 0, 0, 0]$), MD 2–3 water is freely allocated ($24.00 \times 10^6 \text{ m}^3$ in 2021–2022 and $24.00 \times 10^6 \text{ m}^3$ in 2022–2023) because $\alpha = 1.000$ for wheat and cotton at MD = 2.5. Profit is nearly identical to that of the graded schemes (377.97×10^6 CNY), but the annual salt increment is 7.1% higher (0.4266 vs. 0.3984 g/kg/yr), and the time to mild salinization drops from 6.02 to 5.63 years. Removing the penalty therefore shifts the MD 1–2 and MD 2–3 water from wheat (lower unit-area salt increment) to cotton (higher unit-area salt increment), increasing salt accumulation and in turn indicating that γ_k is an essential ecological safeguard even though its precise magnitude is not critical.
- (3) The brackish-water volumes remain at their binding limits, but the penalty shifts the MD 1–2 and MD 2–3 water from cotton to wheat (lower unit-area salt increment), while the MD 3–4 allocation changes only slightly ($18.19 \rightarrow 19.61 \times 10^6 \text{ m}^3$), so the graded penalty internalizes part of the ecological externality without sacrificing gross profit.
- (4) Clear division of roles: θ caps freshwater allocation, while γ_k provides the ecological safeguard. At the base $\theta = 0.75$, θ is the binding determinant of freshwater allocation, capping MD ≤ 1 demand at $171.38 \times 10^6 \text{ m}^3$ and forcing 28–30% brackish water substitution regardless of γ_k . The graded penalty changes the salt-risk outcome: its presence shifts the MD 1–2 and MD 2–3 water from cotton to wheat and reduces salt accumulation by 6.6%, while its calibration (across the 200–1800 range) does not affect allocation. This complementarity indicates that θ can control the freshwater–brackish water balance and γ_k can internalize ecological cost, with small calibration errors in γ_k unlikely to destabilize the optimal allocation.

To further examine how the freshwater-conservation ratio affects the trade-off between economic return and salinity risk, the model was additionally solved across θ scenarios from 0.60 to 0.90 (step 0.05). Figure 21 reports the resulting profit–salinization frontier: as θ increases, net profit rises while the weighted salt increment declines, confirming that θ is a binding policy lever for balancing economic and ecological objectives.

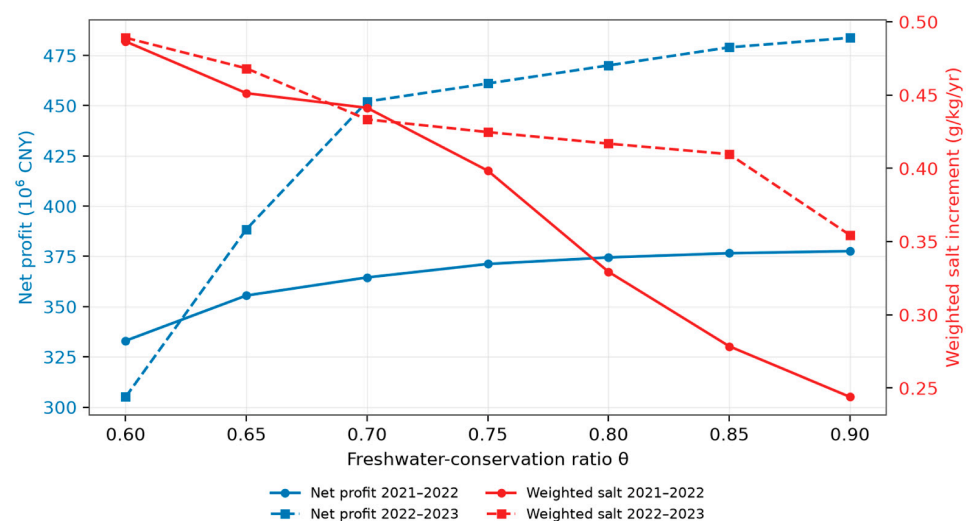


Figure 21. Profit–salinization frontier across freshwater-conservation scenarios ($\theta = 0.60$ – 0.90) under the recommended graded γ_k scheme for 2021–2022 and 2022–2023.

4. Conclusions

This study developed a water-quality-integrated irrigation allocation model for Yingjisha County, an extremely arid region in Xinjiang, incorporating the Maas–Hoffman yield reduction coefficient, a surface-water allocation variable, soft constraints, a graded salt damage penalty, and a freshwater conservation constraint.

- (1) Graded penalty enables economically viable brackish-water use. MD 1–2 water supplies $23.00 \times 10^6 \text{ m}^3$, MD 2–3 supplies $24.00 \times 10^6 \text{ m}^3$, and MD 3–4 supplies $19.61\text{--}24.60 \times 10^6 \text{ m}^3$. Freshwater dependency is governed by the freshwater-conservation ratio θ (base 0.75, explored over 0.60–0.90), under which a 25% freshwater buffer is preserved; internalized salt cost remains low at $6.72\text{--}8.02 \times 10^6 \text{ CNY}$.
- (2) Economic and ecological gains are jointly achieved. Gross agricultural profit rises 16.98% (2021–2022) and 13.59% (2022–2023), close to the no-penalty baseline, while unit water profit improves from 1.40 to 1.56 CNY/m³ and from 1.58 to 1.90 CNY/m³ in the two periods. A fresh-water-only counterfactual confirms that this joint gain is enabled by brackish-water substitution: without it, the freshwater cap would force a 26–35% contraction of the irrigated area and a 44–53% decline in gross profit.
- (3) Crop and water allocation are restructured by quality tier. Fruit and vegetables expand, cotton increases in 2021–2022 but declines in 2022–2023, wheat is cut to its historical minimum and corn falls 25.0%; wheat remains viable under the graded penalty, and cotton serves as a designated brackish-water consumer. Fruit, vegetables, and corn use only MD ≤ 1 water, while wheat uses MD 1–2 and MD 2–3 water in 2021–2022, and cotton uses MD 1–2 and MD 3–4 water in 2022–2023.
- (4) Long-term salinization risk is substantially reduced. Weighted salt increment drops from 0.4266–0.4474 to 0.3984–0.4247 g/kg/yr, extending the time to mild salinization from 5.36–5.63 to 5.65–6.02 years, while retaining 28–30% brackish substitution and wheat production.

Overall, the graded salt penalty plus freshwater conservation constraint creates an economic gradient that directs each water quality tier to its most valuable use, improving profit, conserving freshwater, and slowing salinization relative to the no-penalty baseline. Future work should focus on local parameter calibration, dynamic multi-year optimization with salt-accumulation feedback, and water–energy–food nexus integration.

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