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Study of Water Scarcity Based on Water Resources Carring Capacity Model

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Abstract

Aiming at the problem of water scarcity in many areas, this paper is to analyze regional shortage situation and develop a corresponding intervention model to ease the tension of water supply. The paper comprehensive evaluation of regional water resources carrying capacity model (WRCC) and intervention model of water desalination facilities to solve water scarcity of Shandong Province. Besides, a grey forecasting model is established to predict the future index value. And we arrive at a conclusion that fresh water will be moderately exploited and water resources supply will just narrowly meet the demand in the next 15 years. According to the relevant data, this paper calculates the number of annual seawater desalination projects in the future finally.

Keywords

Fresh water, water scarcity, grey forecasting model, seawater desalination.

1. INTRODUCTION

Clean water is a necessary resource for human as well as natural environment. It is considered as the most essential natural resource all over the world. Over the past few decades, climate change and human socioeconomic development have greatly changed global hydrological cycles, threatening human water security, the health of aquatic environments and river biodiversity. Given this situation, increasing attention has been paid to water scarcity. [1]

Nowadays, most of the researches of the scarcity of water resources aim to intervene and adjust the arrangement and protection of the remaining water's quantity. However, it has not solved the problem fundamentally because most of the regional water scarcity is caused by the shortage of available water. In order to relieving the stress of regional water, we switch in the direction of developing the new water supplement with the scientific and reasonable allocation of water resources. We design a new model of intervention to assess results. For this new intervention model, it is not only designed from the regional water supply capability assessment to the representation of the water pressure region selection, but also from inner to outer in a gradual type analysis. Our terminal goal is to ease the situation of regional water scarcity.

2. NOTATIONS

All the variables and constants used in this paper are listed in table 1.

3. COMPREHENSIVE EVALUATION OF WRCC MODEL

3.1. Analysis Approach

Water resources carrying capacity (WRCC) is defined as a comprehensive target changing with development of social economic and scientific, which shows the maximum load of water resources on agriculture, industry, city size and population. [4] We are required to measure the ability of a region to provide clean water to meet the needs of its population. Given the definition

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of WRCC, this paper mainly studied in the WRCC of a region to reflect its ability of providing clean water. The larger the WRCC is, the more serious the water scarcity will be.

Table 1. Symble Table

No.	Symbol	Symbol Description
1	W	water resources carrying capacity (WRCC)
2	A	comprehensive evaluation value of regional water system
3	a	comprehensive evaluation value of regional social system
4	b	comprehensive evaluation value of regional economic system
5	c	comprehensive evaluation value of regional ecosystem
6	ω_1	weight value of social system
7	ω_2	weight value of economic system
8	ω_3	weight value of ecosystem
9	$\bar{s}$	amount of natural water supply
10	$\bar{d}$	amount of water for people and the environment in previous years
11	u_i	amount of water in the i-th year remission after
12	k	relieve multiplier
13	q	production of each water desalination facility in the future
14	n_i	number of newly built seawater desalination based on previous ones

3.2. The Selection of Evaluation Index

All the evaluation indexes used in this paper are given in Fig. 1.

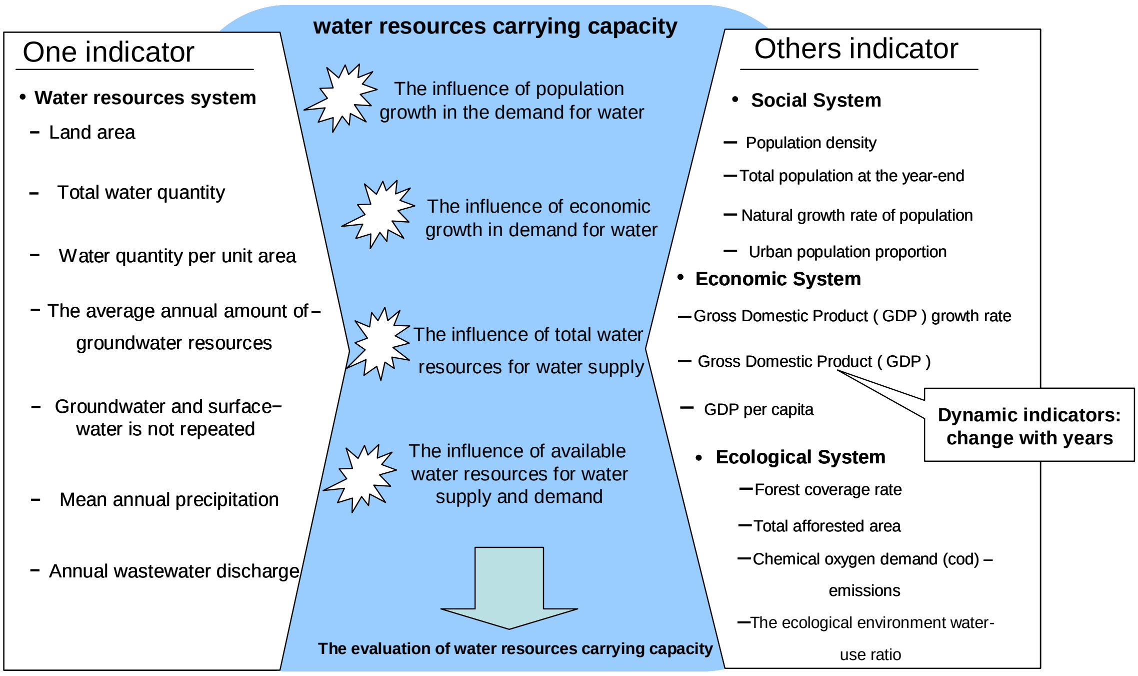

Fig 1. Evaluation Index

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3.3. Model Establishing and Solving

Preprocess of Data

Considering that different indicator data have different dimension and magnitude order, we need to standardize the initial data by using the equation below:

$$x^{*}_{ij} = (x_{ij} - \bar{x}_j) / \sigma^2{}_j \tag{1}$$

Where $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_{ij}$, $\sigma^2{}_j = \frac{1}{n}\sum_{i=1}^{n}(x_{ij} - \bar{x}_j)^2$, $(j = 1,2,3,\cdots)$; and 'x_{ij}' is the initial data, 'x^{*}_{ij}' is the standardized data.

Model Establishing

According to the indexes mentioned before as well as the connection of water, society, economic and ecology, we develop a comprehensive evaluation index of regional WRCC 'W':

$$W = \sqrt{A \times (\omega_1 \times a + \omega_2 \times b + \omega_3 \times c)} \tag{2}$$

Where A is the comprehensive evaluation numerical value of regional water system, a is the comprehensive evaluation value of regional social system, b is the comprehensive evaluation value of regional economic system, c is the comprehensive evaluation value of regional ecosystem; and $\omega_i(i = 1,2,3)$ means the weight value of social system, economic system and ecosystem.

Comprehensive Evaluation Numerical Value of Water System: A

Assuming that A1 is the area of one region and its corresponding weight is θ_1 ; A2 is the total water quantity and its corresponding weight is θ_2 ; A3 is the water quantity per unit area and its corresponding weight is θ_3 ; A4 is the average annual amount of groundwater resources and its corresponding weight is θ_4 ; A5 is the unrepeated water of groundwater and surface water and its corresponding weight is θ_5 ; A6 is the average annual precipitation and its corresponding weight is θ_6 ; A7 is the quantity of effluent and its corresponding weight is θ_7 . We calculate the value of A based on the equation below:

$$A = A_1 \cdot \theta_1 + A_2 \cdot \theta_2 + \cdots + A_7 \cdot \theta_7 \tag{3}$$

Where $\sum_{i=1}^{7}\theta_i = 1$.

Comprehensive Evaluation Value of Regional Social System: a

Assuming that a_1 is the population density of the region and its corresponding weight is α_1 ; a_2 is the total population at the year-end and its corresponding weight is α_2 ; a_3 is natural population growth rate and its corresponding weight is α_3 ; a_4 is urban population proportion and its corresponding weight is α_4 . We calculate the value of a based on the equation below:

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$$a = a_1 \cdot \alpha \ + a_2 \cdot \alpha_2 + a_3 \cdot \alpha_3 + a_4 \cdot \alpha_4 \tag{4}$$

Where $\sum_{i=1}^{3} \alpha_i = 1$.

Comprehensive Evaluation Value of Regional Economic System: b

Assuming that b_1 is the GDP growth rate of the region and its corresponding weight is β_1; b_2 is the GDP of the region and its corresponding weight is β_2; b_3 is the Gross Domestic Product Per Capita (GDPPC) of the region and its corresponding weight is β_3. We calculate the value of b based on the equation below:

$$b = b_1 \cdot \beta_1 + b_2 \cdot \beta_2 + b_3 \cdot \beta_3 \tag{5}$$

Where $\sum_{i=1}^{3} \beta_i = 1$.

Comprehensive Evaluation Value of Regional Ecosystem: C

Assuming that c_1 is the forest coverage rate of the region and its corresponding weight is γ_1; c_2 is the total afforested area and its corresponding weight is γ_2; c_3 is chemical oxygen demand (COD) emission and its corresponding weight is γ_3. We calculate the value of c based on the equation below:

$$c = c_1 \cdot \gamma_1 + c_2 \cdot \gamma_2 + c_3 \cdot \gamma_3 + c_4 \cdot \gamma_4 \tag{6}$$

Where $\sum_{i=1}^{3} \omega_i = 1$.

Overall Comprehensive Evaluation Value of the Three System: B

We calculate the value of B based on the equation below:

$$B = \sqrt{\alpha_1 \times a + \alpha_2 \times b + \alpha_3 \times c} \tag{7}$$

In conclusion, the value of comprehensive evaluation index of regional WRCC 'W':

$$W = \sqrt{A \times B} \tag{8}$$

Where $0 \le W \le 1$.

Value of weights: $\omega_i (i = 1,2,3)$

Aiming at the weights mentioned above, we use entropy evaluation method to calculate. Information entropy is the disorder of the metric system and information is the orderly degree of measurement system. They have equal absolute value but instead plus-minus sign. According to the degree variation of all indexes of various systems of regions mentioned above, we use the

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information entropy tools to calculate the weights of every index. The specific steps are as follows:

Calculate the index proportion p_{ij} :

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{9}$$

Calculate the entropy No.j indicator e_j :

$$e_j = -k\sum_{i=1}^{m} P_{ij} \ln P_{ij} \tag{10}$$

Where $k > 0, k = 1/\ln(n), e_j \geq 0$.

Calculate the coefficient of variance g_i :

For a given j, when the smaller the coefficient of variance of x_{ij}, the greater the e_j will be. When all the x_{ij} are equal, $e_j = \max e_j = 1$, and at this time x_{ij} make no difference. So we assign g_i :

$$g_j = 1 - e_j \tag{11}$$

Calculate the weights:

$$\omega_j = \frac{g_j}{\sum_{k=1}^{m} g_k}, \quad (j = 1,2,\cdots.m) \tag{12}$$

Comprehensive Evaluation Metrics of Regional WRCC

Table 2. Comprehensive Evaluation Metrics of Regional WRCC

W	0.00~0.20	0.20~0.40	0.40~0.60	0.60~0.80	0.80~1.00
Load level	Reasonable load	Slightly loaded	Moderately loaded	Heavily loaded	Over-loaded
Water stress	Water surplus	Slightly exploited	Moderately exploited	Heavily exploited	Over-exploited

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3.4. Analysis of Water Scarcity of Shandong

3.4.1 Analysis Approach

The main reason for regional water resources shortage is physical scarcity or economic scarcity. Material deprivation is that a region does not have enough water to meet the local needs. Economic scarcity concerns the presence of water, as a result of mismanagement and lack of infrastructure security, which limits the availability of clean water. Shandong province is an area of the problem of water scarcity. The geographical position of Shandong Province is shown in Fig.2.

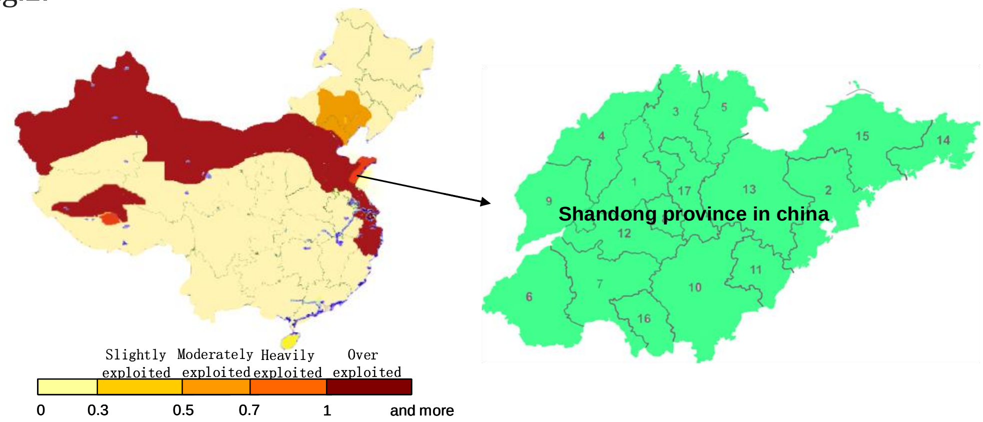

Fig 2. Geographical Position of Shandong Province

Physical Scarcity

By comparing the amount of per capita water resources in Shandong province from 2004 to 2013 and the per capita amount of water resources in China, it can be seen that the average stable data of per capita water resources was 337.40 cubic meters per person in Shandong province in the past 10 years. Compared with the average figure in China, this figure is minimal. So we think the lack of water quantity of Shandong is the reason for water use present scarcity.

Table 3. The Relative Value of Per Capita Water Resources

Year	2004	2005	2006	2007	2008
Per capita water resources (m^3)	380.68	449.67	214.61	413.27	349.06
Shandong province water resources quantity proportion of the whole country	1.14%	1.48%	0.79%	1.53%	1.20%
Year	2009	2010	2011	2012	2013
Per capita water resources (m^3)	300.9	322.4	360.7	282.99	299.7
Shandong province water resources quantity proportion of the whole country	1.12%	1.00%	1.49%	0.93%	1.04%

Shandong province is surrounded by sea on three sides. It is located in the temperate monsoon climate zone. Also, it has large amount of rainfall and precipitation. Shandong province's average annual precipitation is 717.39mm, while Chinese annual average precipitation is 633.33mm. We can learn that the level of the average annual rainfall in

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Shandong province is more than the national average level. According to the average amount of annual rainfall in Shandong province from 2001 to 2012, compared with the national average annual precipitation, we can see that Shandong province has more rainfall, which is shown in Fig.3.

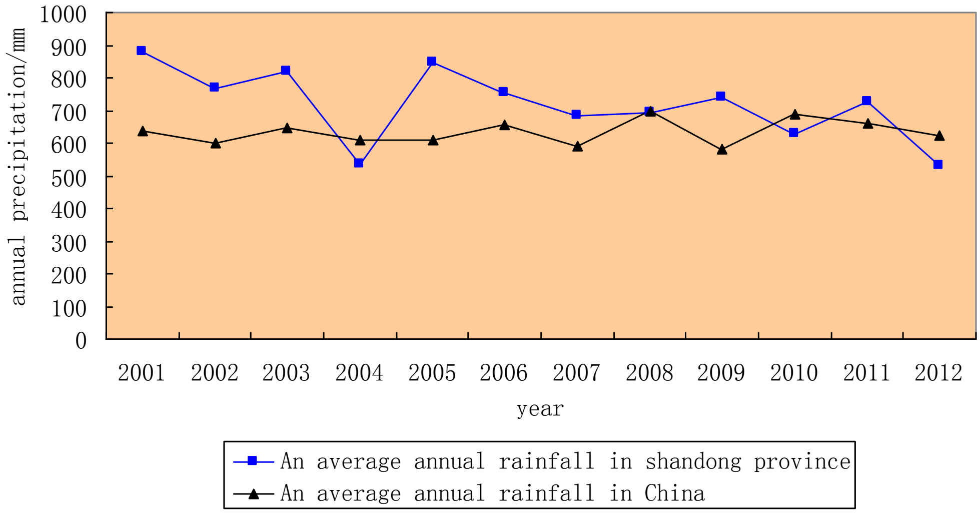

Fig 3. The Contrast Relationship in Rainfall between Shandong and China

According to the analysis above, we can learn that there is less freshwater but sufficient water flow in Shandong. Due to the weak storage capacity of water, the water use in Shandong exists great stress. Plenty of annual precipitation loses from the surface and surface erosion is serious. Then it gets a vicious circle and makes the water storage capacity decline. Finally, we can see that available water is indeed scarce.

Economic Scarcity

Low Utilization Rate of Water

No matter the total water resources, precipitation, or excellent geographical location, the reason of water scarcity in Shandong Province is not the lack of resources. That is to say, water resources are adequate. But from Table 3, the average amount of water use is 218.42 cubic meters, accounting for 68.31% of the total water resources. There are about 32% of the water is wasted.

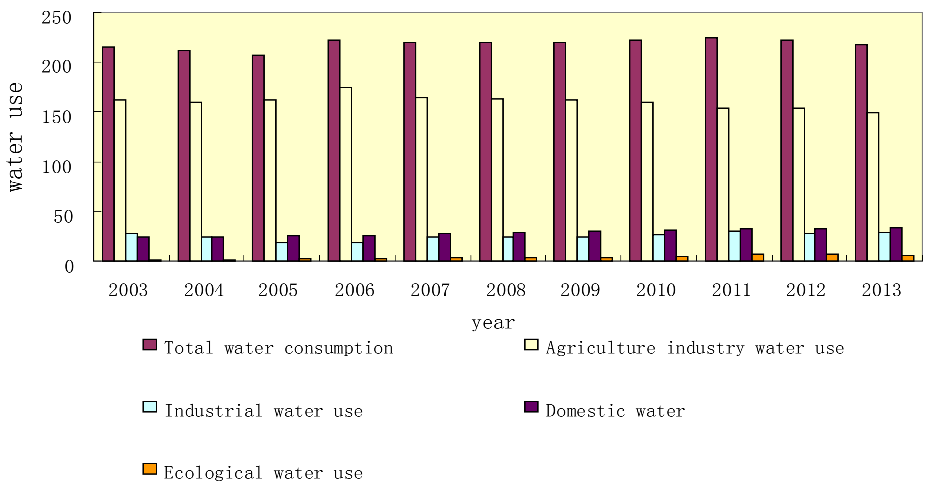

Fig 4. The Usage of Water Resources in Shandong Province

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Increasing Discharge of Wastewater

The proportion of waste water emissions accounting for the total water resources is increasing year by year, which can be observed in Fig.5. It can reflect the unreasonable situation in the utilization of water resources. According to the data, the ownership of water resources per capita is low. Although the land is vast, the amount of population is larger. Cultivated land resources, population and the imbalance of water resources cause the contradiction between supply and demand in Shandong. [5]

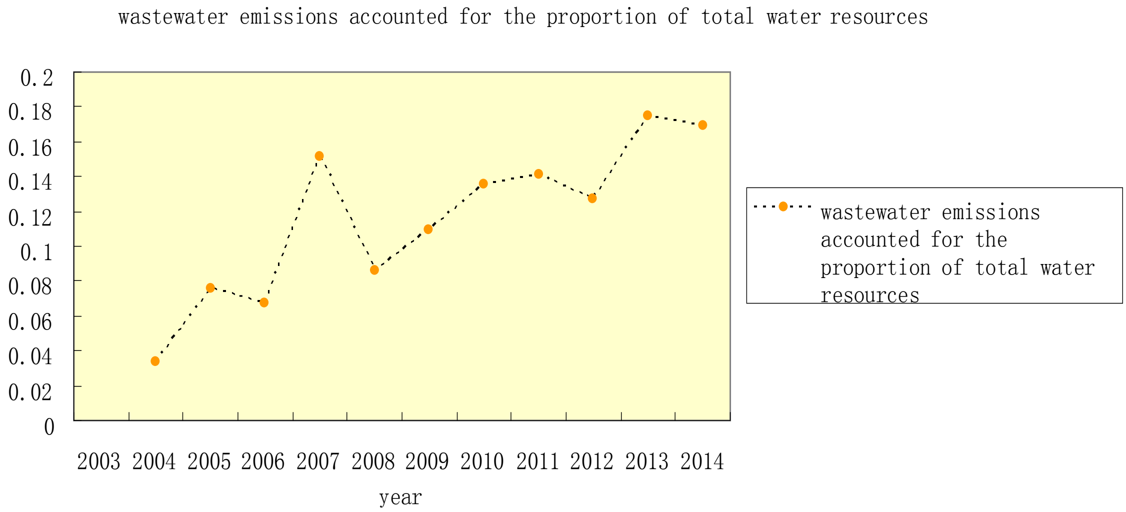

Fig 5. Proportion of Wastewater Emissions Accounting for Total Water Resources

Impact on Social and Economic System

It can be observed from the previous analysis that the regional water scarcity leads to serious soil erosion, which causes the destruction of land resources and water loss. Besides, it accelerates land desertification and soil fertility decline. The decreasing water-holding capacity of fields leads to the imbalance of water allocation. Certainly, the decreasing production of crops limits the economic development. Further more, the increasing emission of pollutants has a serious obstacle to economic development.

3.4.2 Water Shortage Degree

It is not hard to see from the above analysis that Shandong is not a water-lack province. But the phenomenon of water scarcity is an objective existence. Currently, the imbalance of regional development and the low utilization of water resources lead to the water scarcity. Lifestyle, production mode and management methods all cause lots of unattainable aspects. We utilize the WRCC model to evaluate the degree of Shandong province’s water scarcity in recent ten years.

Entropy Method to Calculate Weight Value of Each System

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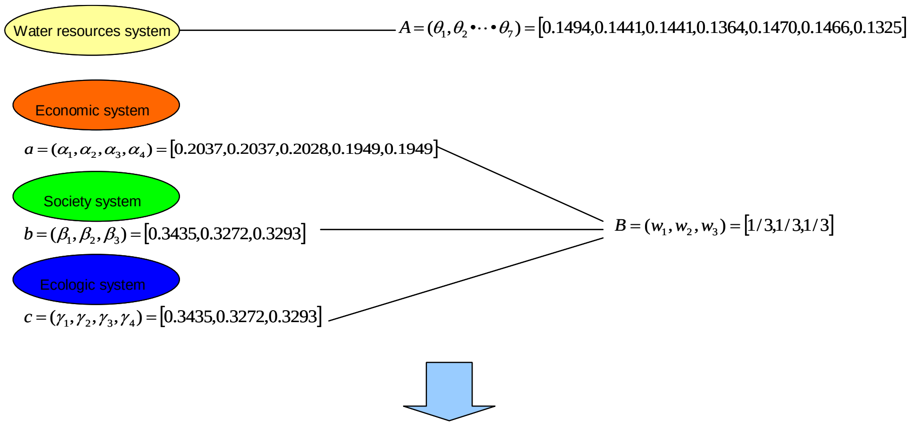

$$W=\sqrt{A\times(\omega_1\times a+\omega_2\times b+\omega_3\times c)}$$

year	2003	2004	2005	2006	2007
degree evaluation	0.7029	0.7041	0.7111	0.7034	0.7243
2008	2009	2010	2011	2012	2013
0.6978	0.6902	0.691	0.6926	0.6857	0.6856
On the verge of overload of 0.40 ~ 0.60, the water stress; Mild overload of 0.60 ~ 0.80, the shortage of water resources					

Fig 6. The Degree of Water Resources Scarcity in Shandong from 2003 to 2013

According to the consequences of Fig.6, the range of water scarcity degree of Shandong is from 0.60 to 0.80 in the nearly decade, which reflects that the water is heavily overloaded. Unreasonable development of water, disorder development of water, the emissions of wastewater and sludge are largely beyond the environmental carrying capacity. Hence, we should take systematic measures as the starting point to understand the current water problems. Also, we should evaluate the type of water scarcity correctly. [6] The most important thing is that providing a basis for the development of science strategy and implementing the sustainable utilization of water resources.

4. GREY FORECASTING MODEL

4.1. Analysis Approach

Purposing on using the regional water resources carrying capacity to analysis the water supply capacity of Shandong in the future 15 years, firstly we need to predict the indexes mentioned in Task 1 in the next 15 years. Then we evaluate water resources carrying capacity based on the comprehensive evaluation model, so as to show what the water situation will be in 15 years. In addition, the model contains environmental driving factors.

In control theory, the amount of information is shown by the color shades of the system. Color grey is between black and white, which means jusy part of the information is already known. Gray Model is usually used to establish differential models to get the fitting of given data, so as to forecast the development trend of the data. GM(1, N)is the most commonly used Grey Model, where '1' means the order number of differential equations and 'N' means the number of variables. This article adopts the simplest Grey Model: GM (1, 1).

4.2. Model Establishing and Solving

In which, $Z^{(1)}(k)=0.5x^{(1)}(k)+0.5x^{(1)}(k-1), k=1,2,\cdots n$

Model Establishing

We establish grey differential equation as followed:

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$x^{(0)}(k) + az^{(1)}(k) = b, k = 2,3,\cdots,n$

And the corresponding bleaching for differential equation is:

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = b \tag{13}$$

Then we assume that $a = (a,b)^{\mathrm{T}}$ is, so we can get:

$$Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix}, \quad B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & 1 \\ -z^{(1)}(n) & 1 \end{bmatrix}$$

By using the least square method, we can gain the estimated value of a, which makes $J(u) = (Y - Bu)^T (Y - Bu)$ achieve the minimum, and it satisfies:

$$\hat{a} = (B^T B)^{-1} B^T Y \tag{14}$$

Solving equation (14), we can get the result as followed:

$$\hat{x}^{(1)}(k+1) = (x^{(0)}(1) - \frac{\hat{b}}{\hat{a}})e^{-\hat{a}k} + \frac{\hat{b}}{\hat{a}}, k = 0,1,\cdots,n-1\cdots \tag{15}$$

Model Solving

In order to make high accuracy of the results, we find nearly 11 years of index data mentioned in Task 1 of Shandong Province from 2003 to 2013 as the basic of prediction. The paper use Grey Prediction model combined with the MATLAB software to predict the index data from the year of 2014 to 2028, and predicted results are shown in the following table.

Evaluation of Future Water Resources Carrying Capacity

Based on the predicted data of Shandong Province from 2014 to 2028, we evaluate the water resources carrying capacity. The results are shown in the following Table.4

Table 4. Results of WRCC From 2014 to 2028 of Shandong

Year	2014	2015	2016	2017	2018	2019	2020
W	0.6669	0.6553	0.6433	0.6311	0.6186	0.6061	0.5937
2021	2022	2023	2024	2025	2026	2027	2028
0.5814	0.5701	0.5608	0.5514	0.5419	0.5324	0.5230	0.5138

From Table 4, we can see that the water resources carrying capacity of Shandong is heavily loaded on the whole in the next 15 years, which means that water resources are insufficient to meet the water demand. In this situation, the water demand of the social, economic and ecological development can not be satisfied, which leads to the poor quality of human life, the limited development of local economic is and the negative influence on ecological environment.

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5. INTERVENTION MODEL OF SEAWATER DESALINATION

5.1. Analysis Approach

There are many reasons of regional water scarcity, we sum up the reasons into two aspects. One is the area itself lacking the sources of water; another reason is the unreasonable use of water and environmental deterioration, causing water pollution, even water deficiency. For the former reason, it is necessary to increase the source of water, while the latter needs to improve the management of water so as to improve the situation of local water scarcity. According to the reduction of world's total area water resources, it is essentially to improve the situation of water scarcity. Exploring new sources of water is the most fundamental solution. With the continuous development of science and technology, the seawater desalination technology continues to be mature. More and more coastal areas have to carry out the construction of desalination facilities in order to ease the tense strain of water.

5.2. Model Establishing and Solving

Model Preparation

We design a value about area future expectation relieved degree of water use. We regard the value as intervene to achieve goals. Also, we contract the number of new seawater desalination facilities in different years through the difference between the amount of target and the amount of natural water supply in the area. Then establish the intervention of desalination facilities model.

Model Establishing

For an area, the natural water supply capacity can be regarded as roughly constant. Then consider the area is in the stage of water scarcity. So the annual human and total water for ecologic use are also basically maintained constant. Then we can take the average value of the previous year to represent a degree of water use and water supply in the water shortage stage of this region. $\bar{s}$ is the amount of natural water supply. $\bar{d}$ is the amount of water for people and the environment in previous years.

We define k as the relieve multiplier based on $\bar{d}$ to calculate the amount of water consumption in the future constant years:

$$u_i = u_{i-1} \cdot k \tag{16}$$

We define q as the freshwater production of each water desalination facility. Because seawater desalination technology is not very popular in terms of production water available, the lack of water yield which achieve to meet the expected targets to ease is not provided by the whole desalination facility engineering. We define c (c is a constant) is the proportion of the water scarcity. We used $\bar{s}$ for natural water supply remains the same in the future region. In the following i-th year, the number of newly built seawater desalination based on previous ones is denoted as n_i .

$$n_1 = \frac{c \cdot u_1 - \bar{s}}{q} \tag{17}$$

$$n_i = \frac{c \cdot u_i - \bar{s}}{q} - \sum_{i=1}^{m-1} n_i \tag{18}$$

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In order to make the region to achieve the expected water consumption standard in the future, we can intervene the number of the region's new desalination facilities.

5.3. Other Inventions

In addition to the application of seawater desalination technology, the rational use of water resources, effective management, conservation, reasonable allocation and protection are also efficient measures for the development of water resources. All of these human inventions are essential way to ease the shortage of water supply in Shandong.

Rational Use of Water Resources

Priority Principle of Local Water Demand

Give priority to meet the demand of domestic water. Then reuse water for agricultural irrigation. Finally, reuse water for industrial use.

Priority Principle of Water User

Under the precondition of no mandatory requirements, local citizens are given the priority to use water resources.

Encouragement of Unconventional Water Sources

Develop use of unconventional water sources such as seawater, brackish water, rainwater for agricultural irrigation and housing construction, etc.

Principle of Saving Water

Encourage the principle of efficient use of water resources. When the water supply is in short supply, government could increase the price of water.

Purification of Polluted Water Resources

For slightly polluted water resources, we can strengthen the effect of traditional water treatment technology, such as coagulation, precipitation, filtration, etc. Add pre-treatment process before the conventional treatment. Add optimization technology after conventional treatment.

Setting up the septic tank can pollute water pipes, resulting in serious water waste. Add chlorine into water cannot effectively kill pathogens, virus and pathogenic organisms. Instead, large amount use of organic chlorides will cause water pollution. So we discard chemical treatment methods and advocate the use of biological reactor methods, such as membrane separation technology, biological treatment of sewage and solid-liquid separation, etc.

5.4. Impact on Surrounding Area

Setting up factories and the implementation of seawater desalination technology can fundamentally increase the amount of water resources, because we can get inexhaustible water from sea. Although the seawater desalination technology has great potential for development, we must be cautious about the problem of environmental protection, otherwise all the effort will be wasted.

Impact on Surrounding Land

Development of desalination technology in coastal cities, in fact, increases the total amount of water resources, which can save more available freshwater for inland city.

Seawater concentration process will lead to increased salt concentration of seawater, which has bad effects on the growth of marine organisms, thus decreasing the production of seafood.

For the regional economy, the establishment of seawater desalination plant requires a large number of labor, which provides more employment opportunities for residents in surrounding area.

Impact on Surrounding Sea

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Emission of seawater desalination by-product, such as high concentration saline, heavy metal, chemical additives, occurs mainly in the abstraction of seawater and water desalination process. Secondary improper handling will seriously pollute the surrounding seawater, resulting in excess salt concentration of surrounding seawater.[7]

The water intake system of the sea water desalination plant has threatened or even killed the fish and the smaller organisms in the intake port, which are the basis of ecosystem food network, thus affecting the marine species and ecological balance of surrounding sea.

The discharge water from the seawater desalination plant will lead to the increase of the temperature in the sea area, which will directly affect the growth and reproduction of marine life.[8] At the same time, the density of discharge water is higher than the density of the seawater itself. The settlement of the water in the sea is at the bottom of the sea, which hinders the vertical mixing of the seawater and forms a high salt desert near the port.

6. FUTURE DEVELOPMENT OF INTERVENTION

According to the water resources data of 2003~2013 in Shandong Province (The data can be seen in Appendix Table 3), we calculate the quantity of natural water supply $\overline{s}$ in previous years and $\overline{s} = 219.6770 \times 10^8 m^3$. Besides, we also get $\overline{d}$, the amount of water used by people and the environment in the past years. Assuming remission rate is 1%, so remission multiplier k=1.01, which means the assumption of water after intervention grows at a speed of 1.01 times. In addition, we assume c=0.5 so that we can get the amount of water provided by the sea desalination facilities in Shandong in the next few years based on the intervention model. And the results are shown in Table 5

Table 5. The Amount of Water Provided By the Sea Desalination Facilities

Unit: $\times 10^8 m^3$

Year	2014	2015	2016	2017	2018	2019	2020
u_i	0.4612	1.5642	2.6783	3.8034	4.9399	6.0876	7.2469
2021	2022	2023	2024	2025	2026	2027	2028
8.4178	9.6003	10.7947	12.0010	13.2194	14.4500	15.6929	16.9482

Due to the differences among different seawater desalination facilities, we assume that annual fresh water output per set of seawater desalination facilities is $q = 0.73 \times 10^8 m^3$. So we can calculate the number of yearly new seawater desalination facilities based on equation (17) and equation (18), as shown in Table 6.

Table 6. The Amount of Water Provided By the Sea Desalination Facilities

Year	2014	2015	2016	2017	2018	2019	2020
n	1	1	1	1	3	1	2
Sum	1	2	3	4	7	8	10
2021	2022	2023	2024	2025	2026	2027	2028
2	2	1	2	2	1	2	2
12	14	15	17	19	20	22	24

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It can be seen from Table 6 that, in order to achieve the desired ideal water situation in Shandong, 1~3 new sets of seawater desalination facilities can be set up every year in the future. In 2018, the total number of facilities in Shandong will reach 24.

Obviously, through the intervention of expanding the number of seawater desalination facilities in Shandong province, the problem of water scarcity can be effectively eased.

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