

SUSTAINABILITY ISSUES OF WATER USE ON THE DEVELOPMENT OF HETAO IRRIGATION DISTRICT, THE YELLOW RIVER BASIN

QUESTIONS DE LA DURABILITÉ DE L'UTILISATION DE L'EAU DANS LE DÉVELOPPEMENT DU DISTRICT D'IRRIGATION DE HETAO, DU BASSIN VERSANT DE JAUNE

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ABSTRACT

Sustainable water management is essential for addressing the water–energy–food nexus, particularly in irrigation districts facing climate variability and increasing inter-sectoral water competition. In arid and semi-arid regions, agricultural water use must be improved without compromising food production, farmer livelihoods, or ecological stability. This study analyses water management modernization in the Hetao Irrigation District (HID) of the Yellow River Basin through the framework of transitional change. Based on recent research, this study characterizes implemented modernization measures, including off-farm canal upgrading, improved on-farm surface irrigation, crop and soil management, drainage and salinity control, autumn irrigation regulation, and the expansion of drip irrigation systems. The results show that modernization has improved canal regulation, water delivery reliability, and field-level irrigation efficiency. Optimized border irrigation and precision land leveling reduced irrigation redundancy and improved water distribution uniformity, while drip irrigation enhanced precise water application and crop water productivity in suitable areas. However, the modernization process also revealed important trade-offs. The expansion of high-value cash crops may increase structural water demand, weakening expected water-saving effects. Reducing autumn irrigation can ease seasonal water pressure but may disturb salt leaching and increase salinization risks. In addition, advanced irrigation technologies require investment, energy, maintenance capacity, and farmer training, which may limit adoption among smallholders. Overall, irrigation modernization in the HID should be understood as an integrated transition rather than a single technological upgrade. Sustainable outcomes require coordinated engineering innovation, adaptive water allocation, crop-structure optimization, salinity monitoring, financial support, and institutional reform.

Keywords: Irrigation Modernization; Water–Energy–Food Nexus; Hetao Irrigation District; Water-Saving Irrigation; Soil Salinization.

RESUME

Une gestion durable de l'eau est essentielle pour traiter le lien entre eau-énergie-alimentation, en particulier dans les périmètres irrigués confrontés à la variabilité climatique et à une concurrence intersectorielle croissante concernant l'accès à l'eau. Dans les régions arides et semi-arides, l'utilisation agricole de l'eau doit être améliorée sans compromettre la production alimentaire, les moyens de subsistance des agriculteurs ou la stabilité écologique. Cette étude analyse la modernisation de la

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gestion de l'eau dans le périmètre irrigué de Hetao (HID) du bassin versant de Jaune dans le cadre du changement transitoire. Sur la base de recherches récentes menées, cette étude caractérise les mesures de modernisation mises en œuvre, y compris l'amélioration des canaux hors exploitation, l'irrigation de surface améliorée à la ferme, la gestion des cultures et des sols, le contrôle du drainage et de la salinité, la régulation de l'irrigation d'automne et l'expansion des systèmes d'irrigation goutte à goutte. Les résultats montrent que la modernisation a amélioré la régulation des canaux, la fiabilité de l'approvisionnement en eau et l'efficacité de l'irrigation au niveau du champ. L'optimisation de l'irrigation par planches et le nivellement de précision des terres ont réduit la redondance de l'irrigation et amélioré l'uniformité de la distribution d'eau, tandis que l'irrigation goutte-à-goutte a amélioré l'application précise de l'eau et la productivité de l'eau agricole dans les zones appropriées. Cependant, le processus de modernisation a également révélé d'importants compromis. L'expansion des cultures commerciales de haute valeur pourrait augmenter la demande structurelle en eau, ce qui donnera lieu à l'affaiblissement des effets attendus d'économie d'eau. La réduction de l'irrigation d'automne peut atténuer la pression hydrique saisonnière mais peut perturber le lessivage du sel et augmenter les risques de salinisation. En outre, les technologies d'irrigation avancées nécessitent des investissements, de l'énergie, des capacités de maintenance et de la formation des agriculteurs, ce qui peut limiter leur adoption par les petits exploitants. En général, la modernisation de l'irrigation dans périmètre irrigué de Hetao (HID) doit être comprise comme une transition intégrée plutôt qu'une simple mise au point technologique. Des résultats durables nécessitent une innovation technique coordonnée, une allocation adaptative de l'eau, une optimisation de la structure des cultures, une surveillance de la salinité, un soutien financier et une réforme institutionnelle.

Mots-clés : Modernisation de l'irrigation; Lien entre eau-énergie-alimentation; Périmètre irrigué de Hetao; Irrigation économe en eau; Salinisation des sols.

1. INTRODUCTION

Sustainable water management is a critical challenge for agricultural development in water-limited regions. Agriculture remains essential for food security and rural livelihoods, but it accounts for about 70% of global freshwater withdrawals, with groundwater supporting a large share of irrigation worldwide (UNESCO, 2024). Climate change is further altering the timing and reliability of water availability, increasing risks from drought, heat stress, floods, and declining soil moisture. Nearly half of the global population experiences severe water scarcity for at least part of the year (Caretta, 2022). Thus, irrigation is no longer only a production input, but also a key component of climate adaptation, water allocation, and environmental governance.

Irrigation plays a disproportionate role in global food production, but its expansion often occurs in regions under water stress. Mehta et al. (2024) reported that the global area equipped for irrigation increased from 297 million ha in 2000 to 330 million ha in 2015, with more than half of this expansion occurring in water-stressed regions. This trend highlights a growing contradiction: irrigation is needed to stabilize crop production, but poorly coordinated expansion can intensify competition for water, increase dependence on river diversions and groundwater, and accelerate ecological degradation. Hence, irrigation modernization must consider not only technical efficiency, but also cropping choices, farmer behavior, energy demand, drainage conditions, and basin-scale water allocation.

In arid and semi-arid regions, irrigation sustainability is closely linked to soil salinity. Salinization reduces crop productivity, damages soil structure, and threatens the long-term viability of irrigated land. A recent FAO assessment estimated that 1.381 billion ha, or 10.7% of the global land area, are affected by salinity, with about one billion additional hectares at risk under climate change and inappropriate land and water management (FAO, 2024). In irrigation districts with shallow groundwater, limited drainage, and high evaporation, water-saving measures can produce both benefits and risks. Reduced irrigation may lower water diversion, but it can also weaken salt leaching and disturb the regional water-salt balance.

The Yellow River Basin provides an important setting for examining these challenges. It accounts for about 2.6% of China's total water resources, and supports major agricultural production and regional development. He et al. (2024) showed that cereal production in the basin increased by 62.2 Mt between 1998 and 2018, while total water withdrawals remained relatively stable at 49.7–51.6 billion m³. This indicates progress in agricultural water-use efficiency, but the basin still faces strong pressure from water scarcity, ecological protection requirements, and sectoral competition. Future irrigation development therefore needs to move beyond isolated water-saving measures toward integrated water governance (Zhang and Oki, 2024).

The Hetao Irrigation District (HID), located in western Inner Mongolia in the upper and middle reaches of the Yellow River Basin, is a representative case of this transition. It is one of China's largest irrigation districts and depends heavily on Yellow River water (Yu et al., 2026). The region has low precipitation, strong evaporation, and a long history of irrigation-based agriculture. Recent studies describe the HID as a large-scale salinized irrigation district with an irrigation area of approximately 1.162 million ha, where irrigation accounts for more than 95% of diverted water use (Feng et al., 2025). Its agricultural productivity depends on a fragile balance among canal seepage, shallow groundwater, drainage capacity, autumn irrigation, and salt transport.

Over the past two decades, the HID has implemented multiple modernization measures, including canal lining, distribution-system upgrading, precision land leveling, improved border and furrow irrigation, optimized scheduling, drainage improvement, autumn irrigation regulation, crop-structure adjustment, and selective drip irrigation expansion (Ao et al., 2024; Cao et al., 2023; Feng et al., 2025). These measures have improved water regulation and field-level irrigation efficiency (Liu et al., 2026). However, important trade-offs remain. Cash-crop expansion may increase farm income but raise structural water demand; reducing autumn irrigation may save water but increase salinity risk; and advanced technologies require investment, energy, maintenance, and technical knowledge, which may limit adoption among smallholders (Grant et al., 2022; Han et al., 2025; Zhao et al., 2025).

Hence, this study examines water management modernization in the HID through the perspective of transitional change. It characterizes implemented modernization measures and evaluates their effectiveness in relation to water saving, agricultural productivity, energy use, labor demand, economic feasibility, salinity control, and ecological sustainability. By synthesizing observed data, official reports, and recent research, this study identifies key constraints and clarifies trade-offs among water conservation, agricultural upgrading, and environmental protection. The findings provide practical insights for integrated water-resource governance in the Yellow River Basin and other arid and semi-arid irrigation regions.

2. MATERIALS AND METHODS

2.1 Study Area

This study focuses on the Hetao Irrigation District (HID), located in western Inner Mongolia, China, within the Yellow River Basin. The HID is one of China's largest irrigation districts and depends heavily on water diverted from the Yellow River. The region has an arid to semi-arid climate, characterized by low rainfall, high evaporation, and frequent soil salinity problems. Agriculture is mainly irrigation-based, with maize, wheat, sunflower, vegetables, and other cash crops as the dominant crops. In response to increasing water scarcity, climate variability, and stricter water allocation policies, the HID has implemented several irrigation modernization measures in recent decades.

2.2 Research Approach

This study adopts a case-study approach to examine irrigation modernization in the HID. Modernization is analyzed as a transition from traditional irrigation management toward an integrated system involving infrastructure upgrading, field-level water-saving technologies, drainage and salinity control, farmer participation, and institutional support. The analysis focuses on the contribution of different modernization measures to water saving, agricultural productivity, economic feasibility, and

environmental sustainability. Particular attention is given to the trade-offs among reducing irrigation water use, maintaining crop production, controlling soil salinity, and supporting farmer adoption.

2.3 Classification of Modernization Measures

The modernization measures analyzed in this study were divided into five main categories:

1. Canal and water-distribution improvements were examined, including canal lining, gate upgrading, flow measurement, and better water-delivery control. These measures were mainly assessed in terms of reducing conveyance losses and improving water regulation.
2. On-farm surface irrigation improvements were analyzed, including land leveling, optimized border irrigation, furrow irrigation adjustment, and improved irrigation scheduling. These practices were evaluated according to their effects on field water distribution, irrigation efficiency, labor requirements, and adoption feasibility.
3. Drip irrigation systems were assessed at both sector and farm levels. The analysis focused on water-saving potential, crop response, energy demand, installation cost, maintenance requirements, and farmer acceptance.
4. Crop and soil management practices were considered, including crop-structure adjustment, mulching, soil fertility management, and improved coordination between irrigation and crop water demand.
5. Drainage and salinity-control measures were evaluated, with particular attention to groundwater regulation, salt leaching, drainage improvement, and autumn irrigation management.

3. RESULTS AND DISCUSSIONS

3.1 Modernization of Canal Distribution and Water Regulation

Off-farm modernization improved canal conveyance and water regulation in the HID, although performance varied among subdistricts. The district-wide canal water-use coefficient increased from 0.52 in 2015 to 0.57 in 2020. Average coefficients were approximately 0.44 in Ulanbh, 0.49 in Jiefangzha, 0.53 in Yongji, 0.58 in Yichang, and 0.54 in Ulat, with larger gains observed where canal lining and structural upgrading were more advanced. For example, coefficients increased from 0.40 to 0.50 in Ulanbh, from 0.45 to 0.55 in Jiefangzha, and from 0.55 to 0.67 in Yichang. However, canal seepage was not entirely lost from the system. About 17% of diverted water was lost through seepage in a typical irrigation–drainage unit, but approximately 12% of the seeped water was reused through groundwater and land-type interactions. Seepage also supplied an estimated $0.32\text{--}0.71 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ to Wuliangsu Lake and other lakes (Feng et al., 2025).

These results indicate that canal upgrading improved delivery reliability, rotational supply control, and quota-based management. However, its net water-saving effect should be interpreted carefully. Canal lining reduces local conveyance losses and improves operational flexibility, but part of the former seepage supported groundwater recharge, wetland replenishment, and internal water reuse. Hence, canal modernization in the HID mainly reduces gross diversion pressure rather than fully recovering all seepage losses. This distinction is important because salinity control and ecological stability remain partly dependent on groundwater and drainage processes (Cao et al., 2023).

3.2 Improvement of On-Farm Surface Irrigation

On-farm irrigation modernization substantially improved water application performance in the HID. Precision land leveling, optimized border irrigation, furrow adjustment, and improved scheduling increased distribution uniformity from 64% to 95%. The border water-use efficiency coefficient rose from

60% to 90%, while deep percolation losses decreased from 39% to 10%. When land leveling was combined with cut-off adjustment, seasonal water use declined from 534 to 350 mm for maize, 434 to 265 mm for wheat, and 435 to 267 mm for sunflower, corresponding to water savings of about 34%, 39%, and 39%, respectively. The increased use of land-leveling and farmland-construction machinery between 2011 and 2017, particularly in Ulat and Jiefangzha, further indicates that field modernization relied on both technical improvement and organized mechanization (Feng et al., 2025).

These results show that optimized surface irrigation is a major modernization pathway in the HID, not merely an interim step before drip irrigation. Its strength lies in its compatibility with the district's gravity-fed system, existing farming practices, and lower energy requirements. It can achieve considerable water savings without the high demands of filtration, pumping, pressure control, and routine maintenance required by pressurized systems. However, performance remains sensitive to inflow rate, cut-off timing, field slope, and scheduling accuracy. Thus, effective surface-irrigation modernization depends on both engineering improvement and stronger management support, including farmer training and extension services (Feng et al., 2025).

3.3 Expansion and Performance of Drip Irrigation

Drip irrigation showed strong potential for precise water control and improved crop water productivity, although its effectiveness varied by crop and water source. Under mulch-drip systems, maize maintained relative yield of 0.92–0.96 at 70–80% irrigation coefficients, while relative water-use efficiency reached 1.0. Sunflower retained a relative yield of 0.88 at a 60% coefficient, also with maximum relative water-use efficiency. Wheat achieved the highest reported water-use efficiency at a 52% coefficient while maintaining a relative yield of 0.94. In contrast, tomato performed best at about an 80% coefficient but declined sharply under stronger deficit irrigation, while muskmelon showed the highest yield and water-use efficiency under full irrigation. Reported annualized costs also varied by water source, reaching about ¥3600 ha⁻¹ for Yellow River systems, ¥2900 ha⁻¹ for lake-sourced systems, and ¥2850 ha⁻¹ for combined well–canal systems (Feng et al., 2025).

These results suggest that drip irrigation should be promoted selectively rather than uniformly. It is most suitable where high-value or water-sensitive crops, reliable water quality, filtration capacity, and maintenance support are available. Water-source configuration is also important because storage, sediment control, and canal cut-off periods affect both cost and reliability. Evidence from a monitored sunflower system further shows that deep water-saving may create hidden ecological risks. Annual irrigation decreased from 386 mm in 2018 to 252 mm in 2023 and 249 mm in 2024, but adjusted crop coefficients declined by about 15%, capillary-rise contribution to evapotranspiration fell by roughly 10%, and actual-to-potential transpiration ratios decreased by 3–11% in cultivated land and 23% near lake margins. Thus, drip irrigation should be evaluated not only by reduced diversion, but also by its effects on groundwater recharge, capillary water supply, and the wider agro-ecological system (Feng et al., 2025; Li et al., 2025).

3.4 Effects of Crop and Soil Management Practices

Crop and soil management practices supported irrigation modernization by improving field water productivity and reducing environmental pressure. Measures such as mulching, soil fertility management, crop scheduling, and closer coordination between irrigation and crop demand were most effective when combined with improved surface irrigation or drip irrigation. In the HID, corn, wheat, sunflower, and other cash crops occupied about 544×10^3 ha, accounting for 85.2% of the irrigated area. From 1995 to 2018, farmland increased by 38.6%, forested land by 74.8%, and facility agriculture by 34.7×10^3 ha, while saline–alkali land declined by 95.9%. Recent watershed modeling also showed that deficit irrigation reduced agricultural non-point source total nitrogen and phosphorus by 7.74% and 35.12%, respectively, while drip irrigation under film reduced them by 9.34% and 40.99%. Crop-structure adjustment alone produced smaller reductions of 2.66–6.80%, but its combination with deficit irrigation showed the best cost–benefit performance for pollution control (Feng et al., 2025; Liu et al., 2024).

These findings show that crop and soil management strongly influences whether engineering improvements generate wider basin benefits. Crop restructuring has improved farm profitability and, in some areas, better matched saline conditions, but the expansion of sunflower and other cash crops may also increase structural water demand. Thus, higher irrigation efficiency does not necessarily reduce total water use. Agronomic measures influence water demand, nutrient loss, and farmer income simultaneously. Irrigation modernization in the HID should therefore be viewed as a coordinated process linking engineering, agronomy, water-quality protection, and economic incentives, rather than as a single-technology solution (Cao et al., 2023; Liu et al., 2024).

3.5 Drainage, Salinity Control, and Autumn Irrigation Management

Drainage and salinity control remain central to irrigation modernization in the HID because high evaporation, shallow groundwater, and long-term irrigation have created a fragile water–salt balance. Autumn irrigation remains an important salt-leaching practice, accounting for more than 30% of agricultural water consumption and covering over half of the irrigated area. Although the autumn irrigation area decreased by 11.02%, irrigation volumes changed unevenly across subdistricts, increasing by more than 50% in Yichang and Jiefangzha, rising by 30–50% in Yongji and Ulat, and decreasing by 32.40% in Ulanbh. A hydro-agro-economic study showed that eliminating autumn or winter leaching irrigation would reduce food-crop area by about 30% and increase salt accumulation by approximately 0.78×10^6 t, highlighting its importance for both production and salinity control (Cao et al., 2023; Feng et al., 2025).

Salt-balance evidence further shows that autumn irrigation cannot be viewed simply as inefficient water use. In a ditch–canal unit in Jiefangzha, autumn irrigation volume reached 78.1% of crop-growth-period irrigation volume, while annual salt discharge accounted for only 56.8% of total salt input. Autumn irrigation contributed 62% of total salt discharge, yet salt still accumulated during this period at a rate of 19.3%, indicating that current leaching and drainage capacity remains insufficient. Plot-scale evidence supports this conclusion: average salinity in the 1 m soil profile was 2.22 g kg^{-1} in cultivated land and 4.09 g kg^{-1} in fallow land, while salt accumulation was faster in fallow blocks than in cultivated fields. A 150 mm spring irrigation event reduced profile salinity by 17.2%, confirming the role of seasonal irrigation in salt leaching. Together, these results show that autumn irrigation, spring irrigation, drainage, groundwater dynamics, and cultivated–fallow exchange jointly regulate soil salinity. Therefore, reductions in autumn irrigation should be spatially targeted and supported by drainage improvement, groundwater monitoring, and salinity risk assessment (Hou et al., 2023).

3.6 Socioeconomic Performance and Farmer Adoption

Modernization measures showed different levels of farmer acceptance (Table 1). Low-cost practices, such as land leveling, cut-off control, optimized surface irrigation, and improved scheduling, were more readily adopted because they matched existing farming systems and required limited additional investment. In contrast, drip irrigation and other pressurized technologies required higher capital input, energy use, technical training, and maintenance capacity, which constrained adoption among smallholders. Economic evidence indicates that incentives for advanced water-saving technologies depend strongly on water scarcity. Under baseline water supply, improving irrigation water-use efficiency by 5%, 15%, 25%, and 35% reduced district net benefits from 6.578 billion Yuan to 6.371, 5.930, 5.455, and 4.947 billion Yuan, respectively. The estimated unit cost of water saving rose from 1.11 to 1.46 Yuan m^{-3} , far above the baseline water cost of 0.03 Yuan m^{-3} . Thus, when water supply is not binding, farmers and local managers have limited economic motivation to adopt capital-intensive technologies (Cao et al., 2023; Feng et al., 2025).

Under water scarcity, however, moderate efficiency gains become more valuable. With a 30% water-supply reduction, district net benefits increased from 5.135 billion Yuan to 5.696 and 5.697 billion Yuan under 5% and 15% efficiency improvements, but declined at higher efficiency levels. Planting area also increased from 328 thousand ha to 476 thousand ha under a 35% efficiency improvement, showing that modernization can help maintain production under water constraints. However, consistent survey-based adoption data remain limited. Overall, irrigation modernization is not only an engineering process; its

success depends on farmers' ability to afford, understand, operate, and maintain the technologies introduced (Figure 1) (Cao et al., 2023; Feng et al., 2025).

Table 1. Performance indicators of irrigation technology

Modernization measure	Main function	Water-saving effect	Economic feasibility	Environmental implication	Main limitation
Canal upgrading	Improve water delivery and regulation	High	Medium	Reduces unnecessary diversion	Requires maintenance and management
Improved surface irrigation	Improve field water distribution	Medium	High	Reduces excessive irrigation	Depends on farmer operation
Drip irrigation	Precise root-zone irrigation	High	Medium to low	Improves water productivity	High cost, energy use, maintenance
Crop and soil management	Match irrigation with crop demand	Medium	High	Improves water productivity	Cash crops may increase water demand
Drainage and salinity control	Maintain water–salt balance	Indirect	Medium	Reduces salinity risk	Needs long-term monitoring
Autumn irrigation regulation	Reduce seasonal water demand	Medium	Medium	May affect salt leaching	Risk of salt accumulation

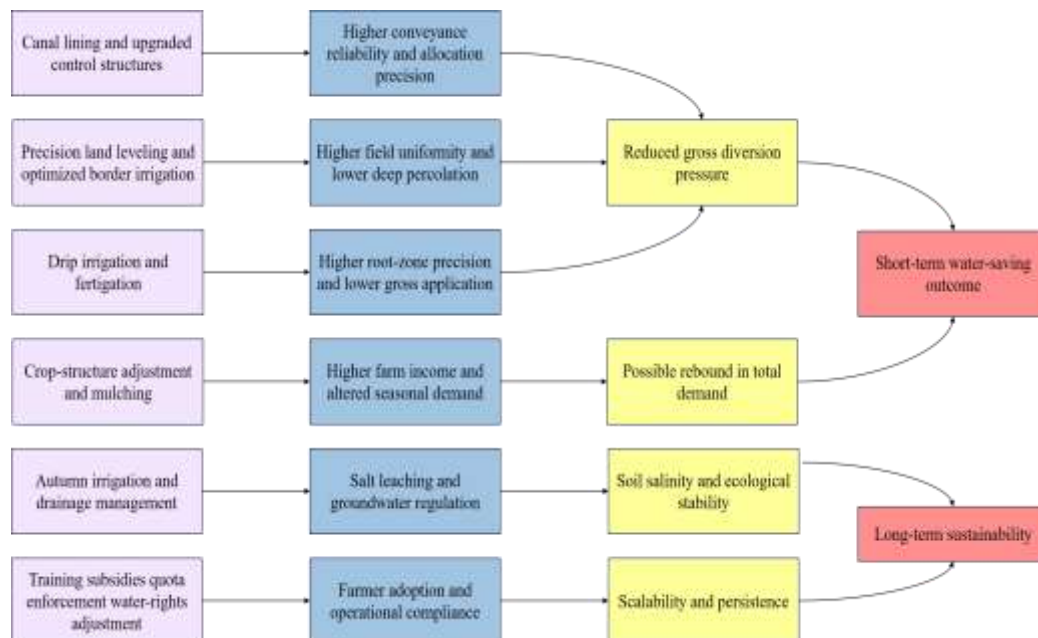


Figure 1. Summary of the interaction among engineering measures, governance instruments, and outcomes

CONCLUSION

This study examined irrigation modernization in the Hetao Irrigation District from the perspective of transitional change. The findings show that modernization has evolved from isolated water-saving measures into an integrated process involving canal upgrading, improved surface irrigation, drip irrigation, crop and soil management, drainage improvement, salinity control, and institutional coordination.

Canal modernization improved water regulation and delivery reliability, while field-level measures such as land leveling and optimized surface irrigation enhanced distribution uniformity and reduced irrigation redundancy. Drip irrigation showed strong potential for precise water application and improved crop water productivity, particularly for high-value crops. However, modernization also generated important trade-offs. Cash-crop expansion may increase farm income but raise structural water demand; reduced autumn irrigation may save water but weaken salt leaching; and advanced irrigation technologies require investment, energy, maintenance, and technical capacity that may limit adoption among smallholders. Therefore, sustainable irrigation modernization in the HID cannot rely on a single technology or policy. It requires coordinated engineering improvement, adaptive water allocation, crop-structure optimization, long-term salinity monitoring, farmer training, financial support, and institutional reform. The HID experience provides useful lessons for the Yellow River Basin and other arid and semi-arid regions, where irrigation modernization should be evaluated not only by short-term water-use efficiency, but also by its long-term contribution to food security, rural livelihoods, and environmental sustainability.

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