Emergy evaluation of human health losses for water environmental pollution

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Abstract

Water pollution in China has not only become one of the most vital factors impeding the social-economic development, but also threatening people's health. In this study, Kaifeng was considered as an example, and the human health risk of drinking water pathway from 2010 to 2017 was evaluated on the basis of drinking water hygiene standards and the human health risk assessment model (HHRA). Besides, the human health loss caused by water pollution was quantitatively evaluated through emergy theory and analysis method. The results showed that the carcinogenic annual risk of carcinogenic pollutants ranged from 2.0×10^{-5} to 6.5×10^{-5}, and the average health risk of non-carcinogenic pollutants was about 1.5×10^{-8}, but the difference between different pollutants was obvious. Affected by water quality, social-economic development, Medicare, etc., the value of human health loss ranked at the top in 2016 with 8.73×10^{18} sej, equivalent to 9.33 million RMB, while in other years, it was around 6×10^{18} sej. It is indicated that among the factors, water quality is the direct inducement of healthy loss, the socio-economic development is the leading force effecting the value, and the Medicare is the final determinant of the public burden.

Keywords: Chemical pollutants; Drinking water source; Emergy theory; Health loss; HHRA; Human health risk

Highlights

- A quantitative method of human health loss based on risk is proposed.
- The number of cancer caused by water pollution accounts for 10–20% of the total cancer.
- The human health loss is affected by water quality, social-economic development, and Medicare.
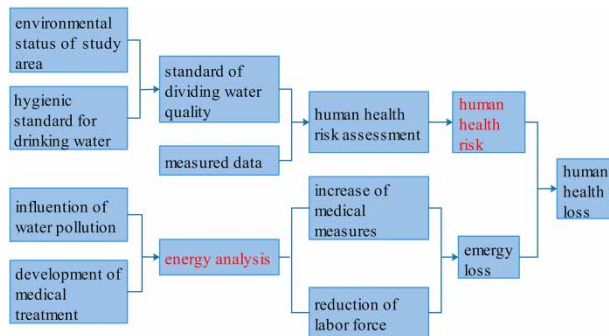
- The loss based on emergy is much smaller than the results calculated by shadow pricing.
- Remarkable achievements have been made in water pollution control in China.

Graphical Abstract

1. Introduction

Water is the basis of life, production, and ecology, which is important for the survival of human beings and the prosperity of social-economy. The reform and opening up has witnessed the rapid economic growth and the urbanization of China. However, due to insufficient understanding of the laws of economy, nature, and ecology, water pollution keeps intensifying, and water crisis has appeared in some regions. According to statistics by the environmental protection department in 2012, 31% of the top 10 river systems and 39% of the 62 major lakes failed to meet the standards of drinking water (Zheng & Sun, 2017). Meanwhile, residential districts with 250 million residents are close to key polluting enterprises and traffic arteries, and 280 million people use unsafe drinking water. As an important part of the living environment, the water environment, especially the drinking water environment, can pose a major threat to people's life, when the pollutants enter the human body through drinking, touching, and breathing. According to the World Health Organization (WHO), 80% of human diseases and 50% of child mortality are related to water pollution, which is also one of the four major factors endangering human health in China (Zhou et al., 2000). To solve the increasingly serious water pollution and ensure the safety of drinking water, a series of documents was proposed by related departments, such as 'Three Red Lines' (TRL) from the No. 1 Central Document (2011), Water Pollution Prevention Action Plan (2015), the River-Chief System (RCS) (2017), and Firmly Fighting for the Pollution Prevention War (2019). In recent years, the intensity of water environment management has been strengthened, the scope of governance has been kept expanding, and the method has grown in number, it shows our country's determination to control pollution and environmental protection by stricter and more in-depth of water pollution prevention policies. To maintain the health of water environment, face up the harm of water pollution (Zhao et al., 2020), it is necessary to evaluate the health risk and pollution loss of water environment.

Water environmental health risk assessment is a quantitative study of the impact of water environmental pollution on human health. It focuses on the quantitative calculation of the relationship

between water pollutants and the damage degree of human health, with risk degree as the index (Zhao *et al.*, 2020). The common evaluation methods can be divided into many aspects, such as risk entropy, Monte Carlo simulation, loss of life expectancy, and health risk assessment four-step method (Zheng & Sun, 2017). After continuous improvement by the U.S. EPA and other agencies, the four-step evaluation method has developed into a human health risk assessment model (HHRA) (US National Research Council, 1983), which has been widely accepted. It has been used to evaluate the human health risks of drinking water (Pérez *et al.*, 2019; Kujlu *et al.*, 2020), surface water (Zhang *et al.*, 2015; Zhu *et al.*, 2015; Li *et al.*, 2020), groundwater (Edokpayi *et al.*, 2018; Adimalla & Qian, 2019), and polluted water by a large number of researchers. Zhao *et al.* (2020) found that the human health risk through drinking water is two to three orders of magnitude greater than that of skin contact after the risk analysis of heavy metal pollution in the surface water of the Three Gorge Reservoir. Adimalla *et al.* (2019), Akale *et al.* (2018), Huang *et al.* (2018), and Zhai *et al.* (2017) found that the order of health risk in various age groups is baby > child > adult female > adult male after evaluating the potential risk of nitrate concentration in groundwater to human health by the model. Gao *et al.* (2019), Ma *et al.* (2014), Khan *et al.* (2013), Holtby *et al.* (2014), and Pérez *et al.* (2019) evaluated the human health risks of drinking water environment by the model. Custodio *et al.* (2020), Genthe *et al.* (2018), and Neogi *et al.* (2018) evaluated the potential hazard risk of metals to human health in untreated coalfield mines and polluted river catchment water. Some scholars combined water environmental health risk assessment with mathematical analysis methods to make the results more authentic (Yang *et al.*, 2011; Wongsasuluk *et al.*, 2014; Sener *et al.*, 2017; Ogbiye *et al.*, 2018; Xu *et al.*, 2018; Zhang *et al.*, 2018; Vu *et al.*, 2019). Although the mathematical methods were different, they all reflected the impact of different pollutants on human health and can judge what should be prioritized according to the risk, which plays a decisive role in the order of pollutant treatment.

HHRA can be used to calculate the impact on human health of each pollution indicator in water and to determine the pollutants that should be treated first, which enhance the possibility of protecting drinking water safety. However, it is only staying with health risk assessment analysis, without further quantifying the possible loss caused by the risk. The emergy theory connects economic society with the ecological environment system and realizes the unified measurement of material and emergy through solar emergy. It overcomes the shortcomings of traditional economics, which is based on monetary theory, and has been widely applied to assess the environmental resource value (Ling *et al.*, 2018; Wu *et al.*, 2018, 2019a, 2019b). In order to evaluate the harm and loss of water pollution to human health and to arouse the great concern of government and the public, the human health risk of drinking water was evaluated by means of HHRA in this study, then the health loss was assessed combining with emergy theory. These efforts can be used to find the relationship between health loss and socio-economic development and to provide references for water pollution prevention and protection.

2. Materials and methods

2.1. Materials

The International Agency for Research on Cancer (IARC) classifies the chemical pollutants in water into carcinogenic pollutants and non-carcinogenic pollutants. Among them, Cd, As, and Cr^{6+} are carcinogenic pollutants; CN^-, F^-, phenol (Vp), NH_3-N, Cu, Zn, Pb, Hg, Fe, and Mn are non-carcinogenic

Table 1. Minimum detection limit and safety limit of main pollutants in drinking water (Unit: mg/L).

Carcinogen	Limit of detection	Safety limit	Non-carcinogen	Limit of detection	Safety limit	Non-carcinogen	Limit of detection	Safety limit
Cd	0.001	0.005	Pb	0.01	0.01	Mn	0.01	0.10
As	0.0005	0.01	Hg	0.00002	0.001	CN^-	0.037	0.05
Cr^{6+}	0.004	0.05	Cu	0.001	1.00	NH_3-N	0.025	0.50
			Zn	0.05	1.00	Vp	0.002	0.002
			Fe	0.03	0.30	F^-	0.06	1.00

pollutants (U.S. EPA, 2005; IARC, 2016). Referring to the minimum detection limit and safety limit (Table 1) of the water quality index in *Standards for drinking water quality (GB 5749-2006)* and the environmental status of the selected study area, the major pollutant indicators were further selected. The water quality detection data of hydrological stations are the basis of subsequent calculation.

2.2. Methods

2.2.1. Human health risk assessment.
According to HHRA, skin contact, direct drinking, and ingestion of food in water are the main ways for humans to come into contact with water pollutants. Among them, direct drinking is the most direct and main way to threaten the health of exposed population (Adimalla & Qian, 2019). In the study, the annual human health risk of drinking water sources was assessed using the HHRA based on the carcinogen and non-carcinogen health risk assessment methods (Adimalla & Qian, 2019), which was proposed by the U.S. EPA. The specific calculation steps are as follows:

• Daily average exposure dose per quality of drinking water can be figured as:

$$D_{ig} = C_i \times IR/BW \tag{1}$$

where i is the pollutant; D_{ig} is the average daily exposure dose per unit body mass of chemical pollutant through drinking water, mg/(kg·d); C_i is the concentration of pollutant in the water environment, mg/L; IR is daily water intake for exposed populations, with the data of 2 L/d (U.S. EPA, 2011); BW is the average body mass of exposed population, which is 66.2 kg (Ministry of Ecology and Environment, PRC, 2013b).
• The human health risk of chemical carcinogens can be computed as:

$$R_{ig}^C = [1 - \exp(-D_{ig} \times q_i)]/A_{ge} \tag{2}$$

$$R^C = \sum_{i=1}^{3} R_{ig}^C \tag{3}$$

where R^C is the annual cancer risk per capita of exposed people through drinking water; R_{ig}^C is annual carcinogenic risk per capita of carcinogenic pollutant i through drinking water; q_i is the carcinogenic intensity coefficient of carcinogenic pollutant i through drinking water, mg/(kg·d), and the value is

shown in Table 2. A_{ge} is the average life of Chinese people, which is 75.8 years old (Ministry of Ecology and Environment, PRC, 2013b).

- The human health risk of non-carcinogenic can be calculated as:

$$H_{ig}^N = (D_{ig} \times 10^{-6}/RfD_{ig})/A_{ge} \tag{4}$$

$$H^N = \sum_{i=1}^{k} H_{ig}^N \tag{5}$$

where H^N is the annual health risk per capita of exposed people through drinking water; H_{ig}^N is annual health risk per capita of non-carcinogenic pollutant i through drinking water; RfD_{ig} is the exposure reference dose of non-carcinogenic pollutant i through drinking water, mg/(kg d), as shown in Table 2.

2.2.2. Emergy assessment of human health loss. There is a large number of pollutants in the flying dust and sewage. After entering the water, some pollutants produce irritant gases, which enter the human body through the respiratory tract, causing various nervous system diseases and respiratory diseases; whereas the other part accumulates in the water and enters the human body through touching, drinking and so on, leading to the occurrence of various chronic diseases and cancers. For example, Pb poisoning affects the people's hemopoietic system and the nervous system, endangering the growth and intellectual development of infants; Cr and Hg have strong carcinogenic effects, but most of them are chronic. After human disease which need medical treatment, all kinds of medical resources are consumed in the process of treatment, which leads to the increase of nursing cost and medical measures, and affects resource investment. Besides, some patients lose their ability to work within a certain period of time, which leads to the decline of the labor force and affects the social output. Therefore, the damage process of water environmental pollution to human health can be summarized as two aspects: the increase of medical measures and the decrease of labor force.

Emergy theory and analysis method is a new environmental-economic axiology and system analysis method established in the 1980s by H.T. Odum, a famous American ecologist and pioneer of system emergy analysis. It has been widely used in the quantitative research on the relationship between human and nature, environmental resources, and social-economy (Lv, 2009). Emergy value theory can be used to analyze the transitions between emergy flow and material in the process of water

Table 2. Carcinogenic intensity coefficient and exposure reference dose of pollutants (Unit: mg/(kg d)).

Carcinogen	q_i	Non-carcinogen	RfD_{ig}	Non-carcinogen	RfD_{ig}	Non-carcinogen	RfD_{ig}
Cd	6.1	Pb	0.0014	Mn	0.0005	Cd	0.0005
As	15	Hg	0.0003	CN^-	0.037	As	0.0003
Cr^{6+}	41	Cu	0.005	NH_3-N	0.97	Cr^{6+}	0.003
		Zn	0.3	Vp	0.3		
		Fe	0.003	F^-	0.06		

All exposure parameters were referenced from *Exposure Factors Handbook of Chinese Population: Adult Volume* (U.S. EPA, 2011) and *Exposure Factors Handbook: 2011 Edition (Final)* (Ministry of Ecology and Environment, PRC, 2013a).

pollution endangering human health from the source, and convert different kinds of non-comparable energy involved to the same standard emergy (solar) (Lan et al., 2002). The emergy system of water environmental pollution endangering human health is shown in Figure 1.

The increased emergy value of medical measures was the value of using medical equipment and therapeutic drugs, which can be divided into seven parts: medicine, cure (including transfusion, nursing, oxygen delivery, etc.), examination (comprising clinical test and inspection), operation (including operation and anesthesia), bed, diagnosis and treatment, and others. Since it is difficult to objectively estimate the value of each operation in the medical process, it was replaced by the per capita treatment cost of cancer, whereas the medical value of other diseases was replaced by the per capita medical cost. Medical expenses involved were pure personal expenses after deducting the social financial reimbursement. The emergy of labor loss was expressed as the value that patients should create in the labor time delayed by treatment. Cancer patients basically lost their ability to work as they are weak during illness, and needed long-term treatment. Therefore, it was appropriated to take the annual delay time as half a year. While non-cancer patients were in poor condition before and after treatment, hence, 2.5 times of the average annual missed working time was desirable. Loss refers to the loss of a person or a thing as a result of an accident. Both losses in this research were considered as additional expenditures due to drinking contaminated water, which can be regarded as the loss of water pollution to human health. Therefore, the loss
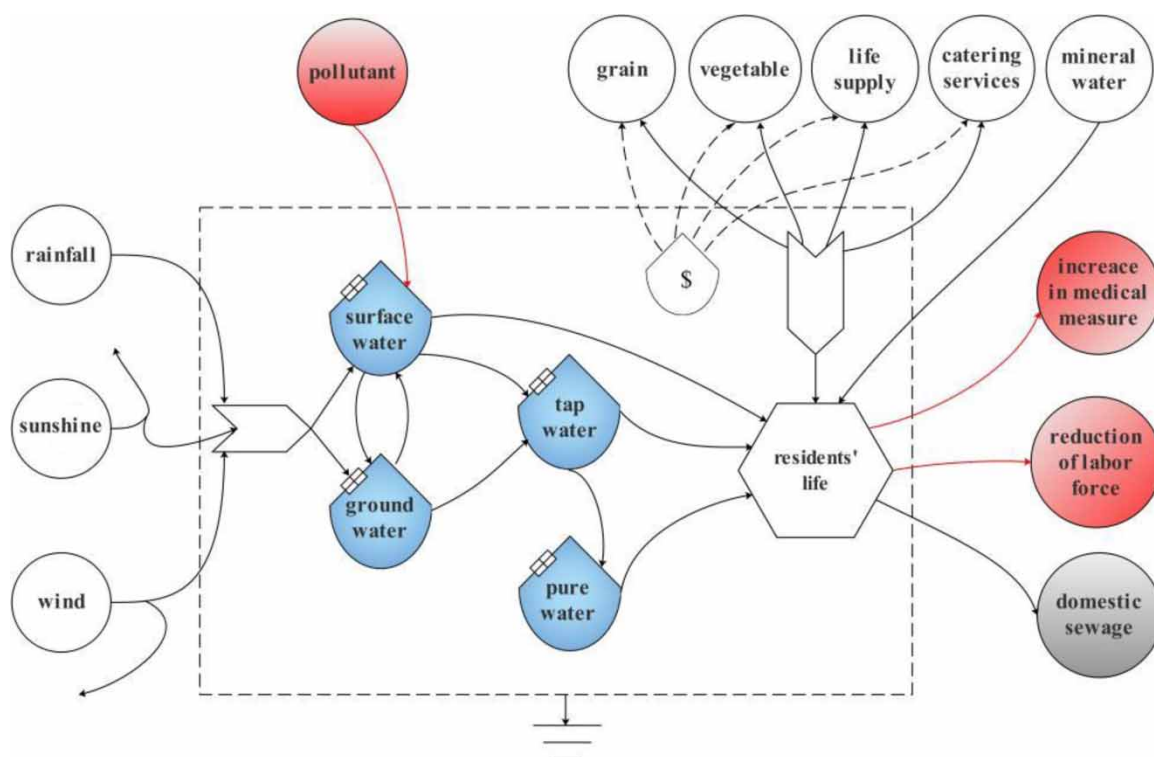

Fig. 1. Emergy system diagram of water pollution endangering human health.

emergy of human health caused by water environment pollution can be quantified as:

$$EM_S = (EM_Y + EM_L) \times P \tag{6}$$

$$EM_Y = EM_1 \times R^C + EM_2 \times H^N \tag{7}$$

$$EM_L = \tau_L \times (T_Y \times R^C + T_L \times H^N) \tag{8}$$

where EM_S is the emergy of human health loss caused by water environment pollution, sej; EM_Y is the emergy of healthcare capacity per capita for water pollution, sej/person; EM_L is the per capita missed work emergy of water environment pollution, sej/person; EM_1 is the per capita healthcare emergy of cancer patients caused by carcinogenic pollutants, sej/person; EM_2 is per capita healthcare capacity of patients with other diseases caused by non-carcinogenic contaminants, sej/person; τ_L is the transformation ratio of solar emergy of human labor service (adult labor force aged 18–59) using 3.49×10^{15} sej/person/year (Lan *et al.*, 2002); T_Y is the average missed working time of cancer patients, a; T_L is the average missed working time of patients with other diseases, a; and P is the total number of people in the study area, person.

3. Application and analysis

3.1. Overview of the research area

3.1.1. Current status of water pollution in Kaifeng City.   Kaifeng is located in the eastern part of Henan Province, the southern part of downstream the Yellow River, with a total area of 6,444 km². It is between 113°52′15″–115°15′42″ E and 34°11′45″–35°0′20″ N, which is 125 km from east to west and 87.5 km from north to south (Cabangon *et al.*, 2003; Cao & Ding, 2005). Besides, there are many rivers in Kaifeng, which belong to the Yellow River basin and Huaihe River basin, respectively. The Yellow River basin occupies a small area, without any obvious sewage discharging into the river; Huaihe River basin is divided into three major water systems: Nansihu, Yinghe, and Wohe. Most rivers in Kaifeng can be categorized as the Wohe system; among them, Huijihe, the largest tributary of the Wohe system, originates in the suburb of Kaifeng and its main stream is 65.9 km in the city. It is an important river integrating flood discharge, urban drainage, irrigation, and other functions, and also the river with the largest pollution carrying capacity in Kaifeng (Zhang, 2012). With the socio-economic development, the water environment in the downstream of Huijihe is deteriorating; thus, the unsafe range of drinking water on both banks is also aggravating, which threatens people's health. It has been decided to comprehensively improve the environment of the Huiji River basin by the government of Henan Province since 2008, and the water quality is getting better recently.

3.1.2. Data source and processing.   According to the geographical location and watershed area of the main tributaries of the Huiji River basin (Kaifeng Section), the monthly water quality concentration of five water-quality monitoring sections in the study area from 2010 to 2017 were collected. The data come from the Kaifeng Hydrology and Water Resources Survey Bureau (http://kf.hnssw.com.cn/). There are five water-quality monitoring sections in the Kaifeng development and utilization zone of Huijihe: Sunlitang,

150 m upstream of the pumping station, 1,000 m below Wangtun Bridge, Zhongzhuzhai Bridge, and Dawangmiao Hydrologic Station, the location is shown in Figure 2. According to the statistics of environmental status and water-quality monitoring data in the study area, Cr^{6+}, Cd, As, Pb, Cu, Zn, CN^-, NH_3-N, Vp, and F^- were selected as evaluation indexes. The annual average concentration was obtained from the average of the 12 monthly measurement data each year. In the case of the absence of measurement or interruption of current in some monthly measured data, the remaining monthly measured data in the year shall be used for calculation. In the process of processing original data from 2010 to 2017 of monitoring sections, '< DL' was replaced by half of the lowest detection limit for this kind of substance, xx was a certain figure, and '< xx' was expressed as half of xx. If the concentration of pollutant index was not detected in some months, it would be supplemented with the minimum detection limit. The final water-quality monitoring data were sorted out as shown in Table 3.

In the original data, monitoring data of Hg, Cd, Cr^{6+}, As, Pb, and Cu were below the minimum detection limit in most cases. The concentration of most pollutants would not cause harm to human health in a

Fig. 2. Water system of Kaifeng and location of monitoring sections.

Table 3. Average monthly data of major chemical pollutants in the monitoring section (Unit: mg/L).

Index	2010	2011	2012	2013	2014	2015	2016	2017
Cr^{6+}	0.0008	0.0013	0.0013	0.0011	0.0013	0.0018	0.0027	0.0020
Cd	0.0004	0.0005	0.0009	0.0005	0.0005	0.0010	0.0007	0.0005
As	0.0019	0.0037	0.0035	0.0024	0.0038	0.0036	0.0039	0.0023
Pb	0.0015	0.0028	0.0028	0.0024	0.0029	0.0025	0.0052	0.0023
Cu	0.0068	0.0058	0.0049	0.0090	0.0252	0.0237	0.0347	0.0201
Zn	0.0065	0.0128	0.0128	0.0123	0.0223	0.0480	0.0433	0.0413
CN^-	0.0018	0.0013	0.0023	0.0018	0.0011	0.0017	0.0027	0.0005
NH_3-N	8.1250	15.6592	13.2504	10.8470	10.0999	7.4987	3.4143	7.8583
Vp	0.0014	0.0106	0.0104	0.0029	0.0041	0.0015	0.0021	0.0010
F^-	0.7005	0.9921	1.0000	0.9154	0.9429	0.9754	1.2617	0.9263

short time, which met the requirements of drinking water quality. However, due to the enrichment of food chain, the harm to people's health will show up after a relatively long time (Geng *et al.*, 2016). The concentration of NH_3-N and F^- were higher than the safety limit of drinking water, which requires more attention. Besides, the measured values in several months were relatively high, which might bring harm. For example, the detected concentration of NH_3-N was greater than 30 mg/L for 10 months and even reached 60 mg/L in January 2011, which may lead to the intestinal diseases as the proliferation of pathogenic microorganisms in the water (Yin *et al.*, 2019; Gao *et al.*, 2020). What's more, F^- concentrations in water samples from January to May 2012 were all greater than 1 mg/L, exceeding the safe concentration in drinking water (0.5–1 mg/L), which would lead to the disorder metabolism of Ca and P, thus adversely affecting the skeletal development of teenagers (Fallahzadeh *et al.*, 2017). The highest concentration of volatile phenol reached 0.09 mg/L. If it is relatively high in a short time, people may suffer from dizziness, nausea, anemia, and various neurological diseases. If people are exposed to it for a long time, it may stimulate the spinal cord and promote cancer.

3.2. Results and discussion

3.2.1. Risk assessment of human health in Kaifeng City.   The carcinogenic risk of pollutants in Kaifeng from 2010 to 2017 was evaluated based on HHRA, the results are shown in Table 4, and the trend is shown in Figure 3. From the table, there was no significant difference in the carcinogenic risk between As and Cr^{6+} from 2010 to 2014. However, the cancer risk caused by these two elements had been changing rapidly since 2015, and the proportion of As had been increasing with years. According to the safety restrictions in drinking water, the minimum concentration requirement of As was lower than

Table 4. Annual carcinogenic risk of carcinogenic pollutants per capita (10^{-5}).

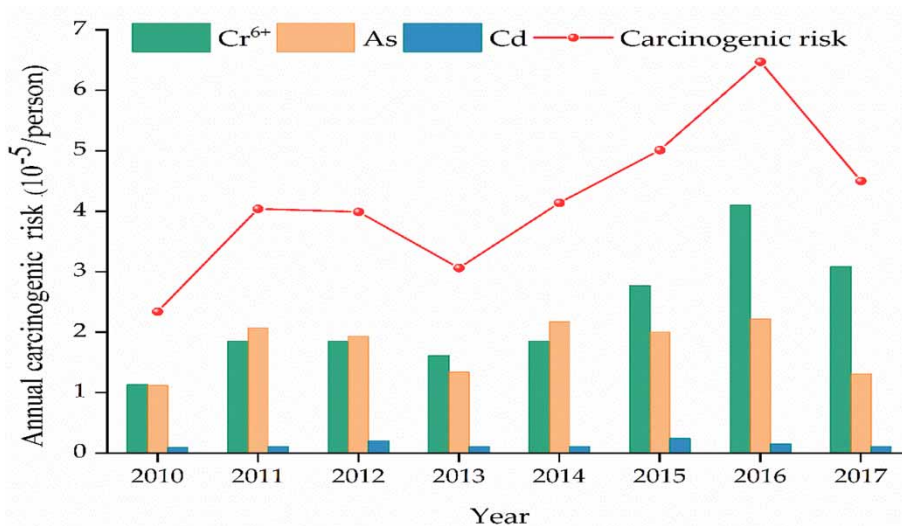| Index	2010	2011	2012	2013	2014	2015	2016	2017
Cr^{6+}	1.13	1.85	1.85	1.61	1.85	2.77	4.10	3.08
Cd	0.09	0.11	0.20	0.11	0.11	0.24	0.15	0.11
As	1.12	2.07	1.93	1.34	2.17	2.00	2.22	1.31
R^C	2.34	4.04	3.99	3.06	4.14	5.01	6.47	4.50

Fig. 3. Annual carcinogenic risk of carcinogenic pollutants through drinking water.

that of Cr^{6+}, but quite to the contrary, the detection concentration of As was higher than that of Cr^{6+}. Given that there was once a village in Kaifeng with a large number of cancer patients, it is necessary to strengthen water-quality monitoring to ensure the health and safety of drinking water, especially the control of As in water sources. However, it is shown that the annual risk of cancer from Cd did not change much, and the risk value was lower than that of the other two pollutants, which may be related to the underdeveloped manufacturing industry on both sides of the Huijihe.

For one pollutant, when the risk of cancer is less than 1×10^{-6}, then the risk of cancer can be ignored, while the risk of cancer is more than 1×10^{-4}, it is considered as harmful and the risk of cancer is high (Mohammadi *et al.*, 2019). The carcinogenic annual risk of Kaifeng was between 2.0×10^{-5} and 6.5×10^{-5}, far lower than the maximum acceptable risk level P ($1 \times 10^{-4}\,a^{-1}$) recommended by the U.S. EPA and ICRA, which was still within the acceptable range. It shows that a series of environmental protection policies in China have achieved remarkable results and water quality has significantly improved, especially the revision of *The Law on Prevention and Control of Water Pollution* and the implementation of *Water pollution prevention and control plan for key river basins*. However, the risk of carcinogens still exceeds the limit of $1.0 \times 10^{-6}\,a^{-1}$ setting by the Chinese government (Gao *et al.*, 2019). The population in Kaifeng is over a million and the incidence rate of cancer in China is around 3‰ (Chen *et al.*, 2016), so it is estimated that there are about 1,500 cancer patients every year. According to the risk assessment, there are about 200 people who have cancer due to water quality per year. The number of cancerous people caused by water pollution accounts for 10–20%, which varies with water quality. Water environment is key consideration to people's health, so it is vital to take effective remedies for water pollution, thus ensuring the safety of the drinking water.

The average monthly concentration of non-carcinogenic pollutants in the monitoring section of Kaifeng development zone of Huijihe from 2010 to 2017 is calculated using Equation (4). Human health risks are shown in Table 5. The maximum and minimum per capita health risks of non-carcinogenic pollutants were in 2016 and 2010, respectively, and the ratio of the maximum to the minimum was

Table 5. Per capita annual health risks caused by non-carcinogenic pollutants (10^{-10}).

Index	2010	2011	2012	2013	2014	2015	2016	2017
Cr^{6+}	0.92	1.51	1.51	1.31	1.51	2.26	3.34	2.51
Cd	2.88	3.76	6.55	3.46	3.76	7.72	5.01	3.76
As	24.83	46.11	42.97	29.70	48.26	44.51	49.28	29.14
Pb	3.86	7.02	7.02	5.97	7.43	6.85	13.87	6.44
Cu	5.19	4.42	3.73	6.70	18.70	17.55	25.80	14.85
Zn	0.08	0.15	0.15	0.15	0.27	0.59	0.54	0.52
CN^-	0.18	0.13	0.23	0.19	0.11	0.17	0.27	0.05
NH_3-N	31.28	61.91	52.02	43.84	41.18	29.98	13.60	31.94
Vp	0.02	0.13	0.12	0.04	0.05	0.02	0.03	0.01
F^-	44.46	61.70	62.48	57.61	59.07	60.49	78.34	57.68
H^N	113.70	186.84	176.79	148.96	180.35	170.16	190.08	146.90

1.68. It was not significant for the inter-annual changes in other years, except for the large increase in 2010–2011. Figure 4 shows that the health risk of different pollutants was significantly different. For example, the health risk of Zn, CN^-, and Vp was of the order of 10^{-12}, accounting for a very small proportion. However, As, NH_3-N, and F^- have a risk magnitude of 10^{-9}, with a contribution rate of more than 75% to the total health risk. Besides, the annual health risk of F^- accounted for 41.2% of the total annual risk in 2016, which was the highest single contribution rate; the lowest single contribution rate occurred in 2015, which was the risk of NH_3-N with a number of 17.6%. There are some reasons for this phenomenon: firstly, both sides of Huijihe are residential gathering places, and there is considerable ammonia nitrogen and fluoride in domestic sewage. Secondly, the centralized processing of domestic sewage in urban areas in China has not yet fully covered, the local residents' opinions varied for domestic sewage treatment, which have been significantly improved after 2016. In a word, non-carcinogenic pollutants may not cause serious diseases in a short time, but the harm they bring to human health still cannot be ignored. Moreover, the key pollutants of non-carcinogenic pollutants are obvious, which is easy to concentrate and should be given high priority to remedy.
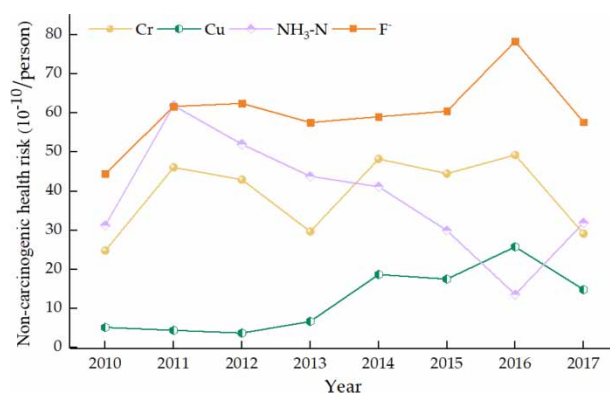

Fig. 4. Annual health risk changes of key non-carcinogenic pollutants.

3.2.2. Quantitative analysis of health loss of water environmental in Kaifeng City.   The health loss caused by water environmental pollution in Kaifeng City from 2010 to 2017 was evaluated using emergy theory and methods, and the results are shown in Table 6. From the table, the annual change of per capita medical emergy value of cancer was not significant and declines generally, with a significant decrease of 24.38% in 2016–2017. While the trend of medical emergy per capita of patients with other diseases was the opposite, increasing year by year. The annual change trend of per capita nursing emergy value was consistent with and greatly affected by that of cancer, while the per-capita cure emergy for other diseases was almost negligible due to its risk order of magnitude. Figure 5 shows that the health risk of carcinogenic pollutants was not completely correlated with the per capita nursing emergy of cancer, the same to the health risks of non-carcinogenic pollutants and the medical nursing emergy of other diseases, influenced by many factors. But medical care emergy and labor losses with same rise and fall in a great measure. As the cure emergy was mainly reflected from the treatment cost, when the emergy monetary ratio was gradually reduced, the emergy had a small change, which indicated the superiority of China's medical security system. As for the basic medical insurance system in urban and rural areas (Liu *et al.*, 2020), it focuses on making overall plans for major diseases and settling indisposition claims, which has been gradually well-developed since was basically achieved in 2010. The government took a series of measures such as lowering the line of deductible, improving the policy of serious illness insurance, increasing the proportion of financial reimbursement, and narrowing the gap of reimbursement ratio between policy and actual. These efforts have greatly reduced the medical burden of urban and rural residents and also avoided the poverty and returning to poverty caused by illness to some extent.

The per capita emergy of missed work is related to two factors: health risk and lost time. When the absenteeism time of cancer patients was 0.5 year and other patients' absenteeism time did not change much, water quality plays a leading role, and the trends were consistent with changes in health risks. The ratio of emergy absenteeism emergy value to medical emergy per capita increased from 0.05 to 0.10, which reflected China's efforts in remedying water pollution and bringing down the medicine price. The inter-annual change of human health loss caused by water environment pollution was not large,

Table 6. Human health loss of water environmental pollution in Kaifeng City.

Index	2010	2011	2012	2013	2014	2015	2016	2017
P (10^6)	5.04	5.06	5.09	5.11	5.14	5.17	5.20	5.23
R^C (10^{-5})	2.34	4.04	3.99	3.06	4.14	5.01	6.47	4.50
H^N (10^{-8})	1.14	1.87	1.77	1.49	1.80	1.70	1.90	1.47
EDR (10^{11})	17.86	15.52	14.08	12.64	10.99	10.12	9.36	8.70
EM_1 (10^{16} sej/P)	3.62	3.25	2.95	3.86	3.53	2.96	2.42	1.83
EM_2 (10^{15} sej/P)	2.66	2.80	2.92	2.94	2.84	3.02	3.14	3.29
T_L (d)	8.90	9.00	8.80	8.90	8.90	8.90	8.80	8.60
EM_Y (10^{11} sej/P)	8.46	13.16	11.8	11.7	14.60	14.83	15.67	8.24
EM_L (10^{10} sej/P)	4.08	7.05	6.96	5.33	7.22	8.74	11.29	7.86
EM_S (10^{18} sej)	4.47	7.02	6.34	6.30	7.88	8.12	8.73	4.72

EDR: the emergy currency ratio of Kaifeng City, which can be calculated in this study; EM_1: the treatment cost, which can be obtained from different references (Dong *et al.*, 2015; Hung et al., 2016; Bai *et al.*, 2019; Wan, 2019; Yuan *et al.*, 2019); EM_2: the per capita health cost, which can be obtained from the national statistical yearbook; T_L: the average treatment day, which was obtained from the statistical data of various hospitals in the *National Statistical Yearbook*.
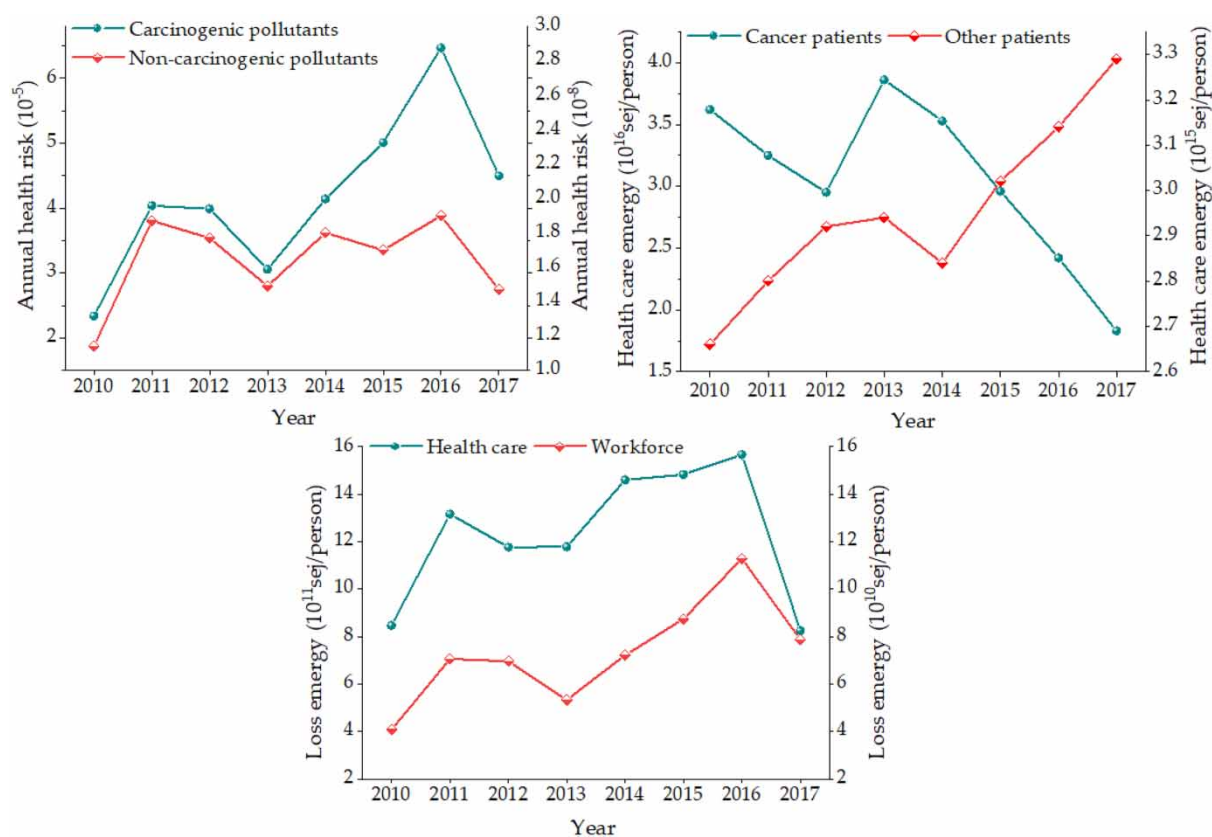
Fig. 5. Trends in health risks and energy losses from water environmental pollution.

as the maximum value of 8.73×10^{18} appeared in 2016, which was 1.86 times of the minimum year in 2010. This may be due to insufficient monitor data, because there were only monitoring data from January to May 2016, during which, there were small surface basic flow, low temperature and self-purification capacity, resulting from little change in coastal discharge capacity. Therefore, the annual average pollutant concentration and annual health risk were high in 2016, as a result, the other data in 2016 were also large.

Combined with the emergy currency ratio, the human health loss of water pollution was about 2.5 million to 9.33 million RMB, which was still a large number. It reminded us that water pollution does great harm to human health, which needs to be pay long-term attention. There is still a long way to go to control water pollution in our country. The overall loss of human increased firstly and then decreased due to the national efforts to protect water resources and the development of Medicare. In general, the value of human health loss is affected by water quality, socio-economic status, Medicare, etc. Among them, the water quality is the inducing factor. In addition, the governance policy was affected by social-economic status, and the public burden and loss value were determined based on the level of medical security.
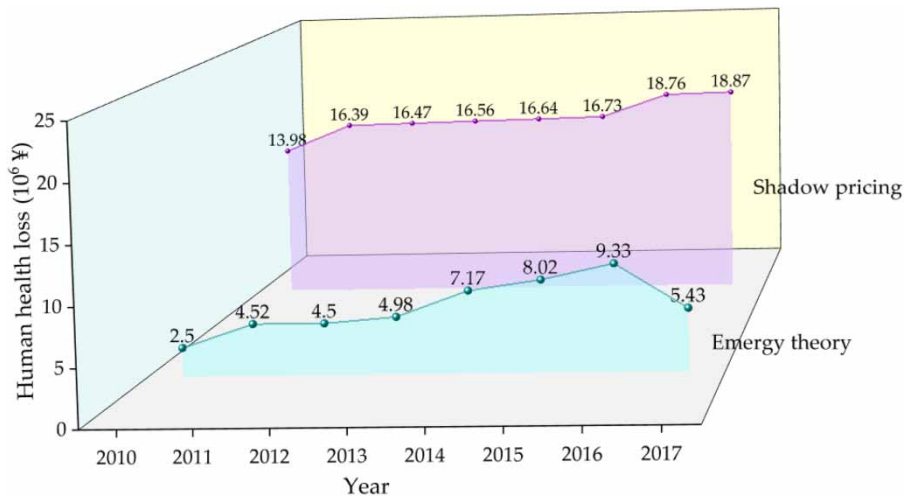
Fig. 6. Human health loss based on shadow pricing and emergy theory.

3.3. Comparison and analysis

Human Capital Approach and Medical Expenditure Approach were usually applied to assess the impact of the water environment on human health. Medical cost and emergy theory were combined to obtain the human health loss based on health risk in this study, and human capital was used for comparative analysis. Water pollution has reduced the supply quality of waterworks, which can be improved by a large number of medicament and purification facilities and technology; all are belong to production cost. On the contrary, health level of human beings would be greatly reduced without those costs. To ensure the comparability of results, the loss of human health can be expressed as the volume of water intake and production cost.[1] As shown in Figure 6, the gap of human health loss calculated by the shadow price method and emergy theory was narrowing with years, but the results were still quite different. The former was based on market demand and price changes, with single influencing factors and small inter-annual variation, which cannot truly reflect the impact of water pollution on human health. The latter was based on the current situation of water quality and the degree of social development, and fully considered the possible impact of different pollution levels. Although the result was small, it was more scientific and objective.

4. Conclusions

It is feasible to further quantify the risk of water environment health risk based on emergy theory and obtain the health loss of urban residents caused by water environment pollution, which is more scientific than the results calculated by economic methods directly. The human health risk of drinking water in Kaifeng from 2010 to 2017 was evaluated with HHRA in this study, and the human health loss

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[1] According to Notice on adjustment of water supply price in Kaifeng City published by the Development and Reform Commission of Henan Province, the water price in Kaifeng City has been adjusted from 1.10 to 1.50 ¥/m^3 since February 1, 2010, and then adjusted to 1.75 ¥/m^3 after trialing 1 year. Water resources fee of 0.2 ¥/m^3 was added on December 1, 2015.

caused by water environmental pollution was quantitatively estimated with the emergy theory. The results showed that the carcinogenic annual risk of carcinogenic pollutants ranged from 2.0×10^{-5} to 6.5×10^{-5}, without a significant difference; the average health risk of non-carcinogenic pollutants was about 1.5×10^{-8}, but the difference between different pollutants was obvious. It is also indicated that the human health loss value of water environmental pollution in Kaifeng City is affected by water quality, social-economic status, Medicare, etc. Among them, the water quality is the direct inducement, socio-economic status is the leading factor, and the public burden is determined by the Medicare, which is the final determinant. Except for the obvious change of the loss in individual years, the overall loss of value has not changed much. The case in point is the value of human health loss ranked at the top in 2016 with 8.73×10^{18} sej, equivalent to 9.33 million RMB, while in other years, it was around 6×10^{18} sej, which was smaller than the result calculate by shadow pricing. Combining the economy, society, and environment, the impact of water environmental pollution on cities was analyzed from the perspective of human beings with the emergy theory. Through the specific loss of value, the result is more intuitive. It reflects the practical significance of the government to ensure residents' drinking water safety and to improve the Medicare to some extent, which is a bold attempt. Last but not least, it is an arduous task to implement water resources protection and pollution prevention to ensure the safety of drinking water. It requires not only the efforts of the government but also the strength of the public's awareness of water conservation and environment protection, which need to be put into action for a long time.

However, there are still some deficiencies due to data limitations, which can through assessing the emergy value of each medical measure into its input and output after in-depth researches to make the results more reliable. It is desirable and essential to add the risk evaluation of skin contact pathway and food intake pathway to realize the all-around value of water environmental pollution loss in the future.

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Data availability statement

All data generated or analyzed during this study are included in this published article. All relevant data are included in the paper or its Supplementary Information.

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