Postprint: Water Efficiency Changes in Irrigation Districts under Integrated Management in the Shiyang River Basin

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Abstract

The irrigation districts of the Shiyang River Basin represent areas where human-land-water conflicts are highly concentrated and serve as focal regions for comprehensive watershed management. Their water use efficiency profoundly influences oasis stability and the harmonious development of the production-living-ecology system. Employing the DEA model, this study measured changes in agricultural water use efficiency across 13 irrigation districts before and after implementation of the Shiyang River Basin Management Plan. Results indicate significant spatiotemporal variations in water use efficiency among districts, with 2007 serving as an inflection point, showing an overall trajectory of fluctuating decline in the early period followed by stable improvement in the later period. Efficiency rankings follow: midstream well-spring irrigation districts > midstream mountain-river irrigation districts > downstream mixed mountain-river-well irrigation districts, reflecting the substantial impact of watershed governance. Key management areas exhibit higher efficiency than non-key areas, though the downstream Hongyashan Reservoir irrigation district maintains low efficiency. Water and land redundancy constitute common factors affecting efficiency across all districts. Water redundancy is lower in well-spring districts than mountain-river districts, yet both redundancy and slack variables are decreasing, indicating enhanced water conservation. Pre-management land redundancy was highest in well-spring and mixed districts; post-management reductions in land redundancy are observed in mountain-river and downstream Hongyashan Reservoir districts, demonstrating the effectiveness of the "well closure and land reduction" policy in well-spring districts.

Full Text

Preamble

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Change in Water-Use Efficiency of Irrigated Areas Before and After Integrated Management in Shiyang River Basin

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Abstract

The Shiyang River Basin represents one of three major continental river basins in the Hexi Corridor and faces the most severe water resource pressures in the region. Water utilization efficiency not only affects sustainable socioeconomic development but also influences national ecological security. In arid inland river basins, irrigated areas constitute the largest water consumption zones and are highly contested multi-use areas, making comprehensive watershed management essential. Water-use efficiency profoundly impacts oasis stability and harmonious socioecological development in these regions. This study employed the Data Envelopment Analysis (DEA) model to measure agricultural water efficiency and its influencing factors across 13 irrigated areas in the Shiyang River Basin from 2000 to 2010. Results revealed significant temporal and spatial differences in water-use efficiency before and after integrated management measures. Efficiency fluctuations during early management stages stabilized by 2007. The ranking of water-use efficiency by irrigation source type was: middle-reach well-spring irrigation areas (W-S) > middle-reach river irrigation areas (R) > downstream river-well-spring mixed irrigation areas (R-W-S), reflecting the strong influence of watershed management measures. Key control regions demonstrated higher water-use efficiency than non-key areas, though the downstream Hongyashan Reservoir irrigation area remained notably inefficient. All irrigation areas exhibited varying degrees of water and land redundancy, though both redundancy levels and slack variables decreased over time, indicating strengthened water conservation. Before integrated management, well-spring and mixed irrigation areas showed the greatest land redundancy; after management, land redundancy decreased in river irrigation areas and the downstream Hongyashan Reservoir area, demonstrating that “well closure”and “farmland compression” policies had clear effects.

Keywords: irrigated area; agricultural water-use efficiency; DEA model; Shiyang River Basin; integrated management

1. Study Area Overview

The Shiyang River Basin is a typical arid inland river basin located in the eastern Hexi Corridor of Gansu Province, west of Wushaoling and at the northern foot of the Qilian Mountains (104°41 -104°16 E, 36°29 -39°27 N). The basin' s tributaries can be divided from east to west into the Dajing River system, Liuhe River system, and Xida River system—three relatively independent inland river systems. The Dajing River system belongs to the Dajing Basin, where river water is transformed and utilized within the basin. The Liuhe River system belongs to the Wuwei South Basin; after exiting the mountain pass, water is essentially fully impounded by reservoirs and then diverted into canals for irrigation, undergoing transformation within the Wuwei South Basin before converging into the Shiyang River and entering the downstream Hongyashan Reservoir. The Xida River system upstream consists mainly of the Xida River, which irrigates the Minqin irrigation area, joins the Jinchuan Gorge Reservoir, and after utilization and transformation, enters the Jinchuan-Changning Basin where it is completely consumed. Consequently, the entire basin forms a pattern of Xida River mountain-water irrigation, middle-reach mountain-water irrigation, Dajing River mountain-water irrigation, Hongyashan Reservoir irrigation, middle-reach well-spring irrigation, and downstream mountain-well-spring mixed irrigation areas [Figure 1: see original paper].

The Shiyang River Basin currently has 30×10 hm^2 of irrigated land, with total agricultural water consumption of 24.34×10 m^3, accounting for 85.7% of total water use. Total water consumption has exceeded the total water resources available, with a water resource development degree of 172% and consumption rate of 109%, far surpassing the basin' s carrying capacity. The entire basin includes Wuwei and Jinchang cities, with Wuwei being the key region for economic and social development, accounting for 78.4% of the basin' s population, 70% of GDP, and 70% of total grain output. Due to significant differences between Wuwei and Jinchang (which belongs to the Xida River system and is industrially oriented), this study focuses on irrigation districts within Wuwei' s jurisdiction, excluding Anyuan and Zhucha irrigation districts in Tianzhu County as they fall outside the comprehensive management zone .

2. Research Methods and Data Sources

Water resource efficiency evaluation can be categorized into single-factor water efficiency (PFWE) and total-factor water efficiency (TFWE). PFWE, indirectly represented by water consumption coefficients such as average irrigation water use, is simple to calculate but ignores substitution effects between water and other inputs. TFWE, which considers contributions from other inputs, provides more meaningful results. The two main approaches for measuring water efficiency are Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA). DEA is a systematic analysis method based on the concept of relative efficiency, evaluating the relative effectiveness or performance of similar decision-making units according to multiple inputs and outputs.

Assuming constant returns to scale (CRS), the model calculates pure technical efficiency of water resource utilization, which primarily reflects management level and water diversion allocation technology influences. When irrigation districts exhibit variable returns to scale, the model extends to the BCC model to calculate scale efficiency (SCALE) and returns to scale status. CRS_TE = VRE_TE × SCALE, where CRS_TE represents total efficiency under constant returns to scale, VRE_TE represents pure technical efficiency, and SCALE represents scale efficiency.

Total-factor water efficiency (TFWE) can be defined as the ratio between target water use and actual water use. The key is determining slack variables and redundancy rates for each irrigation district. Slack variables measure the difference between each input variable and its linear optimum—the greater the redundancy rate, the lower the comprehensive water efficiency, and the larger the improvement potential.

Given that over 90% of water is used for farmland irrigation, primarily for grain production, land can be considered a fixed input factor while water resources are variable inputs. This study selected irrigation water consumption, canal system density, and number of water user association households as input variables, and actual irrigated area, grain yield, and number of benefiting farmers as output variables .

Data were primarily obtained from the *Wuwei Water Resources Statistical Yearbook* (2000–2010), with supplementary data from the Cold and Arid Regions Science Data Center. All variables showed significant variation, with strong positive correlations between them, particularly between irrigation water consumption and total grain yield (correlation coefficient 0.8625), indicating water's decisive role in irrigation district production .

3. Results Analysis

3.1 Significant Temporal and Spatial Differences in Water-Use Efficiency Before and After Integrated Management

Using an input-oriented DEA model, we analyzed the water resource technical efficiency and scale efficiency of 13 irrigation districts in the Shiyang River Basin from 2000 to 2010. The average pure technical efficiency was 0.8101, with well-spring irrigation areas showing the highest efficiency and downstream mountain-well-spring mixed areas the lowest. Temporally, both middle-reach mountain-water and well-spring irrigation areas improved, particularly after 2005, while downstream mixed areas continued declining until the 2007 watershed management plan implementation, after which they improved significantly.

Average scale efficiency across all districts was 0.9375, with well-spring irrigation areas generally higher than mountain-water areas. The lowest scale efficiency occurred in Gulang District (0.8837). Most districts operated near the efficiency frontier, though middle-reach mountain-water areas like Yongchang, Donghe, and Gufeng were significantly lower. Hongyashan Reservoir and Huangyang districts exhibited decreasing returns to scale, indicating the need for substantial input reduction to achieve optimization.

Total-factor water efficiency analysis revealed that middle-reach mountain-water and well-spring irrigation districts showed relatively stable efficiency with clear increases after management implementation. However, downstream mixed areas displayed pronounced volatility—declining continuously before 2005, then rising steadily afterward. This pattern indicates that middle-reach districts responded more rapidly to management measures, while downstream areas, particularly Hongyashan Reservoir District, experienced dramatic changes [Figure 2: see original paper].

The integrated management timeline aligns closely with efficiency changes. After 2000, traditional water use patterns continued with efficiency declines. The 2003 provincial water allocation scheme and management measures began restraining traditional practices, limiting water use and boosting efficiency. The 2007 State Council approval of the *Shiyang River Basin Key Management Plan* and provincial water management regulations marked strong state intervention, with well closure and farmland compression policies producing clear efficiency gains .

3.2 Clear Differences Between Key and Non-Key Management Regions

The comprehensive management scope covered the entire Shiyang River Basin except the Dajing River system and Gulang' s Yellow River diversion area, with priority given to Hongyashan Reservoir and Huanhe irrigation districts. Hongyashan Reservoir District' s efficiency remained far below other types until the State Council plan approval, reflecting the severity of accumulated downstream problems. Huanhe District, influenced by well-spring characteristics, maintained stable effective status. Middle-reach mountain-water districts, though within the management zone, showed less efficiency improvement due to their upstream location and lower water pressure. The key management area of Hongyashan Reservoir District achieved average annual water-saving irrigation area of 0.246×10 hm^2, higher than non-key areas, with the most significant decline in water consumption per unit area (from 714 m^3 to 493 m^3), though its canal system utilization coefficient remained the lowest .

3.3 Water and Land Resource Waste as Common Factors Affecting Efficiency

When production efficiency is non-effective (TFWE < 1), input transformation capacity is limited and input redundancy exists. In 2000, eight irrigation districts were non-effective, with water use slack variables and redundancy rates varying significantly. Jinta District showed maximum redundancy (830.84×10 m^3, 54.62% redundancy rate), while Huanhe District showed minimum. By 2010, the number of non-effective districts decreased, average irrigation water redundancy rates dropped by more than half, and most districts reduced redundancy, indicating gradual improvement in water conservation .

Land redundancy analysis revealed that in 2000, seven districts had excessive land use, with redundancy rates ranging 2%–50%. Changning District showed maximum land redundancy (48.05%). Well-spring and mixed irrigation areas in middle and downstream regions had relatively high land redundancy rates. By 2010, all districts except Hongyashan Reservoir and Jinyang reduced land redundancy, with middle-reach mountain-water and downstream well-spring areas showing the most significant decreases, demonstrating that water resource allocation reduction forced land use optimization .

4. Conclusions and Recommendations

Analysis of 13 irrigation districts in the Shiyang River Basin revealed significant temporal-spatial differences in agricultural water-use efficiency before and after integrated management, with an overall pattern of early-stage fluctuation followed by stable improvement. Efficiency rankings of middle-reach well-spring > middle-reach mountain-water > downstream mixed irrigation areas reflect management impacts. Key management regions outperformed non-key areas, though downstream Hongyashan Reservoir District remained inefficient. All districts exhibited water and land resource waste, but redundancy and slack variables decreased, indicating strengthened conservation. Before management, middle-reach well-spring and downstream mixed areas showed maximum land redundancy; after management, middle-reach mountain-water and downstream Hongyashan Reservoir areas reduced land redundancy, proving "well closure and farmland compression" policies effective.

The Shiyang River Basin management follows a "water saving first, water transfer second" principle. Given limited total water resources and large transfer project costs, building a water-saving society is fundamental. This requires establishing a water rights management system, an economic structure coordinated with water resource carrying capacity, and a water conservancy project system adapted to optimal allocation. Key measures include controlling irrigation area while reducing quotas, combining canal and field water saving (emphasizing field savings), integrating engineering and management measures, and linking agricultural water saving with comprehensive water conservation.

Irrigation district water redundancy rates serve as reference systems for improving technology and management. Results show substantial improvement potential remains. Reducing agricultural land, renovating field projects, and implementing water-saving irrigation are key efficiency enhancement pathways. Water users' behavior is the most fundamental factor determining efficiency. After implementing water rights systems, water user associations, and water pricing mechanisms, association numbers and benefiting farmers increased continuously, particularly in key management districts like Xiying (benefiting households increased from 3,200 to 6,219) and Hongyashan Reservoir (from 1,200 to 4,218), demonstrating that market mechanisms and interest-sharing systems can fundamentally improve water-use efficiency and benefits.

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Data Source: Wuwei City Water Affairs Bureau. *Wuwei Water Resources Statistical Yearbook* (2000-2010).

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