Water resources carrying capacity model and prediction in Shandong Province based on social and economic factors

Modèle et prévision de la capacité de charge des ressources en eau dans la province du Shandong sur la base de facteurs socio-économiques complets

Juan Du[1], *JingTao* Wang [2], *Tao* Zhang[1], and *Shuang* Wang [3*]

[1] Water Supply Bureau of Shandong Yellow River Bureau, YRCC, 250013, Jinan, Shandong, China

[2] Shandong Provincial Party School Library and Culture Center, 250103, Jinan, Shandong, China

[3] Shandong Jianzhu University, 250101, Jinan, Shandong, China

Abstract. In this paper, considering the influence of economic, social, resource and environmental factors on water resources in Shandong Province, a fuzzy comprehensive evaluation model of water resources carrying capacity is established based on DPSIR index system, to evaluate the annual change of water resources carrying capacity in Shandong Province. Then the main influencing factors of total social water consumption are obtained by grey correlation, and the functional relation of total social water consumption is established on regression model. Finally, the development trend of social total water consumption is predicted by time series. The results show that: the development and utilization of water resources in Shandong Province has reached a very high level, water resources are in the stage of scarcity, and the shortage of water resources will continue to intensify in the future. Therefore, it is suggested that comprehensive water resources management policies should be formulated to save and use water resources intensively, in order to ensure the optimal allocation and scientific sustainable utilization of water resources in Shandong Province.

Résumé. Cet article examine l'impact des facteurs économiques, sociaux, de ressources et environnementaux de la province du Shandong sur la capacité de charge des ressources en eau. Premièrement, un modèle d'évaluation complet et flou de la capacité de charge des ressources en eau est établi sur la base du système d'indicateurs de la force motrice driving force-pression-situation-impact-réponse (DPSIR en anglais). Il analyse et

* Corresponding author: wangshuang@sdjzu.edu.cn

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évalue des changements interannuels de la capacité de charge des ressources en eau dans la province du Shandong. Ensuite, il applique la méthode de corrélation grise pour obtenir les principaux facteurs d'influence de la consommation sociale d'eau et établit la relation fonctionnelle de celle-ci sur la base du modèle de régression. Enfin, il utilise des séries chronologiques pour analyser et prédire la future tendance de développement de la capacité de charge des ressources en eau. Les résultats montrent que le développement et l'utilisation des ressources en eau dans la province du Shandong ont atteint un niveau très élevé. Les ressources en eau sont dans une phase de pénurie, pénuries qui continueront de s'intensifier dans le futur. Par conséquent, il est suggéré d'élaborer une politique de gestion intégrée des ressources en eau, d'optimiser continuellement la structure de l'allocation de ces dernières, d'économiser et d'utiliser intensivement les ressources en eau et d'assurer l'allocation scientifique et l'utilisation durable des ressources en eau dans la province du Shandong.

1 Introduction

Water resource is an essential natural resource for human survival and development, which is related to people's life, sustainable development of economy and society and benign cycle of ecological environment. In recent years, the deterioration of water environment and the shortage of water resources have seriously affected the security of water resources and restricted the sustainable development of economy and society. Through reasonable adjustment of water resources utilization strategy, it can increase the vitality of ecological environment and release the potential of regional economic and social development. In a specific historical development stage, water resources carrying capacity (WRCC) refers to the maximum supporting capacity of a region's social and economic development after reasonable optimal allocation of water resources. It is based on the predictable level of technological, economic and social development, on the principle of sustainable development, and on the condition of maintaining a virtuous cycle of development of the ecological environment. [1] In the past, the evaluation method of WRCC was single and static quantitative calculation analysis and qualitative comprehensive evaluation. In recent years, it has gradually developed into a dynamic evaluation model which integrates system dynamics method, conventional trend method, comprehensive evaluation method and multi-objective decision-making method [2-5] and other methods.

Shandong Province is a big economic and cultural province in eastern China. The shortage of water resources is not only the basic situation of Shandong Province, but also an important restricting factor of national economic and social development. By describing the relationship between water resources and social, economic, ecological and other factors, this paper constructs a fuzzy comprehensive evaluation model of WRCC, analyzes the influence of various factors on WRCC, establishes a regression model to analyze their functional relation, and finally predicts the total social water consumption in Shandong Province in the future. It is helpful for the rational development and utilization of water resources and the construction of ecological civilization in Shandong Province.

1 Study area

Shandong Province is located in the east coast of China and the lower reaches of the Yellow River. The average annual precipitation of the whole province is 680.5mm, and the average annual total water resources account for 1.1% of China's total water resources. The per capita (for each person) water resources are only 315 cubic meters, less than 1/6 of the national per capita, and 1/24 of the world's per capita. The total amount of water resources in Shandong Province is insufficient, and the distribution of water resources is unevenly in time and space, which has a great dependence on external water transfer, severely unmatched with the layout of productivity development. Especially in recent years, extreme climate has led to urban and rural water supply crisis; regional, seasonal and industrial water shortage problems occur frequently. The utilization of water resources in some areas has far exceeded the carrying capacity of local water resources environment, resulting in water ecological problems such as river cut-off, wetland shrinkage, groundwater overdraft, seawater intrusion and so on.

2 Data and methods

2.1 Data sources

The original data in this paper are mainly from the *Shandong Province water resources bulletin* of Water Resources Department of Shandong Province and the *Shandong Statistical Yearbook* of Shandong Provincial Statistic Bureau from 2007 to 2019. [6-7].

2.2 Evaluation model of WRCC

2.2.1 Index selection and model construction

The influencing factors of water ecosystem are complex. Natural, social, economic and cultural factors are not independent, but interrelated. In the evaluation of WRCC, it is necessary to build a system reflecting its characteristics first. At present, there are two ways to form the evaluation index system: one is based on the theory of sustainable development which divided the index system into interrelated and independent subsystems [8] with different levels and elements; the other is to take the fixed model as the framework of index selection, and the fixed model includes the Pressure-State-Response (PSR) Model [9] and the Driving force-state-response (DSR) Model [10] and the Driving force-Pressure-State- Impact -Response(DPSIR) Model [11]. Considering the relationship between water resources and various influencing factors and take into account both feasibility and scientific character of data sources, we divided the evaluation indexes into target layer, criterion layer and index layer, and established the evaluation index system by using the Driving force-Pressure -State-Impact- Response (DPSIR) Model.

DPSIR model is widely used in environmental system at present. In this model, the evaluation indexes are classified into five types: driving force, pressure, state, influence and response [12]. DPSIR model comprehensively reflects the impact of social, economic development and human behavior on the environment, as well as the reaction of human behavior and environmental conditions on social and economic development. Driving force index refers to the potential causes of water resources change, which is not only the main index of social and economic development, but also the internal driving force of water resources change, such as population index and economic development index. Pressure index refers to the pressure factors that directly affect the water ecological environment due to the destruction of human behavior, such as production and domestic water consumption. State system refers to the status of water resources under the current ecological pressure, including indexes of water resources development and utilization capacity, such as effective irrigation area. Impact system refers to the impact of water resources system state on population and socio-economic situation. Response system refers to the strategies and actions formulated by human beings to promote the balanced development of economy, society and ecological environment, such as the governance scheme for the development and utilization of water resources system.

Table 1. Evaluation index classification of water resources carrying capacity in Shandong Province.

Note: PC stands for positive correlation, NC stands for negative correlation.

Target layer	Criterion layer	Number	Index layer	Unit	V_1	V_2	V_3	Indicator type
Index system of WRCC	Driving force system	X_1	population density	person / km^2	<550	550-600	>600	NC
		X_2	per capita GDP	10^4 RMB	>6	4-6	<4	PC
		X_3	per capita water resources	m^3 / person	>300	200-300	<200	PC
		X_4	Total consumer price index	dimensionless	>700	600-700	<600	PC
	Pressure system	X_5	Eco-environmental water consumption rate	%	>3	2-3	<2	PC
		X_6	domestic water consumption per capita	L	>130	120-130	<120	PC
		X_7	water consumption per unit GDP	m^3 /10^4 RMB	<40	40-70	>70	NC
		X_8	total social water consumption	10^8 m^3	>220	210-220	<210	PC
	State system	X_9	effective irrigation area	10^6 HA	>5	4-5	<4	PC
		X_{10}	total water resources	10^8 m^3	>300	200-300	<200	PC
		X_{11}	precipitation	mm	>700	600-700	<600	PC
		X_{12}	water production modulus	10^4 m^3 / km^2	>20	10-20	<10	PC
	Impact system	X_{13}	urbanization rate	%	>50	40-50	<40	PC
		X_{14}	GDP growth rate	%	>1.1	1.0-1.1	<1.0	PC
		X_{15}	groundwater level funnel area	10^3 km^2	<12	12-13	>13	NC
	Respons e system	X_{16}	agricultural water quota	m^3 / 10^4 RMB	<60	60-100	>100	NC
		X_{17}	industrial water quota	m^3 / 10^4 RMB	<2	2-3	>3	NC
		X_{18}	industrial wastewater discharge rate	%	<35	35-45	>45	NC
		X_{19}	domestic sewage treatment rate	%	>90	80-90	<80	PC

In this paper, 19 representative indexes are selected to establish the comprehensive evaluation index system of WRCC in Shandong Province, and the reasonable grading standards and intervals are shown in Table 1. According to the positive and negative effects on the water ecological environment cycle, the selected indicators are divided into types of positive correlation and negative correlation. The larger the positive correlation index, the stronger the WRCC. The negative correlation index is just the opposite. The impact of each evaluation index on water resources carrying capacity is divided into three levels $\{V_1, V_2, V_3\}$. Wherein the level of V_1 indicates that the impact of the index on WRCC is at a good level, within which the WRCC is strong and the supply exceeds the demand; the level of V_3 indicates that the impact of the index on WRCC is extremely sensitive In this range, the WRCC is weak, and the supply cannot meet the demand, which easily leads to the shortage of water resources and restricts the social and economic development; V_2 level is a critical level between V_1 level and V_3 level, which indicates that the WRCC can effectively support the regional social and economic development, but the potential space is insufficient.

2.2.2 Fuzzy comprehensive evaluation model

Fuzzy comprehensive evaluation method is widely used in fuzzy mathematics [13-16]. Since the affairs that need to be evaluated are determined by many factors, we should not only evaluate each factor, but also make a comprehensive evaluation on the basis of considering all factors on the basis of individual evaluation of each factor, which is the comprehensive evaluation problem. The fuzzy comprehensive evaluation model can evaluate the WRCC under multiple levels and factors, and more comprehensively reflect the situation of regional water resources. The evaluation and calculation process is as follows:

(1) Establish the factor set $U = \{u_1, u_2, \ldots, u_n\}$ and $V = V = \{v_1, v_2, \ldots, v_m\}$. The evaluation criteria are shown in Table 1. The interval membership function and trapezoidal function are adopted to get rid of the jump between different levels.

(2) Then the membership matrix R is defined by Formula (1),

$$R=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{1}$$

where r_{ij} is the degree of membership of the value of u_i to V_j, r_{ij} is calculated by trapezoidal function described by step (1). The i-th line $R_i = \{r_{i1}, r_{i2}, \ldots, r_{im}\}$ in matrix R is the single factor evaluation result of each evaluation factor u_i in the i-th year.

(3) The weight value ω_j of single index j is determined according to the overall change range and dispersion degree of the data. Hence, the weight of each index is obtained from the entropy weight method [17].

(4) The result of fuzzy comprehensive evaluation is $D = \omega.R = \{D_1, D_2, \cdots, D_n\}$, wherein Di is the comprehensive evaluation value in the i-th year, the higher the value Di is, the better the water resources carrying capacity is. Di is obtained by the weighted average operator as follow:

$$D_i = \frac{\sum_{j=1}^{m} \omega_j r_{ij}}{\sum_{j=1}^{m} r_{ij}} (i = 1,2,\cdots n) \tag{2}$$

2.3 Analysis and prediction of total social water consumption

2.3.1 Correlation factors analysis based on grey correlation

As a method to measure the degree of correlation between factors, grey correlation analysis aims to seek the numerical relationship between subsystems (or factors) in the system through certain methods, which provides a quantitative measurement for the development and change of a system and is very suitable for dynamic process analysis.

It is assumed that the water demand in the past n years is the reference sequence $x_0=[x_0(1),x_0(2),\ldots,x_0(n)]$ and the factors influencing the water demand in the corresponding years are taken as the m sequences $x_i=[x_i(1),x_i(2),\ldots,x_i(n)]$, $i=1,2,\ldots,$ m. The correlation relationship between different influential factors and the total social water consumption are analyzed as follows:

(1) Firstly, the data of the sequence are dimensionless.

$$x_i^0(j)=\frac{x_i(j)}{x_i(1)},x_i(1)\neq 0 \tag{3}$$

(2) For the j-th year, the correlation coefficient between the comparison sequence Xi and the reference sequence X_0 is as follows:

$$\xi_i(j)=\frac{\min_i \min_j \Delta_i(j)+\rho \max_i \max_j \Delta_i(j)}{\Delta_i(j)+\rho \max_i \max_j \Delta_i(j)} \tag{4}$$

$$\Delta_i(j)=\left|x_0^0(j)-x_i^0(j)\right| \tag{5}$$

(3) Calculate the correlation degree:

$$\gamma_i=\frac{1}{n}\sum_{j=1}^{n}\xi_i(j) \tag{6}$$

According to the value of the comparison sequence, we can determine which factors are top infection on water demand.

2.3.2 Construction of social total water consumption model

The prediction function of water supply is established by multiple linear regression. The total social water consumption is taken as the target variable y, and the top n influential factors with high correlation are selected as the independent variables $\{x_0,x_1,x_2\cdots x_n\}$. The regression equation is $y=\beta_0+\beta_1x_1+\beta_2x_2+\cdots\beta_nx_n$, wherein the $\{\beta_0,\beta_1,\beta_2\cdots\beta_n\}$ are unknown regression parameter. Select m groups of data X to calculate the coefficient that makes the sum of squares of deviation minimum. To evaluate the predictive performances of the model, an evaluation index is utilized for the examination, wherein SSE is the sum of squares of regression and SSR is the sum of squares of residuals.

$$F=\frac{SSE/n}{SSR/(m-n-1)} \tag{7}$$

2.3.3 Development trend prediction

The time series analysis establishes a mathematical model which can reflect the dynamic dependency relationship in the time series according to the limited length of the operation records of the system, so as to forecast the future of the system. Generally, it is only applicable to short-term forecast. In this section, we use the time series model GM (1,1) to predict the development trend of total social water consumption. Firstly, the data from 2007 to 2017 are the original data to calculate the model parameters, then the predicted values are compared with the actual data of 2018 and 2019 to verify the effectiveness.

3 Result Analysis

3.1 Evaluation results of WRCC in Shandong Province

Table 2. Comprehensive score of WRCC in Shandong Province.

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
The score	0.54	0.49	0.40	0.48	0.49	0.40	0.45	0.41	0.44	0.46	0.46

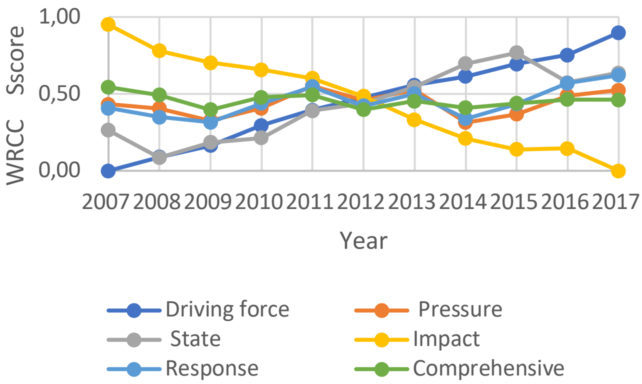

Fig. 1. Weight distribution of comprehensive evaluation indexes of WRCC.

Comprehensive evaluation index of WRCC is a comprehensive index to measure the degree of WRCC. The higher the evaluation index is, the better the situation of WRCC is, and the capacity of water resources carrying social, economic and ecological development is constantly improving. The evaluation results of WRCC in Shandong Province show that the score fluctuates in the small range of 0.40-0.54 from 2007 to 2017. The lowest comprehensive evaluation index was 0.40 in 2009 and 2012, followed by 0.41 in 2014, and the highest comprehensive evaluation index was 0.54 in 2007. The change trend of the evaluation index is basically consistent with the actual situation of water resources in Shandong Province, which shows that the evaluation index decreased significantly from 2007 to 2009, fluctuated significantly from 2010 to 2013, and began to rise slowly after 2014. The basic situation of water shortage in Shandong Province determines that the WRCC index is always in the stage of moderate shortage. With the economic and social development, the contradiction between supply and demand of water resources has become increasingly prominent. From 2007 to 2009, the WRCC index began to decline. By strictly protecting water resources and improving the utilization efficiency of water resources, the contradiction between supply and demand of water resources was alleviated to a certain extent, and the evaluation index of WRCC began to rise slowly (2014-2017) after the fluctuation stage (2010-2013).

For each subsystem, the contribution of influence subsystem is the largest, with an average value of 0.454, followed by response subsystem of 0.450, driving force subsystem of 0.449, pressure subsystem of 0.437 and state subsystem of 0.436, and scores of each subsystem is relatively balanced.

(1) Impact subsystem. The past decade is a period of rapid economic and social development in Shandong Province. The average annual GDP growth rate and population growth rate have been maintained at more than 6% and 5% respectively, and the urbanization level has increased from 36% to 61%, which has exerted great pressure on water resources. The over exploitation of groundwater has increased the area of groundwater funnel area and

exacerbated the contradiction between supply and demand of water resources. The comprehensive evaluation score of the influencing subsystem is decreasing year by year (see Figure 2), and the influence of the influencing subsystem is lower than that of other subsystems after 2012.

(2) Response and pressure subsystem. The contribution of response subsystem and pressure subsystem to the system is the second and the fourth respectively, and their exponential trend is similar to that of composite index. The response subsystem mainly represents the countermeasures taken in recent years to coordinate the development of society, economy and ecological environment. Among them, the industrial and agricultural water quota has been reduced by about 50% in the past ten years, the industrial wastewater discharge rate has been reduced by 42%, and the domestic sewage treatment rate has been increased to 95%. The pressure subsystem reflects the impact of human behavior on the natural environment. On the basis of ensuring the total amount of social water consumption and per capita daily domestic water consumption, the water consumption rate of ecological environment is increased from 1.46% to 5%, and the water consumption per unit GDP is reduced by 67%.

(3) Driving force and state subsystem. The contribution of driving force and state subsystem to the system is the third and the fifth respectively, and their exponential change trend increases year by year. The driving force system is the root cause of environmental change, and the state system is the state after the interaction of society, environment and human behavior. Shandong Province is in the critical period of accelerating the transformation and development. Through reasonable water resources management, the contradiction between supply and demand of water resources can be well handled, and the development of society, economy and environment can be coordinated. Therefore, the above two subsystems have a positive impact on WRCC.

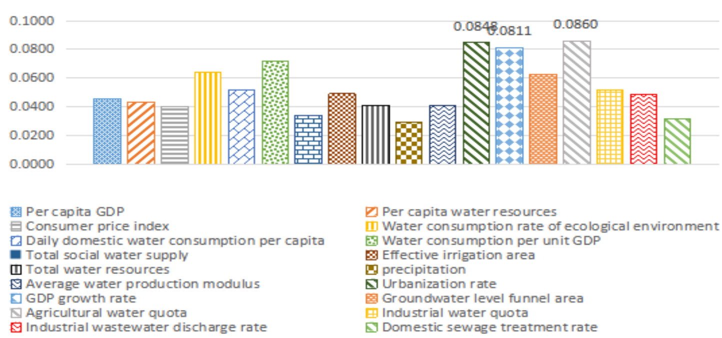

Fig. 2. Scores of the impact indices.

In terms of single factor, the top three contributing factors were agricultural water quota, urbanization rate and GDP growth rate (0.086, 0.0848 and 0.0811 respectively). As a major agricultural province, Shandong Province has made great efforts to change the agricultural irrigation mode and develop agricultural water-saving technology. and the saved water resources have played a greater social and ecological value. The urbanization rate has increased from 36.69% in 2007 to 61.18% in 2017, and the GDP growth rate has changed from 6% to 20%. The rapid development of urbanization and economy has brought new demand for water resources and adjusted the supply and demand pattern of water resources to a certain extent.

3.2 Trend prediction of total social water consumption in the future

Taking the total social water consumption as the reference sequence, the correlation degree between other indicators and the total social water consumption is calculated. It is found that among the other 18 indicators, the one with the largest correlation with total social water consumption is per capita water resources, per capita daily domestic water consumption, total amount of water resources, urbanization rate, water quota for agriculture and treatment rate of sanitary sewage. The above correlation factors were set as X_1, X_2, X_3, X_4, X_5 and X_6 respectively, and the total social water consumption of Shandong Province was taken as the dependent variable y. According to the original data from 2007 to 2017, the multiple linear regression model is obtained as follows:

$$Y = 202.7 + 0.24 \cdot X_1 + 0.04 \cdot X_2 - 0.23 \cdot X_3 - 0.5 \cdot X_4 - 0.03 \cdot X_5 + 0.4 X_6 \tag{18}$$

The correlation coefficient is about 0.99, f is about 56.4, which is far greater than 1, indicating that the regression effect is significant (see Figure 3).

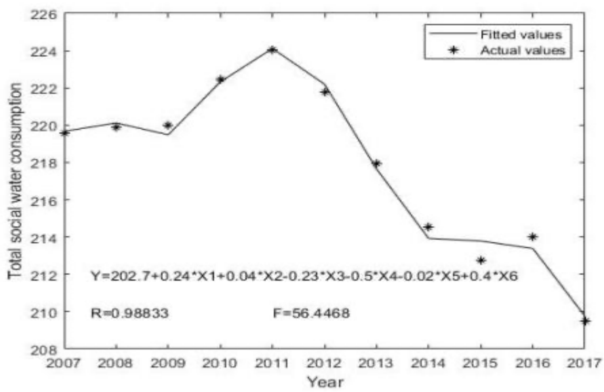

Fig. 3. Linear regression fitting results of total social water consumption.

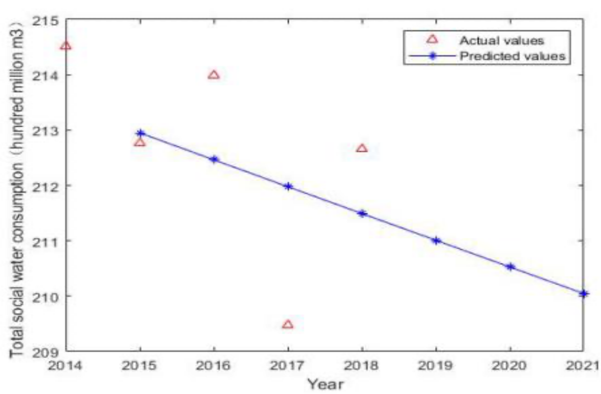

Fig. 4. Prediction results of total social water consumption.

The correlation coefficient is about 0.99, f is about 56.4, far greater than 1, indicating that the regression effect is significant.

Multiple linear regression model is applied to analyze the trend of total water consumption from 2014 to 2018. As shown in Figure 4, the total water consumption of Shandong Province has decreased year by year since 2014. Then, the total social water consumption in 2020 and 2021 is predicted. The fitting value is 21.05 billion cubic meters in 2020 and 21 billion cubic meters in 2021.

4 Conclusion

Based on the relevant data of economy, society, resources and environment from 2007 to 2017, this paper analyzes the dynamic changes of WRCC in Shandong Province, finds out the main factors affecting the total social water consumption, and fits the model of the total social water consumption, and forecasts its changes over a period of time, in order to provide reference for sustainable utilization of water resources and ecological civilization construction in Shandong Province. The results show that: the WRCC of Shandong Province shows a fluctuating development trend on the time, and the change trend of each subsystem is not the same; economic and social development factors are the leading factors of the change of WRCC. The ability of water resources security in Shandong province is insufficient, and the basic situation of water resources shortage in the future is difficult to change for a while. It is necessary to take reasonable water resources management measures to fully guarantee the social, economic and ecological development and avoid adverse effects. The following suggestions are put forward:

First of all, the fundamental principle is to optimize the allocation of water resources and make good use of all kinds of water resources. By playing the role of the East Route Project of the South to North Water Diversion Project, the water resources of the Yangtze River and the Yellow River should be rationally allocated to improve the total amount of water resources in Shandong Province and promote the formation of a multi-source allocation pattern. In combination with the local reality and hydrological characteristics, water conservancy projects such as rivers, reservoirs, ponds, water depressions and other technical means are used to store rainwater and flood, so as to increase the utilization of rainwater and flood resources and increase the regional water supply capacity. Through the construction of efficient modern water network and water system connection project, we can enhance the allocation capacity and utilization efficiency of water resources; through strengthening the development and utilization of unconventional water resources such as reclaimed water, seawater, brackish water, mine water, etc., and bringing them into the unified allocation of regional water resources.

Secondly, the economical and intensive use of water resources is the key to the current use of water resources. The state has formulated the strictest water resources control system to control the total amount and intensity of water resources consumption, and comprehensively promote the construction of a water-saving society. Through the transformation of industrial and agricultural water-saving technology and the construction of urban domestic water-saving facilities, the development of water-saving technology in key areas is continuously promoted to reduce the waste of water resources; through the construction of water-saving publicity and education and water-saving incentive mechanism, the citizens' water-saving consciousness is cultivated to promote the formation of a resource-saving society.

Third, water conservancy project construction is the hardware support of water conservancy development in Shandong Province. We will continue to promote the construction of urban and rural water supply projects, farmland water conservancy projects, flood control and drought relief projects, water conservancy information projects, especially major water conservancy projects, and make up for the shortcomings in the construction of projects, so as to ensure the sound utilization of water resources and improve the carrying capacity of water resources.

Fourth, the comprehensive management ability of water conservancy is the software support of water conservancy development. We should constantly improve the legal level of water industry management, improve the level of water public services, actively explore the water price formation mechanism and water rights transfer system, innovate the water development and management mode, and use laws, systems and other software to support the development of water resources governance capacity.

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