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Evaluation of the Benefits of Urban Water Resource Utilization Based on the Catastrophe and Emergy Methods

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Abstract
The evaluation of the benefits of urban water resource utilization, which include supporting life and industrial and agricultural production, is important for decision-making and policy formulation in urban water management. However, since life cannot be quantified in terms of economic value, it is difficult for traditional economic analysis methods to comprehensively evaluate the benefits of urban water resource utilization. Output per unit water and the proportion of water to resource inputs were proposed to evaluate these benefits. An evaluation index system was established based on catastrophe theory, which evaluates the system under the condition that the relative importance of indices is determined and the exact weights are unknown. Emergy theory, which reflects the process of energy conversion, was introduced to analyze various benefits of urban water resource utilization. By applying these methods to evaluate these benefits in Zhengzhou, China, the author verified the rationality of the proposed methods, providing new ideas to evaluate these benefits.

Keywords Catastrophe evaluation · Emergy · Water resource utilization · Benefits

1 Introduction

Water is an indispensable resource for human survival and social development (Li et al. 2018a, b). With rapid economic growth and social development, many regions around

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the world have been confronted with increasingly severe water scarcity due to the overuse of water resources, unreasonable industrial, agricultural and domestic utilization, and negative natural responses to human activities (Chen et al. 2018; Wu et al. 2019a, b). Especially in urban areas with large populations and high water consumption, the discharge of water pollutants and the exploitation of water resources pose a daunting challenge to the sustainable development of the economy and society (Jia et al. 2018). Currently, the water crisis in almost all countries has not been solved fundamentally and is becoming more serious. Accordingly, performing relative studies on the benefits of water resource utilization is beneficial to the reasonable utilization and protection of urban water resources (Li et al. 2017).

Economic analysis, which adopts economic value as a target, is often used in the evaluation of water resource utilization benefits (Brown 2015; Ge et al. 2017). Wang (2009) proposed a system of integrated benefit assessment indices (SIBAI) with comprehensive reflections on social, economic and environmental interests based on the concept of sustainability and cyclic economic philosophy. Zhang et al. (2014) established a model for optimal agricultural water resource allocation by taking the maximization of the net irrigation benefit as a target. Alcon et al. (2013) compared the costs and benefits of reclaimed water use on an experimental mandarin farm in southeastern Spain with those of using surface water and a mixture of water sources. Based on 2010 figures, Fan et al. (2015) analyzed the costs and benefits of reclaiming and reusing Beijing's municipal wastewater. Cheng et al. (2016) developed a new bilevel optimization problem based on the 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. Varouchakis et al. (2016) applied cost-benefit risk analysis in water resources and Bayesian decision analysis to aid decision-making on whether to construct a water reservoir for irrigation purposes. Fu et al. (2018) provided a water resource allocation model and multi-objective optimization based on a cost-benefit analysis of watershed water resources. Song et al. (2018) measured province-level water resource efficiencies in China from both static and dynamic perspectives, applying the undesirable-output-based Malmquist-Luenberger productivity index to panel data for 30 provinces in China from 2006 to 2015. In addition, some new methods have been proposed to evaluate the benefits of water resource utilization. Meng et al. (2018) developed an inexact two-stage stochastic programming (ITSP) model for supporting water resource allocation for the four main water use sectors (industry, municipal, environmental and agriculture) and the total amount control of pollutant emissions. Xu et al. (2018) established an optimal water allocation model for industrial sectors based on water footprint accounting.

However, not only does the complexity of the water cycle contrast strongly with the poor data availability (Buytaert et al. 2012), but there are also difficulties in determining the economic value of life and the accurate weights of indices (Li et al. 2018a, b; Ge et al, 2020), limiting the practicability of analytical methods and the objectivity of the results. Therefore, the catastrophe and emergy methods were introduced to evaluate the benefits of urban water resource utilization, aiming at providing guidance on decision-making and policy formulation in urban water resource management.

2 Material and Methods

2.1 Profile of Urban Areas

Zhengzhou is the capital of Henan Province in China and is located north of the center of the province. Its total area is 7446.2 km^2. The amounts of its surface water resources are 867 Mm^3, its underground water resources are 865 Mm^{3,} and the repeated calculation are 393 Mm^3.

By the end of 2018, Zhengzhou had a population of 10.2 million. The gross domestic product (GDP) of industry and agriculture from 2012 to 2016 is shown in Table 1.

2.2 Benefits Analysis of Urban Water Resource Utilization

2.2.1 Categories of Urban Water Resource Utilization Benefits

Benefit of Supporting Life The primary function of an urban area is to provide a living space and an environment for its residents (Cai et al. 2016). Therefore, supporting life is the most important benefit provided by urban water resources. The input of various resources and energy enables residents to recover their labor and thus maintain their livelihoods. The labor recovery benefit of water resources is reflected mainly in the maintenance of human life and health, which is generally measured by the contribution of maintaining normal labor.

Benefit of Industry Production Most urban areas have well-developed industries to produce various kinds of goods for society, in which water resources are a kind of indispensable raw materials. The benefit of water resources for industrial production is reflected mainly in the aspects of raw materials and ensuring normal production (Bao et al. 2006).

Benefit of Agricultural Production In the suburbs of most urban areas, some agricultural production occurs, providing various kinds of food for urban residents (Ran et al. 2016). Water is a key restricting factor of agricultural production (Biggs et al. 2015) and plays a similar role to that in industrial production.

2.2.2 Index Analysis of Urban Water Resource Utilization Benefits

Output per Unit Water The output-input ratio can be used to effectively measure the value of raw materials. Therefore, output per unit water is one of the indices to evaluate the benefits of water resource utilization. Generally, as output per unit water increases, the benefits of water resource utilization increase.

Table 1 GDP of industry and agriculture in Zhengzhou (¥/billion)

Item	2012	2013	2014	2015	2016
Industry	293.31	322.86	348.71	360.42	379.69
Agriculture	14.05	14.49	14.71	15.09	15.64
Total	307.36	337.35	363.4.2	375.51	395.33

The Proportion of Water to Resource Inputs Not only water but also electricity and oil are raw materials to support life and/or the production of industry and agriculture. Typically, as the proportion of water to all resource inputs decreases, the efficiency of water utilization and the benefits of water resource utilization increase.

2.3 Evaluation of Urban Water Resource Utilization Benefits Based on Catastrophe Theory

2.3.1 Catastrophe Evaluation

Catastrophe Theory Catastrophe theory, which originated from the Whitney singularity theory of smooth mapping and the Poincare-Andronov equilibrium state bifurcation theory of dynamic systems, was systematically expounded by Thom (1977) in “The stability of structure and morphogenesis” and has been used to supervise the transition of a system from one state to another when control variables are changed.

Commonly Used Catastrophe Evaluation Model By studying the change in the minimum value of the state function (potential function) $F(x)$, the characteristics of the discontinuous change state near the critical point can be determined. Despite the profound mathematical knowledge of topology and singularity theory, the application models of catastrophe evaluation are relatively simple. The catastrophe evaluation method derived from catastrophe theory quantifies the relative importance of indices according to the internal contradictions and mechanisms in the normalization equations of the system and effectively reduces subjective factors in the evaluation. The method has been widely used in water system evaluation (Ahmed et al. 2015; Chen et al. 2016), water resource location (Sadeghfam et al. 2016), flood management (Al-Abadi et al. 2016), consequence evaluation of dam breaches, and so on (Ge et al. 2019).

When there are less than four control variables, there are at most seven forms of potential function $F(x)$. The commonly used types of mutations corresponding to the first four of the seven potential functions are the folding catastrophe, cusp catastrophe, swallowtail catastrophe, and butterfly catastrophe (Thom 2018). In a catastrophe model, normalization equations are used to convert different type states of control variables into the same type of comparable quantitative states, as shown in Table 2.

Then, the catastrophe evaluation value of the system can be obtained by a recursive calculation of the corresponding potential functions.

Standardization of Indices Due to the different dimensions involved, the indices should be standardized. The basic principle of “the-more-the-better” is adopted to standardize the indices.

Table 2 Commonly used catastrophe models

Type	Potential function	Normalization equation
Folding	$F(x) = x^3/3 + ax$	$x_a = a^{1/2}$, $x_b = b^{1/3}$
Cusp	$F(x) = x^4/4 + ax^2/2 + bx$	$x_a = a^{1/2}$, $x_b = b^{1/3}$, $x_c = c^{1/4}$
Swallowtail	$F(x) = x^5/5 + ax^3/3 + bx^2/2 + cx$	$x_a = a^{1/2}$, $x_b = b^{1/3}$, $x_c = c^{1/4}$, $x_d = d^{1/5}$
Butterfly	$F(x) = x^6/6 + ax^4/4 + bx^3/3 + cx^2/2 + dx$	$x_a = a^{1/2}$, $x_b = b^{1/3}$, $x_c = c^{1/4}$, $x_d = d^{1/5}$, $x_e = d^{1/6}$

The equation used to standardize the indices according to “the-bigger-the-better” is as follows:

$$R_i = \frac{r_i - r_{\min}}{r_{\max} - r_{\min}} \tag{1}$$

The equation used to standardize the indices according to “the-smaller-the-better” is as follows:

$$R_i = \frac{r_{\max} - r_i}{r_{\max} - r_{\min}} \tag{2}$$

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

2.3.2 Evaluation Index System of Urban Water Resource Utilization Benefits

The intrinsic mechanisms of catastrophe models mean that the importance of control variables should be reduced from left to right (Thom 2018). Therefore, combined with the analysis of categories and indices, a catastrophe evaluation index system of water resource utilization benefits was established, as shown in Fig. 1.

2.4 Emergy Analysis of Urban Water Resource Utilization Benefits

2.4.1 Emergy Theory

Emergy values are used to evaluate the flows of energy and resources that sustain the biosphere, including the economy of humans (Brown and Ulgiati 2018). Emergy measures the value of both energy and material resources within a common framework and has been used in water resource management (Wu et al. 2017), social value analysis (Wu et al. 2019a, b), ecological benefit evaluations and so on (Lv and Wu 2009; Brown et al. 2016; Sun et al. 2017; Wu et al. 2018).

Since solar energy is the original form of all energy, it is commonly used to quantify other forms of energy and is expressed in solar emjoules, abbreviated as sej. The amount of emergy

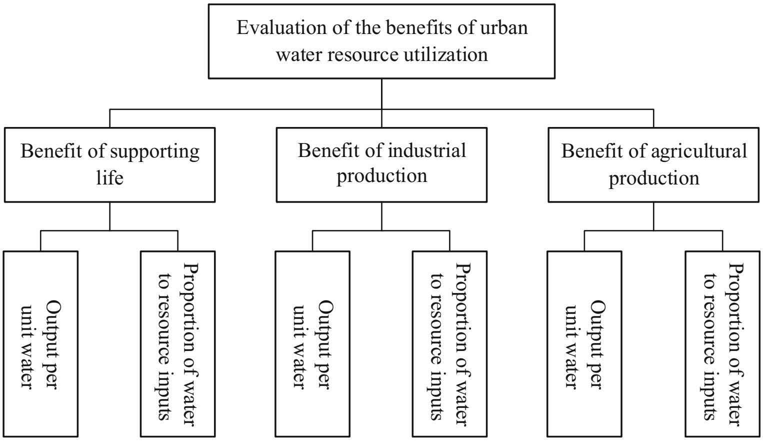

Fig. 1 Catastrophe evaluation index system of urban water resource utilization benefits

needed to generate one unit of product or service is defined as updated emergy transformity (UEV) and expressed with sej/unit (i.e., sej/g or sej/J) (Chen et al. 2017).

The conversion equation between emergy, substance and energy is as follows:

$$EM = \tau \times B \tag{3}$$

where EM is emergy (sej), τ is the emergy transformation ratio (sej/g or sei/J), and B is the amount of energy or substance.

2.4.2 Emergy Calculation of Urban Water Resource Utilization Benefits

Emergy Analysis of the Benefit of Supporting Life Residents mainly make use of the chemical energy of water in their daily lives. Meanwhile, water can be used as a medium for heat transfer. The process of water utilization in life can be abstracted as the input-output process. The input items are domestic water and other basic living materials such as grain and vegetables, and the output item is labor recovery. The proportion of water to resource inputs can be defined as the water contribution rate for life (WCR_l), as expressed in Eq. (4).

$$WCR_l = \frac{E_W}{E} \tag{4}$$

where E_W is emergy for per capita water utilization in one year and E is emergy for per capita input items in one year.

The per capita emergy output for water resource utilization for life (OW_l) is calculated by Eq. (5).

$$OW_l = \frac{WCR_l \times EC \times UDI}{10000} \tag{5}$$

where EC is Engel's coefficient, that is, the personal food expenditure/total personal consumption expenditure; UDI is urban per capita disposable income in one year.

Therefore, the emergy output for supporting life per unit water (OW_{ul}) can be calculated in Eq. (6).

$$OW_{ul} = \frac{OW_l}{W_{Cl}} \tag{6}$$

where W_{Cl} is the per capita water consumption amount in one year.

Emergy Analysis of the Benefits of Industrial and Agricultural Production The benefits of water resource utilization in industry and agriculture are reflected mainly in the emergy changes of different types of water after production.

The proportion of water to resource inputs for industrial or agricultural production can be defined as the water contribution rate for industry or agriculture (WCR_x), as expressed in Eq. (7).

$$WCR_x = \frac{E_{Wx}}{E_x} \tag{7}$$

where E_{Wx} is the emergy for water resources for production, E_x is the total emergy for resource inputs for production, and x corresponds to industry (i) or agriculture (a).

The emergy output for water resources for industrial or agricultural production (OW_x) is calculated by Eq. (8).

$$OW_x = WCR_x \times OP_x \tag{8}$$

where OP_x is the total emergy output for production and x corresponds to industry (i) or agriculture (a).

Therefore, the emergy output for production per unit water (OW_{ux}) can be calculated using Eq. (9).

$$OW_{ux} = \frac{OW_x}{W_{Cx}} \tag{9}$$

where W_{Cx} is the water consumption amount for production, and x corresponds to industry (i) or agriculture (a).

3 Results

Using the relevant statistical data and the above emergy calculation method, the benefits of water resource utilization in Zhengzhou from 2012 to 2016 are shown in Table 3.

Based on the catastrophe and emergy methods and the evaluation index system established above, the evaluation results for the water resource utilization benefits in Zhengzhou can be obtained. In addition, the average emergy output per unit water of all categories of water resource utilization ($(OW_l + OW_i + OW_a)/(W_{Cl} + W_{Ci} + W_{Ca})$), the emergy output for supporting life per unit water (OW_{ul}) and economic benefits of industry and agricultural production per

Table 3 Benefits of water resource utilization in Zhengzhou

Item		2012	2013	2014	2015	2016
Life	WCR_l (%)	19.64	16.48	19.83	20.86	19.11
	EC (%)	34.70	32.40	29.60	29.16	29.00
	W_C (¥/hundred)	367.77	406.24	445.65	482.24	516.40
	OW_l (10^{14} sej/人)	2506.46	2169.45	2615.68	2098.53	2861.65
	W_{Cl} (m^3)	89.56	88.47	88.57	88.98	90.12
	OW_{ul} (10^{12}sej/m^3)	27.99	24.52	29.53	23.58	31.75
Industry	E_i (10^{20} sej)	97.72	144.26	187.33	197.71	227.67
	E_{Wi} (10^{20} sej)	1177.64	2021.42	1981.24	2049.38	1946.73
	OP_i (10^{20} sej)	1982.19	2030.46	1785.10	1695.47	1608.10
	WCR_i (%)	8.30	7.14	9.46	9.65	11.70
	OW_i (10^{20} sej)	164.49	144.91	168.79	163.57	188.07
	W_{Ci} (10^8 m^3)	8.95	9.29	11.88	4.82	4.92
	OW_{ui} (10^{12} sej/m^3)	18.38	15.61	14.20	33.91	38.24
Agriculture	E_a (10^{20} sej)	5.78	7.99	8.83	8.05	9.48
	E_{Wa} (10^{20} sej)	75.01	60.54	60.67	58.32	62.52
	OP_a (10^{20} sej)	237.92	233.10	230.06	222.38	207.60
	WCR_a (%)	7.71	13.20	14.56	13.81	15.17
	OW_a (10^{20} sej)	18.34	30.78	33.50	30.71	31.49
	W_{Ca} (10^8 m^3)	4.28	4.43	4.69	4.75	5.12
	OW_{ua} (10^{12} sej/m^3)	4.28	6.95	7.15	6.47	6.15

Table 4 Benefits of water resource utilization in Zhengzhou

Item	2012	2013	2014	2015	2016
Catastrophe method	0.843	0.878	0.848	0.618	0.837
Average emergy output	0.340	0.351	0.317	0.280	0.267
Emergy output for supporting life	0.280	0.245	0.295	0.236	0.318
Economic benefits of production	0.232	0.246	0.219	0.238	0.231

unit water $((\mathrm{GDP}_i + \mathrm{GDP}_a)/(W_{Ci} + W_{Ca}))$ were adopted for comparison. For comparative analysis, all data were processed in the range [0,1]. The results are shown in Table 4.

The results are shown in Fig. 2.

4 Discussions

(1) From 2012 to 2016, the catastrophe evaluation results of the water resource utilization benefits in Zhengzhou exhibited a similar trend, with the average emergy output per unit water of all categories. However, due to the lowest emergy output for supporting life (0.236), which is the most important benefit of urban water resource utilization, the catastrophe evaluation value in 2015 (0.618) was the lowest under the condition that the average emergy output per unit water was relatively low (0.280). The results show that the methods proposed in this paper effectively consider the relative importance of indices in the process of evaluating water resource utilization benefits, whereas single emergy theory does not.

(2) The benefits of water resource utilization in Zhengzhou based on catastrophe theory for 2015 (0.618) were lower than those found using data for 2014 (0.848), which were consistent with the average emergy output for all categories (0.280 in 2015, 0.317 in 2014) and emergy output for supporting life (0.236 in 2015, 0.295 in 2014) per unit water. However, the economic benefit of production in 2015 (0.238) was higher than that in 2014 (0.219), which focused on the benefits of industrial and agricultural production but ignored the benefit of supporting life. Therefore, it is difficult for the

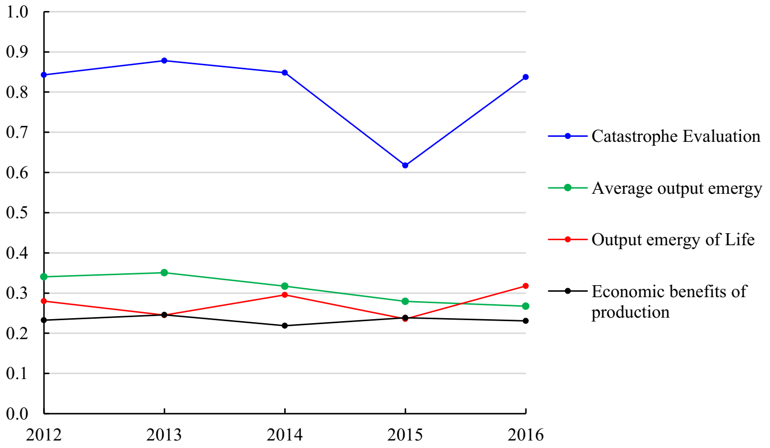

Fig. 2 Evaluation of urban water resource utilization benefits of Zhengzhou

current economic analysis method to comprehensively evaluate the benefits of urban water resource utilization.

(3) The emergy output for supporting life per unit water in 2013 (0.245) was relatively lower than that in 2012 (0.280) and 2014 (0.295). Nevertheless, the per capita water consumption amount in 2013 (88.47) was the lowest of all. Therefore, the benefits of urban water resource utilization in 2013 (0.878) based on catastrophe theory were the highest, in accordance with the results of average emergy output per unit water of all categories (0.351 in 2013). The results verify that not only output per unit water but also the proportion of water to resource inputs plays an important role in determining the benefits of urban water resource utilization. Therefore, on the basis of ensuring resident life, further water-saving measures should be taken to reduce per capita water consumption.

(4) The benefits of water resource utilization in Zhengzhou did not effectively improve from 2012 to 2016. Therefore, further measures that target the three benefits of supporting life, industrial production and agricultural production should be taken to increase the benefits of urban water resource utilization. In addition, attention should be paid to both the promotion of output per unit water and the reduction of the proportion of water to resource inputs. Due to the generality of the analysis method, the measures offer significant guidance for decision-making and policy formulation for other urban areas toward the promotion of water resource utilization benefits.

5 Conclusion

The scientific evaluation of benefits is of great significance for the rational planning of urban water resource utilization. Many indices affect the benefits of water resource utilization, for which accurate weights are difficult to determine. Meanwhile, some indices do not apply to the quantification of economic value. Therefore, evaluation indices and models based on catastrophe theory were established to evaluate urban water resource utilization. In addition, emergency theory was introduced in order to analyze energy conversion in the process of water resource utilization to measure the benefits. Taking Zhengzhou, China, as an example, the benefits of water resource utilization from 2012 to 2016 were analyzed, and the mechanisms of impact indices were identified. The methods proposed in this paper can be effectively used to guide the utilization and management of urban water resources.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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