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Early-warning system analysis for water resources security in Tianjin city

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ABSTRACT

Based on the analysis of water supply and water demand in Tianjin city, the early-warning index system of water resources was determined. Then, applying the relative principle of catastrophe theory, all kinds of the slope change-points of early-warning index curves, including the differences of water supply and water demand, water supply, water demand, increasing curve of population in Tianjin, total industrial output value and increasing curve of GDP are obtained by the rate analysis for slope change-point. So, the slope change-points model is established for early-warning system of water resources security in Tianjin City. After applying the theory of set pair analysis, which set a pair of "water-rich state (flood disaster)" and "water-shortage state (drought disaster)", early-warning threshold and degree of water resources security are uniformly presented by the index of difference of water supply and demand. In this way, we could illustrate the early-warning degrees. Finally, according to the division of early-warning in "water-rich" state and "water-shortage" state of water security in Tianjin, some effective measures are proposed to alleviate the conflict between the supply and demand water.

Keywords: Water resources; Early-warning; Slope rate change-point analysis; Set pair analysis (SPA)

1. Introduction

As the population of world grows, human activity intensifies, the ecological environment problems become prominent, and the pressure of globally available water resources will be increasingly fierce. Water safety, as the basic guarantee of survival and development of all countries, has become the focus of the whole world. At the same time, in order to meet the needs of war, with the emergence of radar and the computer, radar warning system was born, and the

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concept of the early-warning system was slowly improved. With continuous development of system science, all fields and disciplines have rushed to apply the thought and method of scientific warning, so warning system method has been widely used in economy, society, population, resources, environment, and other areas, water resources is no exception.

Internationally, since 1972 the Club of Rome issued an important academic research book about early-warning of global development, "Blueprint for Survival", an American scholar Gelbert White and a British scholar Slesser, respectively, established a risk decision-making system of flood warning and the Evolution of Capital Creation Options model, which can improve the environment capacity options. Our country has a late start in the early-warning. Early in the 2001, projected by the National Ministry of Science and Technology, the Ministry of Water Resources, the China Meteorological Administration, the State Oceanic Administration, and the Ministry of Environmental Protection together carried out "the research of key technology on Chinese water resources security system". Since 2001, the National Ministry of Science and Technology has been carrying on the research on "water resources security measures." Experts have studied from different aspects. In 2001, Wang et al. [1] also established an early-warning model of comprehensive, coordinated and sustainable development of a river basin, based on the system dynamics method. He adjusted the target basin development strategy through the sustainable development capacity index, and then developed the appropriate policy options for the basin development planning and provided the theoretical, methodological, and evidential support for formulating development planning and adjusting policies for the basin. In 2002, Guo et al. [2] studied the water security early-warning mechanism in-depth. They described the architecture of principles of water safety warning system, based on 3-level water security concept. In 2004, Deng [3] established a regional early-warning indicator system framework for water resources, using analytic hierarchy process. He also established regional water resources sustainable early-warning model, whose assessment indicators were the driving force of regional water resources. In 2006, Wen et al. [4] analyzed the study schools on the regional early-warning system and the regional water resources for sustainable use of early-warning systems. But, in general, there are few study of regional water security warning, and the research contents generally laid particular stress on qualitative analysis and rarely on quantitative analysis, especially the uniform water safety measurement method and warning index system need further discuss. In this paper, after conducting early-warning analysis on the regional water current situation, we established water safety warning system based on the analysis of the supply and demand of water resources in Tianjin city. First, we determined the Tianjin early-warning index system of water resources with the qualitative and quantitative method. Then we analyzed all the warning index with the slope change-point analysis, and thus identified water security mutations points. Then, with the set pair analysis (SPA) theory, regarding the "water-rich state" and the "water-shortage state" as a set, and we could uniformly describe the warning threshold and warning degrees of water resources security in Tianjin by the difference between supply and demand indicators of water. Combined with the actual status of water resources in Tianjin, a variety of early-warning measures to ease the water degrees and the supply-demand contradiction were put forward. Technical route chart is shown in Fig. 1.

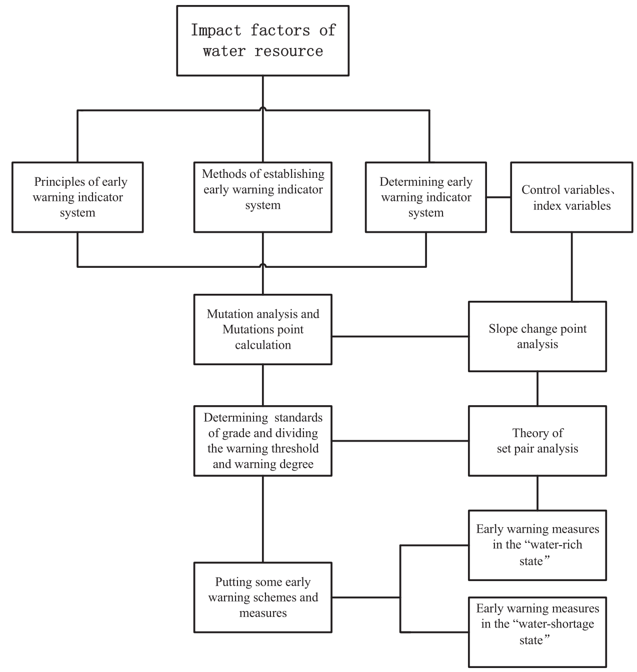

Fig. 1. Technical route of early-warning systems analysis of water resources.

2. Status of water resources in Tianjin

In Tianjin, the total volume of annual surface water is 1.055 billion m^3 and groundwater resource is also 832 million m^3 on average; so the total water resources mean for 1.816 billion m^3 (double counting is 70.8 million m^3) and 340 m^3 per capita, which is far less than the world water shortage tipping point recognized as the amount 1,000 m^3 per capita. So the scarcity situation is enormous. Meanwhile, during a year, the distribution of the total amount of water resources is very uneven due to the runoff conditions and precipitation of distribution. There are various differences in different places because of the ability to adjust in different basins and the form of runoff supply. In general, water resources are abundant in the northern part and poor in south. While, the layout of the water storage works is opposite: small storage capacity in north and large in south. This contradiction leads to depletion of water in some reservoirs in the southern areas generally.

At present, the development and utilization of water resources shown in south is higher than in the north of Tianjin. Now there is almost no water in Daqing River, which was previously the major source of water surface. The completed projects have a large capacity of storage, even more than the available water resources. The surface water is no longer potent for further development. While the surface water in the north is relatively abundant. The Beiyun, Chaobai, and Jiyun Rivers all have a large entry of water. The completed projects have less storage capacity. So the surface water can be developed further. There are also contradictions in development and utilization of water resources in Tianjin [5]. On the one hand, there is water shortage and on the other hand water is wasted. Some industrial products need lots of water and the urban water supply leakage is serious. In agriculture, the common traditional irrigation and the comprehensive utilization coefficient are low.

3. Water supply and demand analysis of Tianjin

The amount of water supply is the supply of different water users and different districts to a certain quality requirements, which means the water amount for the production, life, and ecology through the water supply project facilities. The amount of water demand is the amount which is in order to meet the needs of different kinds of fields for the economic and the social development in some time, considering the sort of available saving methods. We can get the amount of water supply in Tianjin during 1991 to 2008 from relevant references. The amount of water demand can be obtained from the water Quota Act method. Both the amounts are listed in Table 1.

Based on the above data of water supply and demand, rearranging the calculated total data water of demand from small to large, and through multivariate regression analysis with SPSS, you can gain of the total water supply curve, and the total water demand curve regression equation as follows:

Table 1
Annual water supply and demand table during 1991–2008 in Tianjin ($10^8 m^3$)

Year	Supply	Demand			
		Demand of domestic water	Demand of industrial water	Demand of agricultural water	Total
1991	24.65	3.64	8.08	29.21	40.93
1992	25.71	3.46	8.00	28.68	40.14
1993	23.41	3.33	7.92	27.52	38.77
1994	23.56	3.41	7.84	27.79	39.04
1995	24.38	3.59	7.77	28.15	39.51
1996	24.80	3.57	7.70	28.24	39.51
1997	23.91	3.75	7.64	27.77	39.16
1998	24.50	4.02	7.58	25.82	37.42
1999	25.50	3.96	7.51	25.24	36.71
2000	22.64	3.82	7.46	23.5	34.78
2001	19.14	4.47	7.39	22.26	34.12
2002	19.96	4.28	7.34	21.61	33.23
2003	20.53	4.18	7.29	20.47	31.94
2004	22.06	4.08	7.23	21.32	32.63
2005	23.10	4.10	7.19	21.84	33.13
2006	22.96	3.93	7.15	21.83	32.91
2007	23.37	4.13	7.10	18.34	29.57
2008	22.33	4.24	7.06	18.33	29.63

$$\begin{cases} Q_{\text{Supply}} = 17.149 + 0.102x - 0.006x^2 - 8.5 \times 10^{-5}x^3 \\ Q_{\text{Demand}} = 2.988 + 1.212x - 0.009x^2 \end{cases} \quad (1)$$

Combined with the equation above, we can get the supply–demand curve, as shown in Fig. 2. Thus, water supply–demand difference equation can be obtained as:

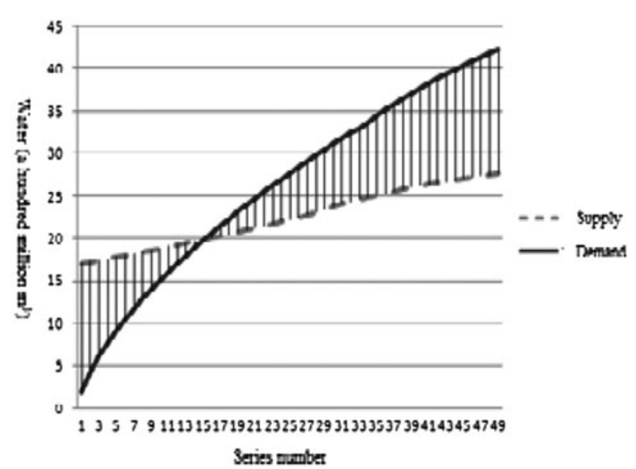

Fig. 2. Analysis graphics of water supply and demand.

$$Q_{\text{Difference}} = Q_{\text{Supply}} - Q_{\text{Demand}} \quad (2)$$

In Fig. 2, we can see the Tianjin water supply and water demand curve cross at the area of the water in the value of about 2.0 billion m^3. It means that the water balance position is near the value of 2.0 billion m^3 area, when the difference between water supply and demand is 0.

4. Early-warning index system

In order to establish water resources security warning index system, the factors which affect the water resources security should be analyzed first. Combined with the analysis results of coordination of supply and demand and the research in the present situation of water resource in Tianjin, the regional water security warning factors can be determined finally.

The factors are very complex. They mainly include two aspects—natural environmental factors and socioeconomic factors [6]. From the change of the actual water resource situation in Tianjin, we can know that main factors come from human activities. So, we focus on the influence that the socioeconomic factors exert on the change of water resources carrying capacity of Tianjin. In accordance with the principles of relevant selecting, we picked seven factors as follows: X_1, the total population (10^4); X_2, GDP (10^8 yuan); X_3, the amount of industrial water (m^3); X_4, the amount of domestic water (m^3); X_5, the amount of agricultural water (m^3); X_6, gross industrial output value (10^8 yuan); X_7, the water consumption for ten thousand industrial output (m^3); and Y, total water consumption (m^3). Then, we can make principal component analysis using the statistical software-SPSS. See the results in Table 2.

From Table 2, we know that the seven influence factors of the water resources carrying capacity exist correlation to the different degree, among them with x_1, x_2, x_6, x_2, and x_6 has larger relevance, for which the correlation coefficient were 0.982, 0.983, and 0.945, respectively. From the first principal component we can see that it has a major relationship with the x_1, x_2, and x_6. The x_5 and the second principal components are largely related. The x_3 and third principal components are largely related. By making a quantitative analysis of the three main factors which affect the amount of water demand, X_1, X_6, X_2. the fitting equations between the amount and the population are:

$$y_S = 0.083x_{\text{population}} - 39.157 \quad (3)$$

$$y_S = 20.524 + 7.421 \ln x_{\text{GDP}} \quad (4)$$

$$y_S = 2.057 + 5.089 \ln x_{\text{GDP}} \quad (5)$$

Their contribution value (weight) to the amount of water demand can be determined with the principal component analysis method. They were 0.334, 0.324, and 0.342. Therefore, according to the water resources situation of Tianjin and the analysis of supply and demand balance, the regional water security warning factors can be obtained from the analysis of the first and second principal components. They included the difference of supply and demand (DSD), the amount of water supply, the amount of water demand, total population, gross industrial output value, and GDP. The Tianjin early-warning index system of water resources was established. And set the amount of water supply and demand as the warning index, set difference of water supply and demand as the control variables. At the same time, the influence factors of the amount of water demand include population, gross industrial output value and GDP, which can determine the level of regional water security warning analysis framework.

Table 2
The related coefficient matrix of water resources carrying capacity change variables' driving force

Variable	X_1	X_2	X_3	X_4	X_5	X_6	X_7
X_1	1.000						
X_2	0.982	1.000					
X_3	−0.825	−0.811	1.000				
X_4	−0.714	−0.780	0.734	1.000			
X_5	0.247	0.371	−0.104	−0.513	1.000		
X_6	0.983	0.945	−0.862	−0.708	0.158	1.000	
X_7	−0.849	−0.743	0.692	0.373	0.183	−0.894	1.000

5. Mutations points analysis

In the research of water resources, we often find that a curve of water demand rises gradually and will burst to speeding up after a special moment. Or, sometimes the curve starts falling faster when it meets another one, and will fall down slowly until flattened gradually to a certain point. Of course, there are other situations. The curve began to fall down slowly, when it met a point, the falling speed became fast and it fell along the oblique line. Sometimes, in a curve, the first half is the sudden acceleration and the second half is a sharp slowdown, etc. The sudden change of the "the turning point" is often important, which usually had a relationship with some specific problems or specific meanings. So it is very important to accurately determine the point. Such "turning points" are called curve slope mutations points, slope mutations points in short. In this paper, we apply slope change-point analysis to make an early-warning system for water resources mutation analysis. After the analysis of the internal rules of warning index changes, which contains the difference in water supply and demand, water supply, water demand, population, gross industrial output value and GDP, etc. the mathematical model can be established. Combining with the geometric singularities, topology, quality theory of differential equation, and stability mathematical theory, we can do some research with the critical point where the mutation of the warning index happened, which was called warning threshold.

The basic principle of slope change-point analytic method is: for most of the measurement data of discrete points, they are apart and the intervals are long and hard to form a continuous curve, so we cannot get the slope of each point through the method of derivation. But, we can calculate the linear regression coefficient of the points nearby, then we can get the linear slope of both sides of the point within a short time. And the difference between both sides of the selected point reflects the changing scope of the slope of both sides (i.e. first-order difference). When the interval of points is the same, the slope's change of the second-order difference can reflect the accelerated (decelerated) speed of the changes of the slope. By looking for the local maximum value of the accelerated (decelerated) speed of the change slope, the unit interval which contains the slope changing point can be found out. Then we can calculate the mode, so we can estimate the slope mutations point of quantitative. The next step is linear interpolation, so we can get the accurate slope change-point—t^*. The computation formula is as follows:

$$t^* = t_{i-1} + \frac{\nabla^2 S(t_i) - \nabla^2 S(t_{i-1})}{\left[\nabla^2(t_i) - \nabla^2 S(t_{i-1})\right] + \left[\nabla^2(t_i) - \nabla^2 S(t_{i-1})\right]} \times (t_i - t_{i-1}) \quad (6)$$

Table 3
Influence factors and corresponding mutation point

Influence factor	Mutation point	Influence factor value (10^8 yuan)	Corresponding difference (10^8 m^3)
Gross industrial output (10^8 yuan)	5.00	90.89	5.87
	12.00	135.08	3.22
	33.67	1491.70	−9.07
	36.84	2068.73	−17.97
GDP (10^8 yuan)	5.00	67.49	−2.41
	12.00	139.77	−5.03
	36.16	1724.43	−13.62
Total population (10^4)	5.17	585.98	8.26
	33.83	880.87	−9.00

where t_i is the i-th point; $\nabla^2 S(t_i)$, $\nabla^2 S(t_i)$, $\nabla^2 S(t_i)$ were the second-order difference value of t_{i-1}, t_i, t_{i+1} points.

When using slope change-point analysis in water resources system [7], at first we should use Eq. (6) to solve each index variables, including the mutations point of the curve of difference of water supply and demand, water supply curve, water demand curve, population growth curve, gross industrial output value curve, and GDP curve. The mutation points of the water demand curve and water supply curve can directly reflect on the difference of water supply and demand curve, and population growth curve, gross industrial output value curve, and GDP curve affect water demand curve through Eqs. (3)–(5), which reflects on the curve of difference of water supply and demand (in Table 3), so that we can solve a series of values which reflect the changing characteristics of the difference on water supply and demand curves. Thus, we can make an early-warning analysis on the regional water system. The mutations points of water supply curve, water demand curve (warning index), as well as the difference between water demand and supply curves (control variables) are shown in Table 4.

Table 4
The curves mutation point of the supply, demand, and the water difference between supply and demand

Options	Supply		Demand		Difference		
Mutation point	9.00	37.83	20.17	22.83	12.86	34.47	41.04
Water (10^8 m^3)	18.49	24.99	23.77	25.97			
Difference (10^8 m^3)	5.32	−10.97	−2.82	−4.38	2.19	−9.76	−12.00

6. Early-warning system analysis

Warning degrees are the main goal of establishing the regional water security warning system. In order to accurately forecast the warning degrees, we must scientifically analyze and study the effects that various factors have on the regional water resources. Regional water safety warning degrees and alarm limit have a close relationship with the mutation point above. The division of warning degrees and warning threshold can be determined according to the position of the mutations points and the corresponding difference of water supply and demand, and then we can determine whether a warning index is alarming. With the theory of SPA [8] we can set the water resources situation in Tianjin "water-rich" state (i.e. water supply greater than water demand, appear flood disaster) and "water-shortage" state (i.e. water supply less than water demand, appear drought disaster) as a set. Then we make the analysis of water security warning system in Tianjin.

6.1. The warning threshold of water safety warning

Its very complex and difficult to determine the warning threshold. In order to carry on comprehensive appraisal, we need to eliminate the influence of dimensional index, so we should deal with the related initial data of the mutation point normalization. Through Eq. (7), normalize the initial data, all the indexes of the absolute value will fall into the interval of (0, 1).

$$x' = x/(x_{\max} - x_{\min}) \tag{7}$$

where x is the difference of water supply and demand, and x' is the normalized values for the difference of water supply and demand. The normalized value of the difference of water supply and demand at the balance position is 0. The extreme value of "water-rich" state is 1; the extreme value of "water-shortage" state is −1. Therefore, we can obtain the normalized values sorting table for the difference in water supply and demand.

6.2. Warning degrees of water early-warning

After calculating three curves for water supply, water demand and DSD of the regional water resources in Tianjin city, we can find the balance of supply and demand, for which we can set a balance point of 0.0. Then we should calculate the control variables, index variables and mutations points of influence factors curve. With the application of SPA, the safety degree (S) can be introduced, namely:

$$S = x' - x'_{\text{balance}} \tag{8}$$

When $S \in (0, 1)$, it shows that in the "water-rich" state in this region, that is, water supply is greater than water demand, and the larger the S value, the more serious the regional "water-rich" state, and higher the warning degree, the greater the chance of flooding. Until S value is 1, it means that extreme floods happened in this region. When $S \in (-1, 0)$, it shows "water-shortage" state in this region, that is, water supply is less than water demand, and the larger the absolute value of S, the more serious the regional "water-shortage" state, and the higher warning degree, the greater the chance of drought disaster. Until S value is −1, it means extreme drought disasters happened in this region.

Considering the balance between the supply and demand of water resource in Tianjin and the predicted error theory [9], it allowed the range of plus or minus 5%. The interval after normalization is (0.05, 0.05) which is as the balance interval for water supply and demand. The corresponding difference interval of water supply and demand is (−1.31, 1.31), and the corresponding water changing interval is (18.69, 21.31) million m^3. The warning threshold and warning degrees division are shown in Table 5 in detail.

6.3. Warning control proposal

Although the mutations are inevitable, we can take corresponding measures to control variables to avoid mutations or prevent the phenomenon continue to deteriorate.

When the system is in "water-shortage" state, we need to seek the warning source of "water-shortage," and take emergency measures, such as: increasing discharge water from reservoirs, at the same time with the guarantee of the people's basic living water, decreasing water supply time for living and limiting the supply of industrial, agricultural water, etc. And we can also use the unconventional water such as recycled water, brackish water, and seawater. Organizing implementation of artificial precipitation is necessary. At the same time, there are five projects that contain the protection of water source of Water Diversion Project from Luanhe River to Tianjin City, urban water conservation, agriculture water conservation, water reuse, and seawater desalination. Meanwhile, construction of culverts for Luanhe river diversion, transforming water supply network, controlling special industries water supply, spreading the water-saving instruments, and improving water price, we can save some water and take the government emergency

Table 5
The warning threshold and warning degree table in "water-rich" and "water-shortage" state

State	*S*	Warning degree	Corresponding difference (10^8 m^3)
"Water-rich"	(−1.00, −0.66)	Very very heavy warning	(−∞, −11.43)
	(−0.66, −0.56)	Very heavy warning	(−11.43, −9.79)
	(−0.56, −0.25)	Heavy warning	(−9.79, −4.38)
	(−0.25, −0.16)	Middle warning	(−4.38, 2.82)
	(−0.16, −0.00)	Light warning	(−2.82, 0.00)
	(−0.05, 0.00)	No warning	(−1.31, 0.00)
"Water-shortage"	(0.00, 0.05)	No warning	(0.00, 1.31)
	(0.05, 0.12)	Light warning	(1.31, 3.22)
	(0.12, 0.21)	Middle warning	(3.22, 5.60)
	(0.21, 0.31)	Warning	(5.60, 8.26)
	(0.31, 1.00)	Very heavy warning	(8.26,+∞)

plans, so as to make the system gradually returned to normal state.

When the system is in "water-rich," state we need to seek the warning source of "water-rich," and take emergency measures, such as: reinforcing the dilapidated reservoirs, increasing flood storage capacity of reservoirs, making full use of the maximum storage capacity of the reservoir and the rivers. And at the same time, releasing the extra parts of water in floodplains, repairing levee, enhancing flood control ability, dredging river and removing obstacles in the river, and building new drainage engineering and rebuilding the old and so on. And the relative department of the government should take emergency measures to resettle the people affected by the disaster, and do their best to protect people and property. Through these measures, we can make the water resources system to gradually return to its normal standard of living.

6.4. Early-warning analysis and verification testing in Tianjin

According the actual data of Tianjin in 2000, 2001, and 2007, we make analysis and validation to the warning system, shown in Table 6.

From Table 6, we can know the warning degrees of water resources in the year 2000, 2001, and 2007 in Tianjin were, heavy water shortage, very very heavy water shortage, and middle water shortage. In fact, there had been continuous drought in Tianjin from 1997 to 2004 resulting in serious urban water supply crisis. To solve the problem, there had been four water emergency diversions from Yellow River in 2000, 2002, 2003, 2004, respectively. In 2000, it was dry continuously any and the total rainfall depth was only 424.4 mm that is 24.95% less than the average annual depth, and it caused tremendous influence on Tianjin. Residents' daily water content was reduced to 31.0%, resulting in serious consequences of domestic water problems. To deal with the water shortage, the government issued three-saving orders consecutively and took 26 water-saving measures, including ceasing agricultural water, closing all flushing points, strictly controlling corporate consumption water, limiting the amount and time of living water supply, raising water prices, etc. In 2007, water shortage was also serious. However, the government took active measures. In conlusion, the calculation result from the paper's warning degrees divided model is consistent with the reality of local water resources. The established early-warning system of regional water resources is feasible, and it can provide a decision basis for water safety analysis in Tianjin [10].

Table 6
Data and warning degrees of early-warning analysis and validation in Tianjin

Year	Supply (10^8 m^3)	Demand (10^8 m^3)	Difference (10^8 m^3)	S	Warning degrees
2000	22.64	34.78	−12.14	−0.46	"Water-shortage" heavy warning
2001	19.14	34.12	−14.98	−0.57	"Water-shortage" very very heavy warning
2007	23.37	29.57	−6.20	−0.21	"Water-shortage" middle warning

7. Conclusions

The general design ideas based on the early-warning system is that through analysis of the water supply and demand in Tianjin to determine early-warning indicator system, set the water supply and demand as the early-warning indicator and the difference between supply and demand of water as a control variable. Furthermore, we introduce the slope of the change-point analysis to the research of regional water security. We calculate the mutation points of curves of indicator variables, and combined it with the theory SPA, we set "water-rich" state (floods) and "water-shortage" state (drought) as a set of pairs, by using the difference between water supply and demand to describe warning threshold and warning degrees. When the water safety $S \in (0, 1)$, the regional water status is in "water-rich" state; when water safety $S \in (-1,0)$, the regional water status is in "water-shortage" state. Combined with water supply and demand situation in Tianjin, we propose a variety of police degree program to alleviate the water shortage, which provided the basis for decision-making for water security analysis in Tianjin. If we can expand the scope of early-warning indicators, combined with environmental factors, the water security situation can be reflected more fully.

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