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Water efficiency evaluation of a regional water scheme – Zhengzhou, China, using a water ecological–economic system (WEES) and based on emergy theory

Zening Wu, Xi Guo, Xinjian Guan, Cuimei Lv and Huiliang Wang

ABSTRACT

With the rapid development of society and the economy, the shortage of water resources and the deterioration of the water environment has resulted in restriction of the development of society and the protection of ecology and the environment. Consequently improving water efficiency is the key to realizing the sustainable utilization of water resources, and water efficiency evaluation is an important part of water resources management. Emergy theory aims to convert different dimensions of material and energy into solar energy, which can be analyzed and compared uniformly. Therefore, a new approach to assessing the economic efficiency of water resources, based on the water contribution to economic production, is evaluated using an emergy theory model. Water efficiency and system sustainability are explained by variables and emergy indicators in a regional water ecological–economic system (WEES) for Zhengzhou, China. The general status and economic efficiency of water resources in Zhengzhou are identified from the WEES. The average water contribution quantity and water contribution rate were 50.99×10^{20} sej and 6.13% during 2000–2011, respectively. Results also show that industrial water efficiency is higher than that of agriculture. This quantification method will help decision-makers to adjust water prices and provide better water services.

Key words | emergy indices, water ecological–economic system, water efficiency

Zening Wu
Xi Guo
Xinjian Guan
Cuimei Lv
Huiliang Wang (corresponding author)
School of Water Conservancy and Environment Engineering,
Zhengzhou University,
No. 100, Kexue Rd,
Zhengzhou City,
Henan Province 450001,
China
E-mail: *wanghuiliang@zzu.edu.cn*

INTRODUCTION

Water is the source of life, the focus of production, and the basis of ecology. In China, water is one of the most precious non-renewable natural resources. A previous study has shown that water resources are severely limited in many areas of China, especially during periods of drought. Water is the key factor in economic and population growth, and is crucial to human and environmental health. Water resources are necessary for household consumption and economic production in sectors such as agriculture, commercial fishing, forestry, industry (e.g., power plants), and tourism, and the global community has recognized that climate change will affect freshwater availability (IPPC 2007). In addition, population growth is placing stress on water availability in many places worldwide, including China (Vörösmarty *et al.* 2000; Carrillo & Frei 2009). Growing populations require additional goods and services from agriculture and industry, which exerts greater pressure on water resources (Micklin 2000). Therefore, the quantitative analysis of water resource economic efficiency in a regional water ecological–economic system (WEES) framework has global relevance for understanding water resource issues in the 21st century.

Although water is a limited resource, it is an essential and basic human need for urban, industrial, and agricultural use. Water efficiency is defined by the accomplishment of a function, task, or process with a minimal amount of water

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(Vickers 2002). Many studies have focused on irrigation water efficiency (McGockin *et al.* 1992; Omezzine & Zaibet 1998; Kar *et al.* 2007; Zhou *et al.* 2007; Zhang *et al.* 2010), but in other research areas, water resource studies tend to be qualitative rather than quantitative. Li & Xia (2007) developed a coupled hydrological–economic model, and provide one of the few quantitative studies in this field of research.

There are some economic disadvantages to the increased pressure on water resources, such as the rising marginal costs of water. The easiest and cheapest opportunities for capturing and distributing water are no longer available, and new schemes cost several times more per unit of water than previously. Unless there is a monumental advance in technology (e.g., greatly reduced transport costs), the cost of providing water will continue to rise. The other aspect of the problem is that water is no longer available for purely public purposes. It is not possible to provide every individual with as much water as they require, and suitable mechanisms must be used to appropriately ration or allocate water among users.

Different rules and mechanisms apply in different systems, such as water resources systems, ecosystems, and socio-economic systems. To understand emerging interactions between humans and ecological processes, human activities (e.g., transformation processes, land conversions, and resource use) and biophysical agents (e.g., geomorphology, climate, and natural cycles) need to be considered together. To meet this need, emergy analysis was proposed in the 1980s (Odum 1983, 1996) and has been used as an environmental accounting method to evaluate different resource-use categories with reference to their environmental cost (Bastianoni *et al.* 2001, 2007; Björklund *et al.* 2001; Chen *et al.* 2008; Paoli *et al.* 2008; Zhang *et al.* 2009). Since emergy theory was proposed, it has been widely used in many fields, such as the assessment of the value of water resources systems, ecological systems, and economic systems (Pulselli *et al.* 2007; Chen *et al.* 2008, 2009a, 2009b; Paoli *et al.* 2008; Lv & Wu 2009).

This study focuses on developing a comprehensive efficiency evaluation of water resources in a WEES. By calculating ecological and economic inputs and outputs, both inside and outside a complex system, the contribution of water resources to an economic system is defined using the Zhengzhou WEES case study as an example. The results will not only help scientists, engineers, and planners understand the complexity of the WEES, but also aid local authorities to efficiently manage water resources.

METHODS

WEES

Water resources are not only a fundamental component of ecosystem structure and function, but also an important material foundation for economic and social development. The WEES refers to the interaction between ecological systems and socio-economic systems, and is a major sub-system of the complete ecological–economic system. It also emphasizes the utilization and protection of water resources, and the organic connection between water use in social, economic, and natural systems.

Figure 1 shows the structure of the WEES, including the organic relationship between water resources, socio-economic systems, and other natural resources. The WEES couples traditional water resource systems with ecosystems and socio-economic systems. The main difference between the WEES and traditional water resource systems is that the latter are based on engineering technology that has an economic function but ignores ecosystems. The WEES, on the other hand, has a wider scope and considers both natural and economic systems. In the WEES, water is the core of the system and flows from ecosystems into economic systems, passes through a production phase, becomes polluted, and returns to the environmental system. Water flow links human actions and economic production with ecosystems. Despite the significance of the WEES, it remains poorly understood (Wu 2004; Lv & Wu 2009).

As important components of natural ecological systems, water resources have organic links with various elements through the natural water cycle; together, the water resources and elements constitute the morphological structure of the natural ecological system. With growing economic development, human interference with the natural water cycle is enhanced in order to meet the water requirements of social and economic systems, including irrigation, power generation, shipping, recreational and aquaculture.

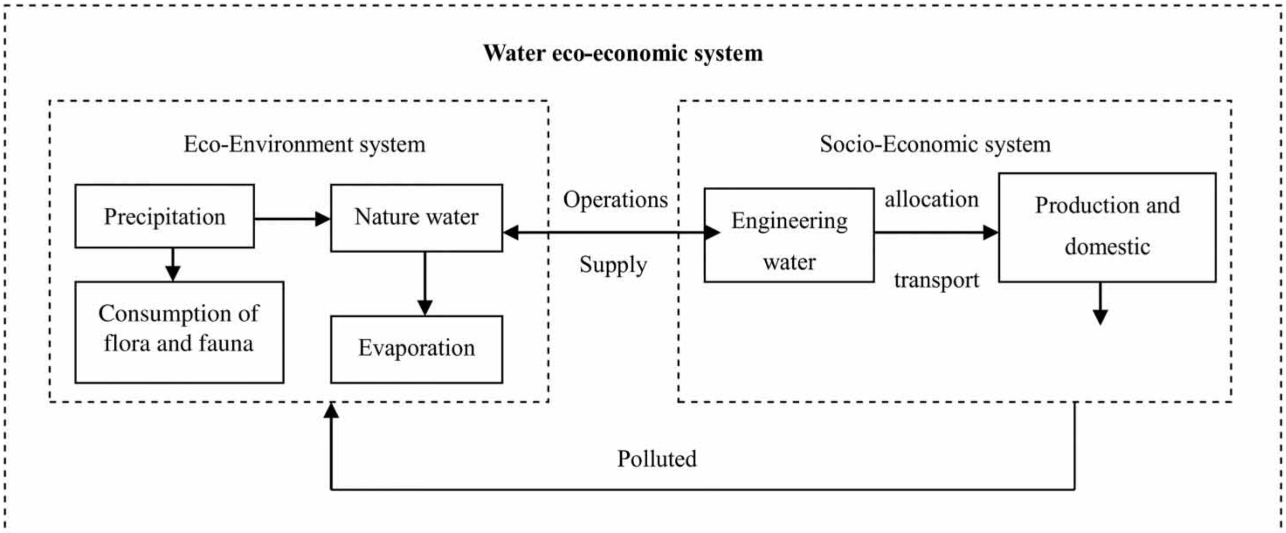

Figure 1 | Diagram of WEES structure.

Emergy theory and methods

Odum (1996) claimed that 'A science-based evaluation system is now available to represent both the environmental values and economic values with a common measure. EMERGY, spelled with an "m", measures both the work of nature and that of humans in generating products and services' (p. 3). Emergy is the energy memory or the total energy embodied in any product or service. It is defined as the sum of all the inputs of energy needed directly or indirectly to make any product or service (Odum 1996). The use of a common basis (solar equivalent joules, sej) accounts for all energy contributions required for a certain product or service. The relationship between emergy and energy is given by the transformity (sej/J), which is the emergy needed to obtain 1 J of a product or service, directly or indirectly. In some cases, using emergy per unit (such as mass) is a convenient way to transform quantities into emergy. Transformity measures the inputs of emergy per unit output and is calculated as the ratio of the emergy needed to produce a flow or storage to the actual energy of that flow or storage (Ulgiati & Brown 2002). The transformity is expressed as solar emergy joules per joule of output flow (sej/J). For certain products or flows that are easily quantifiable in units of mass (or money), a conversion value (named specific emergy) expressed in sej/g (or sej/$) can be used.

The values of emergy and transformity are path dependent; i.e., they are readily influenced by the materials and energy used at each step of the production process. The transformities of ecological services and products have been estimated by Odum (1996), but the transformities of industrial and agricultural products and services depend on the selected raw material and must be evaluated case-by-case.

Figure 2 shows a typical emergy flow diagram for industrial processes. The emergy flows represent three categories of resources: renewable resources (R), non-renewable resources (N), and inputs from the economy (F). All three categories are fundamental for emergy accounting and for

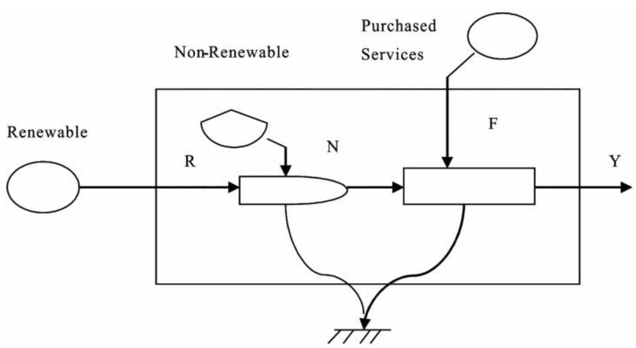

Figure 2 | Emergy flow chart for local renewable emergy inputs (R), local non-renewable inputs (N), purchased inputs from outside the system (F), and system yield ($Y = R + N + F$).

understanding the system interactions with the environment. The R and N flows are provided by the environment and are economically free, but while renewable resources can be replaced at the same rate at which they are consumed, non-renewable resources are depleted faster than they are replaced. Economic inputs, F, are provided by the market and are related to economic fluxes. The outputs, Y, may include products, services, and also emissions released to the environment. Emergy accounting is based on the assumption that energy flowing through hierarchical patterns in systems obeys a universal law, claimed by Odum (1996) to be the fifth law of thermodynamics. In these hierarchies of energy or matter, units placed higher in the hierarchy are assumed to have more influence on system function than units lower in the hierarchy (Grönlund *et al.* 2004).

Since the early 1980s, emergy analysis has been widely used to examine a diverse range of systems, including ecological, industrial, economic, and astronomical systems (Odum 1996; Brown & Ulgiati 1997, 2002; Lagerberg & Brown 1999). In recent years, many researchers have applied emergy theory to economic systems. Ulgiati & Brown (2002), for example, proposed an emergy-based method to quantitatively study the function of the environment in absorbing and diluting byproducts generated by an emissions process. Bakshi (2000) introduced an emergy analysis method for waste treatment in industrial systems. In this example, waste was handled not only by an end-of-pipe treatment approach and ecosystem dilution, but also by waste recycling techniques. Yang *et al.* (2003a, 2003b) proposed a new emergy analysis method for waste treatment and reuse, and Brown & Buranakarn (2003) evaluated the emergy used in the life cycles of building materials as well as the emergy inputs to waste disposal and recycling systems. A new energy index for sustainable development (EISD), proposed by Lu *et al.* (2003), considered not only the ratio of the sum of inputs from the economy (F) and non-renewable resources (N) to renewable resources (R) but also the extent of pollution.

WEES evaluation model system

Evaluation theory

Various forms of energy are translated into solar energy equivalent or solar emergy using a conversion factor (transformity) to reflect the energy's qualitative value in emergy analysis. By multiplying the inputs and outputs by their respective transformities, the emergy amount of each resource, service, and corresponding product can be calculated. Based on the same unit, these amounts can be analyzed easily through a series of emergy-related ratios and indices. These indices indicate various performance characteristics of the system in terms of efficiency and sustainability (Campbell 1997). Figure 3 shows an aggregated emergy diagram of a WEES, based on the energy circuit symbols developed by Odum (1996), fundamental data, and the operation mechanism. This figure illustrates the ecological and economic inputs and outputs, both inside and outside the complex system.

In theory, water exists at different scales in different biogeochemical processes, resulting in different emergy values and transformities. Water consumed by the system is assumed to be divided into two types: water derived from local precipitation (local water, WL), and water diverted from the exterior domain (WE). The local water can also be divided into local surface water (WLS) and local groundwater (WLG). The transformities of WLS, WLG, and WE are calculated using the method developed by Buenfil (2001).

In Figure 3, inputs to the WEES are categorized into four major types (Bastianoni *et al.* 2001; Lefroy & Rydberg 2003): renewable local resources (R) such as sunlight, rain, and wind; non-renewable local resources (N) such as soil erosion; purchased inputs (IMP) such as non-renewable purchased fossil fuels and chemical fertilizers, and renewable purchased inputs such as water resources; and export resources (EXP) such as products and labor exported externally. The system yield (Y) refers to the products of the system, such as industrial and agricultural products. The total emergy of system U is the vector sum of inputs and exports, and is formulated as $U = R + N + IMP - EXP$. The emergy flows of water in the system are categorized as follows: the total emergy of the water (WR), defined as the sum of surface water and groundwater within the system; emergy of consumed water (WC), defined as the emergy of water consumed by the system; emergy of local water (WL), defined as consumed water derived from local precipitation; and emergy of water diverted from the exterior domain (WE).

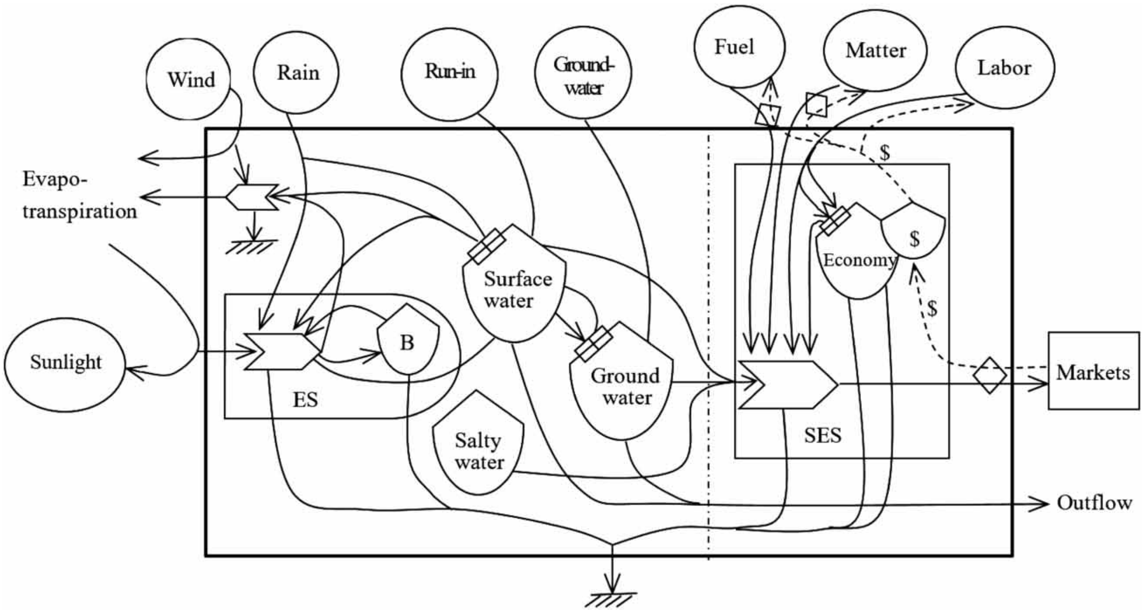

Figure 3 | Diagram of ecological and economic inputs and outputs, inside and outside the WEES (B = biomass, ES = environmental system, SES = socio-economic system).

For the overall WEES of a region, the time required for the system analysis is generally accepted to be 1 year, as most data are collected on an annual basis. The key to calculating emergy values is the solar transformities of different resources, products, or services of interest. During the past three decades, the transformities for various products and services have been calculated (Odum 1996; Brown & Ulgiati 1997; Lan *et al.* 2002).

Evaluation methods and steps

The WEES feasibility study methodology summarized in Figure 4 was developed by considering economic, technological, social, and environmental factors.

According to this framework, seven hierarchical levels should be distinguished to analyze water efficiency in the WEES. The first step involves collecting reliable data,

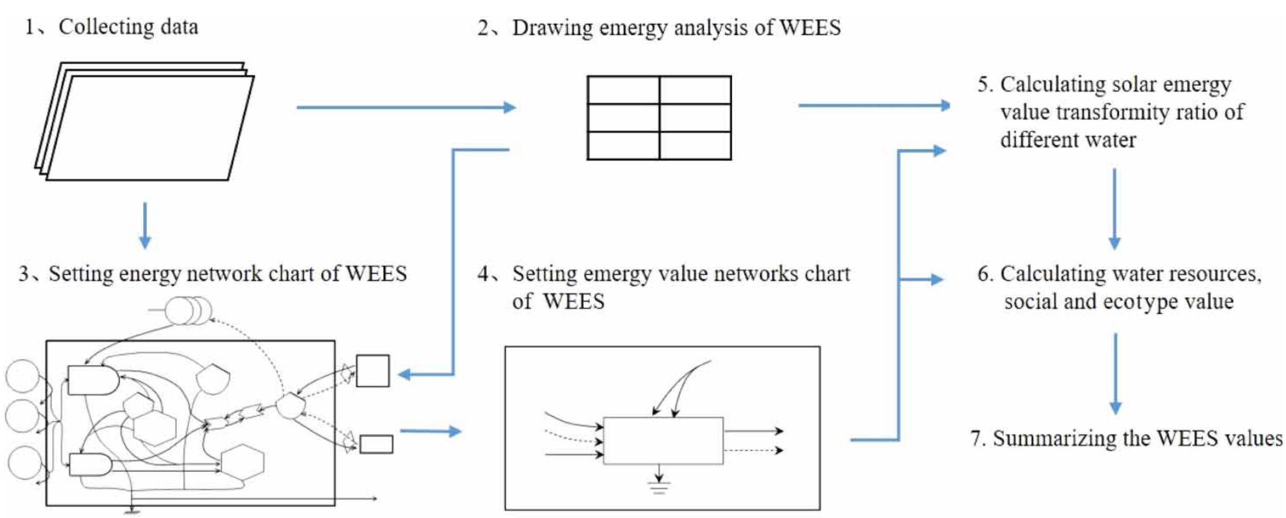

Figure 4 | Emergy analysis diagram of WEES.

indicators, or information. Basic records that need to be collected include the following:

1. Water supply and demand.
2. Water and wastewater management agencies in the area.
3. Regional water and wastewater facilities (in operation and planned).
4. Environmental setting (climate, geography, and topography; surface and groundwater resources).
5. Land use and population (current state and projections).
6. Ecological and hydro-geological boundary conditions.
7. Water-related socio-economic factors (water supply restrictions on domestic, industrial, and/or irrigation use).
8. Status of public acceptance of water reuse.

The second step is the action level; for example, drawing an emergy analysis table for the WEES, including the identification of all material and emergy flows within a system and the calculation of emergy flows (sej) using the transformity factor, and the conversion of solar emergy to more familiar monetary units. The third step involves establishing an emergy network chart for the WEES to provide an overview of the study area and identify the sources of flows and major processes. This step shows the main components and pathways using emergy system language. The remaining steps involve: creating an emergy value networks chart for the WEES; calculating a solar emergy value for different water sources; quantifying water resources, and social and ecotype values; and summarizing the WEES values.

Emergy indices for the contribution of water resources

Here, the word 'contribution' means the action of giving one's share to help a joint cause that helps society or the state. The concept of the contribution of water resources to economic production can be defined as the share of water resources in economic production in the WEES that can be utilized by energy conversion processes and finally embodied in a variety of high-quality economic products. More specifically, the concept emphasizes the importance of water resources in economic production processes in the WEES. Higher contributions of water resources to economic production result in higher water-resource use efficiency in the WEES. In other words, the contribution of water resources to economic production reflects water efficiency in the WEES.

This study uses the input–output relationship model in the WEES to measure the contribution of water resources to economic production. Water exists on various scales in different biogeochemical processes, resulting in different emergy values and transformities. Emergy analysis (Odum 1983) is able to consider both natural and economic systems and to compare their products. For comparative purposes, environmental factors, production factors, technological factors, and economic indicators can be transformed into the same 'emergy'. From an equity point of view, there are two key concepts in the field of water services: water resources contribution quantity (WCQ) and water resources contribution ratio (WCR). WCQ is defined as emergy values from water resource output emergy in economic systems, less the emergy used in economic systems to exploit water resources. Water contribution is therefore the net output emergy value generated by water resources. WCQ is an absolute index for measuring the contribution of water resources to economic production. Large economic systems have a high output emergy from water resources, use less emergy to exploit water resources, and therefore have a high WCQ during a certain period in a certain region. WCR is defined as the ratio of the WCQ to the net output emergy generated by the economic production system. WCR is a relative index for measuring the contribution of water resources to economic growth.

Figure 5 presents a comprehensive emergy schematic diagram for the agricultural and industrial economic subsystems in the WEES. The agricultural economic subsystem is used as an example to illustrate emergy change. Input emergy is primarily natural environmental emergy (EM_{AR}) and feedback emergy of the economic system (EM_{AF}), and output emergy is primarily the emergy of farm produce (EM_{AY}). Table 1 lists the different indices and expressions extracted from Figure 5.

According to the concept of the contribution of water resources to economic systems, the contribution can be expressed as follows:

$$EM_{AN} = EM_{AY} - EM_{AF} \quad (1)$$

$$EM_{IN} = EM_{IY} - EM_{IF}$$

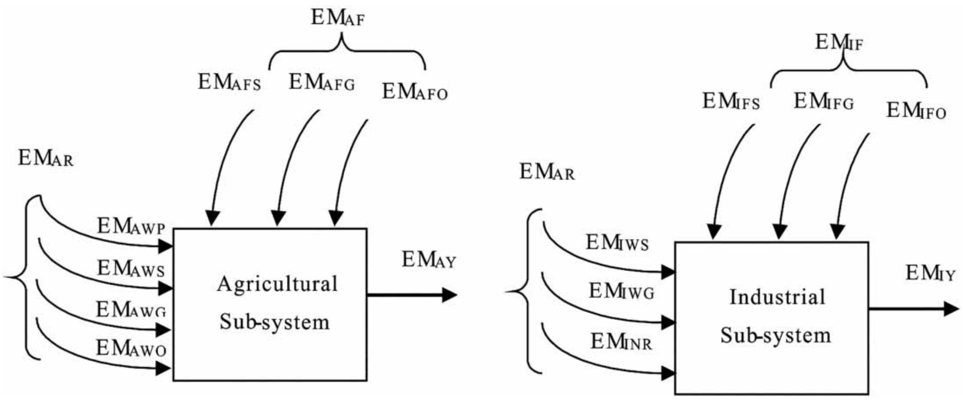

Figure 5 | Comprehensive emergy diagrams for the agricultural and industrial production sub-systems. (a) Agricultural sub-system. (b) Industrial sub-system.

Table 1 | Emergy indices in agricultural and industrial economic systems

Indices	Expression
Input	
$EM_{AR}EM_{IR}$	Natural environment emergy in agricultural and industrial systems, respectively.
$EM_{AF}EM_{IF}$	Feedback emergy of economic system in agricultural and industrial systems, respectively.
EM_{AWP}	Rainfall emergy in agricultural system.
EM_{AWS} EM_{IWS}	Surface water emergy in agricultural and industrial systems, respectively.
EM_{AWG} EM_{IWG}	Groundwater emergy in agricultural and industrial systems, respectively.
$EM_{ARO}EM_{IRO}$	Other environment emergy in agricultural and industrial systems, respectively.
$EM_{AFS}EM_{IFS}$	Feedback emergy of developed surface water in agricultural and industrial systems, respectively.
$EM_{AFG}EM_{IFG}$	Feedback emergy of developed groundwater in agricultural and industrial systems, respectively.
$EM_{AFO}EM_{IFO}$	Other feedback emergy in agricultural and industrial systems, respectively.
Output	
$EM_{AY}EM_{IY}$	Output emergy of all kinds of farm produce in agricultural and industrial systems, respectively.

$$WCQ_A = \frac{EM_{AW}}{EM_{AU}} \times EM_{AY} - EM_{AFW} \quad (2)$$

$$WCQ_I = \frac{EM_{IW}}{EM_{IU}} \times EM_{IY} - EM_{IFW}$$

where EM_{AN} and EM_{IN} are the net output of energy in agricultural and industrial systems, respectively; EM_{AW} and EM_{IW} are water-resource emergy inputs to agricultural and industrial sub-systems, respectively; EM_{AU} and EM_{IU} are the input emergy to agriculture and industry, respectively; and EM_{AFW} and EM_{IFW} are the emergy feedbacks for developing water resources in the economic system.

The contribution ratio of water resources to agricultural and industrial sub-systems can be expressed as follows:

$$WCR_A = \frac{WCQ_A}{EM_{AN}} \times 100\% \quad (3)$$

$$WCR_I = \frac{WCQ_I}{EM_{IN}} \times 100\%$$

The total quantity and ratio of water resources to economic production (WCQ and WCR) can be calculated as

$$WCQ = WCQ_A + WCQ_I \quad (4)$$

$$WCR = \frac{WCQ}{EM_{AN}+EM_{IN}} \times 100\% \quad (5)$$

Odum (1983, 1996) and Brown & Buranakarn (2003) investigated the transforming ratio of emergy including wind energy, chemical energy of rainwater, and tidal energy, and found that it was only weakly influenced by spatial and temporal differences. Although water resource transforming ratios for different regions were not addressed in these studies, they can be calculated according to different water resource conditions. This study uses the common transforming ratio of sub-system emergy (Odum 1983, 1996; Lv 2009).

Description of the study area

Geography

Zhengzhou City, the capital of Henan Province, is located in the middle of the southern Huabei plain and on the south bank of the Yellow River (113 °39′E, 34 °43′N) (Figure 6). The city is supplied with surface water from the Yellow River, which is transported 160 km across the northern part of Zhengzhou City. Zhengzhou has a warm continental climate, with four distinct seasons. The average maximum temperature is 27.3 °C in July, while the average minimum temperature is 0.2 °C in January. The average annual rainfall is 640.9 mm, the average frost-free period is 220 days, and the average number of hours of sunshine is 2,400.

The abundant natural resources in Zhengzhou include 34 types of mineral deposits, including coal, bauxite, refractory clay, and oil stone. Of these deposits, coal is the most abundant (50×10^8 t). The reserves of refractory clay and bauxite reserves (1×10^8 t) account for 50% and 30% of the reserves in the whole province, respectively. Furthermore, the high quality of petroleum in Zhengzhou makes the region one of the main producers of this mineral in China.

Economic and social characteristics

Zhengzhou is the political, economic, and cultural center of Henan province. It is an open and culturally rich city, an important site of industry, and an important national communications hub. As such, the ecosystem health of

Figure 6 | Location of Zhengzhou City in China, and a simplified map of city boundaries.

Zhengzhou is of great significance to the sustainable development of the entire region. The city includes 12 counties, with an urbanization level of 59%. The total area of Zhengzhou City is 7,446 km^2, and the population was 8.9 million in 2011.

The economic production of Zhengzhou showed a rapid increase during the 11th five-year plan (2006–2011). In 2011, the city's gross domestic product (GDP) was 498 billion Yuan (US$81.67 billion). The annual average amount of total output per person and population density is US$9,218 and 1,189 persons/km^2, respectively. The annual average amount of water available in Zhengzhou is 1.40 billion m^3, corresponding to 158 m^3/person or 4,922 m^3/ha. This water availability represents only half the Henan Province average, and this amount ranks tenth among all Chinese cities. Both the Henan and Chinese averages are lower than the global average (650 m^3/person and 8,870 m^3/ha).

Data for the 12 years considered in this study (2000–2011), as sourced from annual statistical yearbooks compiled by local government, environmental protection agencies, and the industrial, agricultural, and import and export sectors, were classified and sorted into the emergy flow table for the Zhengzhou WEES. Tabulated data for 2000–2011 included variables such as population, GDP, added value of industry and agriculture, and precipitation (Table 2). Figure 7 shows agricultural, industrial and domestic water use for 2000–2011.

Water resource characteristics

The total precipitation in Zhengzhou during 2010 was 630.7 mm, but the spatial and temporal distributions of precipitation are uneven. The total amount of available water was 11.4×10^8 m^3 in 2010, and the per capita water availability was 128.7 m^3, which is just 9% of the national per capita water resources. Accordingly, Zhengzhou has a serious lack of water resources.

In addition, the actual total water consumption in Zhengzhou is 20.2312×10^8 m^3. Within that, the industrial water consumption is 5.4756×10^8 m^3 and the agricultural water consumption is 4.7608×10^8 m^3, which account for 27.1% and 23.5% of the total amount respectively.

RESULTS AND DISCUSSION

In this section, a series of emergy indicators based on the emergy accounting of the Zhengzhou WEES are analyzed and discussed. In Zhengzhou, the WEES is defined as the amount of water consumed from the Yellow River. Solar

Table 2 | Basic data for Zhengzhou City during 2000–2011

Year	Population (10^4)	GDP (10^8 Yuan)	Added value of industry (10^8 Yuan)	Added value of agriculture (10^8 Yuan)	Total industrial output value (10^8 Yuan)	Total agricultural output value (10^8 Yuan)	Precipitation (mm)
2000	666	738	310	42	1,005	73	752.50
2001	677	828	345	45	1,113	79	464.40
2002	688	928	379	47	1,212	82	620.70
2003	698	1,102	456	49	1,481	86	980.30
2004	707	1,378	588	63	1,879	110	719.60
2005	716	1,661	760	72	2,412	126	702.60
2006	724	2,014	944	77	3,072	134	661.00
2007	736	2,487	1,315	79	3,945	137	519.10
2008	744	3,031	1,459	94	4,930	151	560.00
2009	752	3,327	1,552	103	5,351	184	615.70
2010	866	4,123	1,996	125	6,794	221	630.70
2011	886	4,980	2,277	132	8,341	235	721.20
Average	738	2,216	1,031.750	77.333	3,461.250	134.833	662.32

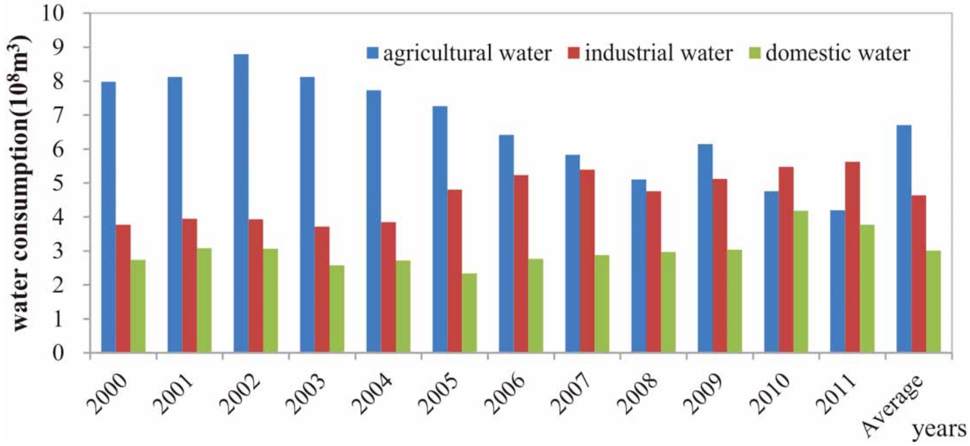

Figure 7 | Water use in Zhengzhou City (2000–2011).

transformities for different resources and products are keys in calculating emergy values. The main emergy flows in the Zhengzhou WEES for 2011 are shown in Figure 8.

Assessment of water efficiency

Table 3 lists the water resource emergy transforming ratios for Zhengzhou City during 2000–2011. The transforming ratio of surface and groundwater solar emergy shows a decreasing trend, suggesting rapid socio-economic development. The range in the transforming ratio of surface water emergy is 1.11 to 1.91×10^5 sej/J, and the range in the ratio for groundwater is 2.28 to 3.08×10^5 sej/J. The transformity of groundwater is twice that of surface water because of the longer groundwater renewal period.

Table 4 and Figure 9 show the results of the contribution of water resources to economic production in Zhengzhou. As shown in Table 4, the average WCQ of Zhengzhou during 2000–2011 is 50.99×10^{20} sej, and this had an increasing effect on the economy over time (see Figure 9). This result is consistent with economic development, and the decrease of water utilization in Zhengzhou City. The WCQ_A in agricultural systems is more than the WCQ_I in industry during 2000–2004, although the opposite is true during 2005–2011 (Table 4 and Figure 9). This change is related to the adjustment in industrial and

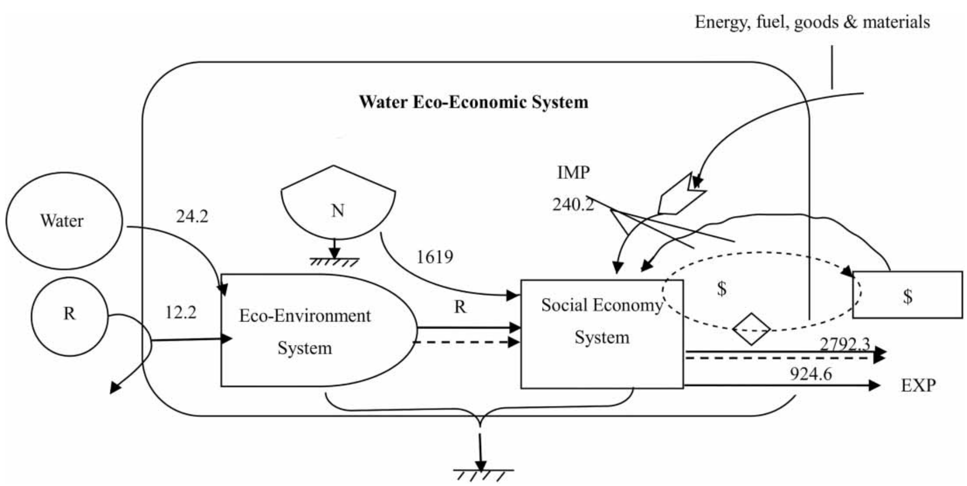

Figure 8 | Aggregated diagram of WEES emergy flows (units: 10^{20} sej).

Table 3 | Results of water resources emergy transformity during 2000–2011 in Zhengzhou WEES

Items	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Average
Surface water (10^5sej/J)	1.44	1.64	1.22	1.11	1.27	1.27	1.27	1.20	1.79	1.91	1.13	1.28	1.38
Groundwater (10^5sej/J)	2.65	2.28	2.54	2.78	2.67	2.74	2.95	2.50	3.08	2.90	2.49	2.60	2.68

Table 4 | Results of the contribution of water resources to economic production during 2000–2011

Items	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Average
WCQ (10^{20}sej)	28.54	35.99	40.61	51.37	44.60	50.55	61.70	42.61	70.98	68.08	52.42	64.39	50.99
#WCQ_A	18.96	18.00	20.78	24.57	22.38	22.45	27.20	17.07	24.13	24.18	17.53	19.30	21.38
#WCQ_I	9.58	17.99	19.83	26.81	22.21	28.10	34.50	25.54	46.85	43.90	34.90	45.09	29.61
WCQ of per m^3 water (10^{12}sej/m^3)	1.28	1.94	1.80	1.88	1.95	2.22	2.77	2.14	3.52	3.14	2.6	3.02	2.35
#Agriculture	1.02	1.23	1.11	1.04	1.18	1.25	1.60	1.17	1.61	1.52	1.20	1.24	1.26
#Industry	2.54	4.55	5.12	7.22	5.78	5.85	6.59	4.74	9.15	7.63	6.37	8.01	6.13
WCR (%)	8.61	9.58	9.21	9.27	6.29	5.24	5.81	3.56	4.73	4.19	3.42	3.69	6.13
#WCR_A	20.41	18.04	19.82	21.47	17.33	16.03	17.17	12.96	16.46	15.33	10.95	11.71	16.47
#WCR_I	4.01	6.52	5.90	6.10	3.83	3.41	3.82	2.40	3.46	2.99	2.55	2.85	3.99

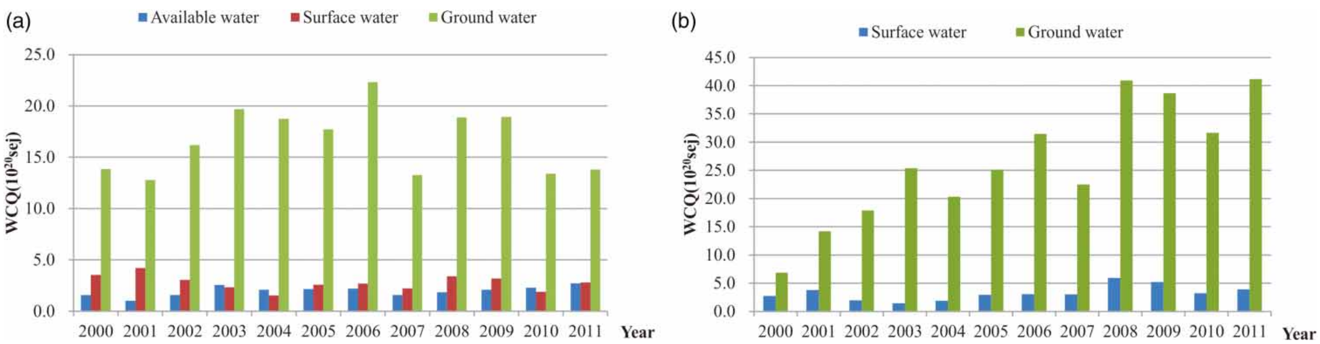

Figure 9 | Diagram showing WCQ to economic production in Zhengzhou during 2000–2011. (a) Agricultural sub-system. (b) Industrial sub-system.

water-use structures in Zhengzhou, with increased water saving and improvements in productive technology. Therefore, agricultural technologies and water saving measures also require further adjustments and improvements. This result also indicates that Zhengzhou is still under-industrialized compared with other cities in China, such as Jiangsu and Beijing.

The contribution ratio of water resources to the economy is much higher for agriculture than for industry (Table 4). The average WCR was 6.13%, and it showed a decreasing trend during 2000–2011. This trend is related to the development of water saving technology, improvements in productive technology, and other factors related to water resources. The average WCR_A during 2000–2011 was 16.47%, with a maximum of 20.41% in 2000 and a minimum of 10.95% in 2010. The average WCR_I was 3.99%, with a maximum of 6.52% in 2001 and a minimum of 2.40% in 2007. 'Water is the source of life, the focus of production, and the basis of ecology.' In order to realize the normal operation of industrial and agricultural production, the contribution of water resources is essential, and WCQ and WCR are both indications of the importance of water resources.

The average contribution to the agricultural and industrial economies of each cubic metre of water was 1.26×10^{12} sej and 6.13×10^{12} sej during 2000–2011, respectively (Figure 10). This shows that the efficiency of industrial water use is higher than that of agricultural water use. As shown in Figure 10, the contribution per cubic metre of water to the economy has an increasing trend. Rapid industrialization and modernization in recent decades have resulted in severe environmental impacts in Zhengzhou. This is illustrated by the per cubic metre contribution of water to the industrial economy, which increased from 2.54×10^{12} sej in 2000 to 9.15×10^{12} sej in 2008. Water scarcity has gradually become one of the most limiting factors for development in Zhengzhou.

As the concept of emergy is abstract, the results of the WCQ in Table 5 are transformed to a comparative currency (Renminbi, ¥). As shown in Table 5, the average WCQ of Zhengzhou City is estimated to be ¥ 115.96×10^8, the average WCQ_A is ¥ 44.89×10^8, and the average WCQ_I is ¥ 71.07×10^8. The average contribution of water is 5.42 ¥/m^3, and the contribution of water to agricultural and industrial systems is 2.73 and 14.02 ¥/m^3, respectively. These values account for a large proportion in the total production, and these results also show the importance of water resources to economic production and the efficiency of water resources to the economic system. Therefore, the WEES is an important tool for government to use in both providing water services and setting or at least adjusting water prices. When the water efficiency is lower than the average value of nearly 10 years, relevant policies and measures must be taken.

For 10 years, the WCQ presented a rising tendency, with a maximum of ¥ 338.50×10^8 in 2011 and a minimum of ¥ 44.82×10^8 in 2000. The WCQ per m^3 water during 2000–2011 had the same trend, with a maximum of 15.89 ¥/m^3 in 2011 and a minimum of 2.01 ¥/m^3 in 2000.

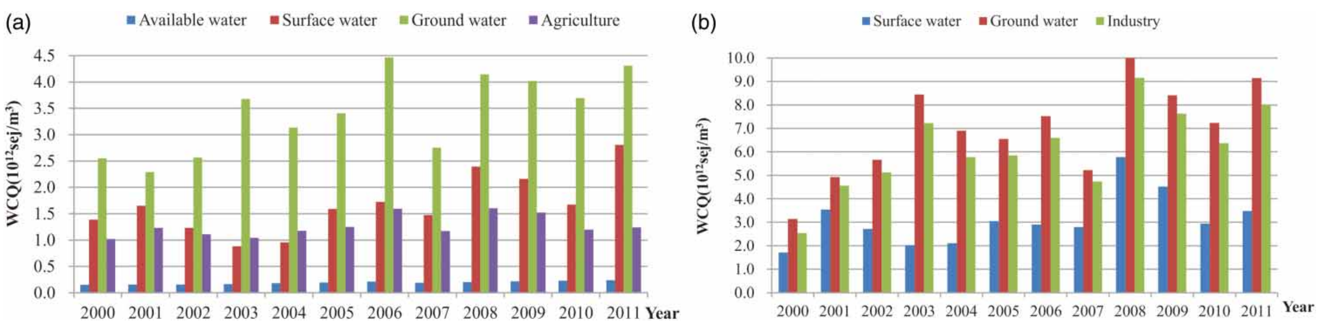

Figure 10 | Diagram showing WCQ per m^3 water to economic production in Zhengzhou during 2000–2011. (a) Agricultural sub-system. (b) Industrial sub-system.

Table 5 | Results transformed to the comparative currency (Renminbi) of WCQ of Zhengzhou City during 2000–2011

Items	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Average
WCQ (10^8¥)	44.82	56.64	60.93	77.45	69.93	69.41	98.03	75.96	160.01	160.59	179.21	338.50	115.96
#WCQ_A	29.78	28.32	31.18	37.04	35.10	30.83	43.22	30.42	54.40	57.04	59.93	101.46	44.89
#WCQ_I	15.04	28.32	29.75	40.42	34.83	38.59	54.81	45.53	105.62	103.55	119.31	237.04	71.07
WCQ per m^3 water (¥/m^3)	2.01	3.05	2.70	2.83	3.06	3.05	4.40	3.81	7.94	7.41	8.89	15.89	5.42
#Agriculture	1.60	1.94	1.67	1.57	1.85	1.72	2.54	2.09	3.62	3.59	4.09	6.52	2.73
#Industry	3.98	7.17	7.68	10.89	9.06	8.03	10.48	8.44	20.63	18.00	21.78	42.12	14.02

CONCLUSIONS

This study proposes a theoretical framework and methodology for developing a WEES. It combines water resources, ecosystems, and economic systems to assess water efficiency based on emergy synthesis. Emergy and materials with different qualities are measured, compared, and aggregated within the complex WEES to provide a synthesis that is complementary to conventional economic and emergy analyses. The mechanisms of the Zhengzhou WEES are also described using emergy-based indices. Based on the emergy analysis, Zhengzhou's ecological economic status is characterized as follows: (1) it is heavily reliant on imported fuels, goods, and services; (2) there are high empower densities and environmental loadings; (3) the actual population of Zhengzhou is 20.1 times more than the bearing capacity of the WEES, resulting in high water-resource pressure; (4) the sustainability index for the Zhengzhou WEES indicates that there is plenty of room for further development, although to sustain development it is crucial to implement water-saving strategies and to search for new water sources; and (5) the contribution of water resources to industrial systems is much higher than for agricultural systems, indicating that water efficiency is higher in industrial systems.

The aim of an emergy evaluation is to assess the exploitation of natural resources (renewable and non-renewable) used in a process or in producing a product. This paper provides a brief overview of important applications of emergy evaluation techniques, and provides an applied example of a regional WEES evaluation method (i.e., an emergy analysis) to estimate the WEES status and water efficiency of Zhengzhou. The results indicate that emergy analysis is a useful way to quantify water efficiency of regions, and this illustrates the importance of water for the WEES and its sub-system. In a word, the water efficiency evaluation method based on emergy analyzes the system input and output in detail and evaluates the contribution of water resources more objectively, which should be included in decision-making processes for the development of efficient and effective strategies for sustainable management and economic development.

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