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Study on Production, Domestic and Ecological Benefits of Reservoir Water Supply Based on Emergy Analysis

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Abstract: As an important water conservancy project, it is necessary to evaluate its water supply benefit. Based on the emergy analysis theory, a reservoir water supply benefits evaluation model (RWSBEM) was established. Firstly, the emergy transformity of natural and engineering water body was calculated. Secondly, the water resource values (WRV) of different water users (industrial, agricultural, domestic, ecological) were calculated. Finally, combined with the water supply situation of the reservoir, the various water supply benefits of the reservoir were calculated. Taking Hekoucun reservoir as an example, its ecological water supply benefit is the largest and agriculture is the smallest, followed by industry and life. The results showed that the trend of WRV was domestic > industry > ecology > agriculture, which reflected the contribution and utility of water resources in different industries. Under the condition of current water resources, the planned water supply benefits of the reservoir can be guaranteed in the wet and normal years, but in the dry years, the ecological benefit will be reduced. Therefore, the industry water-saving needs to be further strengthened, and the interannual regulation function of the reservoir should be applied more effectively to maximize the comprehensive benefits of reservoir water supply.

Keywords: RWSBEM; emergy theory; water transformity; WRV; water supply benefit

1. Introduction

In the past few centuries, population growth and socioeconomic development have multiplied the water consumption, resulting in more intense competition and contradiction in water resources [1,2]. The shortage of water resources has put restrictions on the development of social economic system, leading to the decline in quality of life, the decrease of industrial and agricultural production, the rise of water price and the sharp increase of contradictions among regions and even countries [3,4]. In addition, the shortage of water resources will also cause the imbalance of water ecological environment system, such as deterioration of water environment, water ecological degradation and the failure of ecosystem services, etc [5,6]. Water resources are limited within a certain range of time and space. Therefore, in the human-nature coupling ecosystem, how to coordinate the water use relationship among production, domestic and ecology is particularly important [7,8]. The multifunctional reservoir can optimize the allocation of water resources and coordinate the water conflicts of ecological and economic water as much as possible. The multidimensional benefits of reservoir water supply can quantify the water supply functional value of the reservoir.

With the strong demand for water resources in social economy development, more and more theories have been put forward to quantify the benefits of reservoir water supply mainly by calculating the water resource values (WRV) in various industries and combining with the water supply situation of the reservoir, in order to check and verify the water supply benefits of various industries of the reservoir. Among them, the calculation of WRV mainly adopted by economic methods is the key. At present, marginal opportunity cost model and shadow price model are the most widely used. The marginal opportunity cost model [9] refers to the value of other activities that must be given up when limited resources are engaged in an economic activity; the shadow price model [10] refers to the marginal contribution value of the limited resources to the social goals under the condition of optimal distribution and rational utilization. The benefits of reservoir production and domestic water supply have usually been studied with economic methods from the perspective of market. The economic-based decision models can well quantify the value of water resources. However, depending on economic markets, it is difficult to estimate the natural ecological benefits not closely related to the market economy. A method based on emergy is a supplement to the aspects that are difficult to quantify by the economic method, which is convenient for the unified measurement and calculation of the benefits of production, domestic and ecological water supply. Therefore, it is necessary to propose an evaluation method considering the benefits of reservoir production, domestic and ecological water supply to uniformly measure the benefits of water supply and realizing the optimal allocation of regional water resources.

It is difficult to quantify the ecological benefits and the value of ecological water resources. In the 1980s, the famous American scholar Odum founded the emergy theory system based on the energy system research [11]. As a bridge between ecology and economics, emergy theory can convert those unmeasurable values into quantifiable emergy values, which provides a scientific metric for the measurement value of natural resources [12]. At present, the research achievements of WRV based on emergy are concentrated on agriculture, industry and living system [13], which can give a foundation for the research on the benefits of reservoir production and domestic water supply. Aiming at the value of ecological water resources, it can be studied based on ecosystem service functions. Ecosystem service functions refer to the direct and indirect contributions of ecosystems to human well-being and subsistence [14], which can well represent the value of human-nature coupling ecosystem. At present, the research on ecological service functions has achieved more results [15,16]. Therefore, in view of the existing results, in this paper, the types and characteristics of ecosystem services were further analyzed, and a more complete and comprehensive emergy index system representing ecosystem services was proposed. Then, the benefits of reservoir production, domestic and ecological water supply can be uniformly measured through emergy, so as to realize the comprehensive evaluation and comparative analysis of the benefits of ecology and economics.

In summary, firstly, based on the emergy analysis theory, the RWSBEM was constructed in this paper, including three modules: multisource water body transformity, WRV and water supply benefit calculation module. Furthermore, the value of agricultural, industrial and domestic water resources was calculated by establishing the emergy value analysis table of each industry. The value of ecological water resources was calculated by constructing an ecosystem service function index system. Finally, taking Hekoucun reservoir in Henan Province of China as an example, combined with the planned water use situation of the reservoir, the water supply benefits of various industries in the water supply city were verified and compared. The model is complementary to the decision-making model in water resources economics, which can uniformly quantify the value of water resources in multiple industries. The water supply benefit of reservoirs is often calculated by the Gould–Dincer approach [17]. However, the water supply of a reservoir has multiple objects, and the water supply benefit of each water user should be different. This model can not only calculate the ecological benefits that other models are difficult to calculate but also calculate the benefits of industrial, agricultural and domestic water supply. The research results are expected to provide new ideas and models for the quantification of reservoirs water supply benefits and provide scientific references and technical supports for reservoir operation management.

2. Methods

Emergy is a new concept in the ecological economics that measures the products and processes of natural systems and economic systems. Using the direct and indirect cost of solar energy to evaluate any energy or material, emergy analysis is the new development of energy analysis not only in concept but also on calculation method. Based on the emergy analysis theory, the evaluation model of reservoir production, domestic and ecological water supply benefits were constructed, including three parts: multisource water body transformity, WRV and water supply benefit. Module 1 calculates the transformity of different water body. On this basis, the transformity of the water supply city's surface, underground natural and engineering water bodies are calculated. The results provide support for the WRV accounting modules of various industries in the water supply city. In Module 2, emergy systems of various industries are established by emergy analysis theory, the input–output relationship of each system is analyzed, the value of production and domestic water resources is calculated. Based on ecosystem services, a completer and more comprehensive index system is proposed to express the functions of ecological services. By quantifying these indexes, the value of ecological water resources is calculated. Through Module 2, the benefits brought by each cubic meter of water in various industries was obtained, and the economic development level of each industry and ecological environment was understood. Based on this, Module 3 combines the water supply volume of the reservoir in various industries in the water supply city and the downstream flow of the reservoir to obtain the ecology and economics benefits and total benefits of the reservoir. Through this module, the benefits of industrial, agricultural and domestic water supply of the reservoir can be obtained as well as the ecological benefits brought by the reservoir to the downstream. The water supply benefits of the reservoir are comprehensively discussed, so as to provide references for alleviating the contradiction of water use in various industries and rationally allocating water resources. The model structure is shown in Figure 1.

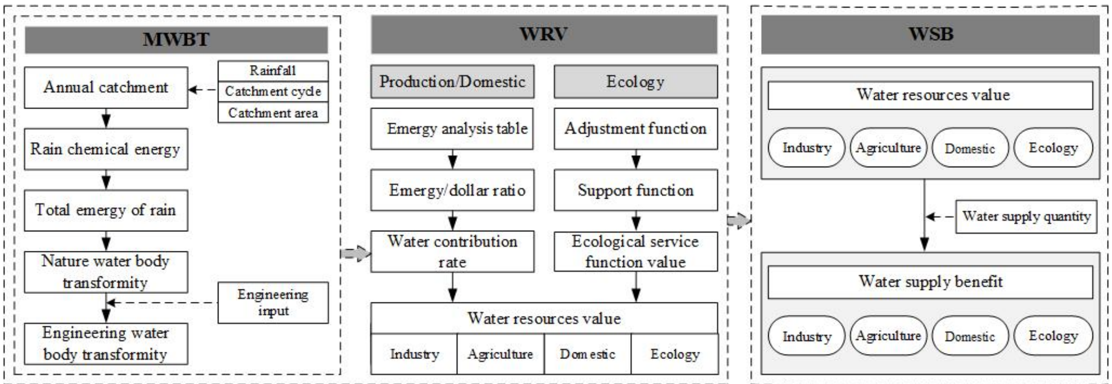

Figure 1. Structural diagram of reservoir water supply benefit assessment model.

2.1. Multisource Water Body Transformity Module

A key skill in emergy accounting is the ability to choose an appropriate transformity factor (or Unit Emergy Value, UEV, as it is often called) for the conversion of energy (in joules or kilowatthours) or matter (in gram or kilogram) to emergy (in sej). The equivalent emergy value per unit substance or energy is called the transformity of the substance or energy. For the ecoeconomic system of water resources supplied by reservoirs to cities, the conversion of rain energy is not enough. A more detailed water solar energy conversion classification needs to be calculated. Considering the characteristics of natural-artificial composite water circulation system, the water body is divided into three categories: precipitation, natural water and engineering water. The natural water refers to the surface water and groundwater formed after the hydrological process of precipitation; the engineering water is the surface and groundwater body with the added value of development after considering the project input. The transformity of natural water is different from that of engineering water. Taking the time difference of water circulation into consideration, that is, the difference of annual rainfall and runoff, the former can be calculated according to the confluence or infiltration process. On this basis, the engineering water also needs to consider the investment of engineering funds, labor and technology. The specific calculation method is as follows:

(1) Natural water transformity

$$\tau_{ik}^{A} = EM_{ik}/AW_{ik} \tag{1}$$

$$EM_{ik} = CE_{ik} \times \tau_p \tag{2}$$

$$CE_{ik} = P_{ik} \times G \tag{3}$$

$$AW_{ik} = (F_i \times P_{ik})/U_{ik} \tag{4}$$

In the above formulae, τ_{ik}^{A} is the transformity of k-th natural water in the i-th city, where k = 1,2, which is expressed as surface and underground successively, in units of sej/J; EM_{ik} is the total emergy of the k-th rainwater in the i-th city, in units of sej; CE_{ik} is the k-th rain chemical energy in the i-th city, in units of J/a; AW_{ik} is the annual catchment of the k-th natural water in the i-th city, in units of m^3; τ_p is the transformity of rainwater, using 18,100 sej/J [18]; P_{ik} is the k-th rainfall in the i-th city, in units of mm; G is Gibbs free energy for rain, using 4.94 × 10^6 [18]; F_i is the catchment area of the i-th city, in units of m^2; U_{ik} is the catchment cycle, in units of a.

(2) Engineering water transformity

In the calculation of engineering water, water conservancy project is regarded as a whole project, and according to the input and output of the engineering system, the engineering water transformity is analyzed and calculated. The calculation formula is as follows:

$$\tau_{k}^{E} = EMI_k/EW_k \tag{5}$$

In the formula, τ_{ik}^{E} is the transformity of the k-th engineering water in the i-th city, in units of sej/J; EMI_{ik} is the annual total emergy inputs of the k-th project in the i-th city, in units of sej; EW_{ik} is the water quantity of the k-th input project in the i-th city, in units of m^3.

2.2. Water Value Accounting Module

The value of water resources is divided into two parts. Part 1: calculation of production and domestic water resource values. The emergy system of different industries in each city within the scope of reservoir water supply is established, the input and output of the material and corresponding emergy in the system are analyzed, the emergy analysis table is compiled and the emergy/currency ratio (EDR), water contribution rate (WCR) and WRV are calculated in turn. Part 2: the total value of ecosystem service function can be obtained by identifying the regulation and supporting service functions of ecosystem and calculating the subdivision items of ecosystem service function of each city. Combining with the regional water resources, the ecological water resource value is obtained.

2.2.1. Production and Domestic Water Resources Value

(1) Emergy/Money Ratio (EDR)

The EDR is defined as the equivalent emergy of the unit currency in a country (or region) [19]. EDR can realize the mutual conversion between currency and emergy. The EDR is calculated by dividing the total emergy used by the GDP for the economy in a given year. Its calculation formula is as follows:

$$EDR_i = EM_{iU}/GDP_i = (EM_{iR} + EM_{iN} + EM_{iF} - EM_{iEX})/GDP_i \tag{6}$$

In the above formula, EM_{iU} is total emergy used for the i-th city, in units of sej; EM_{iR} is renewable emergy, in units of sej; EM_{iN} is nonrenewable emergy, in units of sej; EM_{iF} is feedback emergy, in units of sej; EM_{iEX} is export emergy, in units of sej.

(2) Water contribution rate (WCR)

The WCR is the ratio of water resources emergy value invested in the system to the total emergy value invested. Assuming that the water supply scope of reservoir involves m cities, establishing the *i*-th city's agricultural, industrial and life emergy system, analyzing material inputs and outputs and determining the transformity of each material. The multisource water body transformity adopts the calculation results of Module 1, and the emergy analysis table is prepared. The calculation formulae are as follows:

$$WCR_i^A = WUE_i^A / EI_i^A \quad (7)$$

$$WCR_i^I = WUE_i^I / EI_i^I \quad (8)$$

$$WCR_i^D = WUE_i^D / EI_i^D \quad (9)$$

$$EI_i^A = \sum_{j=1}^{n_1} EI_{i,j}^A \quad (10)$$

$$EI_i^I = \sum_{j=1}^{n_2} EI_{i,j}^I \quad (11)$$

$$EI_i^D = \sum_{j=1}^{n_3} EI_{i,j}^D \quad (12)$$

In the above formulae, for the *i*-th city, WCR_i^A, WCR_i^I and WCR_i^D are the contribution rates of agriculture, industry and domestic water resources, respectively, in %; WUE_i^A, WUE_i^I, WUE_i^D are the emergy of water resources invested by various industries, in units of sej; EI_i^A is the total energy input of agricultural system, with n_1 inputs in total, mainly including renewable resource inputs, such as solar, wind, chemical emergy for agriculture water, etc. and nonrenewable resource inputs, such as topsoil loss, renewable organic energy input, etc. such as human resource, animal power, organic fertilizers, seeds, nonrenewable agricultural auxiliary inputs, etc. such as electricity, diesel, machinery, fertilizers, pesticides, agricultural film, etc. in units of sej; EI_i^I is the total emergy input of industry system, with n_2 inputs in total, mainly including renewable resources inputs, such as solar wind, water chemical energy, etc. and nonrenewable resources inputs, such as raw coal and coal products, electric energy, labor, raw materials, etc. in units of sej; EI_i^D is the total emergy input of life system, which mainly includes basic materials such as domestic water, food, vegetables and nonfood.

(3) Water resources value (WRV)

The water resources value can be defined as the function and utility of water resources in supporting and maintaining the existence and operation of the ecoeconomic system. It is accompanied by the circulation and flow of water resources in the ecoeconomic system and manifested in ecoeconomic functions such as products, labor services, maintaining of ecological balance, improving of social welfare and purifying of sewage waste [20].

$$EP_i^A = (M_i^A / EDR_i) / W_i^A \quad (13)$$

$$EP_i^I = (M_i^I / EDR_i) / W_i^I \quad (14)$$

$$EP_i^D = (M_i^D / EDR_i) / W_i^D \quad (15)$$

$$M_i^A = WCR_i^A \times EO_i^A \quad (16)$$

$$M_i^I = WCR_i^I \times EO_i^I \quad (17)$$

$$M_i^D = WCR_i^D \times EO_i^D \quad (18)$$

In the above formulae, for the i-th city,EP_i^A, EP_i^I, EP_i^D are respectively industrial, agricultural and domestic WRV, in units of Yuan/m^3; M_i^A, M_i^I, M_i^D are the water resources production emergy value of the corresponding industry, in units of sej; W_i^A, W_i^I, W_i^D are water consumption of corresponding industries, in units of m^3; EO_i^A, EO_i^I, EO_i^D are the total output emergy of the corresponding industry, in units of sej.

2.2.2. Ecological Water Resources Value Accounting

In this paper, the economic value of ecological water resources is defined as the economic value corresponding to the maintenance of ecosystem service function within a limited space-time range, that is, the ratio of emergy value generated by ecosystem services to water resources, and then converted to economic value through EDR. The main functions of surface water resources for ecological natural systems services include adjustment and support functions [21]. The adjustment function refers to the environmental condition and utility beneficial to production and life formed by the water ecosystem through its ecological process. Supporting function means the aquatic ecosystem function to maintain natural ecological process and regional ecological environment conditions. The specific functional breakdown items include the followings.

(1) Support service function

a. Biology diversity Value. Biology is an important part of the ecosystem and biological gene bank is a huge treasure trove of information, which contains a variety of genetic materials. The calculation is as follows:

$$EM_b = N \times R \times \tau_b \tag{19}$$

In the above formula, EM_b is the biological diversity value, in units of sej; N is the total number of biological species in the study area; R is the proportion of biological activity area to global area, in %; τ_b is the transformity of global species, using 1.26×10^{25} sej/species [22].

b. Net primary productivity value. Net primary productivity is the energy value that producers can use for growth development and reproduction. It is also the material basis for the survival and reproduction of other biological members in the ecosystem. The calculation is as follows:

$$EM_{bpp} = A_{npp} \times p_{npp} \times \tau_{npp} \tag{20}$$

In the above formula, EM_{bpp} is the net primary productivity value, in units of sej; A_{npp} is the area of aquatic plants in the study area, in units of m^2; p_{npp} is the biomass per unit area of aquatic plants in the waters, in units of g/m^2; τ_{npp} is the transformity of biomass, using 5.11×10^6 sej/g [14].

c. Value of carbon fixation and oxygen release. Photosynthesis is of great significance for achieving energy conversion in nature, maintaining carbon-oxygen balance in the atmosphere and maintaining residents' activities. Water plays an irreplaceable role in photosynthesis. Without water, there will be no photosynthesis. The calculation is as follows:

$$EM_t = \sigma_{CO_2} \times p_t \times S_t \times \tau_{CO_2} + \sigma_{O_2} \times p_t \times S_t \times \tau_{O_2} \tag{21}$$

In the above formula, σ_{CO_2}, σ_{O_2} is carbon fixation and oxygen release coefficient respectively; p_t is the average productivity of vegetation, in units of g/hm^2; S_t is vegetation area, in units of hm^2; τ_{CO_2}, τ_{O_2} is the transformity of carbon dioxide and oxygen respectively, in units of sej/g.

d. Value of nitrogen releasing from sediment. It is greatly significant to reduce water eutrophication. The nitrogen release value of sediment can be calculated as follows:

$$EM_n = V_n \times P_n \times \tau_n \tag{22}$$

In the above formula, V_n is annual runoff, in units of m^3; P_n is the concentration of nitrogen released from the sediment, in units of mg/L; τ_n is the transformity of nitrogen, using 3.8×10^8 sej/g [23]. The calculation formula of ecological support service value is as follows:

$$EM_1 = EM_b + EM_{bpp} + EM_t + EM_n \tag{23}$$

(2) Adjustment service function

a. Self-purification value. Water has a certain self-purification capacity, and the amount of pollutants in water naturally degraded and reduced is the self-purification value of water body. The calculation is as follows:

$$EM_s = \sum_{1}^{n} (M_1 - M_2) \times \tau_{bp} \times Q \tag{24}$$

where, EM_s is the self-purification value of water body, in units of sej; M_1, M_2 is the pollutant content of upstream and downstream section surface water, in units of g/m^3; τ_{bp} is the transformity of each pollutant, in units of sej/g; Q is the river flow, in units of m^3.

b. Value loss of water pollution (negative value). The biggest difference between sewage and purified water lies in the difference of emergy transformity, which is mainly because the work of domestic water production process changes the transformity the water body, making it sewage. Therefore, the value of loss water pollution can be obtained by superscalar of pollutant and corresponding emergy transformity. The calculation is as follows:

$$EM_l = \sum_{1}^{n} (C_1 - C_2) \times \tau_{bp} \times Q \tag{25}$$

where, EM_l is the value loss of water pollution, in units of sej; C_1, C_2 is the measured pollutant concentration in the section and the water quality standard value in the functional area where the section is located, in units of g/m^3.

c. Climatic regulation value. When the water body evaporates, it takes a lot of heat away and changes the climate conditions, such as inducing rainfall and increasing humidity. Therefore, the energy of water evaporation is the energy of water regulating the climate, that is, the emergy of water evaporation is the benefit of regulating climate. The calculation is as follows:

$$EM_x = L \times S_x \times \tau_v \tag{26}$$

In the above formula, EM_x is the climatic regulation value, in units of sej; L is the latent heat of evaporation, and its relationship with temperature t is $L = 2507.4 - 2.39t$, in units of j/g; S_x is evaporative water, in units of g; τ_v is the emergy transformity of vapor, using 12.20 sej/J [24].

d. Sediment transportation value. Sediment transportation is an important hydrological phenomenon in rivers, which has a significant impact on river changes. The sediment transport of river provides conditions for further flood discharge and drainage and greatly improving the flood carrying capacity of the river. The value of sediment transportation is calculated as follows:

$$EM_{st} = R \times S \times \tau_{st} \tag{27}$$

In the above formula, EM_{st} is the sediment transportation value, in units of sej; R is the annual runoff of the river, in units of m^3; S is the sediment-carrying capacity of flow, in units of g/m^3; τ_{st} is the transformity of sediment, in units of sej/g. Ecological regulation service value is calculated, as follows:

$$EM_2 = EM_s + EM_l + EM_x + EM_{st} \tag{28}$$

Ecological water resources value is calculated, as follows:

$$EP^E = (EM_1 + EM_2)/(W \times EDR) \tag{29}$$

In the above formula, EM_1 is the ecological support service value, in units of sej; EM_2 is the ecological regulation service value, in units of sej; W is the regional surface quantity, in units of m^3.

2.3. Water Supply Efficiency Quantitative Model

According to the calculation, the water resources value of each industry in each region can be obtained. Combined with the water quantity provided by the reservoir to various industries and the ecological flow at the downstream of the reservoir, the total benefits of the reservoir water supply can be calculated. The formula is as follows:

$$B = B^A + B^I + B^D + B^E \tag{30}$$

$$B^A = \sum_i^N B_i^A = \sum_i^N EI_i^A \times WC_i^A \tag{31}$$

$$B^I = \sum_i^N B_i^I = \sum_i^N EI_i^I \times WC_i^I \tag{32}$$

$$B^D = \sum_i^N B_i^D = \sum_i^N EI_i^D \times WC_i^D \tag{33}$$

$$B^E = \sum_i^N B_i^E = \sum_i^N EP_i^E \times W^E \times T \tag{34}$$

In the above formulae, B is the total reservoir benefits, in units of yuan; B^A, B^I, B^D, B^E are the agricultural, industrial, domestic and ecological water supply benefits of the reservoir, respectively, in units of Yuan; B_i^A, B_i^I, B_i^D, B_i^E are water supply benefits of various industries in the i-th city, in units of Yuan; WC_i^A, WC_i^I, WC_i^D are the water supply of various industries in the i-th city, in units of m^3; W^E is the ecological flow of the downstream section of the reservoir, in units of m^3/s; T is time conversion unit.

3. Study Area and Data

The research object of this paper is Hekoucun reservoir and the corresponding water supply city. The Hekoucun reservoir, located at the outlet of the last section of the Qinhe River, a tributary of the Yellow River in China, about 9 km below the Wulongkou Hydrological Station, is an important part of the flood control engineering system in the lower Yellow River. The control basin area of

Hekoucun reservoir is 9223 km^2, and the annual average reservoir runoff is 492 million m^3, with a total storage capacity of 317 million m^3. The water supply scope of the reservoir involves Jiyuan City and Jiaozuo City in Henan Province, among them, Jiyuan City includes Jiyuan City Domestic and Industry, Huaneng Qinbei Power Plant, and Jiaozuo City includes Qinbei Industry Cluster and Guangli Irrigation District. In addition, the ecological flow of the Wulongkou and Wuzhi section downstream of the reservoir should be taken into account. The Qinhe River Basin and the water supply city are shown in Figure 2. The location distribution of each water user is shown in Figure 3. According to the hydrological regime for many years, the basic ecological flow of Wulongkou and Wuzhi sections is estimated by Tennant method to be 5.44 m^3/s and 3.84 m^3/s. Based on the current water demand, the government reasonably plans to evaluate the water demand of various industries in 2030, as shown in Table 1. Under the condition that the basic ecological flow of the downstream reaches of the reservoir is up to the standard, the water demand of various industries should be met as much as possible, and the benefit of ecological and economic water supply for the Hekoucun reservoir planning is calculated.

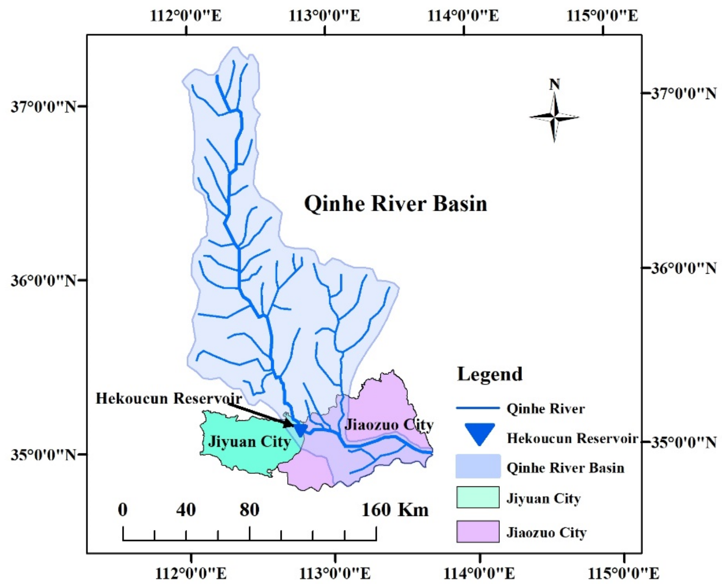

Figure 2. Map of Qinhe river basin and water supply cities.

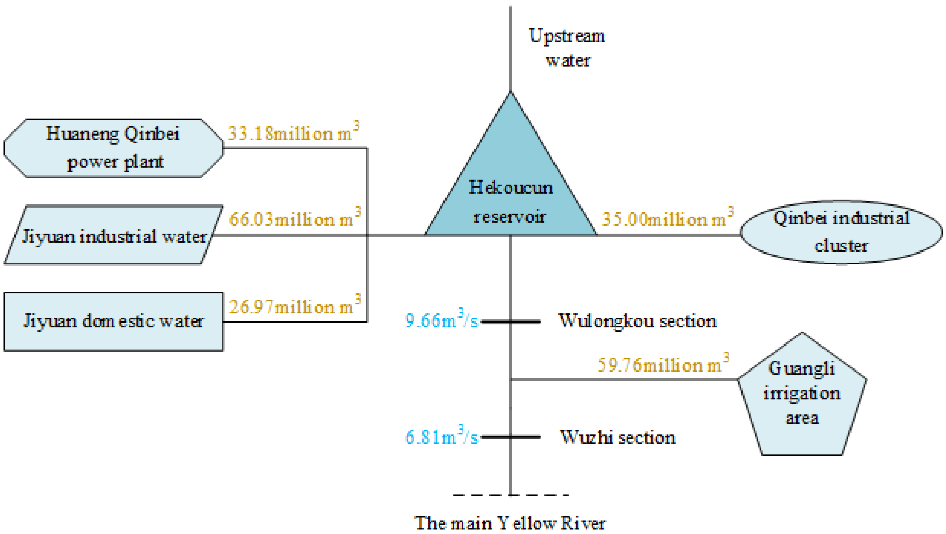

Figure 3. Distribution diagram of water users.

Table 1. Water demand allocation scheme of Hekoucun reservoir in 2030 (million m^3).

Hekoucun Reservoir Water Supply Households				
Items	**Agricultural**	**Industrial**	**Domestic**	**Ecological Flow**
Jiyuan	0	6603	2697	9.66
Jiaozuo	5976	2485	1015	6.81

4. Result

4.1. Natural and Engineering Water Body Transformity

Calculated the natural and engineering water transformity of Jiaozuo City and Jiyuan City in the water supply area of Hekoucun Reservoir through Equations (1)~(5), where, $i = 2$, representing two water supply cities, $k = 2$, representing surface and underground water. According to the collected data, the water resources of Jiyuan and Jiaozuo are shown in Table 2. According to the Equations from (1) to (4), firstly, the annual catchment, rain chemical energy and rain total emergy of urban surface and underground natural water bodies were calculated. Then, the surface and underground natural water body transformity was obtained by dividing the total emergy of rain by the annual catchment. The construction input, operation and maintenance input and other inputs of each city's water conservancy project were aggregated into the total project input emergy value, and the corresponding emergy conversion rates were obtained by dividing the total project input emergy value by the amount of surface and ground water invested in the project.

Table 2. Basic situation of water resources in the study area.

Items	Area (km^2)	Rainfall (mm)	Surface Water Resources (10^8 m^3)	Ground Water Resources (10^8 m^3)	Total Water Resources (10^8 m^3)
Jiyuan	1898.71	664.8	1.60	1.43	3.03
Jiaozuo	4070.10	580.0	2.91	5.27	8.18

Through the calculation formulas of transformity of water body introduced above, the transformity of surface, underground natural water body and engineering water body of Jiyuan and Jiaozuo in 2018 can be calculated. The results are shown in Table 3.

Table 3. Emergy transformity of Jiyuan and Jiaozuo water bodies in 2018 (10^{11} sej/m^3).

Items	Jiyuan		Jiaozuo	
	Surface	**Underground**	**Surface**	**Underground**
Natural water body	7.04	14.24	7.27	13.70
Engineering water body	13.25	16.54	12.08	15.48

4.2. Production, Domestic and Ecological Water Resources Value

(1) Production and domestic

The EDR of Jiyuan and Jiaozuo, the contribution rate of water resources and the value of water resources in various industries (Industry, agriculture and domestic) were calculated through Equations (6)~(18). The industrial emergy system table of Jiyuan City in 2018 was displayed (Table 4), where renewable resources are solar energy and wind energy, and the data of Jiyuan whole area was taken. Nonrenewable resources investment includes energy, raw materials, operating expenses, fixed assets investment, etc. The data of various types of energy was converted into standard coal for easy calculation. Raw materials, labor and fixed assets investment were expressed in monetary quantities.

Table 4. Emergy inputs and outputs within and outside Jiyuan industrial system.

	Items	Raw Data	Unit	Transformity (sej/unit)	Emergy (10^{20})
1	Total inputs				1×10^{22}
1.1	Renewable environmental resources				1.40×10^{20}
1.1.1	Solar	1.07×10^{19}	J	1 *	1.07×10^{19}
1.1.2	Wind	1.60×10^{16}	J	6.33×10^{2} *	9.99×10^{18}
1.1.3	Industrial water	6.11×10^{7}	m^3		1.19×10^{20}
1.1.3.1	Engineering water from surface water	2.50×10^{7}	m^3	1.33×10^{12}	6.73×10^{19}
1.1.3.2	Engineering water from groundwater	3.61×10^{7}	m^3	1.65×10^{12}	5.22×10^{19}
1.2	Nonrenewable environmental resources				9.9×10^{21}
1.2.1	Raw coal and coal products, other fuels	9.68×10^{16}	J	4.00×10^{4} *	3.87×10^{21}
1.2.2	Natural gas	1.04×10^{15}	J	4.80×10^{4} *	4.99×10^{19}
1.2.3	Gasoline and other fuel oil	1.61×10^{14}	J	6.60×10^{5} *	1.06×10^{20}
1.2.4	Electric power	2.58×10^{16}	J	1.60×10^{5} *	4.12×10^{21}
1.2.5	Raw materials, labor, Depreciation of fixed assets	4.01×10^{9}	Yuan	4.35×10^{11}	1.74×10^{21}
2	Total outputs				4.66×10^{22}
2.1	Raw coal production	5.08×10^{16}	J	4.00×10^{4} *	2.03×10^{21}
2.2	generated energy	8.61×10^{16}	J	1.60×10^{5} *	1.38×10^{22}
2.3	Steel	6.77×10^{12}	g	1.40×10^{9} *	9.48×10^{21}
2.4	Aluminum	5.07×10^{10}	g	1.60×10^{10} *	8.11×10^{20}
2.5	Petrol and diesel	1.03×10^{16}	J	6.60×10^{4} *	6.77×10^{20}
2.7	Fuel oil	1.10×10^{15}	J	5.40×10^{4} *	5.96×10^{19}
2.8	Nonferrous Metals	1.32×10^{11}	g	3.57×10^{9} *	4.72×10^{20}
2.9	Gas	9.05×10^{14}	J	6.02×10^{4} *	5.45×10^{19}
2.10	Cement	3.77×10^{12}	g	2.07×10^{9} *	7.80×10^{21}
2.11	Glass	1.69×10^{11}	g	8.40×10^{8} *	1.42×10^{20}
2.12	Plastic	2.20×10^{10}	g	3.80×10^{8} *	8.35×10^{18}
2.13	Ceramic	2.50×10^{9}	g	1.85×10^{9} *	4.63×10^{18}
2.14	Agrochemistry product	2.72×10^{10}	g	2.38×10^{9}	6.47×10^{19}
2.15	Machine paper and cardboard	4.88×10^{11}	g	3.90×10^{9} *	1.90×10^{21}
2.16	Tap water	1.21×10^{13}	g	3.05×10^{7} *	3.70×10^{20}
2.17	Chemical preparation and detergent	6.17×10^{12}	g	1.00×10^{9} *	6.17×10^{21}
2.18	Food	2.38×10^{9}	Yuan	4.35×10^{11}	1.04×10^{21}
2.19	Textile product	1.07×10^{9}	Yuan	4.35×10^{11}	4.65×10^{20}
2.20	Wood processing and machine manufacturing	6.53×10^{8}	Yuan	4.35×10^{11}	2.84×10^{20}
2.21	Mechanical product	6.7×10^{15}	t	6.7×10^{15} *	7.82×10^{20}
2.22	Transportation equipment manufacturing	5.50×10^{8}	Yuan	4.35×10^{11}	2.39×10^{20}
	WCR %				1.32

Transformity of Table 4 marked with "*" from Wu (Wu et al. 2019). Other Tr without "*" are calculated with the original data.

According to Equation (6), the total renewable emergy, total nonrenewable emergy, total feedback emergy and export emergy in Jiyuan City were calculated statistically. By dividing the total emergy value of input by the GDP of Jiyuan City, the EDR of the city was 4.35×10^{11} sej/Yuan. According to Table 4, added 1.1 in table and 1.2 in table to get the emergy total inputs (1 in table). In the table, 1.1.3 divided by the emergy total inputs to obtain jiyuan city industrial WCR was 1.32%. Then, the contribution rate is multiplied by the emergy total outputs to get the industrial water resource production emergy value, which is converted into economic value after dividing by the EDR and finally divided by the total industrial water consumption to get the industrial WRV of Jiyuan which was 15.55 Yuan/m^3.

The agricultural and domestic energy value analysis table were made in turn to obtain the corresponding EDR, WCR and WRV, as shown in Table 5.

Table 5. Emergy/currency ratio (EDR), water contribution rate (WCR) and water resource values (WRV) of each industry.

Items.	Jiyuan Industrial	Jiyuan Agriculture	Jiyuan Domestic	Jiaozuo Industrial	Jiaozuo Agriculture	Jiaozuo Domestic
EDR (sej/Yuan)	4.35×10^{11}	4.35×10^{11}	4.35×10^{11}	3.37×10^{11}	3.37×10^{11}	3.37×10^{11}
WCR (%)	1.32	13.03	21.77	1.30	21.75	23.52
WRV (Yuan/m^3)	15.55	4.56	23.68	16.04	7.35	24.30

(2) Ecology

According to Equations from (19) to (30), the values of ecological services and ecological water in Jiaozuo were calculated. The value of ecological water resources was 8.14 yuan/m^3, as shown in Table 6.

Table 6. Ecological service value of Jiyuan.

Class I	Class II	Emergy(sej)	Money(Yuan)
Adjustment service value	Water Self-purification	1.36×10^{19}	4.04×10^{7}
	water pollution loss	2.21×10^{19}	6.57×10^{7}
	regulation climatic	6.48×10^{19}	1.92×10^{8}
	Sediment transportation	1.31×10^{20}	3.01×10^{8}
	Subtotal	1.87×10^{20}	4.68×10^{8}
Support service value	biodiversity	1.02×10^{21}	3.04×10^{9}
	Net primary productivity	8.61×10^{18}	2.56×10^{7}
	carbon fixation and oxygen release	3.58×10^{19}	1.06×10^{8}
	Nitrogen releasing in sediment	2.37×10^{19}	7.05×10^{7}
	Subtotal	1.09×10^{21}	3.24×10^{9}
	Total	1.28×10^{21}	3.71×10^{9}
Ecological water value (Yuan/m^3)		8.14	

4.3. Benefits of Water Supply in Hekoucun Reservoir

Through the above calculations, the water resources value of Jiyuan and Jiaozuo industries in 2018 can be obtained, as shown in Figure 4. The water supply efficiency of the various industries of Hekoucun reservoir can be calculated through the water supply of Hekoucun reservoir and the ecological flow of the downstream section of the reservoir, as shown in Table 7.

Table 7. Water supply benefits of various industries(10^8 Yuan).

Items	Industry	Agriculture	Domestic	Ecology
Reservoir water supply benefits	14.25	4.39	8.72	24.80

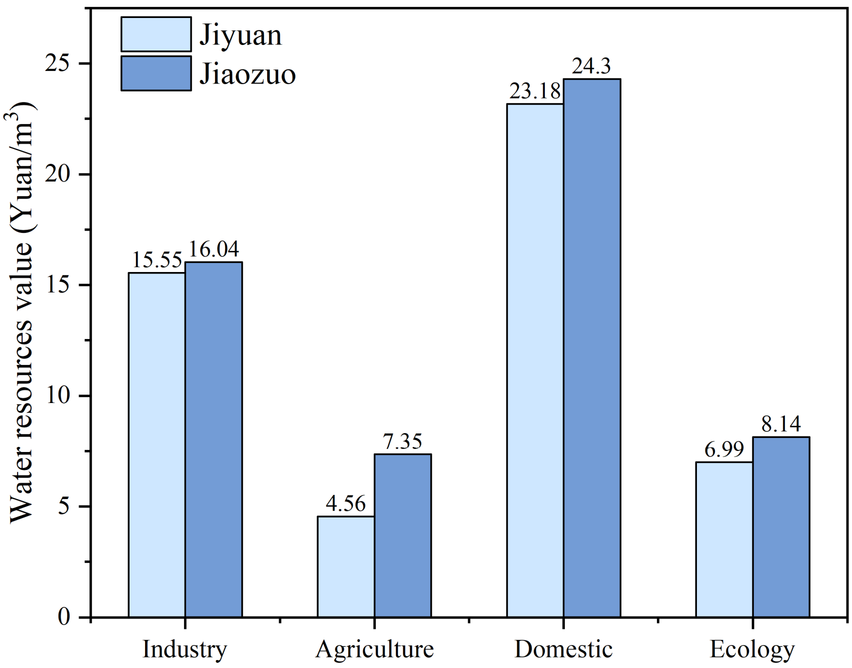

Figure 4. Water resources value of Jiyuan and Jiaozuo.

5. Discussion

5.1. Differences in Water Resources among Industries

Whether in Jiyuan or in Jiaozuo, there are obvious differences in the water resources value of various industries by analyzing the calculation results of water resources value. The trend of water resources value is domestic > industry > ecology > agriculture, as shown in Figure 4, which is consistent with the law of WRV in most parts of the world.

Domestic water supply is a necessary condition for human survival and has the highest priority in reservoir water supply. The research results also show that the value of domestic water resources is the highest. In the operation of reservoir operation, the water can be supplied to other industries after satisfying the basic water demand of human life. In addition, since domestic water is for human consumption, strict water quality requirements are also required. According to China's drinking water sanitation standard (GB5749-2006), the domestic water source should reach the class III water standard. According to the statistics on the water quality status of the reservoirs in Henan Province, only 40% can be up to standard. Therefore, most of the reservoir water sources can be used for domestic water after processing, which also provides the value of domestic water resources. In the production industry, the value of industrial water resources is significantly higher than that of agriculture. Analyzing the reasons, this is in line with the general market economic law that agricultural output is far less than industrial products, but agriculture is the basis of human survival, and national food security is the prerequisite for stable social development. Therefore, agricultural water prices are subsidized by the state government. On the other hand, the guaranteed rate of industrial water (over 95% in China) is significantly higher than that of agriculture (generally over 50% in China). So industrial water is more dependent on reservoir operation. It is difficult for industry to flexibly adjust production to adapt to different levels of annual coming water conditions, while agriculture can change planting structures.

This study analyzes the ecosystem service functions and obtains the value of ecological water resources by quantifying the ecological value generated after satisfying these ecosystem service functions. However, the value of ecological water resources is higher than the actual situation. In fact, on the one hand, the sewage standards are set too low, and humans are overly reliant on the self-purification ability of water bodies. On the other hand, the punishment is relatively low, and the compensation amount is far lower than the treatment cost after humans pollute the water environment.

5.2. Reservoir Water Supply Benefit Analysis

Reservoir water supply benefits are related to emphasis on reservoir function and water resource prices. The calculation results show that in terms of reservoir production and domestic water supply, industry > domestic > agricultural water supply benefits. Analyzing the reasons, the production and domestic benefits are generally in line with the industry's WRV law. However, because the Hekoucun reservoir has provided water for the main industrial areas of Jiaozuo and Jiyuan, the industrial water consumption is much larger than other industries. In order to reduce the pressure of water supply in reservoir planning, it is necessary to further adjust the industrial structure, reduce heavy industry and high-water consumption industry and further improve industrial water-saving technology.

In addition to providing human survival and development, reservoirs also need to protect the ecological environment within a certain range. The suitable ecological flow of Wulongkou and Wuzhi sections in downstream of the reservoir is 5.44 m^3/s and 3.84 m^3/s, respectively. Only by maintaining the suitable ecological flow can the basic ecological benefits of the reservoir be guaranteed. Based on the actual situation of the 59-year runoff data of Wulongkou from 1956 to 2015, the frequency curve is drawn, as shown in Figure 5. It can be seen that in the case of planning, the ecological benefits can be guaranteed in the wet year and the normal year, but in the dry year, the ecological benefits will be destroyed, with a difference of 1.93×10^8 Yuan from the planning year, as shown in Figure 6. Therefore, the interannual regulation function of the reservoir in the medium and long-term planning is very important to ensure that the reservoir can meet the basic ecological benefits at all levels.

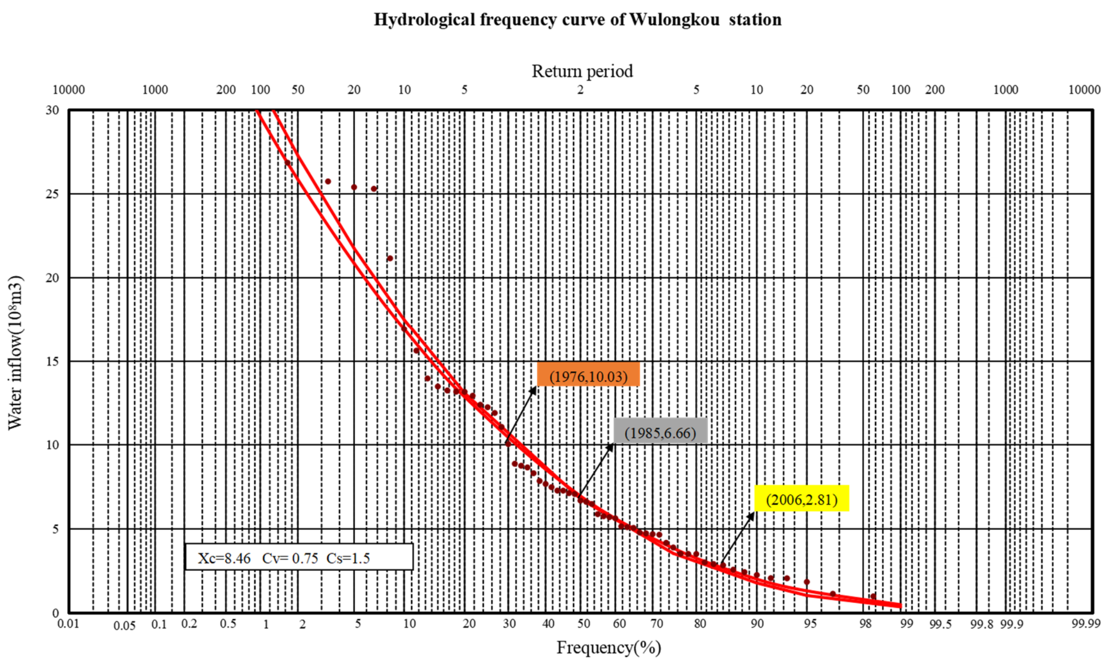

Figure 5. Hydrological frequency curve of Wulongkou hydrological station.

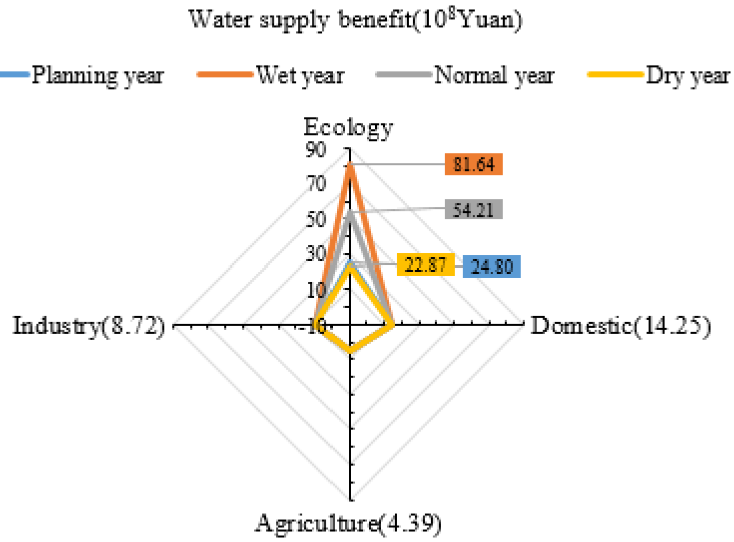

Figure 6. Water supply benefits of Hekoucun reservoir in different types of years.

6. Conclusions

Based on the emergy analysis theory, the evaluation model of reservoir production, domestic and ecological water supply benefits were constructed in this paper, which is complementary to the decision-making model in water resources economics, including three parts: multisource water body transformity, WRV and water supply benefit. Taking Hekoucun reservoir as an example, the results show that, in terms of production and domestic water supply, the benefit of industrial water supply is greater than domestic water supply agricultural water supply. In terms of ecology, the current amount of water resources can only guarantee the ecological benefits in wet and normal years but will be destroyed in dry years. Therefore, the government should take into account the adjustment of industrial structure and the application of the interannual adjustment function of the reservoir, strengthen the ecological environment protection, give full play to the huge benefits of the ecosystem service functions and reasonably allocate water resources.

The study of the multidimensional water supply benefits of reservoirs is beneficial to coordinate the competition among production, domestic and ecological water use, alleviate water conflicts and maximize the water supply benefits of reservoirs. The water supply benefit model proposed in this paper can accurately calculate the benefits of reservoir industry, agriculture, domestic and ecology and has certain application value.

However, the functions of the reservoir cover a wide range. Further research in the future should consider not only the water supply benefits of reservoirs but also take into account and disaster prevention and mitigation benefits of the reservoir. The theories and methods for calculating the value of water resources in various industries proposed in this article can enrich the ecological compensation accounting methods. For the basins or regions, ecological compensation calculation can be carried out by industry. The calculation of the water resources value of each industry, especially the value of ecological water resources, provides support for the calculation of ecological compensation.

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