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Assessing Factors Driving the Change of Irrigation Water-Use Efficiency in China Based on Geographical Features

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Abstract: Changes in irrigation water-use efficiency are related closely to agricultural development. Clarifying the driving factors of irrigation water-use efficiency change at different agricultural development stages is beneficial for buffering the contradiction between the protection of water resources and massive agricultural water consumption. It also has theoretical and application value when it comes to elucidating the driving characteristics of spatial changes in irrigation water-use efficiency observed among the different provinces of China. This paper analyzes driving factors of irrigation water-use change based on a study of literature and a field survey. It selects 21 indices from five aspects of climatic change, resource endowment, economic situation, technological level, and management mode as the system of driving factors for irrigation water-use change. This article then uses statistical data on economic and social development in the 31 provinces of China in 2009, and applies the principal component analysis (PCA) method to extract the main driving factors affecting irrigation water-use efficiency change. After calculation of factor scores, clustering analysis is conducted on the 31 provinces to explore regional differences among the driving factors of irrigation water-use efficiency change. The results show that these can be attributed to the factors of agricultural economic development, water-saving irrigation technology, water resource endowment, and dissipation. The 31 provinces can be divided into five types: agricultural economy strong driving type; agricultural economy dominant type; industrial economy dominant type; agriculture strong development type; and coordinated driving type. In highly agricultural provinces, mature irrigation district management and water-saving measures influence the efficiency of irrigation water-use, making these strong positive driving factors. In highly industrial provinces, changes in irrigation water-use efficiency are mainly driven by economic development and structural adjustment, making these weak driving factors.

Keywords: irrigation water-use efficiency; principal component analysis; cluster analysis; driving factors; geographical features quantification

1. Introduction

Agricultural water use is an important form of Chinese water resource consumption and occupies a large proportion of total water consumption for economic development. However, inter-sector competition for water intensifies as society and economy develops, greatly increasing demand for industrial and domestic water, as well as demand for water for ecological remediation. This, therefore, restricts water usage for irrigation. The proportion of agricultural water-use among total water consumption decreased from 97.1% in early 1949 to about 69% in 2015, and may decrease to 60% in 2030 [1]. In other words, because China has to produce more grain for its large population, it will need to promote greater utilization of agricultural water resources, and agricultural water demand will continue to increase. The sustainable development of agriculture faces severe challenges [2], and water conservation is one of the key measures to ease the pressure of current agricultural water demand. In China, agricultural water use accounts for 63% of total water use [3], with irrigation water use accounting for more than 90% of agricultural water use [4]. Therefore, the first thing necessary for agricultural water-saving is the saving of water during irrigation. The extensive use of agricultural water in China makes the efficiency of irrigation water-use efficiency only about 0.5, while the world's advanced level has exceeded 0.7 [1]. This demonstrates that China's irrigation water-use efficiency has much room for improvement.

In summary, it is of great practical significance to analyze and evaluate irrigation water use in different areas scientifically, and to reveal the main driving factors of water-use efficiency change. To date, many scholars have carried out a thorough analysis of irrigation water-use efficiency change mechanism, and numerous studies have been conducted whose results can be aggregated into four main topics. First has been research on the main factors of screening and the driving forces of irrigation water efficiency change. Multiple expressions of irrigation water-use efficiency were summarized by Pereira, et al. [5], who considered the major factors of irrigation water-use efficiency to be: rainfall on crop growth, irrigation management and technical dimensions, agronomic changes in crop planting, crop adaptability to the environment, and the irrigation water efficiency amplitude. In Jing Xue's study [6] a distributed Soil–Water–Atmosphere–Plant World Food Studies model was used to simulate yield and water productivity (WP) from 2000–2010 in the Hetao Irrigation District, which considered that irrigation schedules and cropping structure could contribute to more sustainable food production in the district. By establishing a regression model of irrigation water and water price, irrigation area, per capita income of farmers and irrigation frequency, it was concluded that water price was the main factor affecting irrigation water-use efficiency in Maher O's paper [7]. The approach of the International Center for High Mediterranean Agronomic Studies–Agronomic Insitute of Montpellier (CIHEAM–IAM) was adopted to assess food security in Mediterranean by Zdruli et al. [8], and this method considered water issues together with those relative to other natural resources: land, climate (and climate change), biodiversity and energy. The factor of land use was added to the CIHEAM–IAM approach by others [9] (Ringler et al.). Based on economic theory, Qin Changhai [10] established a demand function model of agricultural water to study the relationship between agricultural water price and water consumption in the Ningxia region. A second topic has been irrigation water-use efficiency evaluation. Jingjing Gao et al. [11] investigated how the use of a water resources assessment model contributed to one of the first strategic environmental assessments (SEA) conducted for arid/semi-arid regions in China. A temporally and spatially simplified version of the WEAP (Water Evaluation and Planning System) model was then applied to assess the impact of the planned activities on local water resource systems such as irrigation efficiency, treatment, and the reuse of water. Yi Li et al. [12] considered that crop evapotranspiration (ET) was a key parameter in field irrigation scheduling, drought assessment, and climate change research. As such, this paper studied how ET responded after related climatic variables were linearly and non-linearly de-trended from 1961–2013 in the Xinjiang region. Li Haoxin [13] used principal component analysis (PCA) to extract the principal component factors, forming a new index system, so as to establish the PCA–Copula evaluation method. A third topic has been research on the scale effect of irrigation water efficiency. Administrators pay close attention to the water cycle process and the temporal and spatial scales, so the irrigation water-use efficiency calculation method changes according to various management objectives, resulting in a scale effect. Feng Baoqing [14] analyzed the change law of irrigation water-use efficiency in time and space, and used the distributed hydrological model to assess the Shijin irrigation water utilization coefficient threshold, which was the first attempt in China to use scale effect research. Using the soil and water assessment tool (SWAT), Hojat [15] selected Zarrineh River as a case study for evaluating actual irrigation management variables under different irrigation system conditions. Comprehensive calibration was carried out based on extensive hydrological and agricultural variables data. Tao [16] applied the Crop Environment Resource Synthesis (CERES) maize model to simulate the baseline and future climate scenarios of maize production according to the output of 20 climate scenarios (from the Intergovernmental Panel on Climate Change data distribution center panel), taking the changes in average monthly climate variables as the representative station median. A fourth topic has been the irrigation and cropping systems nexus. Drip irrigation and plastic-film mulch have been useful water-saving tools for irrigation in arid north-west China, and You-Liang Zhang et al. [17] studied the positive effect of radiative and thermal conditions on potato growth of the two most commonly used plastic-film mulches (transparent and black). After the field experiments, they found that the daily integral radiation in the black mulch treatment was greater than in the transparent mulch treatment, while the amplitude of soil heat flux in the BM (black mulch) treatment was lower than in the TM (transparent mulch) treatment. Land fragmentation was significantly associated with inefficiency of farm profit in India, according to Manjunatha et al. [18]. However, small farms were more intensive and may be more efficient in the use of inputs than large ones. Climate, cropping orientation, access to land property, and the type of political rule were major factors [18]. Sadras et al. thought innovation-driven development of agricultural water management and the irrigation system are the most important factors [19], and the output of cereals and legume grains under irrigation was steadily increasing and largely exceeded that obtained in rain-fed conditions. Chen et al. focused on research into the use of nitrogen fertilizers and controlled greenhouse gas emissions in cereal production in China [20].

The rich literature from this research effectively reveals the relationship between irrigation water-use efficiency change and different influencing factors. But there are still many aspects worth studying in the current situation. (1) There is no quantitative index system for irrigation water-use efficiency applicable to China. One of the reasons for this is that the contents of the terms for different irrigation water-use efficiency indicators are unclear, resulting in the outcome that many indicators are mixed under different conditions. A second reason is that while the theoretical framework is relatively clear for some indicators, many calculated elements are difficult or impossible to determine in practical applications. (2) The method based on input–output is the main way to evaluate irrigation water-use efficiency in the long term, but the input–output situation of irrigation actions are dependent upon region and time. Research conditions and scholars' considerations about specific research projects vary, so there are major disparities between their results. (3) Research on the driving mechanism of irrigation water-use efficiency changes is generally based on the independent administrative region in order to analyze the driving characteristics of the changes. The research pays less attention to the comparative study of regional differences. This research has not studied differences in the driving force of irrigation water-use efficiency changes and has also ignored the complexity and variability of the level of the scale-dependence [21]. In a word, the cited research does not provide a general conclusion about the characteristics of irrigation water efficiency changes at different stages of agricultural development. Based on data about driving factors collected from multiple perspectives and assessing the irrigation water use efficiencies from 31 provinces of China, the purpose of our study is to identify the distinct irrigation water-use types of Chinese provinces using cluster analysis. We then assess factors driving changes in irrigation water-use efficiency in accordance with spatial distribution characteristics observed among the various provinces. In addition, we provide policy suggestions for improving agricultural water management in specified types of provinces.

2. Materials and Methods

2.1. Irrigation Water-Use Efficiency Calculation at Provincial Scale

The following indicators are applied in irrigation water-use efficiency evaluation: degree of irrigation water consumption (the proportion of crop evapotranspiration to the amount of irrigation water in the field) [21,22]; effective irrigation water-use efficiency (the ratio of crop evapotranspiration to field net irrigation water) [23]; the water-use efficiency of crops is proposed as a new index of irrigation water-use efficiency [24]; Perry [25] proposes to use water consumption, water intake, water storage change, consumption and non-consumption ratio as indicators of irrigation efficiency.

Based on the Chinese research, water is absorbed and converted into foodstuffs through the processes of water supply and distribution, irrigation, crop absorption and mass transformation. The water distribution process and the irrigation process should take as much water as possible into fields and store it in the roots of crops. Therefore, the main consideration in these two processes is irrigation water-use efficiency, representing the water management performance of water distribution and irrigation. The crop absorption and mass transformation processes then apply to efficiently utilize the water in the soil for producing more food, and the main consideration of these two processes is water productivity. In order to evaluate the irrigation water-use efficiency in irrigated areas, the research in this paper relates mainly to the water distribution and irrigation processes, using the term of "irrigation water-use efficiency".

According to rural water conservancy terminologies in China, the irrigation water-use efficiency can be expressed as the ratio of the amount of water available for absorption by crops to the total amount of water introduced by a canal head. "The total amount of water" is used, regardless of the amount of water that may be consumed for other purposes and the water loss in the canal system. "The amount of water available for the crops" in fields refers to the increase in soil moisture content after one irrigation. Through an investigation of the basic database of irrigation areas in China, this paper obtained the irrigation water-use efficiency of each irrigated area. Moreover, irrigation water-use efficiencies of the 31 provinces in China were figured out by employing the weighted area algorithm.

2.2. Driving Factors of Irrigation Water-Use Efficiency Change

The irrigation water-use efficiency is influenced by many factors, such as natural conditions, climate change, irrigation technology, management level, and capital input. On the basis of the statistical data for the years of 1997–2014, driving factors for the irrigation water-use efficiency have been identified. The influencing factors are collected by the method of combining insights in the literature and theoretical analysis. An index system and the meaning of each index are shown in Table 1.

Table 1. Explanation of irrigation water-use efficiency change driving factors.

Index	Explanation of Indices
Annual rainfall (mm)	The direct or indirect effects of natural precipitation on irrigation water-use efficiency.
Annual average temperature (°C)	Impacts of the climate on regional irrigation water use.
Precipitation frequency (%)	Determining the rainfall distribution, which is the input to water resources.
Drought index	Quantifying the drought risk due to meteorological, socio-economic and technological changes.
Ratio of agricultural population of total population	Representing the agricultural labor force in total population.
Cultivated land area (10^3 ha)	A direct relationship between the cultivated land area and the utilization of irrigation water.
Per capita cultivated land area (ha)	Based on the index of cultivated land area, it has the function of characterizing population and resources.
Local water resources (10^8 m^3)	Indicating the differences in water resource endowments between regions.
Per capita income of farmers (yuan)	Comparable conversion of the consumption price index of rural residents.

Table 1. *Cont.*

Index	Explanation of Indices
Per capita water consumption (m^3)	Reflecting the ability to obtain water resources and the allocation of water resources.
Per capita GDP (yuan)	Reflecting the economic development of the region, and affecting the government's attention and input to water conservation measures.
Ratio of first industrial output of GDP (%)	Explaining the contribution of agricultural development to local economic development.
Ratio of paddy rice of total planting area (%)	The difference of irrigation water-use efficiency caused by various regional grain planting structures.
Ratio of crops of total sown area (%)	Irrigation water-use efficiency change caused by regional crop area.
Grain yield (10^4 t)	Macroscopically stating the development degree of regional agricultural economy.
Ratio of technological expenditure of financial cost (%)	Characterization of the industrialization process of water-saving irrigation equipment.
Water-saving irrigation area (ha)	Area of the channel anti-seepage, low-pressure pipe irrigation, sprinkler irrigation, and micro-irrigation.
Irrigated area over 1000 ha	Characterizing the size of large irrigation areas.
Effective irrigation area (ha)	Characterization of the effective use of irrigation water.
Ratio of agricultural expenditure to financial cost (%)	Characterization of government investment in water conservation.
Agricultural water price (yuan)	Water price is an effective factor to stimulate water conservation, indicating that government price controls will influence the water-saving consciousness of farmers.

2.3. Indicators Selection and Data Collection

There are 21 indicators in Table 1, but we end up with an index system comprising 18 indicators because the data of "Annual average temperature", "Ratio of paddy rice of total planting area", and "Ratio of crops of total sown area" are not accessible. These 18 indicators are shown in Table 2, forming a data matrix X.

$$X = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1p} \\ x_{21} & x_{22} & \cdots & x_{2p} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1} & x_{n2} & \cdots & x_{np} \end{pmatrix} \tag{1}$$

In matrix X, n represents the number of samples (31 provinces) and p represents the number of driving factors (18 indicators), where each of the n rows represents the data of one province's 18 indicators, and each of the p columns gives the data of one indicator in 31 provinces.

In order to analyze the driving factors of the irrigation water efficiency change, we collected the related statistics of the selected indicators in China's 31 provinces in 2009 from the China Statistical Yearbook, Water Resources Bulletin, Provincial Statistical Yearbook, Provincial Socio-economic Development Bulletin and Government Work Report. (The differences of irrigation water use efficiencies among China's provinces in 2009 were significant, which was in line with the purpose of this study). Research for this paper involved many primitive indicators, and in order to reduce their complexity, principal component analysis (PCA) was used to synthesize the driving factors into fewer indices.

The analysis methods are as follows. (1) Based on $x^*_{ij} = \frac{x_{ij} - \overline{x_j}}{\sqrt{var(x_j)}}$, $i = 1, 2, \ldots, n; j = 1, 2, \ldots, p$, the original data is standardized. Where $\overline{x_j}$ and $\sqrt{var(x_j)}$ are the mean and standard deviation of the variable j respectively, and n represents the number of samples (31 provinces) and p represents the number of driving factors (18 indicators) in 2009; (2) According to the Kaiser–Meyer–Olkin (KMO) test statistic, Bartlett's spherical chi-square statistical value and significance level, the feasibility of the factor analysis of the original variables is confirmed; (3) To confirm the factor variables and factors' quantity, and to use the rotation method to make the factor variables interpretable, as well as to require the factor variables to basically cover the total information of 18 indicators; (4) To calculate the factor variable score for each sample and derive the load of the principal factor on each variable.

2.4. Cluster Analysis

Cluster analysis is the task of grouping a set of objects in such a way that objects in the same group (called a cluster) are more similar (in some sense or another) to each other than to those in other groups (clusters) [26]. It is a principal task of exploratory data mining, and a common technique in statistical data analysis. Ward's clustering method is an alternative approach. Basically, the Ward cluster analysis is an analysis of a variance problem, instead of using distance metrics or measures of association. This method involves an agglomerative clustering algorithm. Ward's method starts out with n clusters of size 1 and continues until all the observations are included into one cluster. This method is most appropriate for quantitative variables, and not binary variables [27].

Let Y_{knp} denote the value for variable p in observation n belonging to cluster k. The following definitions are significant for Ward clustering method [27]:

(1) Error sum of squares: $ESS = \sum_k \sum_n \sum_p \left| Y_{knp} - \overline{y_{k\cdot p}} \right|^2$, here the individual observations for each variable are compared against the cluster means for that variable. When the error sum of squares is small, the data are close to their cluster means.

(2) Total sum of squares: $TSS = \sum_k \sum_n \sum_p \left| Y_{knp} - \overline{y_{\cdot\cdot p}} \right|^2$, here the individual observations for each variable are compared against the grand mean for that variable.

(3) R-Square: $r^2 = \frac{TSS - ESS}{TSS}$, this r^2 value is interpreted as the proportion of variation explained by a particular clustering of the observations.

All sample units are assumed to be in z clusters of size 1 in ward cluster analysis. In the first step of the algorithm, $z-1$ clusters are formed, one of size 2 and the remaining of size 1. The error sum of squares and r^2 values are then computed. The pair of sample units that yield the smallest error sum of squares (or the largest r^2 value) will form the first cluster. Then, in the second step of the algorithm, $z-2$ clusters are formed from that $z-1$ clusters defined in step 2. Again, the value of r^2 is maximized. Thus, at each step of the algorithm, clusters or observations are combined in such a way as to minimize the results of error from the squares or alternatively maximize the r^2 value. The algorithm stops when all sample units are combined into a single large cluster of size z.

In this paper, SPSS version 22.0 (SPSS Inc., Chicago, IL, USA, IBM, Armonk, NY, USA) was used for cluster analysis. Ward's clustering method was performed using an agglomerative (bottom up) approach and Ward's linkage. At each generation of clusters, samples were merged into larger clusters to minimize the within-cluster sum of squares or to maximize the between-cluster sum of squares. To compare differences between clusters, analysis of variance, Kruskal–Wallis, and chi-square tests were used for parametric continuous, non-parametric continuous, and categorical variables, respectively.

3. Driving Force and Mechanism of Irrigation Water-Use Efficiency Change

3.1. Driving Factors Analysis of Irrigation Water-Use Efficiency Change in 31 Provinces of China

PCA is one multiple statistical method for examining the correlation between multiple variables, revealing the internal structure between the variables. In this study, the statistical analysis software SPSS 22.0 was used for factor analysis, and a standardized processing of the data was conducted to eliminate the influences of different dimensions. PCA was then used to extract the common factor to be analyzed. The statistics of the KMO test of the selected index system reached 0.826 through calculation, and the Bartlett's spherical test chi-square statistic was 925.754. The significance level was less than 0.05. This means the factors were all suitable for factor analysis.

An eigenvalue greater than 1 was the standard for selecting common factors. To explain the meaning of the factor better, the variance maximization orthogonal rotation method was used to achieve maximum differences between the variance of the factors. Loads of the first five main factors on each variable are shown in Table 2, and eigenvalues and contributions of the main factors after rotation are shown in Table 3. The cumulative contribution rate of the first five common factors' eigenvalues reaches 84.737%, which indicates that the five main factors cover almost all the information of 18 indicators.

Table 2. Loadings of the first five principal factors on each variable.

Index	F_1	F_2	F_3	F_4	F_5
Annual rainfall X_1 (mm)	−0.305	−0.322	−0.199	−0.434	0.088
Precipitation frequency X_2 (%)	0.033	0.137	0.133	−0.507	0.044
Drought index X_3 (%)	0.291	0.318	0.750	−0.155	0.030
Agricultural population's ratio X_4 (%)	0.830	−0.324	−0.163	0.027	0.120
Cultivated land area X_5 (10^3 ha)	0.682	0.518	0.454	0.189	0.141
Per capita cultivated land area X_6 (ha)	0.722	0.112	0.122	0.008	−0.123
Local water resources $X_7/10^8$ (m^3)	0.268	−0.341	0.159	0.677	0.080
Per capita water consumption X_8 (m^3)	0.352	0.117	0.810	0.382	−0.024
Per capita income of farmers X_9 (yuan)	−0.863	0.373	0.175	−0.028	−0.069
Per capita GDP X_{10} (yuan)	−0.855	0.211	0.211	−0.074	−0.061
Ratio of first industrial output of GDP X_{11} (%)	0.810	−0.233	−0.128	0.161	0.041
Grain yield X_{12} (10^4 t)	0.497	0.618	−0.548	0.312	−0.210
Ratio of technological expenditure of financial cost X_{13} (%)	−0.855	0.515	0.233	0.163	0.478
Water-saving irrigation area X_{14} (ha)	0.500	0.811	0.034	−0.110	−0.088
Irrigated area over 1000 ha X_{15} (10^4 ha)	0.455	0.683	0.105	0.018	0.007
Effective irrigation area X_{16} (ha)	0.520	0.771	−0.313	0.191	0.017
Ratio of agricultural expenditure to financial cost X_{17} (%)	0.750	−0.587	0.051	−0.028	−0.069
Agricultural water price X_{18} (yuan)	−0.147	0.620	−0.303	0.329	−0.005

Table 3. Eigenvalues, contribution rate and cumulative contribution rate of main factors.

Main Factor	Eigen Value	Contribution Rate/%	Cumulative Contribution Rate/%
First factor (F_1)	6.801	34.660	34.660
Second factor (F_2)	4.408	22.715	57.375
Third factor (F_3)	2.640	13.662	71.037
Fourth factor (F_4)	1.677	7.789	78.826
Fifth factor (F_5)	1.384	5.911	84.737

In order to scientifically classify the characteristics of the driving factors of irrigation water-use efficiency changes in 31 provinces, and further analyze the mechanism of the driving force, the regression method was used to calculate the factor score of each province based on the five main factors extracted. Because the contribution rate reflected the importance of each factor, we took the contribution rate of each principal factor as the weighting coefficient. We then obtained each province's comprehensive evaluation score (S) by weighting calculation based on the five main factors' scores. In accordance with Table 3, the contribution rates of the five main factors are 34.660%, 22.715%, 13.662%, 7.789% and 5.911%, respectively. So the formula of S is:

$$S = 0.347F_1 + 0.227F_2 + 0.137F_3 + 0.078F_4 + 0.059F_5 \tag{2}$$

In the formula, S is the comprehensive score value obtained according to the importance of the five main factor scores. S comprehensively reflects the situation of the driving force of irrigation water-use efficiency changes in each province. The larger the S value, the greater the influence on the irrigation water-use efficiency changes. The comprehensive evaluation scores and rankings of 31 provinces in China are shown in Table 4.

Table 4. Factor scores, comprehensive evaluation scores and ranking of 31 provinces in China.

Province	F_1 First Factor		F_2 Second Factor		F_3 Third Factor		F_4 Fourth Factor		F_5 Fifth Factor		Comprehensive Factor	
	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking
Beijing	−2.1723	30	0.6362	9	1.0132	5	−0.1011	18	0.5922	10	−0.4184	27
Tianjin	−1.9655	29	0.7252	8	0.1078	11	−1.3125	27	0.767	7	−0.5449	30
Hebei	0.5317	8	1.2803	5	−0.8195	29	0.2204	14	0.7696	6	0.4188	4
Shanxi	−0.0503	21	−0.063	16	−0.3487	19	−1.7389	30	0.1053	13	−0.2196	23
Inner Mongolia	0.854	3	1.1257	6	0.3285	7	−0.6138	23	1.6977	2	0.644	3
Liaoning	−0.449	25	0.2978	11	−0.059	12	−0.3789	21	0.671	9	−0.079	16
Jilin	0.3328	14	−0.0315	15	−0.2841	16	−0.5339	22	1.0429	4	0.093	10
Heilongjiang	1.3213	2	1.3177	3	−0.2672	14	−0.0544	17	1.2429	3	0.7773	2
Shanghai	−2.5579	31	0.6199	10	1.2956	3	0.8065	8	−0.2956	20	−0.497	29
Jiangsu	−0.4259	24	1.3152	4	−0.3706	21	0.8562	6	−0.0144	17	0.1662	8
Zhejiang	−1.2752	28	0.2789	12	0.1366	9	0.4935	11	−0.6969	25	−0.3547	24
Anhui	0.4529	11	0.069	13	−0.6771	26	0.6534	10	−1.1124	29	0.0525	12
Fujian	−0.7834	26	−0.4407	21	0.1727	8	0.1366	16	−0.8112	27	−0.3806	26
Jiangxi	0.0615	20	−0.6943	26	−0.2394	13	0.902	5	−0.5045	23	−0.1223	20
Shandong	0.4362	12	1.608	2	−0.9906	30	0.8127	7	−0.2533	19	0.4143	5
Henan	0.7327	4	1.0042	7	−1.6874	31	0.1656	15	−0.4676	22	0.216	7
Hubei	0.3228	15	−0.1832	18	−0.3335	18	0.6873	9	−0.8132	28	0.0245	13
Hunan	0.2157	16	−0.4219	20	−0.5123	24	1.074	4	−0.617	24	−0.0415	14
Guangdong	−1.0226	27	−0.0159	14	0.1349	10	1.5664	2	−0.2483	18	−0.2118	22
Guangxi	0.4258	13	−0.9029	27	−0.3202	17	0.3767	12	−0.7268	26	−0.1171	19
Hainan	0.1215	18	−1.7476	30	−0.3487	20	−0.7059	24	−2.7121	31	−0.6388	31
Chongqing	−0.4084	23	−0.6154	23	−0.449	23	−1.0793	26	−0.3029	21	−0.4466	28
Sichuan	0.4777	10	−0.1063	17	−0.7318	28	1.4008	3	0.1007	14	0.1634	9
Guizhou	0.5049	9	−1.0088	28	−0.5342	25	−0.1848	20	0.7129	8	−0.091	18
Yunnan	0.6215	7	−0.6392	24	−0.6866	27	0.3319	13	0.7853	5	0.0577	11
Tibet	0.723	5	−2.6245	31	1.9192	2	2.0444	1	2.4033	1	0.2735	6
Shaanxi	0.0645	19	−0.2261	19	−0.3955	22	−0.7753	25	0.1779	12	−0.1359	21
Gansu	0.6474	6	−0.4864	22	−0.2745	15	−1.8361	31	0.0042	15	−0.0833	17
Qinghai	−0.162	22	−1.1663	29	0.3904	6	−1.4337	28	0.0018	16	−0.3784	25
Ningxia	0.1865	17	−0.6419	25	1.0281	4	−1.6078	29	0.3332	11	−0.051	15
Xinjiang	2.2382	1	1.7379	1	3.8029	1	−0.1719	19	−1.8314	30	1.511	1

3.2. Influence Analysis of Irrigation Water Efficiency Change Driving Force

In accordance with the results of factor analysis in Table 2, loadings of F_1 on variables of "Agricultural population's ratio" (0.830); "Per capita cultivated land area" (0.722); "Per capita income of farmers" (−0.863); "Per capita GDP" (−0.855); "Ratio of first industrial output of GDP" (0.810); "Ratio of technological expenditure of financial cost" (−0.855); and "Ratio of Agricultural expenditure of financial cost" (0.750) were dominant. All the mentioned variables above were related to agricultural economic development. Then, loadings of F_2 on variables of "Agricultural water price" (0.620); "Effective irrigation area" (0.771); "Irrigated area over 1000 ha" (0.683); "Water-saving irrigation area" (0.811); and "Grain yield" (0.618) were dominant. The corresponding variables of F_2 were relevant to the means of water-saving irrigation technology. In order to analyze the relationships between the main factors and irrigation water-use efficiency, the Pearson correlation coefficient was used to calculate the correlations between them, and the results were in good agreement with the facts. The correlation coefficient between irrigation water efficiency and the first principal factor was −0.420, and they were negatively correlated. The correlation coefficient between irrigation water efficiency and the second principal factor was 0.388, and they were positively correlated.

3.2.1. Impacts of Agricultural Economic Development on Irrigation Water-Use Efficiency

We theoretically assessed the impacts of agricultural economic development on irrigation water-use efficiency in four stages. In this way, the meaning of F_1 could be explained. (1) Agricultural-led economic development stage. In an early stage of economic development, agriculture was dominant and significant freshwater resources were put into agricultural production to sustain its development. However, the individual labor-dominated production mode limited the level of agricultural output, meaning that economic output could not match the investment. The irrigation water-use efficiency declined increasingly. (2) Industry-led economic development stage. When the focus of the national economy shifted from agriculture to industry, the demand for industrial water increased, and the distribution rate of irrigation water decreased. As such, water-saving planting structures and efficient irrigation methods were gradually adopted in agriculture to improve the efficiency of irrigation water use. (3) Industrial restructuring stage. In the developed stage of the economy, the optimization and upgrading of industrial structure brought an increased proportion of high-tech industry and a decrease in the proportion of manufacturing. Because of the large amount of agricultural land irrigation water use, most areas of our country still used methods of open channel diversion and broad irrigation, resulting in the low utilization efficiency of water resources. In such a way, the irrigation water-use efficiency declined in the early stage of industrial structure optimization. From the technical point of view, the development of advanced technology led to a shift in agricultural development from extensive to intensive mode, improving the unit water-use output rate, so the irrigation water-use efficiency rebounded rapidly after a short-term decline. (4) Sustainable development stage. With the development of technology and economy, people's willingness and ability to protect water resources were strengthened gradually, which can ensure that the irrigation water-use efficiency is maintained at a high level. At the same time, in order to achieve sustainable development, the interests of the water-use department shall be strengthened, and the irrigation water supply quantity and water efficiency threshold shall be determined reasonably. Ultimately, irrigation water-use efficiency would stabilize at a certain level.

3.2.2. Influence of Water-Saving Irrigation Technology on Irrigation Water-Use Efficiency

Through the development of agricultural mechanization and the adjustment of planting structures, water-saving irrigation technology plays a significant role in irrigation water efficiency change. The promotion of water-saving irrigation technology and the improvement of infrastructure, such as canal-seepage control, low-pressure pipe irrigation, sprinkler irrigation and micro-irrigation technology, can help to enhance the grain yield per unit area. In the era of the peasant economy (manual labour), continuous improvement in water-saving irrigation technology drove a gradual increase of agricultural investment cost. As the planting structure was still dominated by low-yield crops, this made the emergence of high-efficiency agriculture hysteretic and an increase in investment was not reflected in the economic return. In short, irrigation efficiency declined gradually. In the "leading growers" period, agricultural enterprises focused on mechanized production and were run properly, the irrigation structure was thus optimized, and agricultural output value was rising. At the same time, irrigation water efficiency started to improve. Finally, agriculture would enter the "efficient production era" with modern science and technology, and irrigation water-use efficiency would be maintained at a high level.

3.2.3. Effects of Water Resources Factor on Irrigation Water-Use Efficiency

The areas with much larger space for improving the irrigation water-use efficiency in China are water-rich, while those with limited water resources often have higher water efficiency. That is because areas with a shortage of water resources often distribute limited resources to industries for the most efficient use of resources. The experience of improving water-use efficiency in the areas with water resource shortages is to strengthen resource factor market construction and to promote the marketization of water-saving facilities. In this paper, consequently, the resource factors are stable in the long term, with small fluctuations, so this study accepts this just as the principal component with no in-depth discussion.

4. Regional Comparative Analysis of Driving Factors of Irrigation Water-Use Efficiency Change in China

In order to reflect regional differences in the driving factors of irrigation water-use efficiencies in 31 provinces in China, the five main factors' scores for the provinces, calculated according to Table 4, were used to conduct clustering analysis. The use of the Ward clustering method divided the driving mechanism situation of the irrigation water-use efficiency changes of 31 provinces into five categories (see Figure 1).

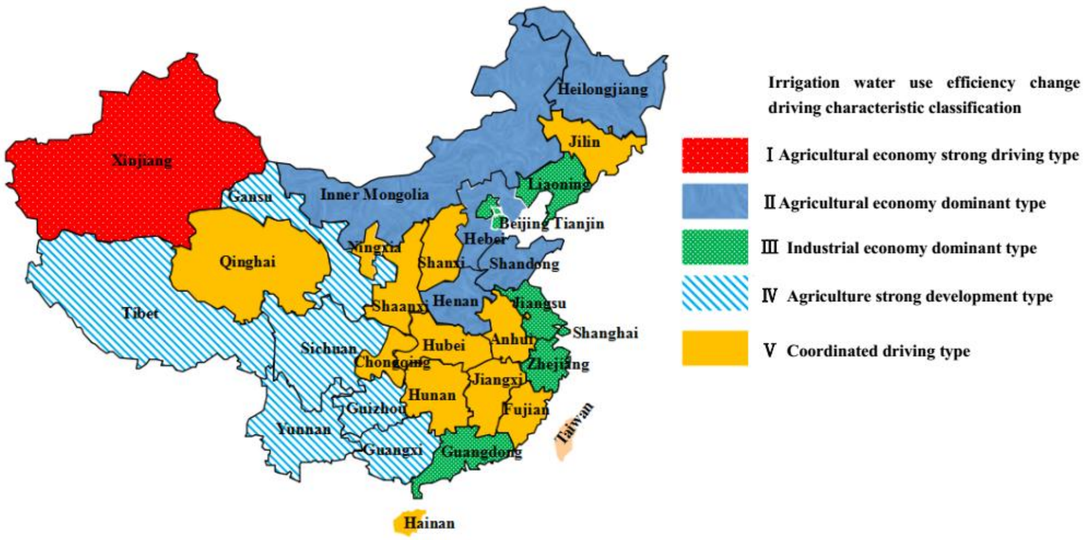

Figure 1. Irrigation water-use efficiency change driving characteristic classification for each province in China in 2009.

4.1. Agricultural Economy Strong Driving Type Provinces

It can be seen from Figure 1, the first category is "agricultural economy strong driving type", and the representative province is Xinjiang. As shown in Table 4, the first principal factor score of

Xinjiang is 2.2382 and the second principal factor score is 1.7379, ranking first in the 31 provinces. It is the province with the largest demand for agricultural economic development and water-saving irrigation. Xinjiang's fifth principal factor score is −1.8314, ranking 30th in all provinces, and this means that water is the most scarce resource in the arid region. Located in the hinterland of the Eurasian continent, Xinjiang is far from the sea and surrounded by mountains, which is the typical temperate continental arid climate. The average annual precipitation in Xinjiang is 190 mm, making it the area with the least precipitation in China. Its production structure is mainly dominated by agriculture and light industry. The development of the agricultural economy in Xinjiang is closely related to the per capita income level, which has resolved the problem of poverty to a certain extent. In turn, the accumulated capital, management and labor quality of the agricultural sector provides a solid foundation for the process of industrialization. Xinjiang's agriculture is a type of irrigated agriculture with irrigation water the main form of water use, accounting for 96% of total economic and social water consumption. However, because agricultural irrigation methods are extensive in many areas, the agricultural output efficiency is not ideal (the production per cubic meter of water is only 1.32 yuan, which is far below the national average of 7.6 yuan) with only 17.1% of the average contribution rate of GDP. Therefore, the key area for saving water in Xinjiang lies in agriculture, and the key to agricultural water-saving is the innovation of irrigation. In order to cope with the scarcity of water resources, Xinjiang farms and corporations have accelerated the innovation and promotion of efficient water-saving agricultural irrigation technology. After years of making these efforts, the application of efficient water-saving irrigation technologies such as drip irrigation under plastic film and sprinkling irrigation is at advanced world levels. Xinjiang's average annual water-saving in agriculture amounts to about 1.0 billion cubic meters, making it the largest high-efficient water-saving irrigation area in China. Xinjiang is the national water-saving technology demonstration area. The successful promotion of water-saving irrigation in Xinjiang shows that the selection of agricultural technology shall reflect factor-scarce inductive technology [28]. The scarce water resources guides the development of agricultural water-saving irrigation technology in Xinjiang (large-scale mechanization with high efficiency). In turn, the innovation of water saving irrigation technology has driven the improvement of irrigation water-use efficiency in Xinjiang, creating a virtuous circle. So for other arid areas, we can learn from Xinjiang in order to build an effective system for eliminating differences in technology choices and encouraging the application of efficient irrigation technology so as to establish a good water-saving irrigation technology selection mechanism.

4.2. Agricultural Economy Dominant Provinces

The second category is agricultural economy dominant provinces, including Henan, Shandong, Heilongjiang, Inner Mongolia and Hebei, whose average scores of the first and second main factors are 0.7752 and 1.2672, respectively. The agricultural economic development and water-saving irrigation techniques have a stronger driving force on irrigation water-use efficiency changes. These provinces, with long-term agricultural development advantages, are the main sources of grain in China. They make full use of the advantages of population and land after drawing on the advanced experience of economically developed cities. Taking the intensive development path, they vigorously promote science and technology investment in agricultural water-saving to achieve efficient agricultural production. As the country's first big agricultural province with the largest population, Henan is one of the provinces in northern China facing serious water shortages, and its per capita water resources occupancy volume is only 1/5 of the national per capita level, making the contradiction between supply and demand of water resources a prominent issue. Irrigation water consumption in Henan accounts for about 70% of its total water consumption, and 98% of the irrigated area is undergoing surface irrigation. Henan's irrigation mode is extensive, and agricultural water-use efficiency is low, with huge waste. Therefore, the promotion of irrigation water saving is the primary task in Henan when it comes to establishing modern agriculture. Agricultural income is the main economic revenue in Henan Province, but due to a lack of technical strength and funds, poor financing channels and low investment efficiency, rural modernization development is limited, resulting in the fact that agricultural resources cannot be utilized fully and water-saving technology cannot be promoted. For this reason, Henan Province takes vigorous action in making the adjustment to the development of water-saving agriculture. By the end of 2008, Henan Province had developed 17.665 million mu water-saving irrigation project areas, accounting for 24% of the effective irrigation area. Among them, the low-pressure pipeline has delivered water for 8.78 million mu lands, and canal-seepage prevention covers 7.06 million mu lands. The area of sprinkling irrigation is 1.67 million mu and the micro-irrigation area is 0.12 million mu. Henan has constructed four water-saving demonstration cities; 14 water-saving production key counties; 33 large-scale irrigation areas and water-saving renovation projects; 1227 state-level water efficient demonstration areas; 510 provincial water-saving irrigation demonstration areas; and 11 rainwater harvesting projects. The development of agricultural water-saving has played an important role in ensuring food security, enhancing drought resistance, improving the ecological environment and building modern agriculture [29].

4.3. Industrial Economy Dominant Provinces

The third category is the industrial economy dominant provinces, including Beijing, Tianjin, Shanghai, Guangdong, Jiangsu, Zhejiang, Liaoning, where economic development has reached the advanced level of industrialization. The average first two main factors' scores are -1.41 and 0.551, respectively, and the scores of F_1 of these seven provinces are all low-ranking. The average score of F_1 of the industrial economy-led provinces is the lowest in five categories, indicating that the impact of agricultural economic development on irrigation water efficiency is not significant and the driving force is weak. Overall, these provinces are small and the proportion of their agricultural population in the total population is small and in decline. Increased economic output depends mainly on secondary and tertiary industries, and the level of industrialization and urbanization is at the forefront within the whole country. The economic development of the provinces at the advanced stage of industrialization is full of vitality and they have higher requirements for resources and energy-use efficiency. Therefore, economic development can promote the adjustment of water-use structure and the generation of advanced technology, which has stronger driving effect on the promotion and update of water-saving irrigation technology. As the province with the highest level of industrialization in China, Jiangsu is also the most developed province for physical manufacturing. By 2012, Jiangsu's large enterprises numbered 43,383, ranking it first in the country. At the same time, the total industrial output value of Jiangsu was 12 trillion yuan (Chinese currency), ranking first in the country. According to Table 4, the scores of the first driving factor and the second driving factor for irrigation water-use efficiency change in Jiangsu rank 24th and 4th, respectively, reflecting a huge disparity. That is because Jiangsu always stresses rural reform and innovation and gave agricultural modernization an important role during the rapid economic development period. The industrial economy drives this new agricultural development, and farmers are encouraged to run large-scale farms. So the impact of traditional agriculture on irrigation water-use efficiency has gradually weakened. At the same time the scale of land management improves the incomes of farmers and, at the same time, continues to promote the progress of water-saving irrigation technology. For these kinds of province, industrial development has reached a high level, so they need to convert the economic benefits of developed industries into progress with water-saving irrigation techniques and the promotion of agricultural production.

4.4. Agriculture Strong Development Provinces

The fourth category is the strong agricultural development provinces, including Guangxi, Sichuan, Guizhou, Yunnan, Tibet, and Gansu. Average scores of the first and second principal factors for these six provinces are 0.5667 and -0.9614, respectively. The driving effect of the first and second main factors on irrigation water-use efficiency in this category is different from that of the third category, such that they represent two extremes. The effect of the development of the agricultural economy in the provinces of the fourth category is very strong on irrigation water efficiency changes, but they lack the support of water-saving irrigation technology. The provinces of the fourth category are superior to those of the third category in terms of agricultural population income, agricultural output or management. However, they are inferior to the third category in terms of water-saving technology investment, mechanization level, and urbanization rate. There is an obvious regional difference between the third and fourth categories. For instance, the agricultural output value of Sichuan has been in the top three in China for a long time, using 4.7% of the country's cultivated land to feed 6.6% of China's population. It also provides a large amount of food and non-staple food for Tibet annually. The degree of industrialization of Sichuan Province is lower than that of the third category of provinces, and its science and technology expenditure accounts for only 0.8% of fiscal expenditure, which is far below the national average. In a word, Sichuan's investment in science and technology and agricultural modernization need to be further strengthened. Under the security of a developed agricultural economy, it is suggested that these provinces in the fourth category should increase investment in water-saving science and technology in order to promote innovation in water-saving irrigation, and should promote water-saving modes in accordance with local situations to ease the pressure of demand for irrigation water.

4.5. Coordinated Driving Type Provinces

The fifth category is the coordinated driving type, including Fujian, Jiangxi, Hainan, Chongqing, Shaanxi, Qinghai, Ningxia, Shanxi, Jilin, Anhui, Hubei and Hunan. Excepting Hainan Province, the remaining 11 provinces belong to the medium or high-level industrialized provinces, with an industrialization rate over 40%. Their first principal factor's average score is 0.0295 and the second main factor's average score is -0.5136. The effect of these two factors on irrigation water efficiency changes is not intense. Although the level of industrial development in these provinces is among the highest in China, their agricultural economic development is still dominated by traditional decentralized farming practices that retain inefficient irrigation. These provinces are in the agricultural structural adjustment period, and the decentralized arable land and irrigation forms are not suitable for high-cost water-saving irrigation technology promotion, which is the main reason for the significant reduction in irrigation water-use efficiency. For these areas, it is suggested that the reform of agricultural industrialization is accelerated under the premise of ensuring the improvement in rural income and eco-environmental quality. Finally, we would promote agricultural modernization through the adjustment of market competition to realize innovation in and the development of water-saving irrigation technology.

It can be seen from Figure 1, the division of the driving effect category characteristics of irrigation water-use efficiency changes is closely related to the developmental stage of the agricultural economy:

(1) Under different economic development modes, the driving force of irrigation water-use efficiency change is significantly different. The provinces of the first category have a high degree of agricultural economy development, and the economic development of the third category is in a high level of industrialization. These two kinds of provinces promote water-saving irrigation technology using different development modes. It can be argued that the provinces with a high level agricultural economy improve irrigation water-use efficiency through strong agricultural development; and the irrigation water efficiency of provinces with high-level industrialization is mainly promoted by economic development and structural adjustment. In addition, the industrial economy's driving force for the development of water-saving irrigation technology is weak.

(2) Even in provinces with similar agricultural development levels, there are differences between the driving forces of irrigation water-use efficiency changes because of the effect of local conditions. For the provinces of the second and forth categories, although they are all in the stage of strong agricultural development, there is a natural distinction in terms of resource endowments, resulting in distinct farming methods. Therefore, the driving force characteristics of the irrigation water efficiency changes are not consistent. The cultivated land scale of the provinces of the second category is more extensive, with larger populations and a high proportion of modern

agriculture, their initial industries are growing faster, and their water-saving irrigation technology is advanced. The scale of the fourth category is larger, but the population is relatively small. The population of the traditional agriculture in fourth category is relatively high, and its development of water-saving irrigation technology is lagging behind.

5. Discussion

5.1. Implications for Similar Research

In this research, based on the status quo of irrigation water resources utilization in China, the country's irrigation water-use efficiency was investigated using the methods of PCA and cluster analysis. By determining driving factors in accordance with the literature and expert consultation, the factors of irrigation water-use efficiency of China were ascertained. Because the change of irrigation water-use efficiency was always driven by multiple factors that included natural conditions, climate, irrigation technology, management level and capital input, we screened the factors according to three rules: (1) Comprehensiveness. The driving factors must be related to the irrigation water-use efficiency closely. (2) Objectivity. The driving factors must be objective, so that the experts could judge the importance of the factors fairly. (3) Availability. We removed the factors whose data could not be collected. It is helpful to decrease the difficulties of such research.

Due to the fact that cluster analysis involved too many variables and the linear correlation issue among variables could not be eliminated, we introduced PCA to overcome the linear correlation issue and to reduce the number of the variables. As a result, a concise and feasible index system of irrigation water-use efficiency was obtained. The effectiveness of PCA for simplifying the index system has been proved by Jia et al. [30]. After PCA, all the data were transformed into "composite variables" in the cluster analysis in order to capture multiple questions in a ranked ordinal scale. As such, we could avoid binary (yes/no questions) variables; and the Ward cluster analysis method used in this paper could be most appropriate for quantitative variables. As a common technique for statistical data analysis, cluster analysis has been widely applied in many fields such as machine learning, pattern recognition, image analysis, information retrieval, bioinformatics, data compression, and computer graphics. But in the field of agricultural water resources utilization, this research represents a pioneering use of this method, which applied the cluster analysis in order to divide the 31 provinces of China into five categories. This may help Chinese governments better manage and allocate water resources, and provides a reference for similar research.

5.2. Future Research Directions

Many scholars are interested in the scale effect of the irrigation water efficiency. Scale effect refers to the correction necessary to apply to measurements made on a mathematical model in order to deduce corresponding values for the full-sized object. The application of the scale effect of irrigation water-use efficiency focuses on two aspects: the first aspect is related to the research of the water-use efficiency driving mechanism, water saving measures, and policies under various scales. The second aspect is to establish the linkages between different scales on the basis of available information. Based on the observed data, we studied the driving factors and the mechanism of irrigation water-use efficiency change at the provincial level. Then the spatial aggregation and variability of the system were analyzed from an objective point of view in this paper, which belongs to the first aspect of the scale effect research.

In the future, we plan to collect the data of irrigation water-use efficiencies for all irrigation districts distributed in the 31 provinces of China, forming a spatial data network. We will then calculate and analyze the temporal and spatial variation of the irrigation water-use efficiencies in the irrigated lands. Spatial autocorrelation analysis will be used to measure the spatial distribution characteristics of irrigation water-use efficiency and its impact on a provincial scale. Finally, according to the variability of irrigation water-use efficiency under different spatial patterns, we will try to reveal the law by which irrigation water-use efficiency in China has evolved.

5.3. Suggestions for Typical Provinces

Different types of province should implement appropriate water protection systems and policies, such as water-pricing policies. Appropriate high water prices curb waste effectively, and are suitable for the coordinated driving provinces. That is because the coordinated driving provinces have a higher level of industrial development and lower agricultural irrigation efficiency. The reasonable price policy can reduce water waste and improve the promotion of the water-saving irrigation mode. Farmers in the coordinated driving provinces are able to bear this economic burden caused by the inflation of water price.

The water-saving technology development factor has the strongest driving force on provinces such as Xinjiang, Henan, so it should be given priority when developing an efficient irrigation industry in these areas. For provinces in the advanced industrialization stage, such as Jiangsu, technological progress and the industrial upgrading are the main driving forces for water-use structure adjustment and the development of the water-saving irrigation technology, and so they should advocate industrial agriculture. Agriculturally strong provinces, such as Henan, have a better farming irrigation base, mature irrigation management experience, and high-quality human resources, so they should make use of state assistance policies and emerging technologies to transform traditional means of irrigation. They should also promote the application of advanced technology in the agricultural economy and optimize planting structures to form a suitable local efficient water-saving agriculture. Provinces such as Zhejiang have developed manufacturing bases, abundant funds, cutting-edge technologies, so they should rely on advanced technologies, large-scale managerial techniques, and self-innovation capacities to improve the overall efficiency of water use. What's more, they should pursue industrial development and the coordination of agricultural development, so as to ease the demand for irrigation water.

According to the driving characteristics of irrigation water efficiency in the third category, for the major grain-producing areas that are in the primary stage of industrialization, the driving force of water-saving irrigation mode is not significant. They should increase agricultural capital investment and improve levels of mechanization and water conservation, so as to improve the efficiency of crop output per unit of water resources. This is an important condition for ensuring the sustainable development of agriculture in these provinces.

6. Conclusions

The high demand for grain production and the serious shortage of water resources caused by a large population are the objective reality faced by China's agricultural development. These issues are practical problems that the Chinese government has been trying to solve. How to use limited irrigation water allocations to produce more food is a challenge faced by modern agriculture, which is also the focus of water-saving irrigation.

China's level of agricultural development has similarities across its regional structure. From the spatial point of view, overall agricultural economic strength is declining from northwest to northeast. In the continuous expanse from the border area to the inland, the level of agricultural development is improving and strengthening gradually. However, from the inland to the coastal areas, agriculture is in reverse development, agricultural development characteristics continue to weaken, and industrial development has become the main theme. By identifying distinct irrigation water-use types of Chinese provinces in this paper, we assess factors driving the change of irrigation water-use efficiency in accordance with spatial distribution characteristics.

Provinces in China can be divided into five types: agricultural economy strong driving type; agricultural economy dominant type; industrial economy dominant type; agriculture strong development type; and coordinated driving type. The types of irrigation water-use efficiency change driving force were influenced by the development stages of agriculture and water-saving irrigation technology. Agricultural high-level provinces have a strong positive driving effect on irrigation water-use efficiency. The industrial high-level provinces' irrigation water-use efficiency changes are mainly driven by effects of economic development and structural adjustment, which represents a weak driving effect. Provinces with similar agricultural development levels have distinct driving forces for irrigation water-use efficiency changes. There is a natural distinction in terms of resource endowments between the second category and the fourth category; therefore, each category should undertake measures to protect water resources based on its actual agricultural development situation.

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