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Research on quantification method of water pollution ecological environment losses

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ABSTRACT

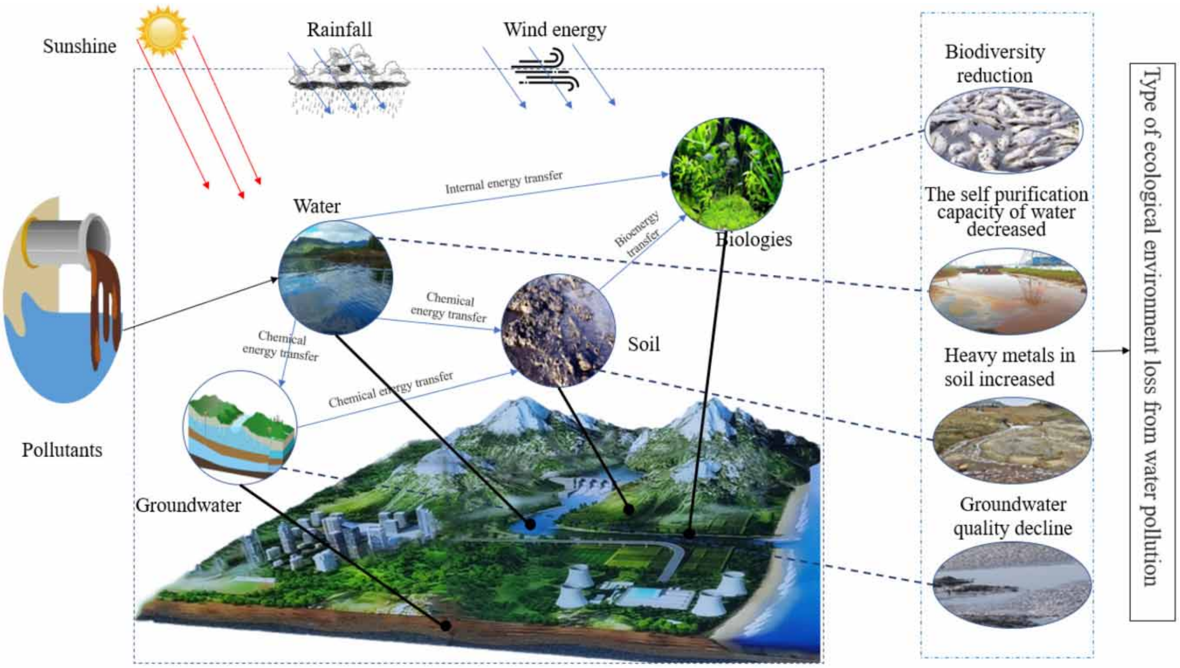
Economic and social development have worsened the situation of water pollution and even the ecological environment. It is helpful to quantify the water pollution ecological environment losses for decision-makers to formulate reasonable pollution control plans. However, the current quantitative analyses led by economic methods are not comprehensive and systematic. Therefore, based on the emergy theory and method system of eco-economics, this study analyzed the internal energy flow process of the water-polluted ecosystem, discussed the composition of water-polluted ecological environment loss, and proposed a quantitative model of water-polluted ecological environment loss based on the emergy analysis method. It can reasonably quantify the ecological environment loss caused by water pollution and provide a reference for optimizing regional industrial layout, scientifically formulating pollution control planning, and promoting the sustainable development of the ecosystem. Taking Kaifeng City in Henan Province as an example, the rationality of the model is verified. The results show that the annual average total energy value of water pollution ecological environment loss in Kaifeng City is 3.83×10^{20} sej, equivalent to 145 million yuan (0.76) of Kaifeng's gross domestic product (GDP) in 2018.

Key words: ecological environment losses, emergy quantification, Kaifeng City, water pollution

HIGHLIGHTS

- This study analyzed the internal energy flow process of the water-polluted ecosystem.
- This study discussed the composition of water-polluted ecological environment loss.
- This paper is based on the emergy theory and method system of eco-economics and proposed a quantitative model of water-polluted ecological environment loss based on the emergy analysis method.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water is a fundamentally natural and strategic economic resource that plays a vital role in promoting economic and social development (Wu *et al.* 2021). But the rapid development of the global economy has aggravated the interference of human activities on natural rivers, which leads to the frequent occurrence of water pollution and the degradation of river ecological functions. As a result, economic, industrial, and social development in most countries have led to an increase in water pollution and to varying degrees of damage to regional ecological systems (Xu 2020). For a long time, River water resources provide a wide range of necessary ecosystem services (Ćosić-Flajsig *et al.* 2020). The role of the ecological environment system in supporting economic and social development is rarely measured by price, so its ecological functions are always regarded as 'free' services for humans (David 1997; Niu 1997). This is not conducive to the benign development of the ecological environment system. Quantitative research on water pollution ecological environment losses is conducive to understanding the threat in front of the ecological environment intuitively, which is of strategic significance for the sustainable regional development.

Several quantitative research on ecological environmental loss focuses on the quantitative assessment of ecological environmental cost and gradually formed the environmental economic loss assessment method system represented by the willingness assessment method, benefit-cost method, and market value method (Jatropha 2007; Yang *et al.* 2015; He & Wu 2017). Kopsidas (2017) used the willingness assessment method to calculate how much they might be WTP (Willing to Pay) for supporting activities concerning the preservation/restoration of the Lake Kastoria and Akhtar *et al.* (2017) used willingness assessment to quantify the willingness of individuals to pay for improved air quality in Lahore, Pakistan. Results revealed that 92.5% of respondents showed a positive willingness to pay and the average predicted willingness to pay by each person was $9.86 per month.

Sun *et al.* (2020) calculated the economic and environmental benefits of rainwater utilization measures in urban sponge community by using the benefit-cost method and made a comparative analysis with its cost, which proved that rainwater utilization in sponge community has better investment benefits. Jia *et al.* (2022) used the VEST model and machine learning method to effectively evaluate the impact of the ecological retreat (ER) project on water conservation in the Yellow River Basin and the specific value of comprehensive water production benefits. In addition, Joseph *et al.* (2021) used the cost-benefit method to analyze the ecological service value of multi-function small reservoirs in northern Ghana and optimize the ecosystem service flow from small reservoirs to wider communities. Cai *et al.*

(2020) used the market value method and other methods to evaluate the farmland ecosystem service value of Qingdao in 1997, 2002, 2007, 2012, and 2017, and established the index system of farmland ecosystem service value. The results showed that the total value of farmland ecosystem services increased year by year. Wang *et al.* (2013) evaluated the ecological environment loss caused by lead pollution of typical lead-acid battery enterprises in Taizhou with the market value method, and the results showed that the total loss of lead pollution was 1.2183 million yuan, of which the cost of soil remediation and monitoring accounted for 77.1%. Gastineau *et al.* (2021) proposed a spatial theoretical framework to calculate some values of ecological compensation.

To sum up, most of the current quantification of ecological environment losses is based on the monetary theory of traditional economics, starting from the externality of the system without analyzing the changes within the system. However, money, essentially the equivalent of human labor, can only reflect the value of human labor. Besides, its circulation is independent of nature, so the environmental losses cannot be measured comprehensively only by the monetary theory. In 1987, Odum proposed the emergy analysis method from the perspective of ecological economics. This method is used in the continuous evaluation research on natural ecosystems, agricultural ecosystems (An *et al.* 1998; Lefroy & Rydberg 2003), urban ecosystems (Huang & Hua 2003), and regional ecosystems (Higgins 2003) widely, and it evaluates the possible impact of human production activities on the ecosystem through the emergy analysis, providing decision-making guidance for ecological management and ecological design (Prado & Brown 1997).

Based on the emergy theory, this paper has discussed the quantification method of water pollution ecological environment losses. According to the flow characteristics of pollutants in water and energy flow in the ecological environment system, the composition of water pollution ecological environment losses has been analyzed for a quantitative method system of water pollution ecological environment losses to be proposed. Kaifeng City, a key promotion city for water ecological civilization construction in Henan Province, should undertake arduous tasks in the prevention and control of water pollution and water ecology. Quantification could intuitively show the amount of water pollution ecological environment losses, supporting decision-making for the protection and governance of the water ecological environment in Kaifeng City in the new era, providing theoretical and methodological references for the quantification of water pollution environmental losses in other areas, and effectively promoting the process of regional ecological protection and high-quality development.

1.1. Overview of study area

Kaifeng City, located at 113°–115 °E longitude, 34.5°–35.5 °N latitude, is about 125 km from east to west and 87.5 km from north to south, with land area of 5,077 km^2 (Feng 2008). The geographical location is shown in Figure 1. There are many rivers in Kaifeng, belonging to the Yellow River and Huaihe River basins, and two Level 1 water functional areas and five Level 2 water functional areas in downtown. According to Kaifeng Municipal Water Resources Bulletin (2018), the discharge of waste water and sewage in Kaifeng City in 2018 was 145.1133 million tons, most of the water function areas were seriously polluted, and only a few months of the year met the standard. Water quality monitoring at five sections of five major rivers, including Kaifeng section of the Yellow River, Guohe River, Jialu River, Huangbian River, and Huiji River, showed that the current water environment in Kaifeng City was worrisome (the water quality of the Yellow River section was Class III, the Guohe River and the Huiji River were in Class IV, and the other rivers were Class V). See Figure 2 for some on-site investigations.

2. RESEARCH METHODS

2.1. Analysis of the composition of water pollution ecological environment losses

Clean water is an indispensable essential resource on which humans and other living beings depend (Wu & Wang 2022). Therefore, it is of great significance to analyze the composition of ecological environment loss caused by water pollution and understand the value of loss for water pollution control. The composition of water pollution ecological environment losses should be analyzed according to the flow characteristics of pollutants in water body and the circulation process of energy in ecological environment system.

1. After entering the water body, pollutants flow with the material circulation process of the ecosystem and cause the accumulation of water pollutant year by year (Jamwal *et al.* 2020). Water pollution damages the aquatic ecosystem, which is aquatic organisms' necessary habitat for survival and reproduction. Aquatic flora and fauna and shoreline plants thereupon reduce and biodiversity gradually decreases.

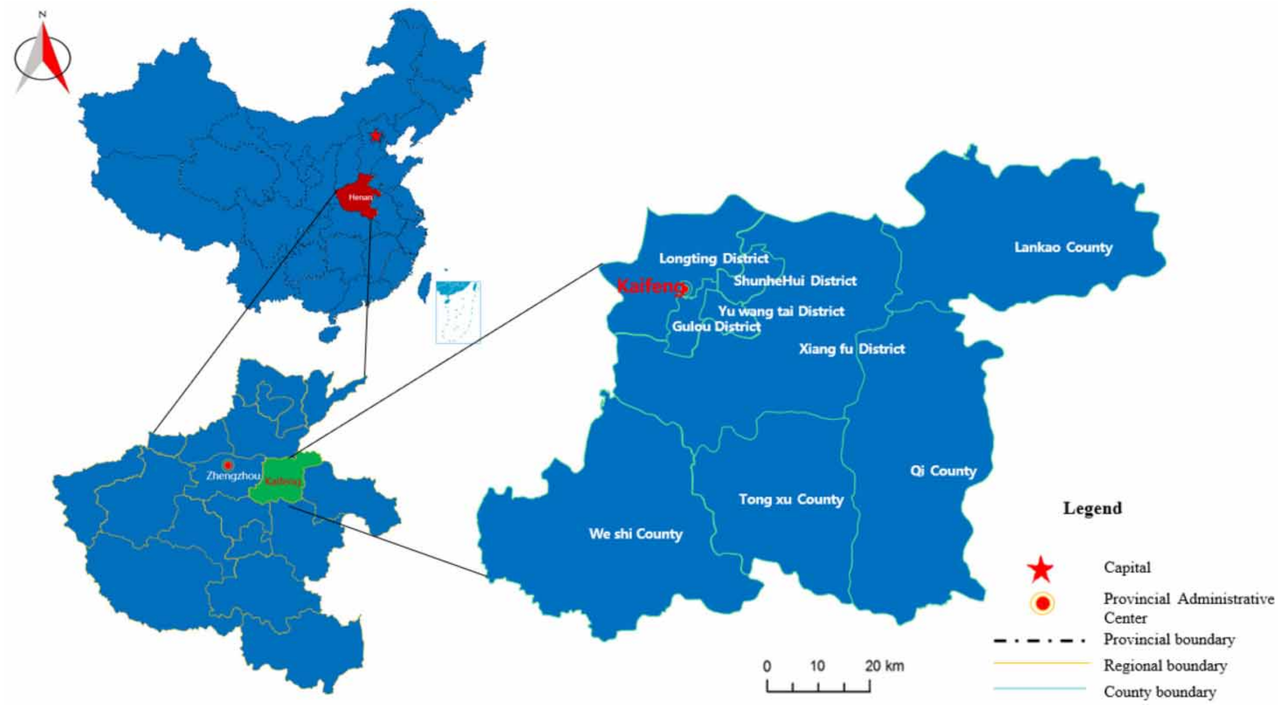


Figure 1 | The geographical location and administrative divisions overview of Kaifeng City.

Figure 2 | Current status of water pollution of Kaifeng City.

2. The self-purification ability of natural water to reduce pollutant concentration through dilution and self-purification is limited. If the concentration of pollutants into the water exceeds the limit, the water quality will continue to deteriorate. Water pollution increases the burden of water self-purification. This leads to a decrease of the self-purification capacity of water body and leads to the water body self-purification loss.
3. As the water cycle processes, pollutants flow along with it, then the pollutants will enter the water body and cause infiltrate. Then, the composition, structure, and function of the soil are changed due to the infiltrated polluted water. Microbial activities in soil are inhibited, so harmful substances and their decomposition products gradually accumulate in soil and cause soil pollution loss.
4. In addition, the chemical composition, physical properties, and biological characteristics of the groundwater would change if contaminated surface water invaded the groundwater aquifer along with the hydrological cycle. Therefore, the decline of groundwater quality leads to the loss of groundwater pollution.

Based on the above analysis for the characteristics of pollutant flow in different stages of water cycle in the ecosystem, the specific composition of water pollution ecological environment loss was proposed as follows: biodiversity loss, water self-purification loss, groundwater pollution loss, and land pollution loss.

2.2. Quantification of ecological environment losses from water pollution

2.2.1. Emergy theory

Th emergy theory was proposed by the famous American Ecologist H. T. Odum in the late 1980s (Lv *et al.* 2020). After continuous enrichment and development, a set of systematic emergy theory and method system has been formed. The emergy analysis method breaks through the limitation that traditional economics and energy analysis methods cannot quantify the value of different qualitative resources uniformly and provides a unified platform for quantitative analysis and the evaluation of natural and economic activity products and services (Lan & Odum 1994). Energy analysis can convert the energy of different types of energy in the ecosystem into the same standard solar energy value through transformity, so that various forms of energy in the system are additive and comparable, which is convenient for quantitative analysis. Some scholars have applied the emergy analysis method to the eco-economic evaluation of water resources system and achieved fruitful results (Brown *et al.* 2010; Wu *et al.* 2018; Lv *et al.* 2020). The formula is as follows:

$$EM = \tau B \quad (1)$$

where EM is solar emergy (sej), τ is transformity (sej/J or sej/g), and B is energy or quantity of matter (J or g).

The emergy theory and analysis method realize the conversion between the solar energy value and traditional currency through the emergy/dollar ratio (EDR), to solve the difficult problem of measuring the values of natural resources and economic and social currency uniformly (Wang & He 2015).

The EDR represents the ratio of the total annual energy input to the national (or regional) economic system to the current year's monetary circulation flux (gross national product (GNP) or gross domestic product (GDP)) through which water pollution ecological environment losses can be monetized. The formula is as follows:

$$CCY = EM/EDR \quad (2)$$

where CCY is currency (¥) and EDR is emergy/dollar ratio (sej/¥).

The emergy theory perfects the insufficiency of traditional economic methods. By the emergy theory, this paper has considered the loss in the process of water pollution fully and established the emergy quantification method for water pollution ecological environment losses from the perspective of ecological methodology.

2.2.2. Energy system diagram for water pollution ecological environment losses

According to the energy flow, conversion and storage process, and the flow path of pollutants in ecological environment system, the various energy flows and logistics in ecological environment system are classified and summarized, and the energy system diagram of water pollution ecological environment losses are shown in Figure 3.

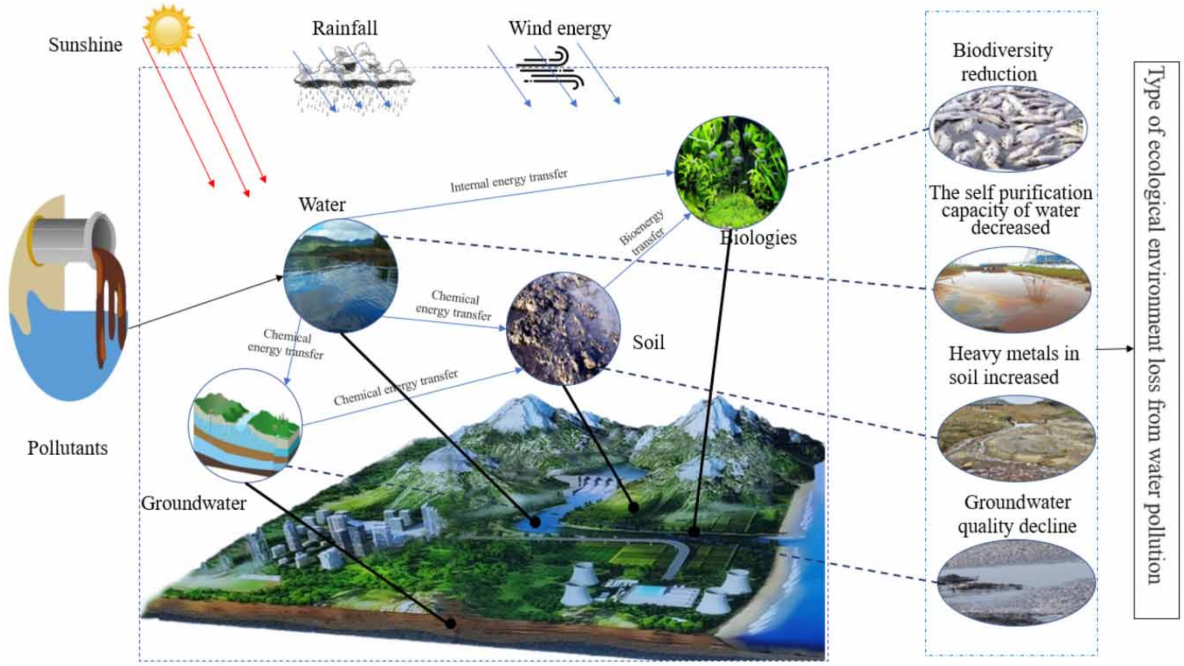


Figure 3 | Energy system diagram of ecological environment loss from water pollution.

In the energy system diagram, the flow, transformation, storage process of the main energy flow, and the flow path of the pollutants in the system can be seen clearly, and the input–output relationship of energy in different links pollutant flow process is clarified. According to the flow process and manifestation of pollutants of water cycle in Figure 3, a quantitative method for the loss of all stages of the material cycle in eco-environmental system caused by water pollution is proposed based on the emergy analysis method.

2.2.3. Emergy quantification method of water pollution ecological environment losses

(1) Biodiversity loss

The aquatic environment provides a necessary living environment for various aquatic organisms. The form and function of plants are largely determined by the availability of water for plants, and it also provides a suitable space for the survival and reproduction of many terrestrial animals, which is called 'Noah's Ark' by many organisms (Wang *et al.* 2020; Randall *et al.* 2021). As shown in Figure 3, the aquatic organisms and the shore slope animals and plants are affected at first when the water environment is polluted, then causing biodiversity loss. The biodiversity loss from water pollution can be calculated by the τ_{Species} (species emergy value), N (the total number of aquatic organisms in the area), and R (the ratio of biological activity area to the global area, $5.21 \times 10^{14}\,\text{m}^2$) (Lv *et al.* 2020). The calculation formula is as follows:

$$EM_{\text{bio}} = \tau_{\text{Species}} \times N \times R \tag{3}$$

where $\tau_{\text{Species}} = 1.26 \times 10^{25}$ sej/Species (Lan & Lu 2002).

(2) Water body self-purification loss

Water and aquatic organisms are the main contributors to the self-purification ability of water body. They absorb, transform, and utilize pollutants in water body by catalyze physical, chemical, and biological reactions directly or indirectly to degrade and remove the pollutants (Chabokpour *et al.* 2020). The self-purification ability of water body is related to the pollutants number in the water body closely. The entering of pollutants into water body can lead to the increase of pollutants number directly. Then, the pollutants work on pure water and generate energy flow. The pure water is turned into sewage. Thus, the self-purification ability of the water body is reduced, resulting in water body self-purification loss. Therefore, the water self-purification loss is calculated by the emergy of pollutants entering river multiply by the self-purification coefficient of polluted water. The calculation formula is as follows:

$$EM_j = \sum_{i=1}^{n} W_i \times f_i \times \tau_i \quad (4)$$

where EM_j is water self-purification loss value (sej), W_i is pollutant emissions into the river (g), f_i is self-purification coefficient of pollutants into river, and τ_i is solar transformity of pollutants into the river (sej/g).

(3) Groundwater pollution loss

Groundwater is an important water supply source of ecological environment system and also a key component of water ecological environment system (Sobia *et al.* 2018). The influence on the health of groundwater environment caused by increasing pollutants in ecological environment system deepens constantly. It can be seen from Figure 3 that when the surface water is polluted, the groundwater is bound to be polluted, resulting in the decrease of groundwater quality. From the perspective of emergy analysis, pollutants do work on the water body during the flow process and change the water transformity. Therefore, the groundwater pollution loss can be calculated according to the difference of solar transformity before and after pollution. The loss calculation formula is as follows:

$$EM_D = (\tau_{WB} - \tau_{WA}) \times W_D \times r_D \times G_D \quad (5)$$

where τ_{WA} is solar transformity of pre-polluted water (sei/J), τ_{WB} is solar transformity of polluted water (sei/J), W_D is quantity of contaminated groundwater (m^3), γ_D is water density (1×10^6 g/m^3), and G_D is Gibbs free energy of water relative to the surrounding environment (J/g).

(4) Soil pollution loss

Soil, water, and atmosphere are the important components of an ecosystem, in which soil is one of the main carriers of various pollutants in the environment. It is also the final destination of some pollutants (Zhu *et al.* 2015). As shown in Figure 3, the water pollution led to soil pollution eventually, which in turn reduced crop yields and quality. Then it caused the loss of soil pollution. The loss calculation formula is as follows:

$$EM_{soil} = Q \times \frac{S_w + S_d}{S_z} (R_i + R_q) \times EDR \quad (6)$$

where EM_{soil} is soil energy loss (sej), Q is gross agricultural production (10^{10}¥), S_w is area of sewage irrigation area (km^2), S_d is cultivated land area in groundwater pollution area (km^2), S_z is total cultivated area (km^2), R_i is agricultural product yield reduction rate, and R_q is quality loss rate of agricultural products. According to the research results of Wei & Su (2004) R_i is 5% and R_q is 10%.

3. RESULTS AND DISCUSSION

In 1980, China was in the early stage of economic development, and the degree of ecological environment damage caused by water pollution was low, which was close to the natural state. Therefore, this paper takes 1980 as the base year and 2012–2018 as the research period to quantitatively analyze the water pollution ecological environment losses in Kaifeng City, Henan Province.

3.1. Quantification of water pollution ecological environmental loss in Kaifeng City

Based on the relevant data in the *Kaifeng City Water Resources Bulletin* and the *Kaifeng Statistical Yearbook*, water pollution ecological environment losses in Kaifeng were calculated by the quantitative formula proposed above. Due to the lack of data on aquatic species in Kaifeng City in 1980, the biological species data of the Henan section of the Huai River Basin were used because most of the area in Kaifeng City belonged to the Huai River Basin. The conversion rate of solar energy value of water body is calculated according to the method proposed by Lv *et al.* (2020), and the conversion rate of solar energy value comes from the achievement of Lanshengfang. Other data sources are clearly given below.

Table 1 | Calculation table of water pollution ecological environment losses in Kaifeng City from 2012 to 2018

Items	Parameter	2012	2013	2014	2015	2016	2017	2018
Water self-purification loss[a]	COD emissions (t)	76,838.42	72,875.24	72,044.89	71,409.43	5,659.03	14,752.33	15,650.46
	Ammonia nitrogen emissions (t)	7,982.00	7,277.52	6,750.70	6,785.17	566.38	2,774.16	2,497.27
	COD water self-purification coefficient (/d)	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	Ammonia nitrogen water body self-purification coefficient (/d)	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	COD transformity (10^4 sej/g)	3.16	3.16	3.16	3.16	3.16	3.16	3.16
	Ammonia nitrogen transformity (10^9 sej/g)	2.80	2.80	2.80	2.80	2.80	2.80	2.80
	COD water self-purification loss (10^{14} sej)	3.73	3.54	3.50	3.47	0.28	0.72	0.76
	Self-purification loss of ammonia nitrogen (10^{18} sej)	4.02	3.67	3.40	3.42	0.29	1.40	1.26
	Water self-purification loss (10^{18} sej)	4.02	3.67	3.40	3.42	2.86	1.40	1.26
Biodiversity loss[b]	Species difference between base year and current year (species)	86						
	Species transformity (10^{25} sej/ species)	1.26	1.26	1.26	1.26	1.26	1.26	1.26
	The ratio of the area of biological activity to the total area of the world (10^{-7})	3.45	3.45	3.45	3.45	3.45	3.45	3.45
	Biodiversity loss (10^{20} sej)	3.74	3.74	3.74	3.74	3.74	3.74	3.74
Groundwater pollution loss[c]	Transformity of water energy value before pollution (10^5 sej/J) (III)	3.73	3.73	3.73	3.73	3.73	3.73	3.73
	Transformity of water energy value after pollution (10^5 sej/J) (IV)	3.83	3.83	3.83	3.83	3.83	3.83	3.83
	Transformity of water energy value after pollution (10^5 sej/J) (V)	3.91	3.91	3.91	3.91	3.91	3.91	3.91
	Contaminated groundwater (10^6 m^3) (IV)	3.53	2.98	3.91	4.06	4.03	4.45	4.59
	Contaminated groundwater (10^6 m^3) (V)	3.53	2.98	3.91	4.06	4.03	4.45	4.59
	Gibbs free energy of water relative to surrounding environment (J/g) (IV)	8.11	6.86	8.99	9.34	9.27	10.23	10.56
	Gibbs free energy of water relative to surrounding environment (J/g) (V)	5.02	5.02	5.02	5.02	5.02	5.02	5.02
	Groundwater pollution loss (10^{17} sej)	4.91	4.91	4.91	4.91	4.91	4.91	4.91
Land pollution loss[d]	Gross agricultural production (10^{10}¥)	2.85	3.07	2.70	2.79	2.88	2.77	2.88
	Total cultivated area (km^2)	3,940.4	3,940.4	3,940.4	3,940.4	3,940.4	3,940.4	3,940.4
	Area of sewage irrigation area (km^2)	66.70	66.70	66.70	66.70	66.70	66.70	66.70
	Cultivated land area in groundwater pollution area (km^2)	99.00	99.00	99.00	99.00	99.00	99.00	99.00
	Soil energy loss (10^{18} sej)	6.09	6.39	5.45	5.14	4.94	3.56	3.32

Note: [a]According to the *Kaifeng City Water Resources Bulletin*, the main pollutants in Kaifeng City's rivers are COD and ammonia nitrogen. The data of pollutant emissions are cited from the Kaifeng City Water Resources Bulletin (2012–2018), and the transformity of each pollutant and self-purification coefficient of polluted water are cited from Research results of Odum (1994) and Zhang *et al.* (2015).

[b]The species data of the base year are cited from the research results of Wei *et al.* (1991), and the species data of research period are data in 2015 and research results of Min *et al.* (2016). The number of species in the base year is 86 more than that of species in research period.

[c]Due to data limitation, the amount of contaminated groundwater is calculated by the area ratio method. The related water transformity refers to the literature, and the data of contaminated groundwater area are cited from the research results of Cui & Xu (2008).

[d]The data of land output value and cultivated land area are from the Kaifeng City Statistical Yearbook (2013–2019) and Kaifeng City Water Resources Bulletin (2012–2018). S_d is the area of cultivated land in the contaminated groundwater area and S_z is the total cultivated land. (The data of area are from the *Special Research Report on the Coordination of Land Use and Ecological Environment Construction in Kaifeng City*).

Table 1 shows that the values of biodiversity loss, water self-purification loss, groundwater pollution loss, and land pollution loss caused by water pollution in Kaifeng City from 2012 to 2018. And the summary of water pollution ecological environment losses is shown in Table 2. Based on the analysis of the proportion of each water pollution ecological environment losses in Kaifeng City in 2012–2018, the proportion chart (Figure 4), an energy value trend map (Figure 5), and a trend map (Figure 6) were drawn.

3.2. Result analysis of ecological environment losses from water pollution

1. The analysis of Figure 4 shows that the values of biodiversity loss, water body self-purification loss, groundwater pollution loss, and soil pollution loss in Kaifeng City from 2012 to 2018 are 3.74×10^{20}, 2.49×10^{18}, 9.98×10^{17}, and 4.99×10^{18} sej and accounted for 82.52, 4.86, 0.79, and 10.83%, respectively. The multi-year average total emergy of water pollution ecological environment losses was 3.83×10^{20} sej, equivalent to 145 million yuan in currency and accounting for 0.76‰ of Kaifeng's gross national income (GNI) in 2018. In general, the biodiversity loss accounts for the largest proportion of all losses, followed by land pollution loss and water body self-purification loss. Groundwater pollution loss accounts for a relatively small proportion. It is related to the actual situation of Kaifeng City that the aquatic organisms are harmed firstly when the water body is polluted. In addition, the time span in this paper is long and the species may change greatly. Secondly, there are sewage irrigation area and groundwater pollution area in the Huiji River Region. The large sewage irrigation area results in a higher proportion of soil loss among ecological environment losses from water pollution.

Table 2 | Summary table of water pollution ecological environmental losses in Kaifeng City from 2012 to 2018

Years	2012	2013	2014	2015	2016	2017	2018	Average
Biodiversity loss (10^{20} sej)	3.74	3.74	3.74	3.74	3.74	3.74	3.74	3.74
Water self-purification loss (10^{18} sej)	4.02	3.67	3.40	3.42	0.29	1.40	1.26	2.49
Groundwater pollution loss (10^{17} sej)	8.94	7.56	9.90	10.30	10.22	11.28	11.64	9.98
Land pollution loss (10^{18} sej)	6.09	6.39	5.45	5.14	4.94	3.56	3.32	4.99
Ecological loss from water pollution (10^{19} sej)	38.50	38.48	38.38	38.36	38.03	38.01	37.97	38.25
EDR (10^{11} sej/¥)	3.39	3.30	3.20	2.92	2.72	2.04	1.83	/
Currency representation (10^{9}¥)	1.14	1.17	1.20	1.31	1.40	1.86	2.08	1.45

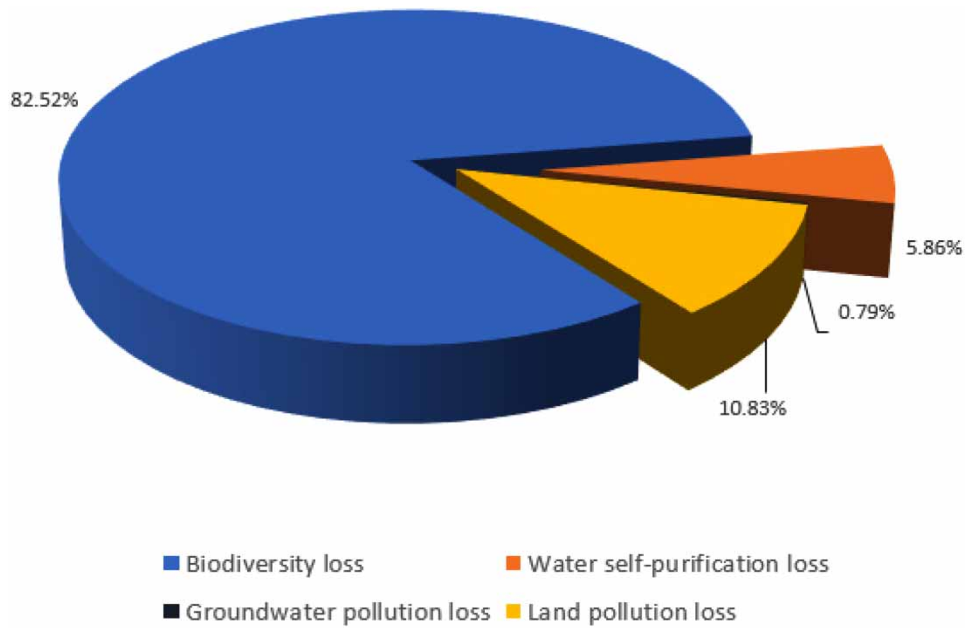


Figure 4 | The percentage of the multi-year average ecological environment losses from water in Kaifeng City.

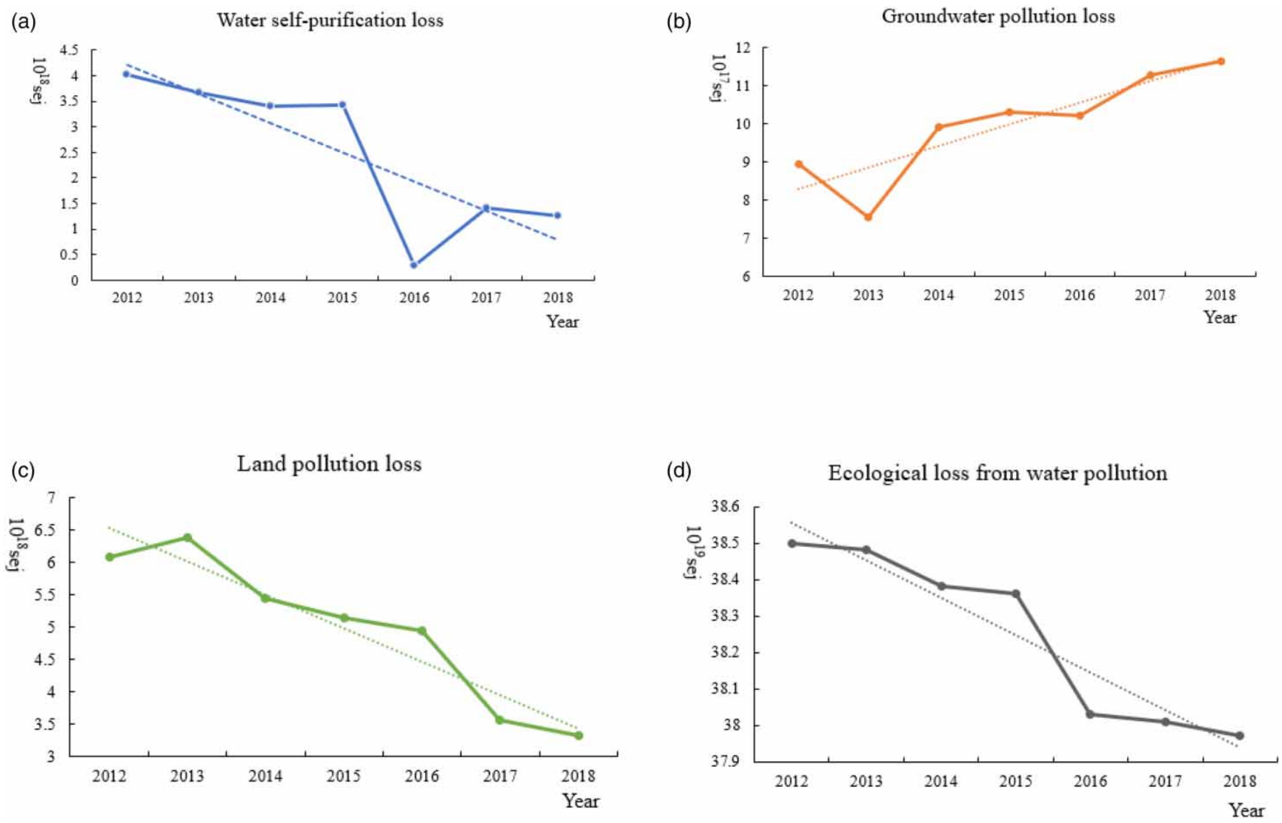


Figure 5 | The emergy expression trend diagram of ecological environment losses from water of Kaifeng City in 2012–2018.

In the research of other scholars, the economic loss of water pollution in each reach of the Xiangjiang River Basin in 2016 was calculated by using the economic loss function of water pollution and one-dimensional water quality model by Liu *et al.* (2020). Loudi Xiangtan Section lost 670.9 billion yuan, accounting for 0.36% of Xiangtan's GDP in 2016. Zhu & Wu (2020) estimated that the total economic loss caused by water pollution in Xinjiang in 2017 was 2.69 billion yuan, accounting for 0.25% of GDP, by using the decomposition summation method to prove the reasonableness of the calculation results of the model.

2. With the introduction and implementation of the 'three red lines (water resources development and utilization control red line, water use efficiency control red line, and water functional area limit pollution red line)' system and the continuous improvement of the river chief system, the losses of water body self-purification and soil pollution are downward steadily. However, in Figure 5, we can see that the groundwater pollution loss is increasing. Though the quantification value of groundwater pollution loss is small, the increasing trend cannot be ignored.
3. The water pollution ecological environment losses in Kaifeng City from 2012 to 2018 have shown different trends in emergy and currency. Referring to Figure 6(b), we find that it is mainly due to the difference in the EDR. It can also reflect the lack of imbalance between economic development and water environment governance in Kaifeng, namely the economic growth rate is greater than the rate of environmental governance. So, it is necessary to persist in overall planning and coordinate the two aspects.

4. CONCLUSION AND OUTLOOK

In this paper, the emergy theory and analysis method was applied to the quantitative study of ecological environment loss caused by water pollution, which enriches the quantitative method of ecological environment value loss caused by water pollution and broadens the thinking of application of the emergy analysis method. Firstly, the energy conversion process in the polluted aquatic ecosystem was analyzed by using the energy value theory. On this basis, the specific components of the water-polluted ecological environment loss were summarized and the calculation system of the ecological environment

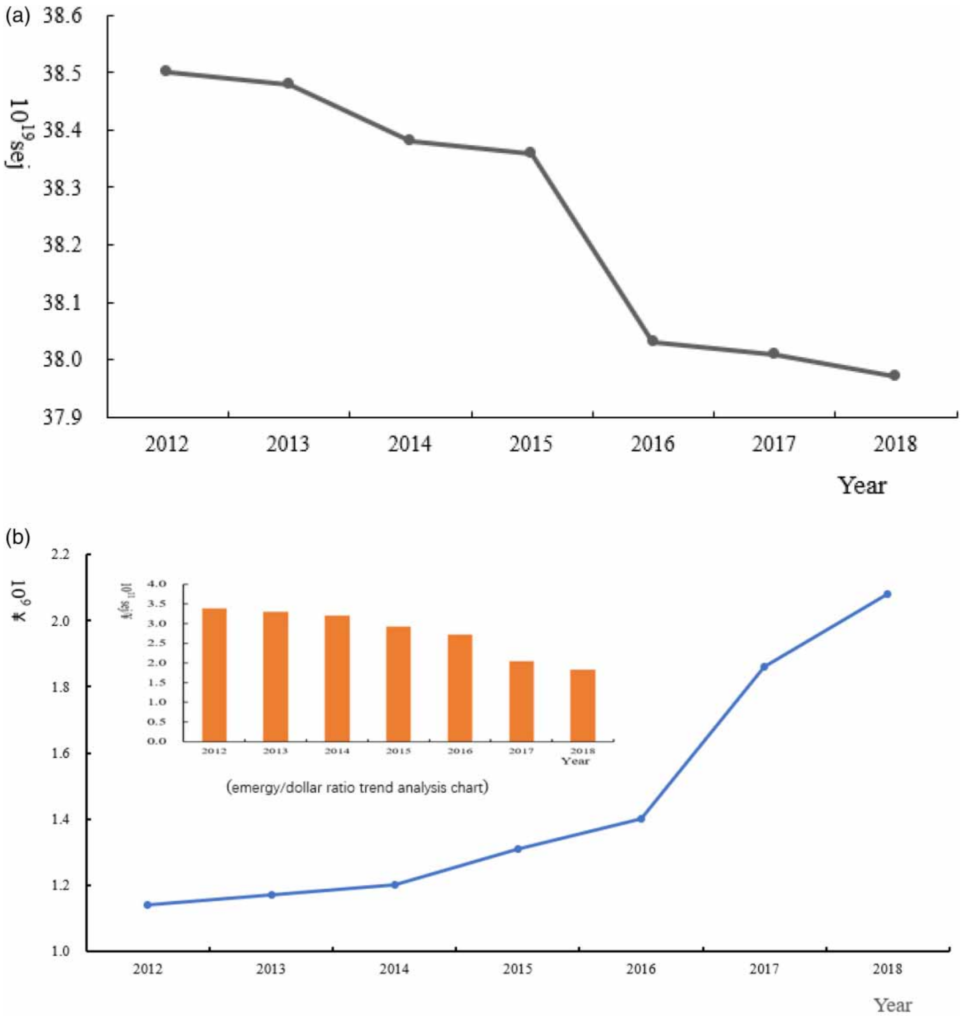


Figure 6 | Trends of ecological environment losses from water in Kaifeng City. (a) Ecological loss from water pollution is expressed in emergy. (b) Ecological loss from water pollution is expressed in currency.

loss was determined. Finally, the specific quantitative method of water pollution ecological environment loss was given and a quantitative model of water pollution ecological environment loss based on energy value analysis was constructed.

The water pollution ecological environment losses in Kaifeng from 2012 to 2018 were calculated. The conclusions are as follows: the multi-year average total emergy of water pollution ecological environment losses was 3.83×10^{20} sej, equivalent to 145 million yuan in currency and accounting for 0.76‰ of Kaifeng's GDP in 2018. In Kaifeng City, the biodiversity loss accounts the largest in the composition of ecological environment losses from water pollution, followed by soil loss, water body self-purification loss, and groundwater pollution loss. This indicates that the treatment of water pollution ecological environment losses in Kaifeng City should mainly focus on the treatment of water body and soil pollution. From the perspective of energy flow, it can be seen that the preliminary development in water pollution control has been achieved in recent years, but the control strength and efficiency should be improved further. The calculation results are helpful for understanding the value of ecological environment loss caused by water pollution in Kaifeng City, causing the protection of water environment, coordinating the relationship between economic development and water environment management, reducing environmental losses caused by water pollution in Kaifeng City, and promoting social and economic development and sustainable development of water ecological environment in Kaifeng City.

This paper still has shortcomings: In the emergy theory, this paper referred to the existing results of solar transformity and other indexes. Since the solar transformity is related to geographical location and other factors, the calculation based on existing results may affect the accuracy of conclusions here. In addition, due to the lack of a continuous biodiversity data, this paper assumed that the number of aquatic organisms did not change in the short term (2012–2018) and cites the data in 2015 as the aquatic life data from 2012 to 2018 in Kaifeng, so the data are inaccurate to some degree. Since the energy conversion of water pollution ecological environment losses is complicated, this paper analyzed and studied the energy flow changes in the certain years and did not consider the integrity of the energy conversion fully. In the future, the pertinence of energy conversion rate and other indicators should be enhanced in the calculation, the calculation method of biodiversity loss value should be improved, and the energy conversion in the multi-level and multi-angle analysis system should be studied to enrich the energy network of the research system.

CONCEPTUALIZATION

C.L. and Y. J. developed the methodology. X.G. conducted formal analysis and investigation. C.L. and Y.J. prepared and wrote the original draft. C.L., Y.J., M.L., and D.Y. wrote, reviewed, and edited the article. X.G. involved in funding acquisition. D.Y. brought resources. M.L. supervised the article.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST STATEMENT

The authors declare there is no conflict.

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