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Comprehensive evaluation of water resources utilization benefits based on catastrophe theory

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A B S T R A C T

The benefits of water resource utilization include social benefits, economic benefits, and ecological environmental benefits, so it is difficult to evaluate them comprehensively by adopting the traditional cost-income analysis method. Catastrophe evaluation method, which majors in dealing with uncertain problems, evaluates system synthetically based on the internal mechanism of the system. It calculates the evaluation value of the system in the condition that the relative importance of the indexes is determined and the exact weights are unknown. In this paper, the comprehensive evaluation model of water resources utilization benefits is established based on the catastrophe evaluation method. Moreover, the method which embodies the important roles of various benefits effectively is applied to evaluate the comprehensive benefits of different water resources utilization schemes from 2000 to 2005 in Zhengzhou City of China. The results show that the method has good flexibility and provides a new idea for a comprehensive evaluation of water resources utilization benefits.

Keywords: Catastrophe theory; Water resources utilization; Benefits; Evaluation index

1. Introduction

With the rapid development of the social economy around the world, the shortage of water resources has been restricting the development of the economy and society [1]. Therefore, surface water and groundwater should be better utilized to meet most demands of production and living [2].

Cost-benefit analysis, which takes maximization of the benefits as a target [3], is often used to assess the benefits of water resource utilization [4,5]. Wang [6] proposed a system of integrated benefit assessment indexes that reflect social, economic and environmental interests comprehensively, and established an integrated benefits assessment model for the interests of urban-water-resource-related policies. Alcon et al. [7] compared the costs and benefits of reclaimed water use on an experimental mandarin farm in the south-east of Spain with those of using surface water and a mixture of water sources. Fan et al. [8] analyzed the costs and benefits of reclaiming and reusing Beijing's municipal wastewater based on the 2010 figures. Varouchakis et al. [9] applied cost-benefit risk analysis in water resources and Bayesian decision analysis to aid the decision making on whether or not to construct a water reservoir for irrigation purposes. Cheng et al. [10] developed a new bilevel optimization problem based on goals at two different levels: minimization of water demands at the lower level and maximization of system benefits at the upper level and used the model to solve a real-world case across Pennsylvania and West Virginia.

However, the above methods have shortcomings in the comprehensive evaluation of water resources utilization benefits that include not only economic benefits but also ecological environmental benefits and social benefits [11].

Catastrophe theory is a mathematics subject that focuses on discontinuous change and mutation. Its basic

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characteristic is to classify the critical point of the system according to the potential function and to study the characteristic of the discontinuous changing state near the classified critical point [12]. The catastrophe evaluation method that derives from the catastrophe theory quantifies the relative importance of indexes according to the internal contradictions and mechanisms in the normalization formula of the system and reduces the subjective factors in the evaluation effectively. The method has been widely used in engineering safety management [13], mapping flood susceptibility [14], sustainable utilization assessment of water resources [15], groundwater vulnerability assessment [16,17] and so on.

2. Methods

2.1. Catastrophe evaluation method

2.1.1. Catastrophe theory

The French mathematician Thom systematically expounded mutation theory in the "The stability of structure and morphogenesis" in 1972, marking the formal birth of catastrophe theory [18].

Catastrophe theory is used to supervise the transition of a system from one state to another when the control variable is changed. By studying the minimum value change of the state function (potential function) $F(x)$, the characteristics of the discontinuous change state near the critical point can be determined.

2.1.2. Common catastrophe evaluation model

There are seven forms of potential function at most when control variables are less than four (people are in a space of four dimensions: three-dimensional space and one-dimensional time, so the control variables that describe the potential function of the system state are generally less than four). The types of mutations corresponding to these seven potential functions are called primary catastrophe, in which the first four catastrophe models are more commonly used, as shown in Table 1.

In the catastrophe model, all critical points of potential function $F(x)$ are combined into a balanced surface. By solving the first derivative of the potential function, the equilibrium surface equation can be attained. On this basis, the bifurcation set B, which reflects the relationship between state variables and control variables, can be obtained, and thereby the normalization formula can be derived.

The normalization formulas of the three most widely used catastrophe types are as follows:

Cusp catastrophe: $x_a = a^{1/2}$, $x_b = b^{1/3}$

Swallowtail catastrophe: $x_a = a^{1/2}$, $x_b = b^{1/3}$, $x_c = c^{1/4}$

Butterfly catastrophe: $x_a = a^{1/2}$, $x_b = b^{1/3}$, $x_c = c^{1/4}$, $x_d = d^{1/5}$

The normalization formula can reduce the different quality of each control variable of the system to a comparable qualitative state Therefore, the normalization formula can be used to quantify the state variable (X, Y). Then the catastrophe value of the system can be analyzed by recursive calculation based on the corresponding potential function.

2.2. Evaluation index system

According to the different functions of water, the benefits of water resources utilization can be roughly divided into three categories: economic benefits, ecological environmental benefits, and social benefits.

2.2.1. Economic benefits

In the economic system [19], the contribution and utility of water resources that meet the needs of economic and social development are called economic benefits, which mainly include the following aspects.

Value of industrial production: as a kind of indispensable element, water resources are used in industry to produce goods.

Value of agricultural production: along with sunlight, water resources maintain the growth of crops [20].

Value of power generation: water flows from the fall of terrain and geomorphology and saves rich potential energy, providing a large amount of electricity through the hydropower stations.

Value of shipping: water resources create the value of shipping by transportation.

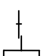
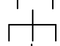
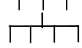
Value of aquatic products: abundant resources of animals and plants in water resources provide the necessary material guarantee for human life and production, producing the value of products.

2.2.2. Ecological environmental benefits

In the ecological system [21], the contribution and utility of water resources that maintain the normal operation of the ecosystem are ecological environmental benefits of water resources, which can be divided into the following categories according to the different functions of the water environment.

Value of water regulation: the value of water regulation is the embodiment of the functions of lakes, swamps, and other storage sources, regulating runoff, supplementation of rivers and groundwater, such as the prevention of flood and drought.

Table 1
Common catastrophe models

Type	Sketch map	Potential function
Folding catastrophe		$F(x) = x^3/3 + ax$
Cusp catastrophe		$F(x) = x^4/4 + ax^2/2 + bx$
Swallowtail catastrophe		$F(x) = x^5/5 + ax^3/3 + bx^2/2 + cx$
Butterfly catastrophe		$F(x) = x^6/6 + ax^4/4 + bx^3/3 + cx^2/2 + dx$

Value of biodiversity regulation: the ecosystem is the carrier of biodiversity, and plays an irreplaceable role in maintaining biodiversity [22]. The aquatic ecosystem, which provides a living environment for all kinds of aquatic organisms, is a place where wild animals live, reproduce, migrate and pass the winter.

Value of purifying environment: the value of water purification is the embodiment of water supplying or maintaining a good physical and chemical metabolic environment of polluted materials and improving the purification function of the regional environment.

Value of climate regulation: water evaporation and plant transpiration increase the air humidity in the region, influence the temperature and humidity of the atmosphere, and then induce rainfall, which has a significant effect on stabilizing the regional climate and regulating the local climate.

Value of transportation: the value of transportation mainly refers to the value embodied by a series of ecological service functions such as sediment transport, transportation of nutrients and silt accumulations into the land.

2.2.3. Social benefits

In the social system [20], the contribution and utility of water resources, which are the maintenance of life and health and the social spiritual needs, are called the social benefits of water resources, mainly include the following three aspects.

Value of labor recovery: the labor recovery value of water resources is mainly the performance that maintains human life and health, and is generally measured by the quantity of the contribution of maintaining the value of normal labor.

Value of leisure and entertainment: the recreational value of water can be divided into two categories according to the different services provided by water resources: one is the value brought by recreational activities and the other is the value produced by the aesthetic enjoyment of services.

Value of scientific research: with the shortage of water resources in the world, water has become an important object of scientific research. Meanwhile, various types of lakes and rivers are also materials for education, especially for environmental education.

According to the above analysis, the comprehensive evaluation index system of water resources utilization benefits can be established, as shown in Fig. 1.

2.3. Standardization of the indexes

Due to different dimensions, the indexes should be standardized [23]. For easier calculation of the benefits of water resources utilization, the "the-more-the-better" principle can be adopted.

"The-bigger-the-better" indexes can be standardized by:

$$R_i = \frac{r_i - r_{\min}}{r_{\max} - r_{\min}} \quad (1)$$

"the-smaller-the-better" indexes can be standardized by:

$$R_i = \frac{r_{\max} - r_i}{r_{\max} - r_{\min}} \quad (2)$$

where R_i is the standard value of index i; r_i is the initial value of index i; $r_{\max}$ and $r_{\min}$ are the maximum and minimum values of all indexes respectively.

2.4. Calculation process

The catastrophe evaluation method uses the recursive principle (from bottom to top) to calculate the catastrophe evaluation value. The calculation process is as follows:

- Establishing an evaluation index system;
- Standardizing the indexes and obtaining the membership values of the underlying indexes;
- Normalizing the membership values of the underlying indexes based on normalization formula;
- Calculating the catastrophe value hierarchically by using the recursive method. Should an obvious interrelation

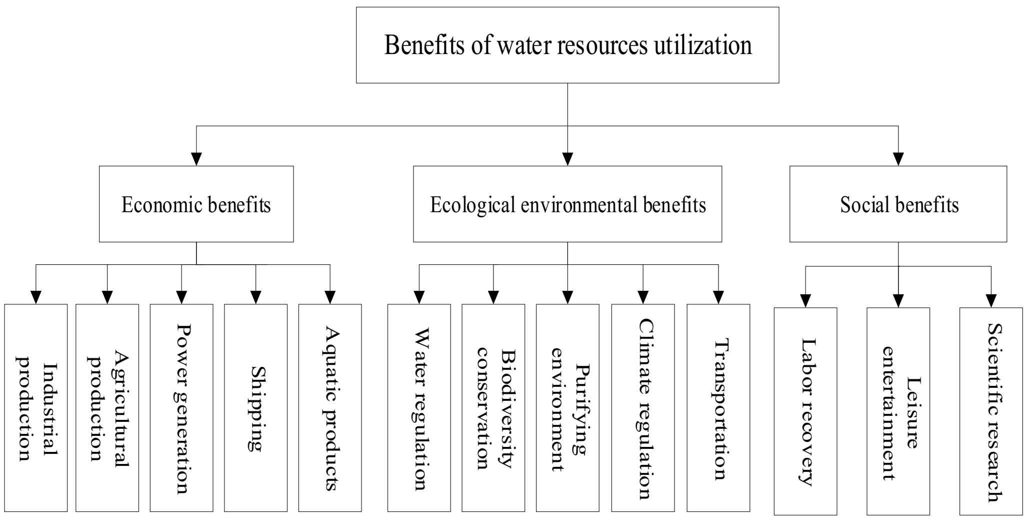


Fig. 1. Comprehensive evaluation index system of water resources utilization benefits.

be between the control variables of the same object, the principle of "complementarity" is adopted, in which the value of the upper index equals the average of normalized lower values? Otherwise the principle of "choose smaller one" is adopted, in which the value of the upper index equals the normalized smallest lower values.

According to Eqs. (1) and (2) and the above recursive calculation, the evaluation value ranges between 0 and 1. The bigger the evaluation result is, the more utilization benefits of water resources are.

3. Results

3.1. Study area

Zhengzhou City is the capital of Henan Province of China, locates in the north of central Henan Province, and has a total area of 7,446.2 km^2. As of the end of 2018, there are 10.2 million residents in Zhengzhou. Its gross domestic product of industry and agriculture is 379.69 and 15.64 billion yuan respectively.

The average water production coefficient of Zhengzhou is 0.28 for a long time. The total amount of water resources in the city is 1,339 Mm^3 (Yellow River is not included), in which the amounts of surface water resources and groundwater resources are 867 and 865 Mm^3 respectively, and 393 Mm^3 are recalculated.

According to the research of Lv [24], the monetary value of water resources utilization of Zhengzhou from 2000 to 2005 is shown in Table 2.

3.2. Catastrophe evaluation results

According to the catastrophe evaluation model established above, the comprehensive evaluation values of water resources utilization benefits in Zhengzhou from 2000 to 2005 can be calculated, as shown in Table 3.

Both monetary values and comprehensive evaluation values are shown in Fig. 2.

4. Discussions

- Due to the different relation degrees between the indexes and human economic activities, the monetary value of water resources utilization has a great difference, even in the aspect of magnitude, as shown in Table 2. Therefore, the monetary value of all kinds of benefits cannot be added directly as the comprehensive benefits of water resources utilization. It is necessary to find a more scientific evaluation method to fully consider the irreplaceable role of all kinds of benefits in maintaining ecological balance and supporting human survival and development.
- According to Table 3 and Fig. 2, we can see that from 2000 to 2002, the catastrophe evaluation values of the comprehensive benefits of water resources utilization in Zhengzhou City had been increasing. However, in 2003 and 2004, there was a turning point, and the benefits of water resource utilization decreased. The main reasons

Table 3
Catastrophe evaluation values of water resources utilization of Zhengzhou

Year	Catastrophe evaluation value
2000	0.5609
2001	0.9063
2002	0.9182
2003	0.7447
2004	0.6031
2005	0.9322

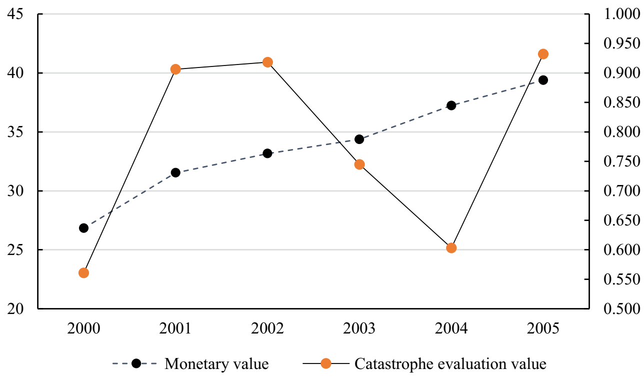


Fig. 2. Benefits of water resources utilization of Zhengzhou City.

Table 2
Monetary value of water resources utilization of Zhengzhou City

Item		2000	2001	2002	2003	2004	2005
Monetary value of water (¥/m^3)	Industrial production	9.79	12.74	13.55	14.94	13.97	15.79
	Agricultural production	4.30	5.04	5.40	5.92	6.56	6.42
	Water regulation	0.91	1.21	0.77	0.64	0.60	0.75
	Biodiversity conservation	0.03	0.07	0.08	0.02	0.02	0.03
	Climate regulation	0.32	0.43	0.70	0.21	0.19	0.26
	Labor recovery	10.93	11.00	11.37	12.49	15.52	15.39
	Leisure entertainment	0.55	1.04	1.29	0.15	0.37	0.74
	Scientific research	0.0007	0.0018	0.0013	0.0005	0.0005	0.002
	Total	26.8307	31.5318	33.1613	34.3705	37.2305	39.3820

were the rapid value reduction of biodiversity conservation, climate regulation, and leisure entertainment. Due to the improvement of the above indexes, the comprehensive benefits of water resources utilization in Zhengzhou improved significantly in 2005. However, those characteristics cannot be reflected by traditional monetary value analysis. The proposed evaluation model fully considers the important roles of each index and makes results more scientific.

- It is very difficult to accurately determine the weights of all kinds of indexes of water resources utilization benefits. Most traditional methods rely on experts' experience to assign weights, leading to the evaluation results being susceptible to subjective preference of experts. The proposed catastrophe evaluation model can effectively analyze the comprehensive benefits of water resources utilization based on qualitative whereas not quantitative determination of the relative importance of each index, which reduces the difficulty of evaluation and improves the objectivity of the evaluation results.

5. Conclusions

The problem of reasonably evaluating the comprehensive benefits of water resources utilization is of great significance for rational planning and administering water resources. Combined with the comprehensive evaluation index system of water resources utilization benefits, the comprehensive evaluation method is established based on catastrophe theory, in which the characteristics of various indexes are taken into account and the benefits of each index are considered evenly and adequately by normalization. Taking the Zhengzhou City of China as an example, comprehensive benefits of water resources utilization from 2000 to 2005 are analyzed, in which the trend and reasons are clarified, reflecting the importance of the role of the indexes with small monetary value.

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