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Analysis and Research of Water Resource Shortage Based on AHP And Grey Forecasting Model

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Abstract

In order to solve the problem of water shortage, we have constructed a comprehensive evaluation index system of water shortage. The index system is designed according to material shortage subsystem and economic shortage subsystem. We determine the weight of the evaluation index by the judgment matrix method, establish the model by the improved AHP, and put forward a water resource comprehensive index WRCI , which reflects the comprehensive situation of water resources in China. According to our model, we have introduced the material shortage parameter λ 1 and the economic shortage parameter λ2 to indicate the material and economic shortage of a country. We tested the model in the Middle East and North Africa, two countries with the most water shortage. According to the sensitivity analysis, these countries are representative in terms of material and economic shortages, which is also in line with our view. Based on this result, we chose Yemen as the object of further study. Firstly, we analyzed how the material and economic shortages affect the comprehensive situation of water resources, and based on the grey prediction model, we built a second model using MATLAB to predict the WRCI value of Yemen in 15 years. Considering these two models, we conclude that by 2033, the WRCI value of Yemen will be stable at about 0.4, which indicates that the comprehensive situation of water resources in Yemen will stagnate and the water shortage problem will become increasingly serious. Secondly, we designed a series of interventions to improve the overall water resources situation in Yemen, and predicted the WRCI value of Yemen and its surrounding areas. The results show that our intervention plan has been successful in alleviating the water shortage in Yemen, and has had a positive impact on the surrounding areas. Finally, the results of the model are visible and easy to understand. Experts can determine whether countries around the world are developing towards a better comprehensive water resources situation through dWRCI, and suggest what they should pay attention to and how to deal with it. At the same time, countries can be ranked by this index, and countries in crisis will be noticed.

Keywords

Water shortage, Analytic hierarchy process (AHP), Water resource comprehensive index WRCI, Grey forecasting model.

1. Backgrounds

Water resource is one of the important resources that people depend on for existence and development. people’s consumption of water is primary. People need to consume large amounts of water to meet normal physiological needs.Water consumption and pollution in human activities also account for a large proportion of the total water consumption.Meanwhile, the increase of population puts great pressure on water resources.According to the Unit- ed Nations, 1.6 billion people (almost one quarter of the world's population) experience water scarcity. Water use has been growing at twice the rate of population over the last century.Furthermore,there are many conditions under which water can be used. For example, water must be liquid water that is moving or fresh water that is readily available.Under these constraints,only a tiny fraction of the planet's water is available. Therefore, the shortage of water resources has aroused public concern and become an urgent problem to be solved.

2. The establishment of a comprehensive evaluation index system for water shortage

The comprehensive evaluation index system of water shortage is a collection of measurable parameters to describe and evaluate the degree of water shortage. The system of evaluation indicators established should be able to describe and reflect all aspects of water shortage levels and conditions at any one time, evaluate and monitor the state of water resources change and trends between different points in time, and measure the extent of water scarcity in an integrated way. Thus, by providing information on the status of water resources development, trends and the degree of coordination among the various factors, it helps policy makers and the public to recognize water resource pressures and promote the sustainable use and green development of water resources.

Because the water shortage system is a multi-objective, multi-functional and complex integrated system, it is necessary to select the factor as the evaluation index. The comprehensive evaluation index of water shortage is an organic unity, and the choice of evaluation index is based on certain principles. In order to construct a reasonable and effective comprehensive evaluation index system of water shortage, we must follow the principles of system, comprehensiveness, dynamics, operability and comparability.

In this paper, according to the two main causes of water resource shortage, material shortage and economic shortage, as the subsystem layer, and according to supply and demand, resources, consumption, etc. as the criterion layer, the index system framework of water resource shortage is designed. The specific framework is shown in Figure 1.

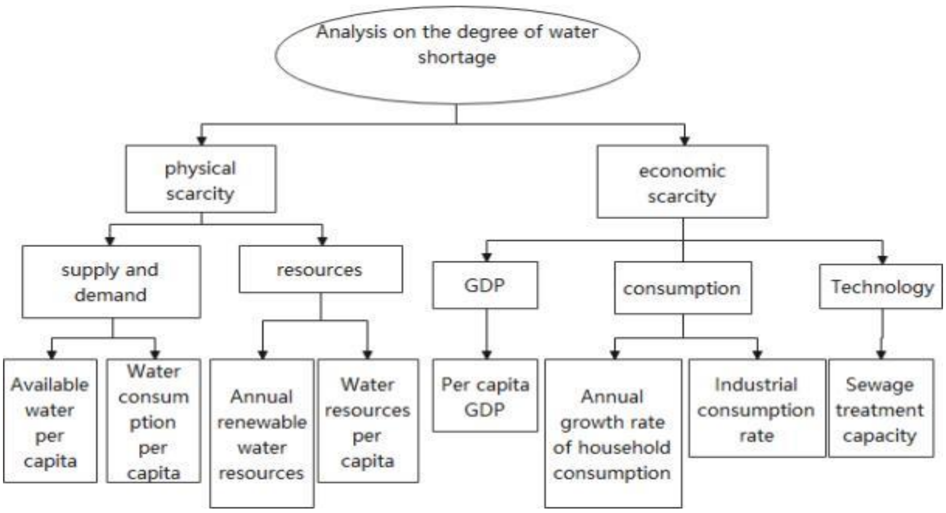

Figure 1: Hierarchy diagram

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2.1. Eight Indicators for Water Shortage Evaluation

The national evaluation index system of sustainable development constructed in Table 2 is divided into four levels:

1. Target layer (A): A level 1 indicator target layer (A)to measure the overall characteristics of water scarcity by targeting the extent of water scarcity.

2. Subsystem layer (B): The secondary indicator is the subsystem layer(B)that constructs the degree of water scarcity, including the following:

(a) Material shortage B1. Material shortage refers to a region's natural water shortage, water cannot meet the needs of people to use.

(b) Economic shortage B2. Economic shortages are where water exists, but factors such as poor management and lack of infrastructure, such as underdeveloped economic conditions, limit the availability of clean water.

3. Standard layer (C): The three levels of indicators are the criterion layer (C), which provides a level of development and a coordinated indicator for the subsystem to which they belong.

4. Indicator layer (D): The four-level index is the indicator layer (D), which is the specific factor for evaluating and evaluating the status of each subsystem, selecting the per capita water supply, per capita water consumption, annual renewable water resources, per capita water resources, etc.

Table 1: Comprehensive evaluation system of water resource shortage

Target layer	subsystem layer	layer criterion	Index layer	unit
Water shortage Degree analysis (A)	Material Shortage ($B1$)	The supply and demand($C1$)	$D1$ Per Capita Water Supply	m^3/(person*day)
			$D2$ Per Capita Water Consumption	m^3/(person*day)
		Resources($C2$)	$D3$ annual renewable water resources	%
			$D4$ Per Capita Water Resources	m^3/(person*day)
	Economic Shortage ($B2$)	GDP($C3$)	$D5$ Per Capita GDP	yuan/person
		Consumption($C4$)	$D6$ Personal Consumption Rate	%
			$D7$ Industrial consumption rate	%
		Engineering Technology($C5$)	$D8$ Sewage Treatment Capability	%

The weight of each indicator is shown in Figure 2.

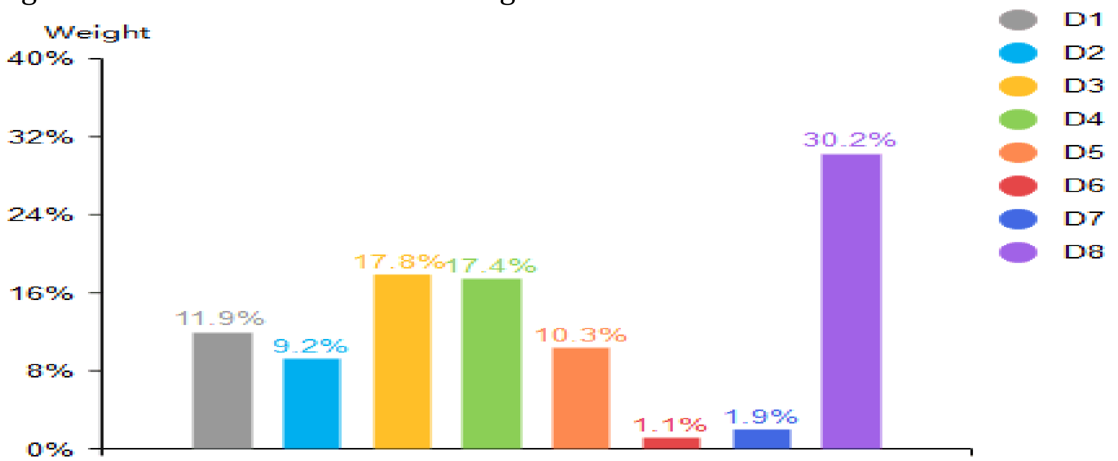

Figure 2: The weight of each indicator

2.2. The normalization of raw data

Since the selected indicators involve all aspects of water resources evaluation [2], their order of magnitude and dimension are different. In order to be able to compare and calculate, they must be standardized [3] .In this paper, the raw data is processed as follows.

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2.2.1 Standardization of raw data of longitudinal evaluation and analysis

The so-called longitudinal evaluation analysis refers to the evaluation and analysis of the water shortage situation of a specific country in different years. For a particular country, in a given time range (assuming m years), each index Di (assuming a total of n indices) in the indicator system listed in Table 1 has m specific values, then the corresponding standardized formula is:

When Di is a positive index (the positive index refers to the index whose value is bigger in the process of national water resources development).

$$v_{ij} = \frac{d_{ij} - \min(d_{ij})}{\max(d_{ij}) - \min(d_{ij})}, i = 1,2,\ldots,n; j = 1,2,\ldots,m \tag{1}$$

When Di is a inverse index (the inverse index refers to the index whose value is as small as possible in the process of national water resources development).

$$v_{ij} = \frac{\min(d_{ij}) - d_{ij}}{\max(d_{ij}) - \min(d_{ij})}, i = 1,2,\ldots,n; j = 1,2,\ldots,m \tag{2}$$

2.2.2 Standardization of raw data for horizontal evaluation and analysis

The so-called horizontal evaluation and analysis refers to the evaluation and analysis of the development status of water resources in different countries in the same year. Assuming that there are m comparable sample countries, and each index Di in the indicator system listed in Table 1(assuming a total of n indices)has m specific values, the corresponding standardized formulas are still equations(9),(10),but the meaning of each variable has changed as follows:

Vij– the standardized value of the i-th index of the j-th sample country.

Dij– the ith index value of the j-th sample country.

$Max(dij)$ – the maximum value of the i-th indicator for all sample countries.

$Min(dij)$ – the minimum value of the i-th indicator for all sample countries.

Using the above method to convert the original data into standard data can effectively eliminate the degree of dispersion between the data.

2.3. Composite Index Weighted Calculation

The four-level indicator value Qij is the basis for the calculation of the water shortage evaluation index, and its value is equal to the value of the standardized indicators:

$$Q_{ij} = v_{ij} \quad (i = 1, 2, \ldots, n; j = 1, 2, \ldots, m) \tag{3}$$

The value P_{kj} of the third-level indicator of the j-th specific year or the kth item of a specific country can be calculated according to the arithmetic mean of all the corresponding four-level indicator values. The calculation formula is as follows:

$$P_{kj} = \frac{\sum_{i=p(k)}^{q(k)} Q_{ij}}{q(k)-p(k)+1} \quad (k = 1, 2, \ldots, l; j = 1, 2, \ldots, m) \tag{4}$$

The value U_{ij} of the second-level indicator of the j-th specific year or the t-th item of a specific country can be calculated by multiplying all the corresponding three-level indicator values by their respective weights and summing them up. The calculation formula is as follows:

$$U_{ij} = \sum_{i=x(t)}^{y(t)} W_i P_{ij} \quad (t = 1, 2, \ldots, s; j = 1, 2, \ldots, m) \tag{5}$$

s—the number of secondary indexes in the evaluation index system.

x(t)—the serial number of the first tertiary index corresponding to the t-th secondary index in the evaluation index system among all tertiary indexes.

y(t)——the serial number of the last three or four indexes corresponding to the t-th second-level index in all three-level indexes in the evaluation index system.

W_i - the weight of a specific three-level indicator.

The comprehensive water resource index $WRCI_j$ of the j-th specific year or a specific country can be obtained by multiplying the corresponding secondary index values by their respective weights and adding them together. The calculation formula is as follows:

$$WRCI_j = \sum_{i=1}^{s} W_i Q_{ij} \quad (j = 1, 2, \ldots, m) \tag{6}$$

W_i - the weight of a specific three-level indicator

We define a water resource comprehensive index $WRCI$. The larger the $WRCI$, the better the water resources comprehensive status of the country. When $d\,WRCI$ >0, the water resource situation of the country is developing in a better direction.

2.4. Model inspection and sensitivity analysis

The data sources we checked included the World Bank [4], the World Resources Institute [5], and the FAO [6]. We selected three of the two most water-scarce countries in the Middle East and North Africa for sensitivity analysis. These countries have a certain representation of material and economic shortages. Sensitivity analysis is the study and analysis of a system (or model) of the state or output of changes in the sensitivity of system parameters or surrounding conditions. Because the water resources composite index *WRCI* changes with the change of the parameters of the degree of material shortage λ1 and the degree of economic shortage λ2, we call the parameters of the comprehensive index of water resources *WRCI* sensitive to the parameters of the degree of material shortage λ1 and the parameters of the degree of economic shortage λ2.We changed λ1 and λ2 as unknown parameters and from 1.0 to 2.0 as unknown parameters for sensitivity analysis, with the results shown in Figure 3 and Figure 4.

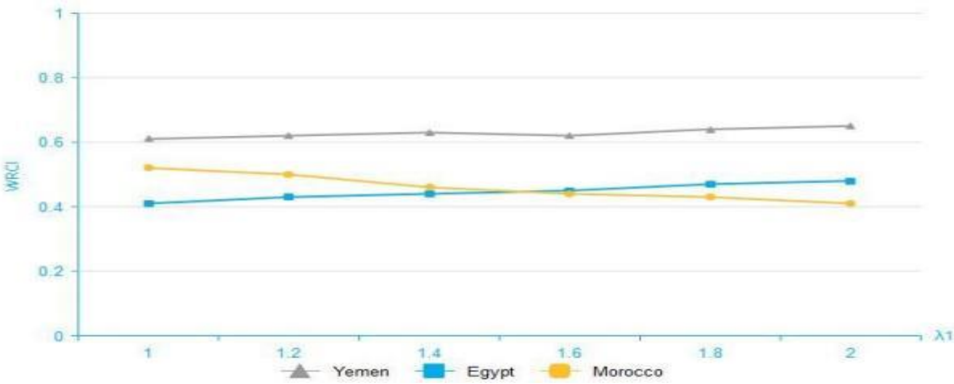

Figure 3: Sensitivity analysis of λ1 for three countries

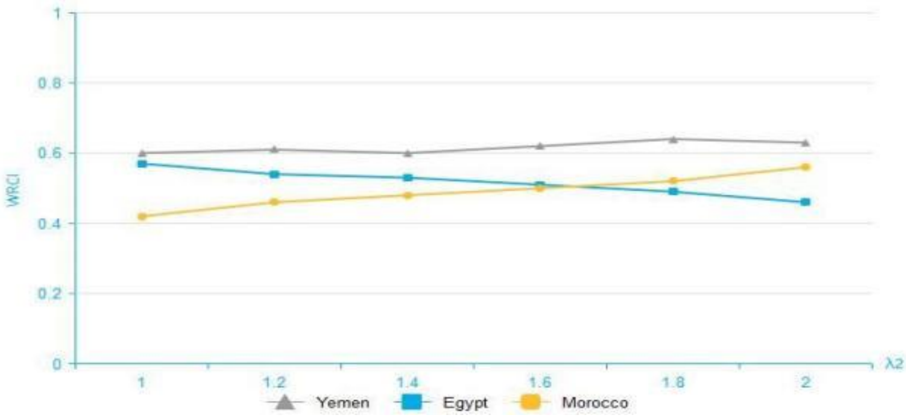

Figure 4: Sensitivity analysis of λ2 for three countries

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3. The current state of water resources in Yemen

Yemen's annual per capita water consumption is less than 135 cubic meters, the lowest in the world, and 13.1 million of its more than 24 million people lack access to standard drinking water and sanitation. The international poverty line for water use is 1,000 cubic meters per capita per year, and the average per capita water consumption in international middle-level countries is 7,500 cubic meters. It is expected that by 2025, the per capita water consumption in Yemen will drop to 65 cubic meters. Yemen's annual renewable water resources are about 2.5 billion cubic meters, while the Middle East's renewable water resources are 348.3 billion cubic meters per year.

An international report estimates that 4.5 million children in Yemen live in households that lack access to clean water. As one of the countries with the most shortage of water resources in the world, the main reason for the deterioration of the water resources situation in Yemen is the serious reduction of groundwater resources, which are 90% of the country's basic water resources. 93% of groundwater is used to irrigate 75% of agricultural irrigated land, resulting in a rapid drop in the water table. 40% of the extracted groundwater is used to water the water-intensive plant Carter, which consumes 800 million cubic meters of water every year. In the past 50 years, the market demand for Carter has continued to increase, which has made the farmer's planting area of Carter continue to increase, and the planting of other crops such as coffee beans, grapes, and food crops has continued to decrease, and agricultural water consumption has increased year by year.

Table 2: Vertical results of comprehensive situation of water resources in Yemen

Evaluation value	year 2013	year 2014	year 2015	year 2016	year 2017	year 2018
WRCI	0.136	0.142	0.098	0.163	0.186	0.157
Supply and demand criteria layer	0.108	0.095	0.102	0.210	0.209	0.198
Resource criteria layer	0.152	0.163	0.129	0.174	0.184	0.182
GDP criteria layer	0.137	0.142	0.116	0.118	0.101	0.113
Consumption criteria layer	0.104	0.107	0.125	0.116	0.112	0.106
Engineering technical criteria layer	0.141	0.128	0.086	0.152	0.148	0.137

4. The reasons for Yemen’s water shortage

According to the available information, the main causes of water shortage in Yemen are material shortage and economic shortage.

4.1. Material shortage

Yemen is located in southwestern Asia, at the southern tip of the Arabian Peninsula. It is bordered by the Kingdom of Saudi Arabia in the north, the Arabian Sea and the Gulf of Aden in the south, the Sultanate of Oman in the east, the Red Sea in the west, and the Strait of Mandela, which has an important strategic position. However, Yemen is short of water resources and mainly relies on groundwater. The trend of water stress is further exacerbated by over-exploitation of groundwater in some places. The per capita water supply, per capita water consumption, annual renewable water resources, and per capita water resources are all in a very low state.

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According to the data given by the World Bank, many provinces and cities in Yemen suffer from water shortages, such as Taiz, Amran, Lahj, Bayda, Hajj, and Sana'a cities are particularly suffering from water shortages and droughts. Water shortage has seriously affected the lives of residents in these provinces and cities, and even forced residents to leave their homes to find water sources. The semi-arid climate is also one of the main reasons for the current water crisis in Yemen. The rapidly falling groundwater level restricts the development of agriculture and the further development of ground water resources , and forms a vicious circle. [8]

4.2. Economic shortage

Yemen has a backward economy and is one of the least developed countries in the world. Economic development mainly depends on oil export revenue. The proven recoverable oil reserves are about 4 billion barrels, and the proven natural gas reserves are 1.85 billion cubic feet. The government attaches great importance to the exploration and exploitation of oil, and overcomes economic difficulties by exporting oil, natural gas and opening up mineral resources. Its gross domestic product (GDP) in 2019 was $20.6 billion, while per capita GDP was only $2,093. The GDP growth rate has not advanced but retreated, only -4.3%[9]. Its backward economic conditions have led to the country's backward infrastructure construction in water resources, and the funds invested in education and research and development are also very limited.

At present, Yemen mainly relies on the exploitation of groundwater resources for agricultural irrigation, industrial production and people's daily life. The whole country has less and less groundwater, and there is a lack of funds for desalination. There is a lot of rain in some areas, but there are no rainwater ground collection facilities. Therefore, Yemen is facing a very serious water crisis. Its capital, Sana'a, is becoming the first capital city in the world to lack a stable water supply due to its growing population. The water table in Sana'a is currently falling at a rate of 2 meters per year, and the water table in the entire city is mostly below 300 to 400 meters. Shallow groundwater has been depleted, and Sana'a city water is mainly drawn from deep water layers below 800 meters. According to the World Bank's forecast, Sana'a will be run out of water in the next few years.

Blocking roads, burning tires, and armed violence because of public protests over water shortages are common. Yemen is now one of the four worst-hit countries in the world. Increased per capita water consumption, excessive groundwater abstraction, lack of water management, and rapid population growth are the most fundamental reasons for the decline in freshwater resources in Yemen. The population has increased from 11 million in 1990 to the current 24 million, and is expected to reach 48 million by 2037. The gap between Yemen's annual recycled water production and actual use reaches 1 billion cubic meters.

The situation of water resources determines the future destiny of the Yemen country, and it is urgent for the ruling authorities to pay enough attention. However, in the current period of political and security turmoil in Yemeni society, it is difficult for the government to prioritize water resources, even if the previous stage has just closed. At the National Dialogue meeting in However, it is urgent to solve the water shortage problem, and the Yemeni government and the international community urgently need to deal with it.

5. Predictions of Yemen’s water resources for the next 15 years

In this part, we use the grey forecasting model hypothesis to predict the change of the water resource composite index *WRCI* of Yemen in the next 15 years.

5.1. Grey forecasting model assumptions

1. In all cases, we assume that the data we use in our models are reliable and accurate.

2. Several factors affecting material and economic shortages will maintain current trends, thereby precluding the possibility of major events on these factors. With its help, we can apply the GM(1, 1) model to these factors.

3. Growth indicators such as per capita GDP and industrial consumption rate remain unchanged at the latest growth rate. This assumption implies that ¬industrial technology and industrial structure have not changed significantly. This assumption allows us to remove uncertainty about the direction and standard of the indicator.

5.2. The introduction to the grey forecasting model

If you predict a gray process that changes over time, a gray forecasting model can give accurate predictions. Based on the model assumptions, we use the GM(1, 1) model to predict the trend of the Yemen Water Resources Comprehensive Index *WRCI* for the next 15 years.

If the time-dependent gray process that varies within a certain range is predicted, the gray prediction model can give an accurate prediction. Based on the model assumptions, we apply the GM(1,1) model to predict the development trend of the Yemen Water Scarcity Composite Index *WRCI* in the next 15 years.

Set $x^{(0)}$=($x^{(0)}$(1), $x^{(0)}$(2),..., $x^{(0)}$(n)) is the original non-negative data column, which we add up one at a time to get the new generated data $x^{(1)}$ (1-AGO sequence of $x^{(0)}$): $x^{(1)}$=($x^{(1)}$(1), $x^{(1)}$(2),..., $x^{(1)}$(n)) ($x^{(1)}$(m)=$\sum_{i=1}^{m} x^{(0)}(i)$,m=1,2,...,n)).

Set $z^{(1)}$ is the adjacent mean generation sequence of $x^{(1)}$, which is $z^{(1)}$=($z^{(1)}$(2), $z^{(1)}$(3),..., $z^{(1)}$(n)) ($z^{(1)}$(m)= σ$x^{(1)}$(m)+(1-σ) $x^{(1)}$(m-1),m=2,3,...,n, σ=0.5).

We call the equation $x^{(0)}$(k)+a$z^{(1)}$(k)=b (k=2, 3, ..., n) the basic form of the GM(1,1) model. *b* represents the amount of ash action and -*a* represents the development coefficient.

Input the original data and make a time series diagram, as shown in Figure 5.

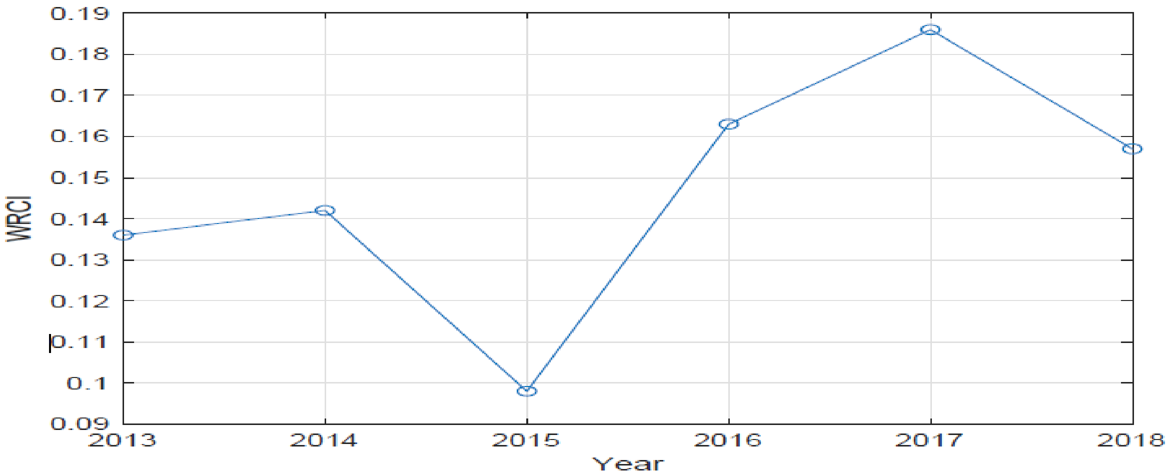

Figure 5: Raw data - Time series

The GM(1,1) model we used is suitable for the non-negative time series with short data periods. The data after one accumulation is tested for quasi-exponential law, and the smoothness is calculated, and the smoothness graph is drawn, and a line of 0.5 is drawn to represent the critical value, as shown in Figure 6.

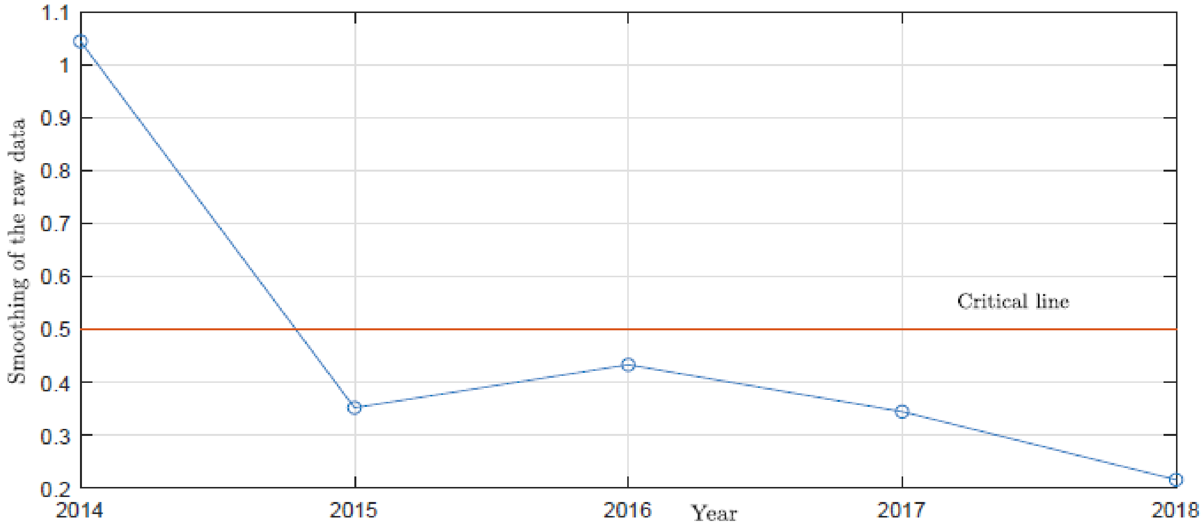

Figure 6: Test of quasi-exponential law

When the amount of data is greater than 4, we use the experimental group to choose whether to use the traditional GM(1,1) model, the new information GM(1,1) model or the metabolism GM(1,1) model, and choose the model with the smallest error to predict, and output the result predicted by the best model, as shown in Figure 7.

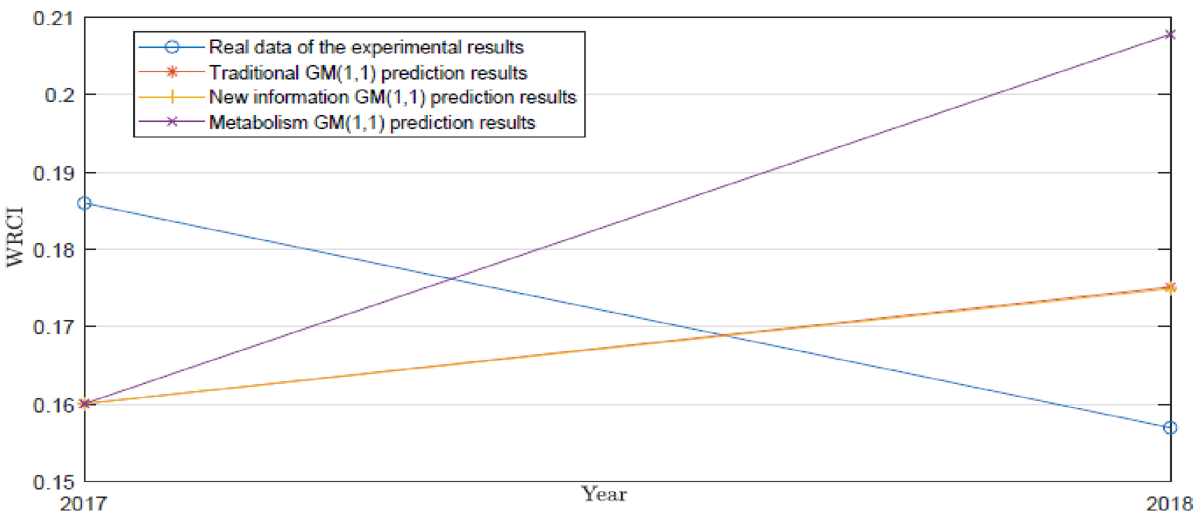

Figure 7: The best model predicts the results

Draw the graphs of relative residuals and grade ratio residuals , and carry out the residual test and grade ratio deviation test (the average relative residual is 0.02995, the results of residual test show that the model fits the original data very well, the average grade ratio deviation is 0.052724, and the results of grade ratio deviation test show that the model fits the original data very well), as shown in Figure 8.

5.3. The sensitivity analysis of WRCI

The sensitivity analysis of WRCI predictions is shown in the Figure 10 and Figure 11.

The results of the sensitivity test are within the acceptable range, which means that the variation of

the variable within a certain range will not have a significant impact on the results of our model and

lead to errors in the results.

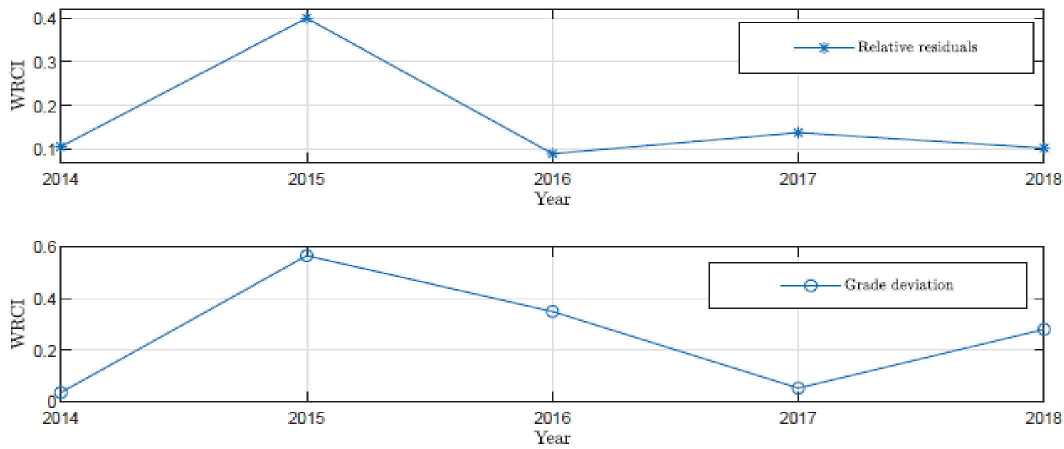

Figure 8: Relative residuals and stage ratio residuals

5. The final prediction rendering is shown in Figure 9.

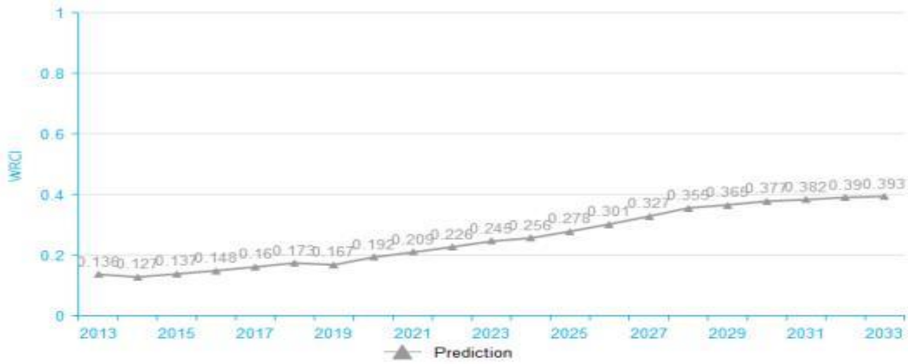

Figure 9: The final prediction effect map

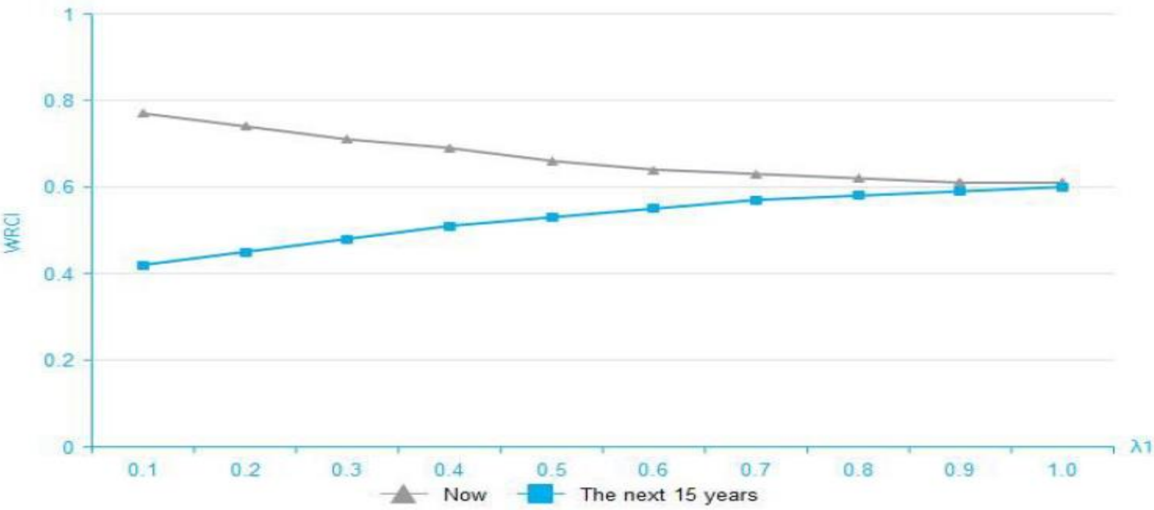

Figure 10: Sensitivity analysis of WRCI prediction with λ1 as variable

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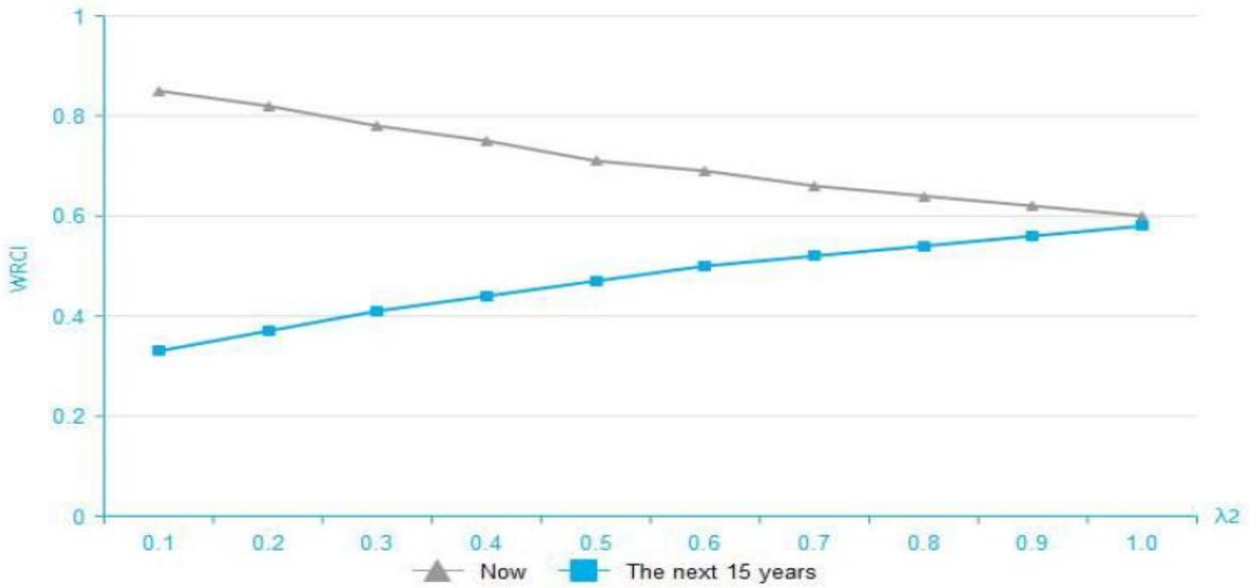

Figure 11: Sensitivity analysis of WRCI prediction with λ2 as variable

6. Our Water Improvement Program for Yemen

To help Yemen out of water scarcity, we decided to develop a series of plans to help Yemen develop its water resources. These plans will improve Yemen's water system from two aspects of the water scarcity assessment system, as shown in figure 12.

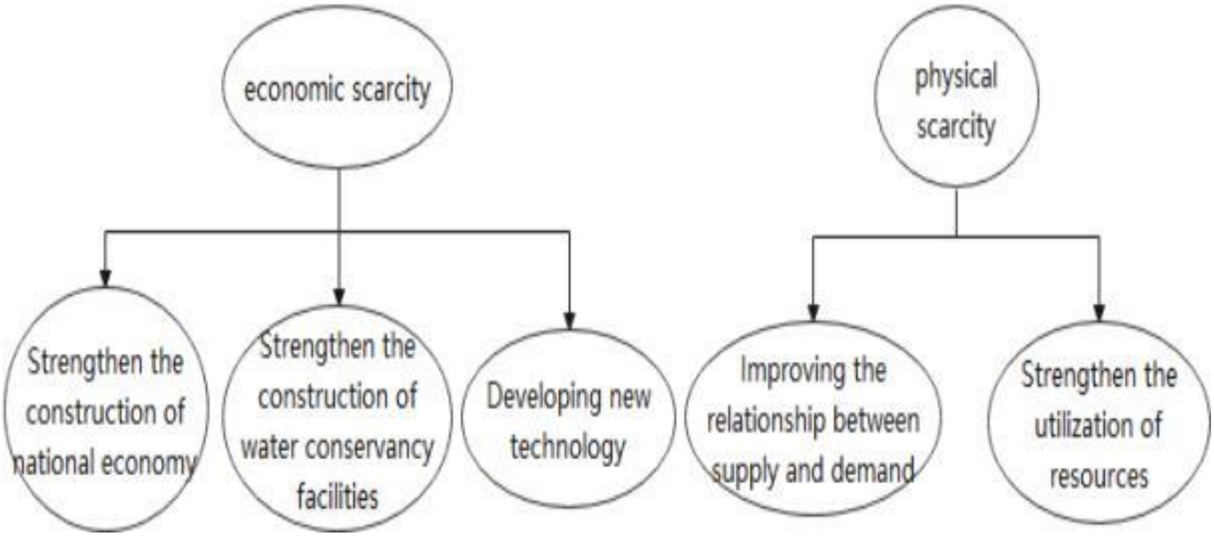

Figure 12: Two Aspects of the Water Scarcity Assessment System

6.1. Material aspect

6.1.1 Improve supply and demand

The government should publicize the importance of water conservation to the public, so as to raise public awareness of water conservation and make everyone aware of the hard-earned nature of water resources. Adopt a tiered charging system and call on people to reuse water. In addition, there is the prevention of water pollution. In addition, water pollution is also an important reason for the shortage of water resources. Strengthen the control of polluting enterprises and prevent industrial waste from polluting the limited water resources. Through these measures, the relationship between supply and demand of water resources can be improved to the greatest extent.

6.1.2 Strengthen resource utilization

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The government should vigorously develop greening and increase the forest area to conserve water. Forests have the functions of conserving water sources, reducing ineffective evaporation and regulating microclimate, and have the significance of throttling water. Forest areas and forest edges are likely to increase precipitation, which is of open source significance. Develop and promote water-saving appliances. The city develops and utilizes sewage resources, develops reclaimed water treatment and sewage reuse technologies. After treatment and purification, the high-quality miscellaneous water produced by industrial production and life in the city can reach a certain water quality standard and be used as non-drinking water in greening and sanitary water.

6.2. Economic aspect

6.2.1 Strengthen the construction of the national economy

Improving the overall economic level of Yemen is also very important to the protection and utilization of water resources in Yemen. When the economy is developed, the government can use more funds to build water conservancy facilities to better protect water resources. There will also be more funds invested in the publicity of water resources protection and the research and development of advanced water utilization technologies.

6.2.2 Strengthen the construction of water conservancy facilities

The government should strengthen the construction of water conservancy facilities, which can alleviate the uneven distribution of water resources in time and space to a certain extent. Water is collected during the rainy season, used during the dry season, and transported to areas where water resources are scarce.

6.2.3 Develop innovative science and technology

The government should develop innovative science and technology such as ozone treatment, ion exchange and other water purification technologies[10], formulate policies to encourage enterprises to develop new technologies, and increase the research and development of new technologies such as seawater desalination that can solve the lack of water resources.

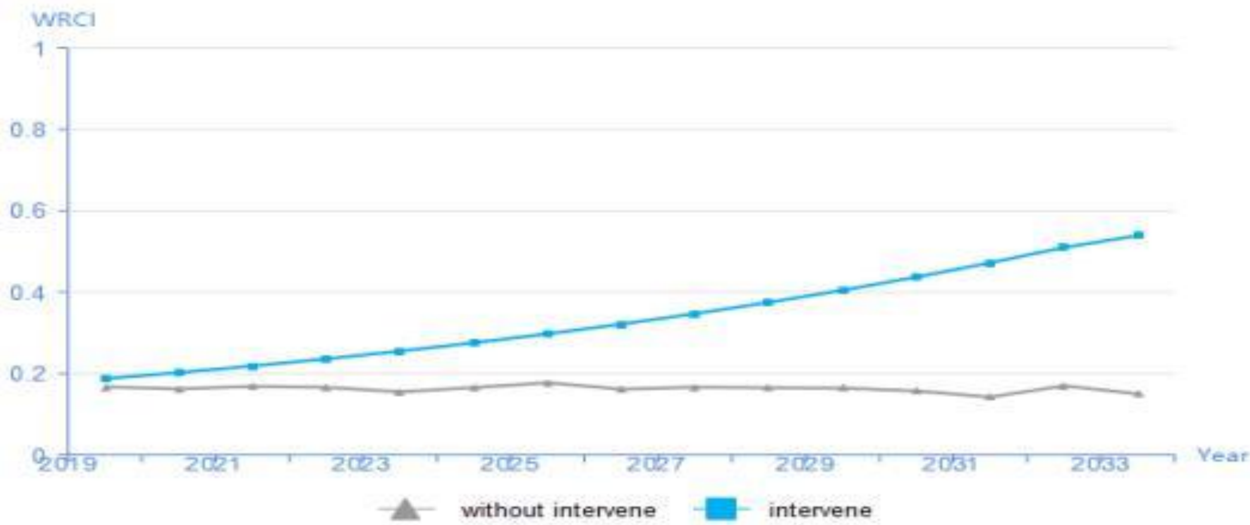

Figure 13: Projections of future water shortages in Yemen under two scenarios

7. The impact of plans

It is expected that after the implementation of these plans, Yemen's economic and material shortages will be greatly improved in the next few years, water supply and demand, lack of degree will be in a good direction.

Figure 13 shows the prediction results of comprehensive water resources index WRCI in Yemen in the next 15 years before and after intervention. It can be seen from the figure that the WRCI index of Yemen's water resources after intervention has been significantly improved compared with that without intervention.

Meanwhile, our intervention plans will have a positive impact on the surrounding areas of Yemen, where water scarcity has improved. The specific situation of the indicator *WRCI* is shown in the Figure 14.

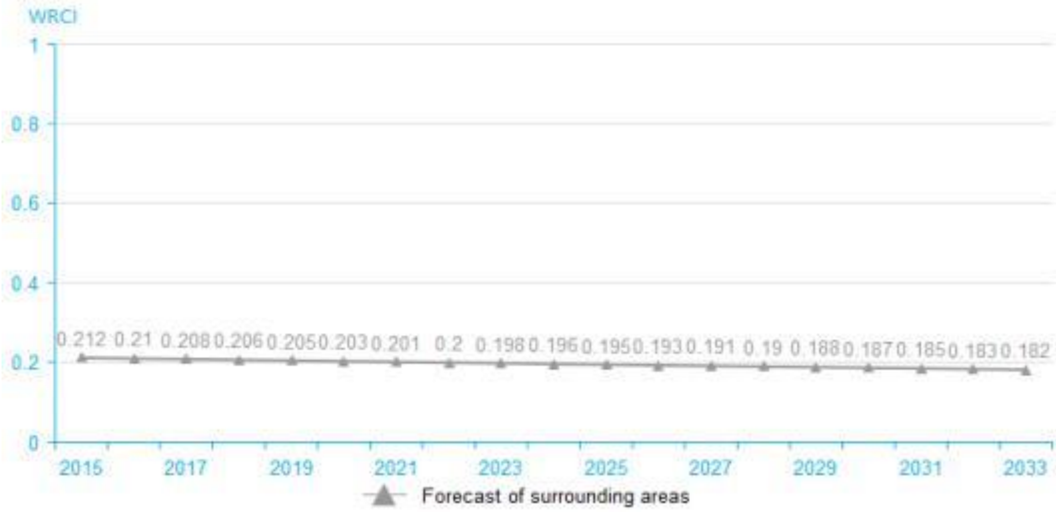

Figure 14: Forecast of surrounding areas

In addition, we forecast the development trends of the Yemen Water Resources Comprehensive Index *WRCI* after the intervention. As shown in the Figure 15, Yemen's water resource comprehensive index *WRCI* will improve slowly but steadily in the future.

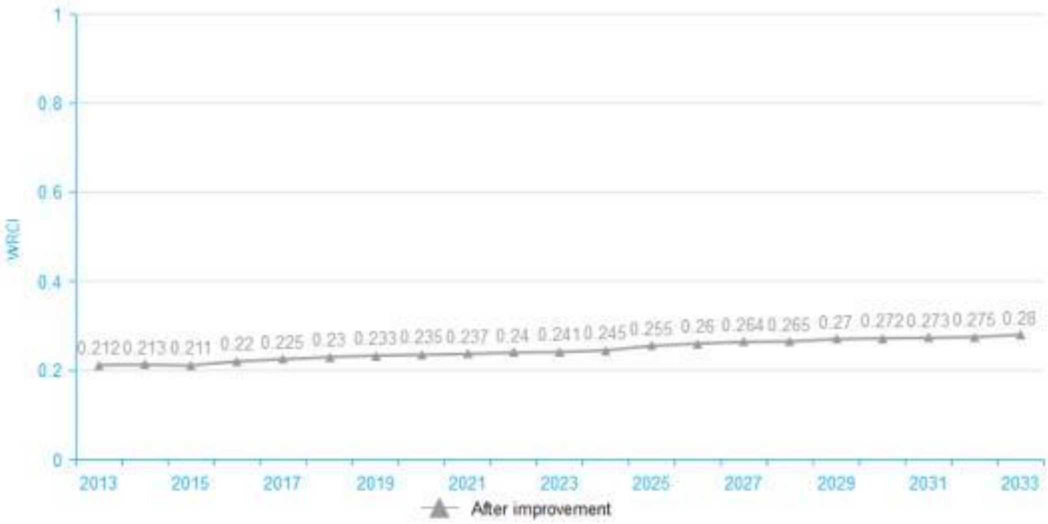

Figure 15: Trends of WRCI after improvement in Yemen

8. Conclusion

We take into account the main factors of water shortage, use eight specific indicators to reflect the comprehensive evaluation system of water shortage, and standardize the data of in different dimensions, and then define a water resource comprehensive index *WRCI* to reflect the country's overall water resources situation. With the development and deepening of research on water resources and the continuous improvement of statistical data, the indicators should be constantly revised and supplemented.

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