Coupled and Coordinated Relationship Between the Development Level of Water-Saving Irrigation and Poverty Reduction Effectiveness in Uzbekistan

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Abstract

To explore the coupling coordination relationship between the development level of water-saving irrigation and poverty reduction effectiveness in Uzbekistan, this study takes 12 regions and 1 autonomous republic of Uzbekistan as research units and selects data from 2018 to 2023. An evaluation index system for the development level of water-saving irrigation and an evaluation index system for poverty reduction effectiveness are constructed, and a comprehensive evaluation model, coupling degree model, and coupling coordination degree model are used to comprehensively examine the coupling coordination relationship between the development level of water-saving irrigation and poverty reduction effectiveness in Uzbekistan. The results show that: (1) The development level of water-saving irrigation in various regions of Uzbekistan exhibits spatial distribution characteristics of higher levels in the central and eastern regions and lower levels in the western region, with an upward trend year by year. Poverty reduction effectiveness shows a pattern of better outcomes in the eastern region and poorer outcomes in the southern and western regions, also with an upward trend. (2) The coupling degree between the development level of water-saving irrigation and poverty reduction effectiveness in all regions shows a fluctuating upward trend, forming a regional agglomeration pattern in which the western and central regions are moderately coupled, while the eastern and southern regions are highly coupled. (3) The coupling coordination degree between the development level of water-saving irrigation and poverty reduction effectiveness in the study area increases year by year, showing distribution characteristics of higher coordination in the central and eastern regions and lower coordination in the western region. Except for the Republic of Karakalpakstan and Sirdaryo Region, all other regions have entered the stage of high-quality coordination. (4) Lagging water-saving development is the key factor affecting the improvement of the coupling coordination degree between the development level of water-saving irrigation and poverty reduction effectiveness.

Full Text

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Coupled and Coordinated Relationship Between the Development Level of Water-Saving Irrigation and Poverty Reduction Effectiveness in Uzbekistan

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Abstract: To explore the coupled and coordinated relationship between the development level of water-saving irrigation and poverty reduction effectiveness in Uzbekistan, this study took the country' s 12 regions and one autonomous republic as the research units, selected data from 2018 to 2023, and constructed an evaluation index system for the development level of water-saving irrigation and an evaluation index system for poverty reduction effectiveness. A comprehensive evaluation model, coupling degree model, and coupling coordination degree model were used to conduct a comprehensive study of the coupled and coordinated relationship between the development level of water-saving irrigation and poverty reduction effectiveness in Uzbekistan. The results show that: (1) The development level of water-saving irrigation in the various regions of Uzbekistan exhibits a spatial distribution pattern in which the central and eastern regions are relatively high and the western region is relatively low, with an overall upward trend year by year. Poverty reduction effectiveness shows a pattern in which the eastern region performs well, while the southern and western regions perform poorly, and it also shows an upward trend. (2) The coupling degree between the development level of water-saving irrigation and poverty reduction effectiveness in all regions shows a fluctuating upward trend, forming a regional clustering pattern in which the western and central regions are moderately coupled, while the eastern and southern regions are highly coupled. (3) The coupling coordination degree between the development level of water-saving irrigation and poverty reduction effectiveness in the study area increases year by year, showing a distribution pattern in which the central and eastern regions have high coordination degrees, while the western region has a relatively low coordination degree. Except for the Republic of Karakalpakstan and Syrdarya Region, all other regions have entered the stage of high-quality coordination. (4) Lagging water-saving development is the key factor affecting improvement in the coupling coordination degree between the development level of water-saving irrigation and poverty reduction effectiveness.

Keywords: Uzbekistan; water-saving irrigation; poverty reduction effectiveness; coupling coordination

Uzbekistan is located in a severely arid region, with scarce precipitation and high evaporation, and its agricultural production is highly dependent on irrigation. Data show that in 2019 the country' s total agricultural land area reached 2.04×10^7 hm^2[1], and agricultural water use accounted for more than 90% of the country' s total water consumption[2]. However, the actual cultivated area was only 4.30×10^6 hm^2[3], and the surface-irrigated area was about 4.20×10^6 hm^2, accounting for 97% of the cultivated land area. Water scarcity and the low level of agricultural water-resource utilization have become key factors constraining the scale and level of agricultural development[4], and have also affected residents' living standards[2,4–5]. As of 2021, 17% of the country' s population remained poor[6], and 75% of the poor population lived in rural areas[7]. It can therefore be seen that the focus of poverty reduction in Uzbekistan lies in improving agricultural productivity and production levels.

As the core link in agricultural production, irrigation has long been regarded as an important pathway for improving agricultural productivity and production levels, as well as an important tool for poverty reduction[8−9]. Many scholars have studied the impact of irrigation on poverty and found that measures such as adopting irrigation technologies and increasing investment in irrigation infrastructure help increase farmers' incomes[10−11], raise employment rates[12], increase land productivity[13], optimize the efficiency of technological allocation[14], and improve food and nutrition security[15]. At the same time, reductions in the poverty rate and improvements in farmers' economic and technical capacities will in turn promote the development of irrigation technologies; therefore, irrigation development and poverty reduction effectiveness have a coupling relationship. On the other hand, the development of irrigation technologies means an increase in agricultural production costs. In particular, the development of water-saving irrigation technologies improves economic benefits while also increasing agricultural production costs, thereby adding pressure to poverty reduction work; thus, the two also have a constraining relationship. To achieve a win-win situation—ensuring the goals of poverty reduction effectiveness while also realizing the sustainable development of water-saving irrigation technologies—it is necessary to maintain good coordination between the development of water-saving irrigation technologies and poverty reduction effectiveness.

As an important indicator for measuring interrelationships among multiple systems and the degree of coordinated development, coupling coordination degree is often used to analyze the coupled and coordinated relationship between two systems, and has been widely applied in fields such as ecology[16−17], environment[18−19], economy[20−21], and society[22−23]. In studies on coupling coordination involving the two major systems of water resources and poverty, Gou Kaige et al.[24] used methods such as the analytic hierarchy process, entropy method, system coupling coordination degree model, and spatial Durbin panel data model to investigate rural water resour-

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the spatiotemporal distribution characteristics and influencing factors of the coupling coordination degree between water-resource poverty and economic poverty. Zhou Kai et al.[25], taking county-level administrative units in Shaanxi Province as the basic research units, used a coupling model, correlation coefficients, and causality tests to conduct comprehensive measurements of water poverty and economic poverty and to analyze their coupling relationship. Wang Shuhe et al.[26], based on panel data from nine provinces in the Yellow River Basin, used a coupling coordination degree model and grey relational analysis to analyze the spatiotemporal evolution characteristics and mutual influence of the coupling coordination degree between water poverty and high-quality economic development in the Yellow River Basin. Wang et al.[27] used an improved coupling coordination degree model and a geographic detector to evaluate the spatiotemporal coupling of water–energy–food and poverty in the Yellow River Basin and its influencing factors. The above studies focus on analyzing, from a macro perspective, the aggravating or mitigating effects of water-resource scarcity or overuse on poverty, clarifying the spatiotemporal coupling coordination relationship between water resources and poverty, and providing a theoretical basis and policy support for the development of water-saving irrigation technologies and the planning of poverty-reduction goals. The application of water-saving irrigation technologies is a key component of water-resource management and the implementation of poverty-alleviation policies; the practical effects it generates drive policy optimization, thereby forming a virtuous cycle of coordinated development. However, there is currently a lack of research on the relationship between water-saving irrigation technologies and poverty-reduction performance, making it difficult to provide a basis for further optimizing and improving the implementation effects of water-resource management and poverty-reduction policies.

Against this background, this study selects data from 2018–2023 and takes the 12 states and 1 autonomous republic of Uzbekistan as the research units. It constructs an evaluation index system for the development level of water-saving irrigation and an evaluation index system for poverty-reduction performance, and uses a comprehensive evaluation model, coupling degree model, and coupling coordination degree model to study the spatiotemporal coupling coordination relationship between the development level of water-saving irrigation and poverty-reduction performance in each state. The research results can be used to delineate coupling coordination zones for water-saving irrigation development levels and poverty-reduction performance, identify abnormal uncoordinated regions, detect problems in the processes of water-saving irrigation development and poverty reduction, clarify the regions where the development of water-saving irrigation in Uzbekistan requires priority intervention, avoid “disconnection” between water-saving irrigation development planning and poverty-reduction goals, improve the adaptability between the development level of water-saving irrigation and poverty-reduction goals, and provide a decision-making basis for formulating water-saving irrigation technology development plans and achieving poverty-reduction goals.

1 Data and Methods

1.1 Overview of the Study Area

The Republic of Uzbekistan, hereinafter referred to as Uzbekistan, is a traditional agricultural country located in the arid inland region of Central Asia. It borders Kazakhstan to the north and northeast, is connected to Kyrgyzstan and Tajikistan to the east and southeast, neighbors Turkmenistan to the west, and borders Afghanistan to the south. Its land area is 4.49×10^5 km^2. The east is mountainous, while the central and western parts consist of plains, basins, and deserts, accounting for about two-thirds of the national territory. Uzbekistan is divided into 1 autonomous republic, 12 states, and 1 municipality directly under the central government (Fig. 1). Uzbekistan has an arid climate: annual precipitation is 80-200 mm in the plains and 600-800 mm in the mountains, and the aridity index is as high as 0.65[28]. The main domestic rivers are the Amu Darya, Syr Darya, and Zarafshan River. Of Uzbekistan' s total available water resources, only about 10% originate within the country, while about 90% come from transboundary water sources[28]. Agricultural production depends almost entirely on irrigation, and its water use accounts for 90% of the country' s total consumption; however, agricultural irrigation water-use efficiency remains at a relatively low level[29]. Agriculture supports the livelihoods of about 60% of rural areas nationwide, thereby affecting improvements in poverty-reduction performance.

Note: The base map was prepared using the standard map of the Ministry of Natural Resources; approval number GS(2020)4393. The boundaries of the base map were not modified. The same below.

Fig. 1 Schematic diagram of Uzbekistan

1.2 Data Sources

This paper takes the 12 states and 1 autonomous republic of Uzbekistan from 2018 to 2023 as the research objects. Data related to the development level of water-saving irrigation and poverty-reduction performance mainly come from the *Statistical Yearbook of Uzbekistan* for 2018-2023; some data come from the Uzbekistan Open Data Portal, the World Bank, and the Food and Agriculture Organization of the United Nations (FAO). DEM data are from the GDEMV3 30 m-resolution digital elevation data of the Geospatial Data Cloud. Qualitative indicator data were assigned values through expert scoring. A small number of missing data were replaced using linear interpolation.

1.3 Construction of Evaluation Index Systems for the Development Level of Water-Saving Irrigation and Poverty-Reduction Performance

1.3.1 Evaluation index system for the development level of water-saving irrigation

The development level of water-saving irrigation is mainly reflected in engineering level, agronomic water-saving level, management level, and water-saving benefits[30]. The selection of evaluation indicators is closely related to the study area, development characteristics, and the scale of the region. Water-saving irrigation in Uzbekistan is still at an early stage of development; engineering water saving and management water saving are the development priorities, while agronomic water saving has developed relatively slowly and lacks

lacking relevant data. Therefore, this study does not include that component in the evaluation indicator system. Based on the principles of scientific validity, completeness, hierarchy, and data availability, and in light of the level of water-saving irrigation technology in the study area, this study draws on relevant research [31-32] to construct an indicator system for the development level of water-saving irrigation in Uzbekistan (Table 1).

1.3.2 Evaluation Indicator System for Poverty Reduction Performance

There are many indicators for evaluating poverty. Many scholars mainly refer to the multidimensional poverty index calculation method of the United Nations Development Programme (UNDP), measuring poverty levels from the three dimensions of "living standards, education, and health" [33-34], or expanding and transforming these dimensions and their corresponding indicators according to research needs. This paper adopts this method and, based on principles such as data availability, combines the poverty situation in the study area and draws on relevant studies [35-36] to construct an indicator system for poverty reduction performance in Uzbekistan (Table 2).

1.4 Research Methods

1.4.1 Weights of Evaluation Indicators

Methods for determining the weights of evaluation indicators include expert scoring, the analytic hierarchy process, and the entropy weight method. To better evaluate the influence of different indicators, this study adopts a method combining subjective and objective weighting—expert scoring and the entropy weight method—to determine the weights [37-38]. The weights obtained by the expert scoring method and the entropy weight method are combined, and the formula for calculating the combined weight is as follows:

$$w = 0.5w_1 + 0.5w_2 \tag{1}$$

where w is the combined weight; w_1 is the expert-scoring weight; and w_2 is the entropy-method weight.

1.4.2 Comprehensive Evaluation Model

Based on the standardized values and weights of the evaluation indicators, the weighted-sum model is used to calculate the comprehensive score U_1 for the development level of water-saving irrigation and the comprehensive score U_2 for poverty reduction performance. The calculation formulas for U_1 and U_2 are as follows:

$$U_i = \sum_{j=1}^{n} w_j \times y_{ij} \tag{2}$$

where U_i is the comprehensive evaluation score of the i-th system; y_{ij} is the normalized value of the j-th indicator of the i-th system; and w_j is the weight of the j-th indicator.

1.4.3 Coupling Degree Model

The coupling coordination degree model is a tool for analyzing the coordinated development level of things and includes two parts: coupling degree and coupling coordination degree. Among them, the coupling degree mainly describes the mutual interaction between systems or elements.

Table 1. Evaluation Indicators for the Development Level of Water-Saving Irrigation

Tab. 1 Evaluation index of the level of water-saving irrigation

Target layer	Criterion layer	Indicator layer	Indicator meaning	Attribute	Weight
Development level of water-saving irrigation	Engineering level	Agricultural water-use efficiency A1	Agricultural GDP / agricultural water use	+	0.0804
Development level of water-saving irrigation	Engineering level	Level of water conservancy development A2	Effective irrigated area / cultivated land area	+	0.0548

Target layer	Criterion layer	Indicator layer	Indicator meaning	Attribute	Weight
Development level of water-saving irrigation	Engineering level	Development scale coefficient of water-saving irrigation A3	Water-saving irrigation area / effective irrigated area	+	0.1184
Development level of water-saving irrigation	Engineering level	Canal seepage-control rate A4	Length of seepage-control canals / total canal length	+	0.0759
Development level of water-saving irrigation	Engineering level	Utilization rate of water conveyance pipelines A5	Length of commissioned water-supply pipeline network / water conveyance distance	+	0.0855
Development level of water-saving irrigation	Management level	Farmers' awareness of water conservation A6	Farmers' cognition of and willingness to implement water-saving technologies and policies	+	0.0498

Target layer	Criterion layer	Indicator layer	Indicator meaning	Attribute	Weight
Development level of water-saving irrigation	Management level	Professional competence of irrigation managers A7	Professional skills, training level, and management ability of irrigation managers	+	0.0825
Development level of water-saving irrigation	Management level	Soundness of water-saving incentive mechanisms A8	Degree of improvement of incentive measures such as water-saving reward policies and tiered water-price mechanisms	+	0.0745
Development level of water-saving irrigation	Management level	Informatization level of irrigation districts A9	Application level of informatization technologies such as digital monitoring and automated control in irrigation districts	+	0.0664

Target layer	Criterion layer	Indicator layer	Indicator meaning	Attribute	Weight
Development level of water-saving irrigation	Management level	Rationality of water price A10	Whether the water price reflects cost, scarcity, and users' affordability	+	0.0728
Development level of water-saving irrigation	Water-saving benefits	Water consumption per 10,000 yuan of GDP A11	Water consumption / gross domestic product	−	0.0483
Development level of water-saving irrigation	Water-saving benefits	Water productivity of typical crops A12	Crop yield / water consumption during the growth period	+	0.0549
Development level of water-saving irrigation	Water-saving benefits	Labor productivity A13	Typical crop yield / population	+	0.0531
Development level of water-saving irrigation	Water-saving benefits	Per capita regional agricultural gross product A14	Agricultural GDP / population	+	0.0402

Target layer	Criterion layer	Indicator layer	Indicator meaning	Attribute	Weight
Development level of water-saving irrigation	Water-saving benefits	Water-body purification efficiency A15	(Pollutants in sewage before purification — pollutants in sewage after purification) / pollutants in sewage before purification	+	0.0424

Note: "+" indicates that the indicator value is positively correlated with the development level of water-saving irrigation; "—" indicates that the indicator value is negatively correlated with the development level of water-saving irrigation.

Table 2. Evaluation Indicators for Poverty Reduction Performance

Tab. 2 Evaluation index of poverty reduction

Target layer	Criterion layer	Indicator layer	Indicator meaning	Attribute	Weight
Poverty reduction performance indicators	Breadth of poverty reduction	Poverty incidence B1	Poor population / total population	—	0.2020
Poverty reduction performance indicators	Depth of poverty reduction	Per capita household disposable income B2	(Total household income — expenditure) / permanent household population	+	0.1615

Target layer	Criterion layer	Indicator layer	Indicator meaning	Attribute	Weight
Poverty reduction performance indicators	Depth of poverty reduction	Per capita household consumption expenditure B3	Total household consumption expenditure / number of permanent household residents	+	0.1753
Poverty reduction performance indicators	Depth of poverty reduction	Living standard of residents B4	Engel coefficient of residents	−	0.1225
Poverty reduction performance indicators	Depth of poverty reduction	Children's school-enrollment rate B5	(Number enrolled in school / population aged 3–6) × 100%	+	0.2104
Poverty reduction performance indicators	Depth of poverty reduction	Child mortality rate B6	(Number of deaths of children under age 5 in the same year / total live births) × 1000	−	0.1283

Note: "+" indicates that the indicator value is positively correlated with poverty reduction performance; "−" indicates that the indicator value is negatively correlated with poverty reduction performance.

the extent of action and mutual influence, representing the correlation effect.

However, the coupling degree cannot indicate whether systems mutually promote each other at a high level or mutually constrain each other at a low level[39]. Therefore, a coupling coordination degree model is further introduced to characterize the equilibrium state and coordination degree of water-saving irrigation and poverty reduction effectiveness under coordination constraints and regulations, with emphasis on analyzing their integrated development and benign interactive relationship.

The formula for calculating the coupling degree[40] is as follows:

$$C = 2 \times \sqrt{\frac{U_1 \times U_2}{(U_1 + U_2)^2}} \tag{3}$$

where: C is the coupling degree value between the development level of water-saving irrigation and poverty reduction effectiveness. A larger C value indicates a higher coupling degree between systems, and vice versa; its value range is $[0, 1]$. U_1 and U_2 are the scores for the development level of water-saving irrigation and poverty reduction effectiveness, respectively, with values in $[0, 1]$.

1.4.4 Coupling coordination degree model On the basis of establishing the coupling degree model, the coupling coordination degree model is further determined to analyze the coupling coordination degree between the development level of water-saving irrigation and poverty reduction effectiveness in Uzbekistan. The calculation formulas are as follows:

$$T = \sqrt{\alpha \times U_1 + \beta \times U_2} \tag{4}$$

$$D = \sqrt{C \times T} \tag{5}$$

where: D is the coupling coordination degree; T is the coordination degree index between the development level of water-saving irrigation and poverty reduction effectiveness, used to express the contribution of the development of the two aspects to their coordination degree. The larger its value, the better the effect of coordinated industrial development; otherwise, the worse. α and β are undetermined parameters, representing the importance of the two subsystems—water-saving irrigation development level and poverty reduction effectiveness—in the operation of the overall system. This paper considers water-saving irrigation development and poverty reduction to be equally important to regional development; therefore, α and β are both assigned a value of 0.5. Referring to previous scholars' evaluation indicators for coupling coordination degree[41−42], the coupling coordination degree is divided into seven levels. On this basis, combined with the score difference between the two systems, the coupling coordinated development types are divided into 21 categories (Table 3).

Tab. 3 Coupling coordination criteria and classification criteria

Value range	Coordination level	Difference between the two systems	Stage
$(0, 0.3]$	I Severe imbalance	$0 \leq \lvert U_1 - U_2 \rvert \leq 0.1$	I 1 Severe imbalance synchronous type
$(0, 0.3]$	I Severe imbalance	$U_1 - U_2 > 0.1$	I 2 Severe imbalance poverty-reduction lagging type
$(0, 0.3]$	I Severe imbalance	$U_1 - U_2 < -0.1$	I 3 Severe imbalance water-saving lagging type
$(0.3, 0.4]$	II Moderate imbalance	$0 \leq \lvert U_1 - U_2 \rvert \leq 0.1$	II 1 Moderate imbalance synchronous type
$(0.3, 0.4]$	II Moderate imbalance	$U_1 - U_2 > 0.1$	II 2 Moderate imbalance poverty-reduction lagging type
$(0.3, 0.4]$	II Moderate imbalance	$U_1 - U_2 < -0.1$	II 3 Moderate imbalance water-saving lagging type
$(0.4, 0.5]$	III Near imbalance	$0 \leq \lvert U_1 - U_2 \rvert \leq 0.1$	III 1 Near imbalance synchronous type
$(0.4, 0.5]$	III Near imbalance	$U_1 - U_2 > 0.1$	III 2 Near imbalance poverty-reduction lagging type
$(0.4, 0.5]$	III Near imbalance	$U_1 - U_2 < -0.1$	III 3 Near imbalance water-saving lagging type
$(0.5, 0.6]$	IV Barely coordinated	$0 \leq \lvert U_1 - U_2 \rvert \leq 0.1$	IV 1 Barely coordinated synchronous type

Value range	Coordination level	Difference between the two systems	Stage
$(0.5, 0.6]$	IV Barely coordinated	$U_1 - U_2 > 0.1$	IV 2 Barely coordinated poverty-reduction lagging
$(0.5, 0.6]$	IV Barely coordinated	$U_1 - U_2 < -0.1$	IV 3 Barely coordinated water-saving lagging type
$(0.6, 0.7]$	V Primary coordination	$0 \leq \lvert U_1 - U_2 \rvert \leq 0.1$	V 1 Primary coordination synchronous type
$(0.6, 0.7]$	V Primary coordination	$U_1 - U_2 > 0.1$	V 2 Primary coordination poverty-reduction lagging type
$(0.6, 0.7]$	V Primary coordination	$U_1 - U_2 < -0.1$	V 3 Primary coordination water-saving lagging type
$(0.7, 0.8]$	VI Intermediate coordination	$0 \leq \lvert U_1 - U_2 \rvert \leq 0.1$	VI 1 Intermediate coordination synchronous type
$(0.7, 0.8]$	VI Intermediate coordination	$U_1 - U_2 > 0.1$	VI 2 Intermediate coordination poverty-reduction lagging type
$(0.7, 0.8]$	VI Intermediate coordination	$U_1 - U_2 < -0.1$	VI 3 Intermediate coordination water-saving lagging type
$(0.8, 1]$	VII High-quality coordination	$0 \leq \lvert U_1 - U_2 \rvert \leq 0.1$	VII 1 High-quality coordination synchronous type

Value range	Coordination level	Difference between the two systems	Stage
$(0.8, 1]$	VII High-quality coordination	$U_1 - U_2 > 0.1$	VII 2 High-quality coordination poverty-reduction lagging type
$(0.8, 1]$	VII High-quality coordination	$U_1 - U_2 < -0.1$	VII 3 High-quality coordination water-saving lagging type

2 Results and Analysis

2.1 Spatiotemporal pattern characteristics of the water-saving irrigation development level and poverty reduction effectiveness

Due to space limitations, this paper only presents the spatiotemporal patterns of the water-saving irrigation development level and poverty reduction effectiveness in Uzbekistan in 2018, 2020, and 2022, and presents the scores of evaluation indicators at the criterion level for 2018-2023 in the time series. This does not affect the accuracy or scientific validity of the conclusions.

2.1.1 Spatiotemporal pattern of the water-saving irrigation development level The water-saving irrigation level in Uzbekistan is divided into three types: high level ($0.48 \sim 0.68$), medium level ($0.28 \sim 0.48$), and low level ($0.08 \sim 0.28$). As can be seen from Figure 2, the regional differences in the development of water-saving irrigation in Uzbekistan are very obvious, showing the characteristics of higher levels in the central and eastern regions and lower levels in the western region; that is, a spatial differentiation pattern of low level centered on the Republic of Karakalpakstan and high level centered on Jizzakh Region. In terms of temporal development, from 2018 to 2022, the water-saving irrigation development level of all regions showed an upward trend. Jizzakh Region consistently maintained the highest score for water-saving irrigation development; the Republic of Karakalpakstan consistently had the lowest score. The reason why Jizzakh Region has consistently maintained the highest score for water-saving irrigation development is that the canal seepage-control rate in this region is the highest, losses during agricultural irrigation water conveyance are relatively small, water-resource utilization efficiency is high, and stable yields also reduce costs, providing a foundation for the region's high labor productivity and high per capita gross agricultural output value. By contrast, the reason why the Republic of Karakalpakstan has consistently maintained the lowest score for water-saving irrigation development is that annual precipitation in this region is less than 100 mm; it is the driest area in Uzbekistan and faces problems such as water-resource shortages and ecological degradation caused by the Aral Sea crisis. Strong evaporation leads to large losses during irrigation in this region, the highest water consumption per 10,000 yuan of GDP, and the lowest crop water productivity.

According to Figure 3, the comprehensive level of water-saving irrigation development showed a significant growth trend from 2018 to 2023. The engineering level, management level,

Fig. 2 Spatial patterns of the level of water-saving irrigation in Uzbekistan from 2018 to 2022

Visible labels: **(a) 2018**, **(b) 2020**, **(c) 2022**; legend: **level of water-saving irrigation** with class values **0.08, 0.28, 0.48, 0.68**; scale: **0–500 km**; north arrow.

Fig. 3 Score of indicators for evaluating the level of water-saving irrigation in Uzbekistan from 2018 to 2023

Visible chart labels: engineering level; management level; water-saving benefit; comprehensive level. Left axis: indicator score. Right axis: comprehensive-level score. Horizontal axis: year, 2018–2023.

The indicator scores for water-saving benefits rank as follows: management level > engineering level > water-saving benefit. Among them, the trend in the management level is consistent with the overall development trend of water-saving irrigation, and it is an important factor affecting the rate at which the level of water-saving irrigation development increases. The engineering level and water-saving benefits have improved slowly overall, becoming the main factors constraining the comprehensive level of water-saving irrigation development.

2.1.2 Spatiotemporal pattern of poverty reduction effectiveness

The level of poverty reduction effectiveness in Uzbekistan was divided into three types: high poverty reduction effectiveness ($0.6 \sim 0.8$), medium poverty reduction effectiveness ($0.5 \sim 0.6$), and low poverty reduction effectiveness ($0.3 \sim 0.5$). As can be seen from Fig. 4, over time, from 2018 to 2022, except for the Republic of Karakalpakstan, which showed a fluctuating upward trend, the poverty reduction effectiveness scores of all other regions showed a steady upward trend. Andijan Region had the largest increase in score, at 61.0%, while Syrdarya Region had the smallest increase, at 27.5%. Spatially, the distribution is characterized by higher poverty reduction effectiveness in the central and eastern regions and lower poverty reduction effectiveness in the southern and western regions; that is, a spatial pattern of low poverty reduction effectiveness centered on Syrdarya and high poverty reduction effectiveness centered on Navoi Region. During 2018–2022, the poverty rate in Navoi Region remained the lowest, while the low child mortality rate and stable enrollment rate indicate that the decline in poverty in Navoi Region provided dual safeguards for health and education, making its poverty reduction effectiveness significant. By contrast, Syrdarya Region has consistently had the highest poverty rate, and its relatively high Engel coefficient has further compressed the space for development-oriented expenditures. Overall, poverty reduction effectiveness in all regions of Uzbekistan has improved, but the problem of uneven poverty reduction improvement among regions remains prominent. If support for areas such as Syrdarya Region is not strengthened, the gap in poverty reduction effectiveness among regions may further widen, which would be unfavorable to overall poverty reduction effectiveness and coordinated regional development.

As can be seen from Fig. 5, the comprehensive level of poverty reduction effectiveness fluctuated from 2018 to 2023 and did not follow a single sustained trajectory. The trend first rose, then declined, and then continued to rise to the highest value of poverty reduction effectiveness. Specifically, from 2018 to 2019, the scores for the breadth and depth of poverty reduction both increased, and the comprehensive level of poverty reduction effectiveness also rose. From 2019 to 2020, the breadth of poverty reduction declined slightly, and the increase in the comprehensive level began to slow. From 2020 to 2021, the breadth of poverty reduction dropped sharply, and the comprehensive level also began to decline. From 2021 to 2023, the breadth and depth of poverty reduction began to rise steadily,

Fig. 4 Spatial patterns of poverty reduction effectiveness in Uzbekistan from 2018 to 2022

Visible labels: **(a) 2018**, **(b) 2020**, **(c) 2022**; legend: **poverty reduction level** with class values **0.3, 0.5, 0.6, 0.8**; scale: **0–500 km**; north arrow.

Fig. 5 internal labels: Legend—poverty-reduction breadth; poverty-reduction depth; comprehensive level. Left axis—indicator score. Right axis—comprehensive-level score. Horizontal axis—year.

Fig. 5 Score of indicators for evaluating the effectiveness of poverty reduction in Uzbekistan from 2018 to 2023

The score for the comprehensive level of poverty-reduction effectiveness also rose steadily. This trend indicates that the breadth of poverty reduction is a key factor influencing the trajectory of the comprehensive level of poverty-reduction effectiveness.

2.2 Coupling and Coordination Characteristics Between the Development Level of Water-Saving Irrigation and Poverty-Reduction Effectiveness

The coupling degree between the development level of water-saving irrigation and poverty-reduction effectiveness in Uzbekistan was divided into three types: high coupling (0.97–1.00), medium coupling (0.87–0.97), and low coupling (0.80–

0.87). As can be seen from Fig. 6, from 2018 to 2022 the coupling relationship between the development level of water-saving irrigation and poverty-reduction effectiveness in Uzbekistan was evident, and the overall coupling degree strengthened in a fluctuating manner. In combination with Fig. 2 and Fig. 4, the minimum and maximum development levels of the two systems both show gaps; the poverty-reduction level is higher than the water-saving irrigation level, and the national poverty-reduction effectiveness developed faster overall than water-saving irrigation. From 2018 to 2020, there were three coupling-degree intervals—high, medium, and low—whereas from 2020 to 2022 there were only two intervals, high and medium. This indicates that the gap between the two systems in the study area as a whole was narrowing, ultimately forming a spatial pattern in which the western and central regions were at medium coupling, while the eastern and southern regions were at high coupling.

According to the criteria for identifying and classifying coupled coordination degree (Table 3), the coupled coordination degree between the development level of water-saving irrigation and poverty-reduction effectiveness in Uzbekistan was divided into three types: primary coordination (0.6–0.7), intermediate coordination (0.7-0.8), and high-quality coordination (0.8–1.0). As shown in Fig. 7, temporally, the study area as a whole exhibited an increasing trend in coupled coordination degree, with most regions developing from intermediate coordination to high-quality coordination. Spatially, from 2018 to 2020 the study area showed a distribution pattern in which coordination was higher in the central and eastern regions and lower in the northwestern region; the Republic of Karakalpakstan was still at the primary coordination stage, while more than half of the regions had entered the intermediate coordination stage. From 2020 to 2022, only the Republic of Karakalpakstan and Syrdarya Region were at intermediate coordination, while all other regions were at high-quality coordination. During 2018-2022, the greatest increase in coordination degree occurred in the Republic of Karakalpakstan; the increase was the most

Fig. 6 internal labels: (a) 2018; (b) 2020; (c) 2022. Legend—coupling degree: 0.8, 0.87, 0.97, 1. Scale—0–500 km. North arrow—N.

Fig. 6 Spatial pattern of coupling between the development level of water-saving irrigation and poverty-reduction effectiveness in Uzbekistan from 2018 to 2022

Fig. 7 internal labels: (a) 2018; (b) 2020; (c) 2022. Legend—coupled coordination degree: 0.6, 0.7, 0.8, 0.9. Scale—0–500 km. North arrow—N.

Fig. 7 Distribution of coupled coordination between water-saving irrigation and poverty reduction in Uzbekistan from 2018 to 2022

Table 4 Evolution of coupling types of water-saving irrigation and poverty reduction from 2018 to 2023

Region	2018	2019	2020	2021	2022	2023
Andijan Region	VI3	VI3	VII1	VII1	VII1	VII1
Bukhara Region	VI3	VI3	VI3	VI3	VII3	VII3
Fergana Region	VI3	VII3	VII3	VII1	VII1	VII1
Jizzakh Region	VII1	VII1	VII1	VII2	VII2	VII2
Karakalpakstan	V3	V3	V3	VI3	VI3	VI3
Kashkadarya Region	VII1	VI1	VII1	VII3	VII1	VII1
Khorezm Region	V3	VI3	VI3	VI3	VII3	VII3
Namangan Region	VI3	VI3	VII1	VII1	VII3	VII1
Navoi Region	VI3	VI3	VII3	VII3	VII3	VII3
Samarkand Region	VII1	VI3	VII3	VII1	VII1	VII1
Syrdarya Region	V3	VI3	VI1	VI1	VI1	VII3
Surkhandarya Region	VI3	VI3	VI3	VII1	VII1	VII1
Tashkent Region	VI3	VI1	VII1	VII1	VII1	VII1

Note: peach = primary imbalance; blue = intermediate coordination; green = high-quality coordination.

the smallest was Fergana Region.

2.3 Evolution of coupling-coordination relationship types between the development level of water-saving irrigation and poverty-reduction performance

On the basis of the classification criteria for coupling-coordination types between the development level of water-saving irrigation and poverty-reduction performance (Table 3), the coupling-coordination degree between the development level of water-saving irrigation and poverty-reduction performance in the 13 regions of Uzbekistan from 2018 to 2023 was divided into 3 major categories and 9 subcategories (Table 4), showing the coupling-coordination level type and stage to which each region belonged.

(1) In terms of changes in the major categories, the coupling-coordination relationship types of all regions underwent type upgrading; Khorezm Region and Syrdarya Region even achieved three-stage upgrading.

(2) In terms of the evolution of the pattern of major categories, different coupling-coordination types existed in every year, indicating that type differences persisted throughout. Beginning in 2020, most study regions entered the stage of high-quality coordination; by 2023, only the Republic of Karakalpakstan remained in the stage of intermediate coordination.

(3) In terms of the evolutionary paths of subtypes, in the early stage the study regions showed a clear feature of lagging water-saving irrigation, which became an important reason for lowering the coupling-coordination level. Since 2020, with improvement in the development level of water-saving

irrigation, the number of synchronous-type regions began to increase, and Jizzakh Region became the only region with a poverty-reduction-lag type.

3 Discussion

In recent years, scholars have begun to focus on using geographical methods to study, from a macro perspective, the coupling-coordination relationships among water resources, the ecological environment, and economic development [43]. From the perspective of technological development, this study focuses on the coupling-coordination relationship between the development level of water-saving irrigation and poverty reduction in Uzbekistan. By examining the coupling-coordination degree between the two, it identifies problems in the processes of water-saving irrigation development and poverty reduction in Uzbekistan, thereby helping the government and relevant institutions formulate more precise and effective policies for water-resource planning, the promotion of water-saving irrigation technologies, and poverty-reduction work. Unlike previous studies that examined the unidirectional influence of irrigation and poverty reduction, this paper, from the perspective of coupling coordination, reveals the asynchronous evolutionary characteristics in which the development of water-saving irrigation was relatively lagging in the early stage while poverty-reduction performance improved rapidly. The study finds that, in the later stage, approximately half of the regions still belonged to the coordination type of "lagging water saving." This result confirms the common problem in agricultural development in arid areas whereby improvements in water-resource utilization efficiency and improvements in people' s livelihoods are prone to imbalance [44–45].

3.1 Analysis of the coupling-coordination relationship between the development level of water-saving irrigation and poverty-reduction performance in Uzbekistan

The evolutionary differences in the coupling-coordination relationship between the development level of water-saving irrigation and poverty-reduction performance in Uzbekistan are, in essence, the result of the combined effects of natural endowments, agricultural production patterns, and the conversion of water-saving benefits. The regions that were the first to achieve the "coordinated synchronous type" were mostly located in the central and eastern parts of the country, such as Andijan Region and Fergana Region. Relying on the topographic advantages along the margin of the Tianshan Mountains and the water-source support of the Zeravshan River, these regions have more favorable conditions for irrigation-infrastructure construction; engineering indicators such as canal seepage-control rate and the utilization rate of water-conveyance pipelines are significantly higher than the national average. In addition, agricultural intensification in these regions is prominent, and cash crops such as fruits, vegetables, and cotton account for a high proportion of planting. The promotion of water-saving irrigation technologies can rapidly increase crop yields and farmers' incomes, forming a positive linkage between technological upgrading and poverty reduction. This is consistent with the conclusion proposed by Hagos et al. [13] that the coupling of irrigation technology with the cultivation of high-value-added crops can strengthen poverty-reduction effects. The regions of the "water-saving-lag type" are mostly located in the central and western parts of the country, such as Bukhara Region, Karakalpakstan, Khorezm Region, and Navoi Region. In particular, the Autonomous Republic of Karakalpakstan had the longest duration of lagging water saving. The country' s annual precipitation is less than 100 mm, water-resource shortages and soil salinization problems are pronounced, irrigation water-conveyance losses remain high, and water consumption per 10,000 yuan of GDP ranks among the highest nationwide, making the demand for water saving especially urgent. However, poor farmers in this region have difficulty bearing the upfront investment, and their willingness to use irrigation technologies and their operational capacity are significantly lower than those in the central regions. At the same time, the economic-benefit conversion cycle of water-saving irrigation technology in this region is long and its added value is low, making it difficult to rapidly support increases in farmers' incomes. This weakens the coupling linkage effect between water-saving irrigation development and poverty-reduction performance, confirming Abdullaev et al.' s [4] research judgment that agriculture in western Uzbekistan is constrained simultaneously by water-resource shortages and ecological constraints. The regions of the "poverty-reduction-lag type" are mainly concentrated in Jizzakh Region, which may be related to the

It is related to the distribution of benefits from water-saving irrigation technology in the region and access to the technology. From the perspective of benefit distribution, Jizzakh Region, as a leading area in water-saving level, ranks first among all regions in canal seepage-control rate, utilization rate of water-conveyance pipelines, and the degree of informatization of irrigation districts. Meanwhile, 61.5% of the region' s irrigated farmland is operated mainly by large growers and agricultural enterprises[46]. Relying on their advantages in capital and scale, such actors have become the principal beneficiaries of the output-increasing gains generated by water-saving irrigation technology. By contrast, poor farmers mostly participate in production through small-scale contracting or wage labor, and can obtain only basic land rent or labor remuneration; their share of the gains from increased output is small, creating a marked mismatch in which technological yield increases do not translate into income growth.

3.2 Evaluation indicators for the coupled coordination between water-saving irrigation development and poverty-reduction performance, and evaluation results of the impact of weights

Indicators and weights can reflect the mechanism of interactions between systems, and also provide a scientific basis for managers to identify problems, predict trends, and formulate regulatory policies. Therefore, when evaluating the coupled coordination of the two systems, evaluation indicators are often used to characterize the internal state and development level of a system, while weights reflect the importance of the indicators[47]; both affect the evaluation results. Static indicators reflect status, whereas dynamic indicators reflect the level of development. However, owing to data availability, limitations of the model itself, and the objectives of the study, most studies use static indicators to conduct coupled-coordination evaluation[48]. This study also uses static indicators to construct the evaluation indicator system. To a certain extent, this enables cross-year comparison and reflects interannual differences, but problems remain: the evaluation indicators are incomplete and cannot fully reflect system characteristics. For example, the evaluation of poverty-reduction performance lacks dynamic evaluation indicators such as the average annual decline in the incidence of poverty, the rate of return to poverty, the multidimensional poverty improvement index, and income stability. The evaluation indicators for the development level of water-saving irrigation lack dynamic evaluation indicators such as the annual growth rate of the effective utilization coefficient of irrigation water, the coverage rate of water-saving irrigation technologies, and the renewal and renovation rate of irrigation facilities. In addition, the evaluation indicators for the development level of water-saving irrigation lack indicators that reflect agronomic level and ecological-environmental benefits; all of these are aspects that need continuous improvement. Indicator weights affect the logic for determining the coupled coordination relationship between the two systems and the explanatory power of the results. Subjective weighting methods depend on researchers' empirical judgments of indicator importance. Objective weighting methods rely entirely on the degree of data dispersion for weighting and ignore the theoretical significance of indicators in real systems, which may lead to misjudgments of coupling relationships dominated by short-term benefits[49–50]. This study adopts a hybrid weighting method, taking into account the advantages of both approaches. However, there is no unified standard for setting the weight-integration coefficient; even slight adjustments to the coefficient may cause the coupled coordination grade to jump across intervals, directly affecting the classification of the co-evolution stages of the two systems and thereby interfering with the basis for formulating differentiated regulation policies. Therefore, it is necessary to further clarify the coupling mechanism and quantitative relationship between water-saving irrigation development and poverty-reduction performance, so as to provide a sufficient basis for determining indicators and weights.

4 Conclusion

By constructing an indicator system for the development level of water-saving irrigation and poverty-reduction performance, this paper uses methods such as the coupling degree model and the coupled coordination degree model to explore the coupled coordination characteristics of the development level of water-saving irrigation and poverty-reduction performance in Uzbekistan from 2018 to 2023. The main conclusions are as follows:

(1) From 2018 to 2022, the development level of water-saving irrigation in var-

ious regions of Uzbekistan showed an upward trend. Management level is an important factor affecting the speed of increase in the development level of water-saving irrigation, while engineering level and water-saving benefits are the main factors constraining the comprehensive level of water-saving irrigation development. Poverty-reduction performance also showed an upward trend, and the breadth of poverty reduction is a key factor influencing the trajectory of the comprehensive level of poverty-reduction performance.

(2) From 2018 to 2022, the coupling degree between the development level of water-saving irrigation and poverty-reduction performance in various regions of Uzbekistan generally showed a fluctuating upward trend. The improvement rate of water-saving irrigation lagged behind the development level of poverty reduction, and the development of the two systems was not synchronized. The increase in coupling degree was relatively pronounced in the Republic of Karakalpakstan and Navoi Region.

(3) From 2018 to 2022, the coupled coordination degree between the development level of water-saving irrigation and poverty-reduction performance in various regions of Uzbekistan showed an increasing trend. Overall, it shifted from primary coordination–water-saving-lag type to high-quality coordination–synchronous type. By 2023, all regions had moved beyond primary coordination, indicating that the system was escaping its former low-level, adverse interaction pattern. Although the development of the two systems was not coordinated in the early stage, the overall trend in the later stage was toward higher-quality and more coordinated future development.

(4) Water-saving lag is the key obstacle to improving the coupled coordination level in Uzbekistan' s regions. The core factors in the development of water-saving irrigation are the relatively slow progress of engineering construction and the conversion efficiency of water-saving benefits, which have failed to effectively support agricultural efficiency gains and increases in farmers' income. This reveals insufficient synergy between development policies in the promotion of water-saving technologies and poverty-reduction goals.

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Coupling and coordination relationship between water-saving irrigation level and poverty reduction in Uzbekistan

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Abstract: In Uzbekistan, this study explored the coupling and coordination relationship between water-saving irrigation’ s development level and poverty reduction’ s effectiveness. As research units, the study chose twelve states and one autonomous republic, selecting data from 2018 to 2023. To conduct the comprehensive study, researchers constructed an evaluation index system for water-saving irrigation' s development level and an evaluation index system for poverty reduction' s effectiveness; they adopted the comprehensive evaluation, coupling degree, and coupling coordination degree models of the coupling and coordination relationship' s effectiveness. Results show: (1) Water-saving irrigation' s development level in Uzbekistan' s various areas is characterized by the spatial distribution pattern of: higher in the central and eastern regions and lower in the western region, with an annual upward trend. Poverty reduction' s effectiveness is better in the eastern region and poorer in the southern and western regions, also with an upward trend. (2) In all areas, the coupling degree between water-saving irrigation' s development level and poverty reduction' s effectiveness fluctuates upward, forming a regional agglomeration pattern of medium coupling in the western and central regions and high coupling in the eastern and southern regions. (3) The coupling coordination degree between water-saving irrigation' s development level and poverty reduction' s effectiveness increases annually, with distribution of high coordination in the central and eastern regions and relatively low coordination in the western region. Finally, all areas except the Republic of Karakalpakstan and the Syrdarya Region have entered the high-quality coordination stage. (4) Water-saving lag is key in restricted improvement of the coupling coordination degree between water-saving irrigation' s development level and poverty reduction' s effectiveness.

Keywords: Uzbekistan; water-saving irrigation; poverty reduction; coupling and coordination

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