Chemical Characteristics of Groundwater in Farmland and Water-Salt Migration Imprints on Different Land Types in the Hetao Irrigation District

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Date: 2024-12-16T00:00:00+00:00

Abstract

To determine the chemical characteristics of farmland groundwater and the water-salt migration and transformation relationships between different types of farmland in the Hetao Irrigation District under intensive water-saving conditions, typical irrigated farmland in the Hetao Irrigation District was selected as the experimental area. Using classical statistics, principal component analysis, and solute dynamics principles, the ion composition of shallow groundwater and variation characteristics of shallow groundwater depth in typical irrigated farmland were analyzed to identify the main characteristic factors affecting groundwater quality; changes in soil ions before and after crop planting were discussed; the contribution of groundwater to salt among different types of farmland was determined using the positioned flux method, and a water-salt balance model was established. The results showed that: (1) The cations in shallow groundwater were dominated by Na++K+, accounting for 53.22% of the total cations, while anions were dominated by SO42-, accounting for 41.04% of the total anions. The main chemical type of groundwater was HCO3 · SO4-Na type. Principal component analysis revealed that the main characteristic factors affecting groundwater quality were TDS, Na++K+, HCO3-, and SO42-. (2) Salt accumulation before and after crop planting was mainly composed of NaCl and Na2SO4. (3) The evapotranspiration (ET) differed among different field types, with ET values of 422.6 mm, 475.6 mm, and 625.8 mm for wasteland, sunflower field, and maize field, respectively. (4) Soils in maize field, sunflower field, and wasteland were all in a state of salt accumulation. The salt entering the wasteland through horizontal infiltration was 1924 kg · hm-2, accounting for 22.00% of the total salt accumulation in the wasteland. (5) A salt transition zone existed between wasteland and cultivated land. It is recommended to plant salt-tolerant

economic crops such as sunflower near wasteland areas. This study can provide guidance for local efficient water resource utilization, soil salinization control, and sustainable agricultural development.

Full Text

Chemical Characteristics of Groundwater and Water-Salt Transport in Different Land Classes in the Hetao Irrigation District

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Abstract

To determine the chemical characteristics of farmland groundwater and the water-salt migration and transformation relationships among different land types in the Hetao Irrigation District under deep water conservation conditions, typical irrigated farmland in the district was selected as the experimental area. Classical statistics, principal component analysis, and solute dynamics principles were employed to analyze the characteristics of shallow groundwater ions and groundwater depth variations, identify the main factors influencing groundwater quality, and examine soil ion changes before and after crop cultivation. The locational flux method was used to quantify groundwater's contribution to salt accumulation across different farmland types, and a water-salt balance model was established. The results indicate that: (1) shallow groundwater cations are dominated by Na^++K^+, accounting for 53.22% of total cations, while anions are dominated by $SO_4{}^{2-}$, comprising 41.04% of total anions, classifying the groundwater as $HCO_3 \cdot SO_4$-Na type; principal component analysis identified Total Dissolved Solids (TDS), Na^++K^+, $HCO_3{}^-$, and $SO_4{}^{2-}$ as the key factors affecting groundwater quality; (2) salt accumulation before and after crop cultivation is primarily composed of Na_2SO_4, with other soil ions showing no significant changes; (3) evapotranspiration varies among land types, with values of 422.6 mm for wasteland, 475.6 mm for sunflower fields, and 625.8 mm for maize fields; (4) soils in maize, sunflower, and wasteland plots are all in a state of salt accumulation, with horizontal infiltration contributing 1924 $kg \cdot hm^{-2}$ of salt to wasteland, representing 22.00% of total salt accumulation; (5) a salt transition zone exists between wasteland and cultivated land, suggesting that salt-tolerant cash crops such as sunflower should be planted near wasteland areas. These findings provide guidance for efficient local water resource utilization, soil salinization control, and sustainable agricultural development.

Keywords: wasteland; soil salinity; groundwater recharge; salt ions; groundwater depth; dry drainage salinity; Hetao Irrigation District

Introduction

The Hetao Irrigation District serves as a crucial commercial grain and oil production base in China. Soil salinization has consistently constrained the district's sustainable development, with approximately 39$×10^{4}$ hm^{2} of saline-alkali land accounting for a significant portion of the total cultivated area. Groundwater acts as the primary carrier for salt transport and is intimately related to soil water-salt movement. High groundwater tables combined with intense evaporation continuously exacerbate soil salinization. The district features abundant solar energy, diverse high-quality crops, and complex internal planting structures, with main crops including maize, sunflower, wheat, and melons. Wasteland, as a special land use type, appears sporadically and interspersed throughout farmland areas, serving as an important region for salt accumulation while groundwater functions as the connecting medium for salt transfer, playing a vital role in the district's water-salt balance.

Previous research has extensively investigated the relationships between soil and groundwater and water-salt migration mechanisms. Studies have shown that when soil surface moderate salinization occurs, the groundwater depth is 2.5 m. Remote sensing data combined with spatial models have demonstrated that land salinization in the Yellow River Delta is closely related to shallow groundwater levels and increasing TDS. Water balance methods have revealed that during irrigation periods, soil water recharges groundwater by 207.73 mm, while during non-irrigation periods, groundwater replenishes soil water through capillary rise at 236.94 mm. Soil column experiments under different groundwater depths have shown that shallower groundwater improves water use efficiency but leads to salt return. Hydrodynamic and solute dynamics methods have established water-salt balance models, revealing that groundwater flows from cultivated land to wasteland to lakes.

In recent years, water-saving renovation projects and deep water conservation policies have reduced Yellow River water diversion, significantly altering irrigation water volumes during both the growing season and spring flooding periods, thereby disrupting the original water-salt balance system. However, the chemical characteristics of groundwater and salt migration patterns among different farmland types under these deep water conservation conditions require further investigation. This study addresses this gap by selecting typical maize-wasteland intercropped farmland in the Hetao Irrigation District to: (1) analyze annual chemical variation characteristics of groundwater; (2) examine ion changes before and after planting across land types; (3) establish water-salt balance models for different plots; and (4) explore the dry drainage function of wasteland. The results provide theoretical support for shallow groundwater utilization and soil salinization prevention in the Hetao Irrigation District.

1 Materials and Methods

1.1 Experimental Area Description

The experimental area is located at the Left Second Branch Canal of Yichang Irrigation Subdistrict in the Hetao Irrigation Region of Inner Mongolia (108°21 N, 41°7 E). The area measures approximately 390 m east-west and 350 m north-south, covering 12.67 hm^2. The region features a mid-temperature arid/semi-arid continental climate with large temperature variations, significant diurnal temperature ranges, and strong evaporation (annual evaporation 2240 mm) compared to precipitation (annual rainfall 56.3–235.4 mm). The average annual temperature is 7.5°C. Groundwater depth ranges from 0.3–3.6 m, with soil pH between 7.8–9.3. The experimental area comprises primarily cultivated land and saline wasteland, with main crops including sunflower, maize, and wheat under border irrigation. The study period was 2023, during which 9 groups of tensiometers, 9 soil micro-lysimeters, and 6 groundwater observation wells were installed. Meteorological data were obtained from the China Meteorological Data Sharing Network (http://data.cma.cn/). The experimental design and water-salt transport principles are illustrated in [Figure 3: see original paper].

1.2 Monitoring Methods

1.2.1 Soil Basic Physical Properties Vertical profiles were established on three land types (maize, sunflower, wasteland) using the ring knife method to test soil physical properties. Soil samples were collected at depths of 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm, with three replicates per layer. Samples were placed in aluminum boxes and sealed bags. Soil physical properties are summarized in .

1.2.2 Soil Monitoring Using a grid method, sampling points were established at 50 m × 50 m intervals, totaling 15 points. Soil samples were collected at depths of 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm every 15–20 days, with intensified sampling before and after irrigation. Soil water content was determined by the drying method. Air-dried and ground soil samples were mixed with water at a 1:5 soil-water ratio, and electrical conductivity was measured using a DDS-307A conductivity meter (Shanghai, China).

1.2.3 Groundwater Monitoring Groundwater level loggers (DATA-6216, Beijing, China) were installed in key observation wells to automatically record water levels. Groundwater samples were collected every 7–10 days, sealed in 500 mL polyethylene bottles, and analyzed within 10–15 days. pH was measured using a glass electrode method, $CO_3{}^{2-}$ and $HCO_3{}^{-}$ by titration, Cl^- by silver nitrate titration, $SO_4{}^{2-}$ by acid titration, Ca^{2+} and Mg^{2+} by EDTA titration, Na^++K^+ by flame photometry, and total alkalinity by acid titration. Na^+ was determined by cation-anion balance.

1.2.4 Soil-Water Potential Observation Three groups of tensiometers were installed in sunflower, maize, and wasteland plots at depths of 20 cm, 40 cm, 60 cm, 80 cm, and 100 cm. Water potential was measured every 2–3 days to calculate hydraulic gradients across boundaries. Darcy's law was applied to compute soil water flux below the root zone.

1.2.5 Irrigation Water and Quality Portable flow meters measured irrigation volumes, with water samples collected in 500 mL bottles (2–3 replicates). Electrical conductivity was measured using a DDS-307A meter. Irrigation conditions and water chemistry are detailed in and .

1.3 Calculation Methods

1.3.1 Conversion of Soil Electrical Conductivity to Total Salt Content

The conversion formula is:

$$C = 3.7657 \times EC_{1:5} - 0.2405$$

where C is soil total salt content ($\mathrm{g \cdot kg^{-1}}$) and $EC_{1:5}$ is the electrical conductivity of 1:5 soil-water extract ($\mathrm{dS \cdot m^{-1}}$).

1.3.2 Soil Salt Content Calculation

$$S = 100 \times \rho_s \times l \times C$$

where S is soil salt content ($\mathrm{kg \cdot hm^{-2}}$), ρ_s is soil bulk density ($\mathrm{g \cdot cm^{-3}}$), and l is soil depth (m).

1.3.3 Groundwater Recharge Calculation The locational flux method was used to calculate groundwater recharge:

$$q = -K(\theta)\left(\frac{\partial h}{\partial Z} + 1\right)$$

$$K(\theta) = K_s \frac{\theta - \theta_r}{\theta_s - \theta_r}\left[1 - \left(1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{1/n}\right)^m\right]^2$$

where q is soil water flux during observation period T ($\mathrm{mm \cdot d^{-1}}$), $K(\theta)$ is unsaturated hydraulic conductivity ($\mathrm{mm \cdot d^{-1}}$), h is soil water potential (cm), Z is depth (cm), θ is volumetric water content ($\mathrm{cm^3 \cdot cm^{-3}}$), θ_s is saturated water content ($\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$), θ_r is residual water content ($\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$), and α, n, m, λ are empirical parameters; K_s is saturated hydraulic conductivity ($\mathrm{mm} \cdot \mathrm{d}^{-1}$).

Total water flow $Q(T)$ during period T:

$$Q(T) = \int_0^T q(t)dt$$

1.3.4 Groundwater Salt Contribution

$$S_b = \sum_{i=1}^{n} \frac{Q_i(z) \times TDS}{\rho_w \times \phi \times Nd}$$

where S_b is salt contributed by groundwater ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$), n is number of soil layers, TDS is average groundwater mineralization ($\mathrm{g} \cdot \mathrm{L}^{-1}$), $Q_i(z)$ is groundwater recharge for layer i (mm), ρ_w is water density ($1\ \mathrm{g} \cdot \mathrm{cm}^{-3}$), ϕ is soil porosity (taken as 0.45), and Nd is calculation coefficient (10).

1.3.5 Conversion Between Groundwater Electrical Conductivity and Mineralization

$$TDS = 0.69 \times EC_w$$

where TDS is groundwater mineralization ($\mathrm{g} \cdot \mathrm{L}^{-1}$) and EC_w is groundwater electrical conductivity ($\mathrm{dS} \cdot \mathrm{m}^{-1}$).

1.3.6 Horizontal Salt Infiltration from Cropland to Wasteland Based on salt balance theory:

$$S_l = \sum_{i=1}^{n} (S_i - S_{i-1}) - S_{ib}$$

where S_l is salt infiltrated horizontally from cropland to wasteland ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$), S_i is wasteland salt storage in period i ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$), S_{i-1} is wasteland salt storage in previous period ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$), and S_{ib} is salt contributed by groundwater to wasteland in period i ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$).

1.3.7 Soil Salt Accumulation Rate The salt accumulation rate represents the increase rate of soil salt content in the 0–100 cm profile between periods:

$$R_s = \frac{S_i - S_{i-1}}{S_{i-1}} \times 100\%$$

where R_s is soil salt accumulation rate (%), S_i is total salt content in period i ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$), and S_{i-1} is total salt content in previous period ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$).

1.3.8 Soil Water Storage

$$W_i = 10 \times \sum_{i=1}^{n} \gamma_i h_i \theta_i$$

where W_i is soil water storage in layer i (mm), h_i is thickness of layer i (cm), γ_i is bulk density of layer i ($\mathrm{g \cdot cm^{-3}}$), and θ_i is mass water content of layer i ($\mathrm{g \cdot g^{-1}}$).

1.3.9 Water Balance

$$ET = P + F + G + I - D - \Delta W$$

where ET is evapotranspiration (mm), P is precipitation (mm), F is horizontal infiltration (mm), G is groundwater recharge (mm), I is irrigation (mm), D is deep percolation (mm), and ΔW is change in soil water storage (mm).

2 Results and Analysis

2.1 Groundwater Chemical Characteristics

2.1.1 Statistical Characteristics of Groundwater Salt Ions Analysis of 45 groundwater samples revealed that irrigation events had minimal impact on overall groundwater chemistry. Groundwater cations concentrated near $\mathrm{Na^+ + K^+}$, while anions clustered near $\mathrm{SO_4{}^{2-}}$ and $\mathrm{HCO_3{}^-}$. Based on milliequivalent calculations, the primary hydrochemical type was $\mathrm{HCO_3 \cdot SO_4}$-Na. Statistical parameters are presented in , with ion distributions shown as box plots and Piper diagrams in [Figure 4: see original paper].

2.1.2 Principal Component Analysis of Groundwater Salt Ions Principal component analysis was performed using eight groundwater parameters ($\mathrm{K^+}$, $\mathrm{Na^+}$, $\mathrm{Ca^{2+}}$, $\mathrm{Mg^{2+}}$, $\mathrm{Cl^-}$, $\mathrm{SO_4{}^{2-}}$, $\mathrm{HCO_3{}^-}$, $\mathrm{CO_3{}^{2-}}$). Three principal components with eigenvalues >1 were extracted, explaining 76.71% of the variance (). The principal component linear expressions are:

$$PCA1 = 0.164K^{+} + 0.466Na^{+} + 0.419Ca^{2+} + 0.284Mg^{2+} + 0.474Cl^{-} + 0.513SO_4^{2-} + 0.474HCO_3^{-} + 0.115CO_3^{2-}$$

$$PCA2 = -0.136K^{+} + 0.606Na^{+} + 0.280Ca^{2+} + 0.240Mg^{2+} + 0.070Cl^{-} + 0.435SO_4^{2-} - 0.756HCO_3^{-} + 0.130CO_3^{2-}$$

$$PCA3 = 0.130K^{+} + 0.115Na^{+} + 0.606Ca^{2+} + 0.419Mg^{2+} + 0.474Cl^{-} - 0.136SO_4^{2-} + 0.070HCO_3^{-} + 0.435CO_3^{2-}$$

The first principal component had high loadings for Na^++K^+, $SO_4{}^{2-}$, and $HCO_3{}^-$, representing the primary salt components (Na_2SO_4 and $NaHCO_3$). The second component showed high loadings for Ca^{2+} and Mg^{2+}, reflecting carbonate mineral dissolution influenced by $HCO_3{}^-$. The third component had high loadings for Cl^-, representing a supplementary factor. Therefore, Na^++K^+, $SO_4{}^{2-}$, and $HCO_3{}^-$ were selected as characteristic factors for studying groundwater salt conditions.

2.1.3 Shallow Groundwater Depth Variations Throughout the observation period, shallow groundwater depths across different land types showed similar trends ([Figure 5: see original paper]). Wasteland groundwater depth patterns matched those in cultivated areas, indicating consistent shallow aquifers at the farmland scale. During irrigation events, shallow groundwater levels rose rapidly and flowed laterally, causing synchronous water level increases across the entire irrigated area and demonstrating active horizontal groundwater exchange.

The first irrigation event (spring flooding before sunflower planting) caused a rapid 0.73 m rise in sunflower plot groundwater, while other plots showed smaller increases. As the growing season progressed, increasing evapotranspiration from maize and sunflower caused continuous groundwater decline. After maize irrigation, groundwater recharge created peak water levels that alternated with declining periods. By the end of the growing season, minimal precipitation and irrigation resulted in maximum groundwater depths averaging approximately 2.8 m.

2.2 Soil Ion Changes Across Land Types

Analysis of soil ion changes before and after crop cultivation ([Figure 6: see original paper]) revealed that for the 0–100 cm profile, maize and sunflower fields had anions dominated by $SO_4{}^{2-}$ (36.80% and 37.89% of total anions, respectively), while wasteland was dominated by $HCO_3{}^-$ (65.34%). All land types showed cations dominated by Na^++K^+ (59.57%, 63.08%, and 82.61% for maize, sunflower, and wasteland, respectively). Soil salt accumulation primarily consisted of Na_2SO_4, with other ions showing minimal changes. Salt accumulation was concentrated in the surface layer (0–20 cm), where wasteland accumulation was 3–5 times greater than in cultivated fields, while mid-deep layers showed similar ion compositions across land types.

2.3 Soil Water Balance Across Land Types

Using the entire observation period (147 days), water balance calculations were performed for representative land types (). Wasteland soil at 60–100 cm depth had an average groundwater recharge rate of 0.72 $mm \cdot d^{-1}$, with no deep percolation occurring. Groundwater recharge patterns aligned with water level changes. After irrigation in maize and sunflower plots, rising groundwater levels replenished deep soil moisture, resulting in higher recharge rates. Sunflower field soil at 60–100 cm averaged 0.32 $\mathrm{mm \cdot d^{-1}}$ (spring flooding stage) and 0.58 $\mathrm{mm \cdot d^{-1}}$ (growing season), while maize field soil averaged 0.68 $\mathrm{mm \cdot d^{-1}}$ and 0.46 $\mathrm{mm \cdot d^{-1}}$ during respective stages ([Figure 7: see original paper]).

Evapotranspiration varied significantly: wasteland (422.6 mm) < sunflower (475.6 mm) < maize (625.8 mm). The higher ET in maize resulted from longer growth periods and greater irrigation volumes.

2.4 Soil Salt Balance Across Land Types

Based on calculated groundwater recharge, salt contributions to sunflower, maize, and wasteland plots were estimated at 132.3 mm, 167.6 mm, and 189.7 mm, respectively. Wasteland received slightly more groundwater recharge, likely due to lower topography receiving lateral flow from cultivated areas after irrigation.

Salt dynamics showed distinct patterns ([Figure 8: see original paper]). During spring flooding (Day 0–50), sunflower fields were irrigated, resulting in salt leaching of 12,776 $\mathrm{kg \cdot hm^{-2}}$ (50.88% desalination). During the growing season without irrigation, salts gradually accumulated, reaching 20,169 $\mathrm{kg \cdot hm^{-2}}$ by Day 147 (29.33% accumulation). Maize fields showed similar patterns during summer irrigation (Day 50–100), with 7,684 $\mathrm{kg \cdot hm^{-2}}$ leached (37.33% desalination), followed by accumulation of 4,214 $\mathrm{kg \cdot hm^{-2}}$.

All land types accumulated salts: wasteland (14,961 $\mathrm{kg \cdot hm^{-2}}$) > sunflower (7,394 $\mathrm{kg \cdot hm^{-2}}$) > maize (4,374 $\mathrm{kg \cdot hm^{-2}}$) (). Groundwater salt contribution was the main component: 6,825 $\mathrm{kg \cdot hm^{-2}}$ to wasteland, 4,982 $\mathrm{kg \cdot hm^{-2}}$ to sunflower, and 4,502 $\mathrm{kg \cdot hm^{-2}}$ to maize. Horizontal infiltration from maize contributed 1,924 $\mathrm{kg \cdot hm^{-2}}$ to wasteland, accounting for 22.00% of wasteland salt accumulation.

2.5 Dry Drainage Salt Process Analysis and Optimization Measures

The maize-wasteland intercropping pattern is typical in the Hetao Irrigation District. During irrigation, concentrated water application (every 20–25 days) and high soil permeability cause leakage before field capacity is reached. Rising groundwater creates hydraulic gradients, driving water flow from irrigated to non-irrigated areas. However, salt movement is bidirectional.

Spatiotemporal analysis of 1 m soil salt content revealed a clear transition zone ([Figure 9: see original paper]). Soil near wasteland had salt content >3.75 $\mathrm{g \cdot kg^{-1}}$ (moderate salinization), decreasing to <2.0 $\mathrm{g \cdot kg^{-1}}$ (light salinization) with distance. This occurs because cultivated land ET exceeds wasteland ET during the growing season, creating water potential gradients that drive water and salts toward wasteland. However, during peak evaporation periods, reverse gradients can move salts back toward cultivated land.

Optimization measures recommend: (1) planting salt-tolerant crops like sunflower near wasteland to reduce yield loss; (2) establishing salt-tolerant vegetation on wasteland to increase ET and enhance dry drainage function.

3 Discussion

Most groundwater ion analyses focus on regional scales. Previous studies using graphical and correlation methods found that water-saving renovations have led to groundwater freshening in the Hetao District, while agricultural irrigation and aridity are primary drivers of salinization. Our results align with these findings, showing irrigation significantly impacts groundwater salt ions at the farmland scale. Post-irrigation, shallow groundwater HCO_3^- content increases noticeably, and salts re-enter soils during subsequent evaporation periods. Na_2SO_4 represents the main salt type exchanged between soil and groundwater.

Channel lining studies have shown hydrochemical type shifts from $Mg \cdot Na\text{-}SO_4 \cdot Cl^-$ to $HCO_3 \cdot SO_4\text{-}Ca \cdot Mg$ type, differing from our $HCO_3 \cdot SO_4\text{-}Na$ type. This spatial variability reflects the district's heterogeneous ion composition. Previous research established that wasteland accumulates salts during irrigation periods and loses them during autumn flooding, functioning as a "salt reservoir." Our study quantifies temporal salt variation patterns across land types and demonstrates that lateral groundwater flow drives salt migration, supporting biodiversity and natural vegetation in wasteland areas.

Recent water-saving policies have reduced Yellow River diversions, breaking the long-established water-salt balance and causing salt redistribution within the district. Wasteland and lakes have become salt discharge zones. Our water balance and solute dynamics analysis of maize-wasteland systems reveals that maize irrigation raises shallow groundwater levels, creating hydraulic gradients that drive water and salts toward non-irrigated areas. The spatiotemporal analysis confirms salt transition zones at cultivated-wasteland boundaries, consistent with previous findings.

4 Conclusions

1. **Groundwater Chemistry:** Shallow groundwater in the Hetao Irrigation District is primarily brackish, with SO_4^{2-} dominating anions (41.04%) and $Na^+ + K^+$ dominating cations (53.22%). The hydrochemical type is $HCO_3 \cdot SO_4\text{-}Na$. Principal component analysis identified TDS, $Na^+ + K^+$, HCO_3^-, and SO_4^{2-} as key factors influencing groundwater quality. Shallow groundwater depth responds actively to irrigation events.
2. **Soil Salt Accumulation:** Before and after crop cultivation, Na_2SO_4 is the primary salt accumulated, with other ions showing minimal changes. Salt accumulation concentrates in the surface 0–20 cm layer.
3. **Water Balance:** Evapotranspiration varies by land type: wasteland (422.6 mm), sunflower (475.6 mm), and maize (625.8 mm). Groundwater recharge rates differ accordingly, with irrigation causing rapid water level rises and subsequent declines due to crop water uptake.

4. **Salt Balance:** All land types accumulate salts: wasteland (14,961 $\text{kg} \cdot \text{hm}^{-2}$) > sunflower (7,394 $\text{kg} \cdot \text{hm}^{-2}$) > maize (4,374 $\text{kg} \cdot \text{hm}^{-2}$). Groundwater salt contribution is the main component. Horizontal infiltration from cropland contributes 1,924 $\text{kg} \cdot \text{hm}^{-2}$ to wasteland (22.00% of wasteland accumulation).
5. **Management Recommendations:** A salt transition zone exists between wasteland and cultivated land. Planting salt-tolerant cash crops (e.g., sunflower) near wasteland is recommended to prevent yield losses. Establishing salt-tolerant vegetation on wasteland can enhance ET and maximize dry drainage benefits.

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Note: Figure translations are in progress. See original paper for figures.

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