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RESEARCH ARTICLE

Emergy evaluation of a pumping irrigation water production system in China

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Abstract The emergy concept was used to evaluate a pumping irrigation water production system in China. A framework for emergy evaluation of the significance of irrigation water and its production process was developed. The results show that the irrigation water saved has the highest emergy value ($8.73E+05\ \mathrm{sej \cdot J^{-1}}$), followed by the irrigation water supplied to farmlands ($1.72E+05\ \mathrm{sej \cdot J^{-1}}$), the pumped water ($4.81E+04\ \mathrm{sej \cdot J^{-1}}$), with the lowest value shown from water taken from the local river ($3.72E+04\ \mathrm{sej \cdot J^{-1}}$). The major contributions to the emergy needed for production are the inputs of soil and water. This production system could contribute to the irrigated agriculture and economy, according to several calculated emergy indices: emergy yield ratio (*EYR*), emergy investment ratio (*EIR*), environmental load ratio (*ELR*), and environmental sustainability index (*ESI*). The comparative analysis shows that the emergy theory and method, different from the conventional monetary-based analysis, could be used to evaluate irrigation water and its production process in terms of the biophysical account. Additional emergy evaluations should be completed on different types of water production and irrigated agricultural systems to provide adequate guidelines for the sustainability of irrigation development.

Keywords emergy, evaluation, irrigation, water

1 Introduction

Global food security will remain a worldwide concern for the next several decades (Rosegrant and Cline, 2003). Agricultural production in irrigated systems is correspondingly expected to increase by 81% from 1998–2030 based on an FAO study (Bruinsma, 2003). Irrigation water plays a major role in both food security, and even poverty alleviation, in developing countries (Chen et al., 2011). Yet irrigated agriculture is facing the risks of water scarcity and environmental concerns. Water productivity is projected to increase through gains in crop yield and reductions in water irrigation (Playán and Mateos, 2006). Thus irrigation systems must be modernized to meet these needs, especially in developing countries where approximately three quarters of the land consist of irrigated. The same is true for the expanse of irrigated agriculture in China. The amount of water used for agriculture accounts for more than 62% of the total water use in China; the average efficiency of irrigation water use is 0.50, and the amount of available water per Mu (667 $\mathrm{m^2}$) for the arable land is only 1,400 $\mathrm{m^3}$ (Wang, 2012). For this reason, the Chinese government issued its first national outline for agricultural water-saving development (2012–2020) in December 2012. According to this plan, the irrigated area will increase from $9.25E+08$ Mu in 2012 to $1.00E+09$ Mu in 2020, and the efficiency of irrigation water use will rise from 0.50 in 2012 to 0.55 in 2020. It is estimated that the investment in agricultural water-saving and irrigation improvement projects will be greatly increased in the near future. Therefore, scientific evaluation of irrigation water, agricultural water-saving, and related improvement projects, are needed for better policy decision-making in irrigation development.

The full value of water, including its specific economic, social, cultural, and environmental benefits, has been gradually emphasized by the international community. A variety of methods have been developed to estimate water value, such as cost analysis, shadow pricing, the fuzzy model, the computable general equilibrium model, the

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contingent valuation method, choice modeling, hedonic price analysis, and the water value-flow concept (Jiang, 1998; Blamey et al., 1999; Faux and Perry, 1999; Shen et al., 1999; Barton, 2002; Seyam et al., 2002; Hussain et al., 2007; Chen et al., 2009a). In addition, several methods were used in previous studies on the assessment of irrigation improvement projects, such as discount cash flow, cost and benefit, cost recovery, and real option analyses, optimization methods, the analytic hierarchy process, linear programming, indicator systems, and synthetic evaluation approaches (Mergos, 1987; Psychoudakis et al., 1995; Singh et al., 1999; Adekalu and Ogunjimi, 2003; Mareels et al., 2005; Olubode-Awosola et al., 2006; Michailidis et al., 2009). However, the main focus of these methods is on the economic values or the monetization of non-economic values of water and other resources. The monetary valuation of natural capital may be useful to demonstrate its economic value, but it is insufficient to measure the intrinsic worth of the life-support function of the ecosystem (Costanza et al., 1998). As for sustainability, attempts to force arguably incommensurable values into a one-dimensional monetary metric can be regarded as particularly counter-productive (Bebbington et al., 2007). Moreover, natural resource over-exploitation and ecosystem degradation often depend on the fact that monetary values are the only parameters driving human actions (Pulselli et al., 2011). Emergy theory, based on thermodynamics, determines the values of natural resources, services, and commodities in common units of solar emergy (Odum, 1996). It has been proven to be a particularly effective method to evaluate water in terms of the biophysical account (Odum, 1996; Buenfil, 2001; Chen et al., 2009a; Pulselli et al., 2011). We demonstrate in this paper the use of the emergy evaluation method on a pumping irrigation water production system in China. The goal of this paper is to increase the current understanding of various water values within the entire process and sustainability of this water production system.

Emergy is the available energy of one kind that is used up in transformations directly and indirectly to make a product or service (Odum, 1996; Yan and Odum, 2001; Lan et al., 2002). Emergy accounts for different forms of energy and resources, including both free environmental and purchased inputs (Yan and Odum, 2001; Chen and Chen, 2011). Thus emergy could put all products of nature, technology, and the economy on a common basis of the prior work required and embodied water (Buenfil, 2001). The emergy contributions of water at different levels of the global and regional hydrological cycle and energy conversion process could be evaluated (Chen et al., 2009a). Emergy evaluation has been used to assess different aspects of water and water systems, such as: 1) the estimation of chemical potential energy and geopotential energy of water (Odum, 1996), 2) the value and allocation of water resources in Florida (Buenfil, 2001), 3) the natural value of water resources in Chinese rivers (Chen et al., 2009a), 4) the energy and material metabolism of the Yellow River basin (Chen and Chen, 2009), 5) the recovery of costs for water services (Brown et al., 2010), 6) the cost-benefit analysis of water conservation engineering (Brown and McClanahan, 1996; Kang and Park, 2002; Chen et al., 2011), and 7) the sustainability of constructed wetlands (Chen et al., 2009b; Shao et al., 2012). The emergy indices of the regional water ecological-economic system were also developed (Lv and Wu, 2009; Chen et al., 2012). However, the emergy concept has rarely been used to evaluate irrigation water. The modernization of irrigation system construction in China and other developing countries highlights the requirement for more objective and comprehensive approaches to evaluate the value of irrigation water and the sustainability of water production systems.

The objectives of this paper are to (i) develop an objective evaluation method of irrigation water, (ii) present a biophysical understanding of water conservation engineering through emergy analysis of a pumping irrigation water production system, and (iii) discuss the related policies on irrigation water management. The remainder of this paper is organized as follows. Section 2 presents a brief overview of the study area and the emergy evaluation methods: the emergy systems diagram for the irrigation water production system, the energy conversion process analysis of river water into irrigation water, and the selected emergy indices to evaluate this system. Results are presented and discussed in Section 3. Section 4 concludes by summarizing the main results and pointing to some suggestions based on these emergy evaluations.

2 Methods

2.1 Study area

The Maozhuang pumping irrigation district is located in a plains area of China, in Yaowang Town, Taixing City of Jiangsu Province, with an irrigated land of about 6.0E + 05 m^2 (Fig. 1). The irrigation water source is from the local river linked to the lower Yangtze River. The old irrigation system consisted of a pumping station and earth canals of 4.9 km. Since these infrastructures were built in the 1980s, the degraded pumping station ran at 56% efficiency, and the water efficiency in earth canal system was only 5% (also due to the leakage of sandy soil). Due to the poor plant pumping efficiency, an improvement project for this district was fulfilled in 2007 to upgrade the irrigation system with a new pumping station and concrete-lined canals. The main objectives of this project were to increase the water efficiency and agricultural production. In this paper, the improved pumping irrigation system in this district is subjected to an emergy evaluation. The different types of water processed through this irrigation water production system are also assessed on the basis of emergy.

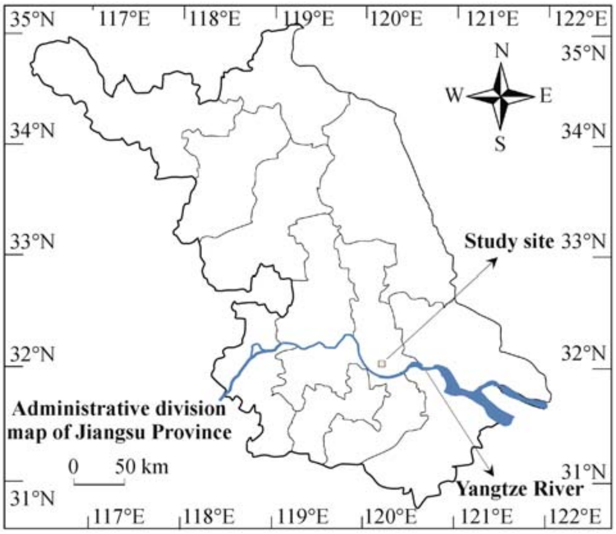

Fig. 1 Location of the study area.

The main data and materials about this system originate from the planning and design report of the project and field survey data.

2.2 Emergy evaluation method

The emergy evaluation of this irrigation water production system can follow the same procedure as the emergy analysis. As a top-down systems approach, the general methodology of emergy analysis consists of three steps: 1) the creation of systems diagrams; 2) the establishment of emergy analysis tables; and 3) the calculation of emergy indices (Brown and McClanahan, 1996; Odum, 1996; Kang and Park, 2002; Chen et al., 2009a).

The diagram for this pumping irrigation water production system depicts the integrated emergy transformation process (Fig. 2). The system consists of two sub-systems: water source and irrigation water production. The energy and materials metabolism of this system is thereby characterized by the combination of natural resources (i.e., sunlight, wind, rain, river water) and the imported social resources and services (i.e., electricity and fuels, materials and resources, labor and services required by the construction and operation of water conservancy facilities). Both the environmental and economic inputs in a specific system could be converted into the standard unit of solar emergy, based on the emergy theory. By multiplying the energy in Joules (or directly from its mass) by specific transformities, the solar emergy of each input and outflow in the process can be calculated. These transformities are mainly derived from previous studies of emergy evaluations (Odum, 1996; Chen and Chen, 2009; Chen et al., 2009a; Pulselli et al., 2009; Chen et al., 2011). The global emergy baseline of reference used here is $9.44\text{E}+24\ \text{sej}\cdot\text{yr}^{-1}$. In addition, this improvement project was assumed to have a 30-year life span under the effective

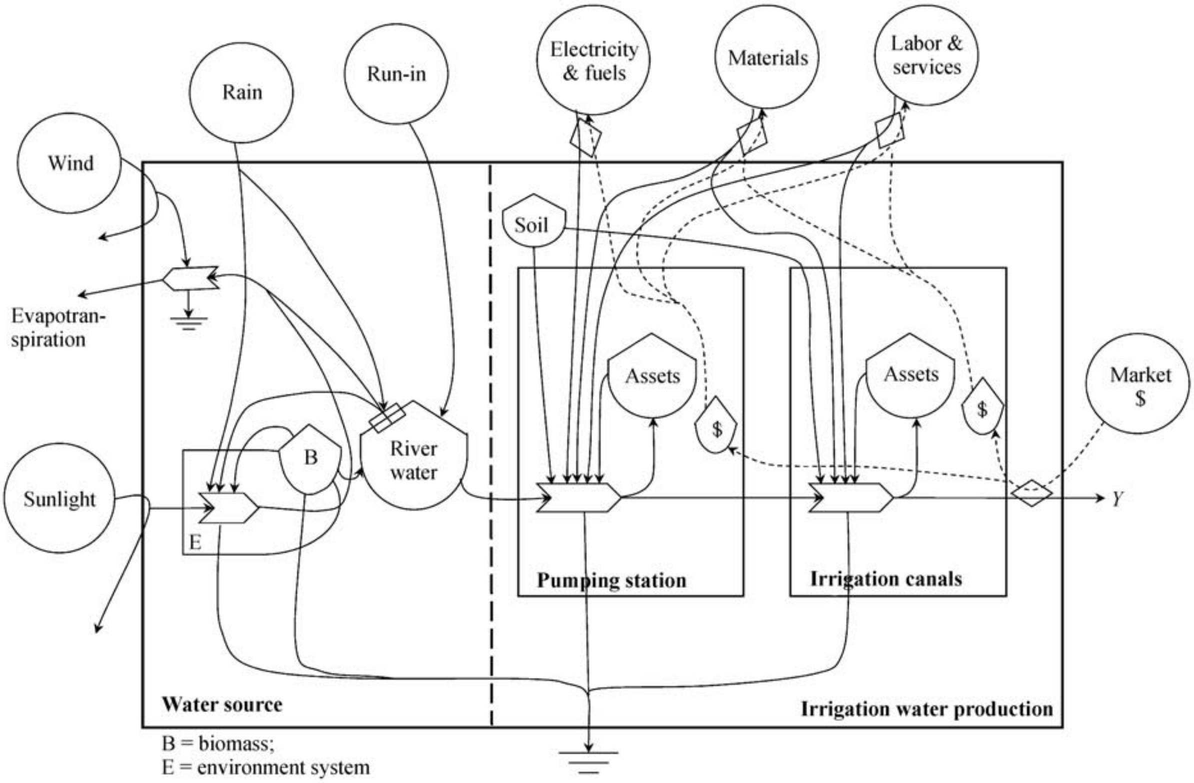

Fig. 2 Energy systems diagram for the pumping irrigation water production system.

maintenance and management. Thus each item was divided by 30 to present data on a yearly basis.

Figure 2 also illustrates the energy conversion process of river water into irrigation water. The water source is from both the nearby Yangtze River and the local water catchment area. The river water is then pumped and delivered into the farmlands for agricultural production. Thus, through this process, different types of water can be evaluated using the emergy analysis method. The total chemical potential energy of the river water was considered as the main energy source for irrigation water production. The transformity of river water was assumed to be that of the Yangtze River ($3.72\mathrm{E}+04$ sej·J^{-1}) (Chen et al., 2009a). The transformities of different types of water were calculated by the specific system analysis. This method consists of: (i) the calculation of the total emergy used for the specific water production in the sub-systems; (ii) the calculation of the chemical potential energy of water by multiplying the annual water (g·yr^{-1}) by the average Gibb's free energy of the water (4.92 J·g^{-1}, assumed to be the same as that of the Yangtze River) (Chen et al., 2009a); and (iii) the calculation of the transformity of water (sej·J^{-1}) by dividing the total emergy used by the chemical potential energy of the specific water.

In addition, the inputs to this irrigation water production system are generally aggregated into renewable environmental resources (R), non-renewable environmental resources (N), purchased electricity, fuels and materials (M), and the labor and services component of purchased inputs (S) (Chen et al., 2011). The emergy yield of this system theoretically equals the total emergy used ($Y = R + N + M + S$) in Odum's energy diagram. Several emergy indices are also used to evaluate this irrigation water production system, including emergy yield ratio (*EYR*), emergy investment ratio (*EIR*), environment loading ratio (*ELR*), and environmental sustainability index (*ESI*). These indices have different calculations with specific ecological implications: (i) $EYR = Y/(M + S)$, the total emergy used per unit of emergy invested; (ii) $EIR = (M + S)/(R + N)$, the emergy investment needed to exploit one unit of local renewable and nonrenewable resource; (iii) $ELR = (M + N + S)/R$, the total nonrenewable and imported emergy used per unit of local renewable resource; (iv) $ESI = EYR/ELR$, the emergy yield per unit of environmental loading (Odum, 1996; Brown and Ulgiati, 1997; Ulgiati and Brown, 1998; Chen et al., 2006; Jiang et al., 2007; Chen et al., 2011).

3 Results and discussion

The emergy evaluation of this irrigation water production system is given in Table 1. Of special importance in this table are the transformity of irrigation water supply to farmlands ($1.72\mathrm{E}+05$ sej·J^{-1}) and the emergy yield of this production system ($4.45\mathrm{E}+17$ sej·yr^{-1}). The water taken from the local river was the source of water in the pumping system. The water yield of the pumping station was the source of water in the irrigation canal system. Thus the emergy inputs and output were evaluated in different subsystems and processes. The emergy required for irrigation water saved was assumed to be the total emergy of the whole system. The construction of irrigation canals (66% of the total emergy yield) represented the greatest emergy input for producing this irrigation water, followed by the emergy of river water (25% of the total emergy yield). In the emergy inputs of irrigation canals construction, soil loss associated with the earthwork was the major cost (46% of the irrigation canals construction; 27% of the total emergy yield). This loss has generally been underestimated in conventional economic analysis based on monetary units, due to the current low unit cost of earthwork (1.8 \$·m^{-3} for manual work or 0.9 \$·m^{-3} for mechanical work) (Chen et al., 2011).

Table 2 shows the results of the emergy evaluation of different types of water in this production process. The first column in Table 2 presents the efficiencies of irrigation water produced: the pumped water accounts for 98% of the water taken from the local river; the irrigation water supplies 90% of the pumped water to the farmlands. The calculated results indicate the significant contribution of different types of water to the production of irrigation water from the pumping station and lined canals. The emergy of water pumped, calculated from the evaluation of the irrigation pumping system (Fig. 2 and Table 1), was added to the value of irrigation water supply to farmlands. The existence of water in different processes resulted in different transformities and emergy values. The value of the irrigation water saved was the highest ($8.73\mathrm{E}+05$ sej·J^{-1}), followed by the irrigation water supply to farmlands ($1.72\mathrm{E}+05$ sej·J^{-1}). The lowest value was that of the water taken from the local river ($3.72\mathrm{E}+04$ sej·J^{-1}); yet the transformities of water in the public systems in Florida varied from $1.39\mathrm{E}+05$ sej·J^{-1} to $1.39\mathrm{E}+06$ sej·J^{-1} due to the different production processes (Buenfil, 2001). The calculated transformity of irrigation water ($1.72\mathrm{E}+05$ sej·J^{-1}) was higher than that for severalessential fuels, e.g., natural gas ($4.80\mathrm{E}+04$ sej·J^{-1}), crude oil ($5.40\mathrm{E}+04$ sej·J^{-1}), and diesel ($6.60\mathrm{E}+04$ sej·J^{-1}) (Odum, 1996). This indicates that irrigation water is as valuable as the main fuels powering the present economy.

The sej·yr^{-1} values in Table 2 represent the emergy required for the specific water type. Those for the irrigation water supply to farmlands and the irrigation water saved were the highest ($4.45\mathrm{E}+17$ sej·yr^{-1}), followed by the water yield of the pumping station ($1.38\mathrm{E}+17$ sej·yr^{-1}), according to the energies of production systems. The sej·m^{-3} values indicate the emergy per volume of water. The last two columns in Table 2 show the emdollar values of different types of water. Due to the different processes for irrigation water production, the calculated emdollar value of irrigation water in this study (0.25 Em\$·m^{-3}) was higher than that in Florida (0.11 Em\$·m^{-3}) (Buenfil, 2001), but

Table 1 Emergy evaluation of the irrigation water production system a)

No.	Item	Raw data		Solar transformity		Solar emergy	
I	Renewable resources					1.09E + 17	sej·yr^{-1}
1	Sunlight	4.20E + 13	J·yr^{-1}	1.00E + 00	sej·J^{-1} b)	4.20E + 13	sej·yr^{-1}
2	Wind, kinetic energy	2.50E + 10	J·yr^{-1}	1.50E + 03	sej·J^{-1} b)	3.76E + 13	sej·yr^{-1}
3	Rain, geopotential	5.94E + 08	J·yr^{-1}	1.05E + 04	sej·J^{-1} b)	6.24E + 12	sej·yr^{-1}
4	Rain, chemical	4.99E + 10	J·yr^{-1}	1.82E + 04	sej·J^{-1} b)	9.08E + 14	sej·yr^{-1}
5	Water taken from the local river	2.94E + 12	J·yr^{-1}	3.72E + 04	sej·J^{-1} c)	1.09E + 17	sej·yr^{-1}
II	Construction of the irrigation pumping station					1.76E + 16	sej·yr^{-1}
6	Soil	5.40E + 06	g·yr^{-1}	1.00E + 09	sej·g^{-1} b)	5.40E + 15	sej·yr^{-1}
7	Cement	8.33E + 05	g·yr^{-1}	3.04E + 09	sej·g^{-1} d)	2.53E + 15	sej·yr^{-1}
8	Water used by cement	1.80E + 06	J·yr^{-1}	3.72E + 04	sej·J^{-1} c)	6.71E + 10	sej·yr^{-1}
9	Sand	2.67E + 06	g·yr^{-1}	1.00E + 09	sej·g^{-1} d)	2.67E + 15	sej·yr^{-1}
10	Stone	3.00E + 06	g·yr^{-1}	1.68E + 09	sej·g^{-1} d)	5.04E + 15	sej·yr^{-1}
11	Steel	6.67E + 04	g·yr^{-1}	6.94E + 09	sej·g^{-1} d)	4.63E + 14	sej·yr^{-1}
12	Brick	4.88E + 05	g·yr^{-1}	3.68E + 09	sej·g^{-1} d)	1.79E + 15	sej·yr^{-1}
13	Labor	5.72E + 01	$·yr^{-1}	3.38E + 12	sej·$$^{-1}$ e)	1.93E + 14	sej·yr^{-1}
14	Machinery	3.46E + 02	$·yr^{-1}	3.38E + 12	sej·$$^{-1}$ e)	1.17E + 15	sej·yr^{-1}
15	Temporary works	3.31E + 01	$·yr^{-1}	3.38E + 12	sej·$$^{-1}$ e)	1.12E + 14	sej·yr^{-1}
16	Other costs (e.g., construction management, production preparation)	4.25E + 01	$·yr^{-1}	3.38E + 12	sej·$$^{-1}$ e)	1.44E + 14	sej·yr^{-1}
17	Residual value of the fixed assets					1.95E + 15	sej·yr^{-1}
III	Operation and maintenance of the pumping station					1.16E + 16	sej·yr^{-1}
18	Electricity	5.97E + 10	J·yr^{-1}	1.59E + 05	sej·J^{-1}	9.49E + 15	sej·yr^{-1}
19	Labor	3.60E + 02	$·yr^{-1}	3.38E + 12	sej·$$^{-1}$ e)	1.22E + 15	sej·yr^{-1}
20	Maintenance	2.53E + 02	$·yr^{-1}	3.38E + 12	sej·$$^{-1}$ e)	8.54E + 14	sej·yr^{-1}
IV	Water yield of the pumping station					1.38E + 17	sej·yr^{-1}
21	Water yield of the pumping station	2.88E + 12	J·yr^{-1}	4.81E + 04	sej·J^{-1} f)	1.38E + 17	sej·yr^{-1}
V	Construction of irrigation canals					2.94E + 17	sej·yr^{-1}
22	Soil	1.35E + 08	g·yr^{-1}	1.00E + 09	sej·g^{-1} b)	1.35E + 17	sej·yr^{-1}
23	Cement	1.06E + 07	g·yr^{-1}	3.04E + 09	sej·g^{-1} d)	3.21E + 16	sej·yr^{-1}
24	Water used by cement	2.29E + 07	J·yr^{-1}	3.72E + 04	sej·J^{-1} c)	8.50E + 11	sej·yr^{-1}
25	Sand	2.76E + 07	g·yr^{-1}	1.00E + 09	sej·g^{-1} d)	2.76E + 16	sej·yr^{-1}
26	Stone	3.43E + 07	g·yr^{-1}	1.68E + 09	sej·g^{-1} d)	5.77E + 16	sej·yr^{-1}
27	Brick	1.95E + 07	g·yr^{-1}	3.68E + 09	sej·g^{-1} d)	7.18E + 16	sej·yr^{-1}
28	Labor	4.19E + 02	$·yr^{-1}	3.38E + 12	sej·$$^{-1}$ e)	1.42E + 15	sej·yr^{-1}
29	Other costs (e.g. construction management, production preparation)	1.60E + 02	$·yr^{-1}	3.38E + 12	sej·$$^{-1}$ e)	5.41E + 14	sej·yr^{-1}
30	Residual value of fixed assets					3.26E + 16	sej·yr^{-1}
VI	Operation and maintenance of irrigation canals					1.29E + 16	sej·yr^{-1}
31	Labor	2.70E + 03	$·yr^{-1}	3.38E + 12	sej·$$^{-1}$ e)	9.12E + 15	sej·yr^{-1}
32	Maintenance	1.11E + 03	$·yr^{-1}	3.38E + 12	sej·$$^{-1}$ e)	3.75E + 15	sej·yr^{-1}
VII	Irrigation water supply to farmlands					4.45E + 17	sej·yr^{-1}
33	Irrigation water supply to farmlands	2.59E + 12	J·yr^{-1}	1.72E + 05	sej·J^{-1} f)	4.45E + 17	sej·yr^{-1}
VIII	Irrigation water saved					4.45E + 17	sej·yr^{-1}
34	Irrigation water saved	5.09E + 11	J·yr^{-1}	8.73E + 05	sej·J^{-1} f)	4.45E + 17	sej·yr^{-1}

a) Data sources and calculations are given in Appendix A. The methods of energy transformation refer to Odum (1996).
b) Transformities from Odum (1996).
c) Assumed the same as that of the Yangtze River (Chen et al., 2009a).
d) Transformities from Pulselli et al. (2009).
e) The emergy/dollar ratio of Chinese economy 2002 is from Chen et al. (2009a).
f) Calculated in this study.

Table 2 Emergy evaluation of different water in the process of irrigation water production system

No.	Water types	Water quantity /($m^3\cdot yr^{-1}$)	Solar transformity /($sej\cdot J^{-1}$)	Solar emegy /($sej\cdot yr^{-1}$)	Emergy per volume/($sej\cdot m^{-3}$)	Water values/ (Em$\$\cdot m^{-3}$)	Water values/ ($CNY\cdot m^{-3}$)
1	Water taken from the local river	5.97E + 05	3.72E + 04	1.09E + 17	1.83E + 11	0.05	0.36
2	Water yield of the pumping station	5.85E + 05	4.81E + 04	1.38E + 17	2.37E + 11	0.07	0.47
3	Irrigation water supply to farmlands	5.27E + 05	1.72E + 05	4.45E + 17	8.45E + 11	0.25	1.67
4	Irrigation water saved	1.04E + 05	8.73E + 05	4.45E + 17	4.30E + 12	1.27	8.48

Table 3 Emergy indices and ratios for the irrigation water production system

No.	Emergy indices and indicators	Expression	Quantity
1	Free renewable resources/($sej\cdot yr^{-1}$)	R	1.09E + 17
2	Nonrenewable resources/($sej\cdot yr^{-1}$)	N	1.26E + 17
3	Total environmental investment/($sej\cdot yr^{-1}$)	$R+N$	2.36E + 17
4	Purchased fuel and materials/($sej\cdot yr^{-1}$)	M	1.92E + 17
5	Services and labor inputs/($sej\cdot yr^{-1}$)	S	1.70E + 16
6	Total feedback emergy/($sej\cdot yr^{-1}$)	$M+S$	2.09E + 17
7	Total emergy yield/($sej\cdot yr^{-1}$)	$Y=R+N+M+S$	4.45E + 17
8	Proportion of total environment investment	$(R+N)/Y$	0.53
9	Proportion of total feedback emergy	$(M+S)/Y$	0.47
10	Emergy yield ratio	$EYR = Y/(M+S)$	2.13
11	Emergy investment ratio	$EIR = (M+S)/(R+N)$	0.89
12	Environmental load ratio	$ELR = (M+N+S)/R$	3.07
13	Environmental sustainability index	$ESI = EYR/ELR$	0.69

lower than that in Texas (0.44 Em$\$\cdot m^{-3}$) (Odum, 1996). The emdollar value per volume of the irrigation water saved was the highest (8.48 $CNY\cdot m^{-3}$), which showed the benefit of water-saving for this irrigation water production system as compared with the old irrigation system. This value was followed by that of irrigation water supply to farmlands (1.67 $CNY\cdot m^{-3}$). However, the actual irrigation price was only 0.07 $CNY\cdot m^{-3}$ (calculated by dividing the price of 40 $CNY\cdot Mu^{-1}$ by the irrigation quota of 585 $m^3\cdot Mu^{-1}$), which only considered the cost of operation and maintenance of this irrigation system rather than its full costs. Based on the concept of revenue capitalization, the estimated irrigation benefit was 0.15 $CNY\cdot m^{-3}$, considering the shadow price of paddy rice (1.2 $CNY\cdot kg^{-1}$) and its yield increase by irrigation improvement (72 $kg\cdot Mu^{-1}$). The emdollar value of irrigation water in this study was higher than these data, but close to the shadow price of raw water for irrigation in Haihe Basin (1.5 $CNY\cdot m^{-3}$) (Qin et al., 2012). This result demonstrates that the values of water are often several times greater than their corresponding market values (Odum, 1996; Buenfil, 2001; Chen et al., 2009a; Chen et al., 2011).

The economic benefit cost ratio of this irrigation water production system from the conventional cost-benefit analysis method was 2.05, indicating its high economic feasibility. To further evaluate its sustainability, several emergy indices and ratios were calculated in Table 3. The total emergy used by the irrigation water production system was 4.45E + 17 $sej\cdot yr^{-1}$. About 53% of the total emergy use in this system was derived from R (water) and N (soil), while 47% was imported from the economy. This reflects the system's high dependence on the local environmental resources, especially the river water (25% of the total emergy use). The *EYR* is used to evaluate how much this irrigation water production system enables a process to exploit local resources in order to further contribute to the agriculture and economy. The value of *EYR* was 2.13, higher than the 1.0 for the balance between the system's output and input from the economy. It is close to the 2.18 value in 2004 for the Chinese agricultural system (Jiang et al., 2007). In view of the *EIR*, the higher its value, the more economic resources have to be used for this irrigation water production. Compared to Chinese agriculture's *EIR* of 1.15 in 2004 (Jiang et al., 2007), the lower the *EIR* (0.89) of this system, the greater the economic benefit. The *ELR* was another important ratio, indicating the environmental impact of this system. The *ELR* for the Chinese agricultural system in 2004 was 2.96

(Jiang et al., 2007). The *ELR* of 3.07, between 3.0 and 10.0, was indicative of moderate impacts (Brown and Ulgiati, 1997). The *ESI* was used to assess the sustainability of this system. Its value of 0.69 was less than 1.0, indicating that this was a consuming economic system (Brown and Ulgiati, 1997; Ulgiati and Brown, 1998). This value is close to the corresponding value of 0.74 for the Chinese agricultural system in 2004 (Jiang et al., 2007).

The emergy evaluation of this irrigation water production system indicates that conventional evaluation methods could underestimate the value of irrigation water and overestimate the feasibility of the system. The possible reasons include the over-reliance on monetization, a rough estimate of environmental costs, and subjectivity to calculations for the conventional evaluation method. The emergy evaluation method could assess some resources, materials, services, commodities, and environmental effects on the basis of emergy that were not included in the conventional method. In other words, this method can identify "leakage" material and energy flows into or out of the system (Mayer, 2008). Yet emergy has also suffered a lot of resistance and criticism, such as theoretical arguments, problems of transformity calculations, accounting procedures, co-products or splits treatment, uncertainty, and sensitivity (Hau and Bakshi, 2004; Sciubba and Ulgiati, 2005; Mayer, 2008; Ingwersen, 2010; Li et al., 2011; Rugani and Benetto, 2012). Despite these dissatisfactions, emergy evaluation is an often-used holistic approach with a uniform unit of measure for quantification or valuation of ecosystem goods and services. Emergy analysis can still provide valuable information as to the contribution of ecosystems to engineering planning and the assessment of engineering systems (Hau and Bakshi, 2004).

In addition, two main objectives of sustainable irrigation water management are irrigated agriculture sustainability for food security and the associated natural environment preservation (Cai et al., 2001). As an important policy tool for sustainable irrigation water management, water pricing can be used to mitigate both the quantity and quality dimensions of water scarcity (Dudu and Chumi, 2008). Meanwhile, a global call for full cost recovery for water infrastructure increases the need to identify the full values of irrigation water and infrastructure (Hussain and Bhattarai, 2005; Ward, 2010). However, accurate water pricing for agricultural use remains a debatable issue (Johansson et al., 2002). Use of the emergy evaluation method, as opposed to the conventional market-oriented analysis, has proven to be a more accurate assessment of the value of irrigation water. The current gap between the value and actual price of irrigation water indicates that a reasonable increase in its price is needed. Yet designing and implementing pricing reforms is a complicated process affected by various forces, thus political economic concepts should be introduced into this process (Dinar, 2000). Moreover, irrigation infrastructure investments are increasing in many irrigated areas to face the problem of aging infrastructure and declining revenues to maintain and repair irrigation structures (Ward, 2010). The feasibility analysis and sustainable assessment of these investments are of vital importance to ensure the efficient use of money (Chen et al., 2011). The emergy indices and ratios could serve as scientific guidelines in public policy decision-making in terms of the concept of ecological economics.

4 Conclusions

Emergy evaluation has the potential to identify and compare the contribution of natural resources and ecosystem services to a production process in terms of the biophysical account. It highlights the role of the natural and environmental resources supporting human activities from the view of sustainable development. Different from conventional monetary-based analysis, the emergy theory and method could be used to evaluate irrigation water and its improvement projects on the unified basis of emergy. Emergy evaluation has also allowed useful indicators to assess long-term sustainability of water production systems. Hence, this method leads to a better description of the value of irrigation water and its production process.

A case study on a pumping irrigation water production system in China illustrated this methodology. The results indicated that conventional evaluation methods could either underestimate or overestimate the subjective appraisements as opposed to those using the emergy theory and method. The emergy evaluation showed that the different types of water in this water production system had distinct values, which were subjected to their places in the processes and hierarchy of the system. The river water, as the source of irrigation, had the lowest emergy value ($3.72\mathrm{E}+04\ \mathrm{sej}\cdot\mathrm{J}^{-1}$). Its emergy value increased as river water was pumped ($4.81\mathrm{E}+04\ \mathrm{sej}\cdot\mathrm{J}^{-1}$) and distributed ($1.72\mathrm{E}+05\ \mathrm{sej}\cdot\mathrm{J}^{-1}$) through the pumping station and canals respectively. The irrigation water saved had the highest emergy value ($8.73\mathrm{E}+05\ \mathrm{sej}\cdot\mathrm{J}^{-1}$) since it used the total emergy inputs in the system. The major contributions to the emergy needed for production were the inputs of soil and water (27% and 25% of the total emergy yield, respectively). The emergy analysis of this water production system revealed that the system could contribute to both irrigated agriculture and the economy. The calculated *EYR* (2.13) and *EIR* (0.89) represented the system's high performance and competitiveness of economic investment. The *ELR* of 3.07 was also indicative of moderate impacts. However, the *ESI* (0.69) signaled that further efforts should be made to improve the emergy indices and sustainability by increasing the efficiency of input use and reducing the dependency on nonrenewable and imported inputs. Furthermore, additional emergy evaluations should be conducted on different types of water production systems and irrigated agricultural systems. The related pricing policies for irrigation water and assessment of irrigation improvement projects should also be improved to further irrigation development sustainability.

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Appendix A

Footnotes to Table 1[1].

1 Sunlight

Area = 9840 m^2

Insolation = $4.94E + 09\ J \cdot m^{-2} \cdot yr^{-1}$

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[1] The original data are from the planning and design report on irrigation improvement projects in Maozhuang Village of Yaowang Town (Maozhuang Village Committee, 2007) (Non-Public/Internal Report) (In Chinese)

Albedo = 13.5% (Lan et al., 2002)
Energy (J) = (9840 m^2) × (4.94E + 09 J·m^{-2}·yr^{-1}) × (1–13.5%)
= 4.20E + 13 J·yr^{-1}

2 Wind, kinetic energy
Density of Air = 1.23 kg·m^{-3} (Odum, 1996)
Average annual wind velocity = 2.43 m·s^{-1}
Drag Coefficient = 1.00E–03 (Odum, 1996)
Energy (J) = (9840 m^2) × (1.23 kg·m^{-3}) × (1.00E-03) × (10/6 × 2.42 m·s^{-1})^3 × (3.15E + 07 s·yr^{-1})
= 2.50E + 10 J·yr^{-1}

3 Rain, geopotential
Rainfall = 1.027 m·yr^{-1}
Average Elevation = 6 m
Energy (J) = (9840 m^2) × (1.027 m·yr^{-1}) × (1E + 03 kg·m^{-3}) × (9.8 m·s^{-2}) × (6 m)
= 5.94E + 08 J·yr^{-1}

4 Rain, chemical
Gibb's free energy = 4.94 J·g^{-1} (Odum, 1996)
Energy (J) = (9840 m^2) × (1.027 m·yr^{-1}) × (1E + 06 g·m^{-3}) × (4.94 J·g^{-1})
= 4.99E + 10 J·yr^{-1}

5 Water taken from the local river
Volume = (5.85 ×10^5 m^3·yr^{-1}) / 0.98 (dividing the volume value of No. 21 in Table 1 by the station's water efficiency of 0.98)
= 5.97 ×10^5 m^3·yr^{-1}
Energy (J) = (5.97 ×10^5 m^3·yr^{-1}) × (1.0×10^6 g·m^{-3}) × (4.92 J·g^{-1})
= 2.94 ×10^{12} J·yr^{-1}

6 Soil
Volume = 60 m^3
Total weight = (60 m^3) × (2.7×10^6 g·m^{-3}) / (30 yrs) (The project was assumed to have a 30-year life span)
= 5.4 ×10^6 g·yr^{-1}

7 Cement
Weight = 25 t
Total weight = (25 t) × (1.0×10^6 g·t^{-1}) / (30 yrs)
= 8.33 ×10^5 g·yr^{-1}

8 Water used by cement
Volume = 0.44 × (25 t) × (1.0×10^6 g·t^{-1}) / (1.0× 10^6 g·m^{-3}) (assumed to be 44% of the weight of cement used)
= 11 m^3
Energy (J) = (11 m^3) × (1.0×10^6 g·m^{-3}) × (4.92 J·g^{-1}) / (30 yrs)
= 1.80 ×10^6 J·yr^{-1}

9 Sand
Weight = 80 t
Total weight = (80 t) × (1.0×10^6 g·t^{-1}) / (30 yrs)
= 2.67 ×10^6 g·yr^{-1}

10 Stone
Weight = 90 t
Total weight = (90 t) × (1.0×10^6 g·t^{-1}) / (30 yrs)
= 3.00 ×10^6 g·yr^{-1}

11 Steel
Weight = 2 t
Total weight = (2 t) × (1.0×10^6 g·t^{-1}) / (30 yrs)
= 6.67 ×10^4 g·yr^{-1}

12 Brick
Volume = 4000 × (240 mm×115 mm × 53 mm) / (1.0×10^9 m^3·mm^{-3})
= 5.85 m^3
Total weight = (5.85 m^3) × (2.5×10^6 g·m^{-3}) / (30 yrs)
= 4.88 ×10^5 g·yr^{-1}

13 Labor
Costs = 1717 $
Yearly costs = (1717 $) / (30 yrs)
= 57.2 $·yr^{-1}

14 Machinery
Costs = 10380$ (Three sets of pumps and other machineries used in 30 years)
Yearly costs = (10380 $) / (30 yrs)
= 346 $·yr^{-1}

15 Temporary works
Costs = 992 $
Yearly costs = (992 $) / (30 yrs)
= 33.1 $·yr^{-1}

16 Other costs (e.g. construction management, production preparation)
Costs = 1274 $
Yearly costs = (1274 $) / (30 yrs)
= 42.5 $·yr^{-1}

17 Residual value of the fixed assets
Energy (sej) = (the sum of No. 6-16 in Table 1) ×10%
= 1.96 ×10^{15} sej·yr^{-1}

18 Electricity
Volume of pumped water = 5.97 ×10^5 m^3·yr^{-1} (No. 5 in Table 1)
Energy (J) = (5.97 ×10^5 m^3·yr^{-1}) / (792 m^3·h^{-1}) × (22 kW) (3.6×10^6 J·kW^{-1}·h^{-1})
= 5.97 ×10^{10} J·yr^{-1}

19 Labor
Yearly costs = 360 $·yr^{-1}

20 Maintenance
Yearly costs = 253 $·yr^{-1} (assumed to be 2% of the construction costs)

21 Water yield of the pumping station
Volume = (5.27 ×10^5 m^3·yr^{-1}) / 0.9 (dividing the volume value of No. 33 in Table 1 by the canals' water efficiency of 0.9)
= 5.85 ×10^5 m^3·yr^{-1}
Energy (J) = (5.85 ×10^5 m^3·yr^{-1}) × (1.0×10^6 g·m^{-3}) × (4.92 J·g^{-1})
= 2.88 ×10^{12} J·yr^{-1}
Required emergy (sej) = (the sum of No. 5-16 and 18-20 in Table 1) – (No. 17 in Table 1)
= 1.38 ×10^{17} sej·yr^{-1}
Transformity = (1.38 ×10^{17} sej·yr^{-1}) / (2.88 × 10^{12} J·yr^{-1})
= 4.81 ×10^4 sej·J^{-1}

22 Soil

Volume = 1500 m^3
Total weight = (1500 m^3) × (2.7×10^6 $g\cdot m^{-3}$) / (30 yrs)
= 1.35×10^8 $g\cdot yr^{-1}$

23 Cement
Weight = 316.8 t
Total weight = (316.8 t) × (1.0×10^6 $g\cdot t^{-1}$) / (30 yrs)
= 1.06×10^7 $g\cdot yr^{-1}$

24 Water used by cement
Volume = 0.44 × (316.8 t) × (1.0×10^6 $g\cdot t^{-1}$) / (1.0×10^6 $g\cdot m^{-3}$) (assumed to be 44% of the weight of cement used)
= 139.392 m^3
Energy (J) = (139.392 m^3) × (1.0×10^6 $g\cdot m^{-3}$) × (4.92 $J\cdot g^{-1}$) / (30 yrs)
= 2.29×10^7 $J\cdot yr^{-1}$

25 Sand
Weight = 829 t
Total weight = (829 t) × (1.0×10^6 $g\cdot t^{-1}$) / (30 yrs)
= 2.76×10^7 $g\cdot yr^{-1}$

26 Stone
Weight = 1030 t
Total weight = (1030 t) × (1.0×10^6 $g\cdot t^{-1}$) / (30 yrs)
= 3.43×10^7 $g\cdot yr^{-1}$

27 Brick
Volume = 160000 × (240 mm×115 mm × 53 mm) / (1.0×10^9 $m^3\cdot mm^{-3}$)
= 234.05 m^3
Total weight = (234.05 m^3) × (2.5×10^6 $g\cdot m^{-3}$) / (30 yrs)
= 1.95×10^7 $g\cdot yr^{-1}$

28 Labor
Costs = 12580 $
Yearly costs = (12580 $) / (30 yrs)
= 419 $\$\cdot yr^{-1}$

29 Other costs (e.g. construction management, production preparation)
Costs = 4802.7 $
Yearly costs = (4802.7 $) / (30 yrs)
= 160 $\$\cdot yr^{-1}$

30 Residual value of the fixed assets
Energy (sej) = (the sum of No. 22-29 in Table 1) ×10%
= 3.27×10^{16} $sej\cdot yr^{-1}$

31 Labor
Yearly costs = 2700 $\$\cdot yr^{-1}$

32 Maintenance
Yearly costs = 1110 $\$\cdot yr^{-1}$ (assumed to be 2% of the construction costs)

33 Irrigation water supply to farmlands
Volume = (585 $m^3\cdot Mu^{-1}$) × (900 Mu) / (1 yr)
= 5.27×10^5 $m^3\cdot yr^{-1}$
Energy (J) = (5.27×10^5 $m^3\cdot yr^{-1}$) × (1.0×10^6 $g\cdot m^{-3}$) × (4.92 $J\cdot g^{-1}$)
= 2.59×10^{12} $J\cdot yr^{-1}$
Required emergy (sej) = (the sum of No. 21-29 and 31-32 in Table 1) – (No. 30 in Table 1)
= 4.45×10^{17} $sej\cdot yr^{-1}$
Transformity = (4.45×10^{17} $sej\cdot yr^{-1}$) / (2.59×10^{12} $J\cdot yr^{-1}$)
= 1.72×10^5 $sej\cdot J^{-1}$

34 Irrigation water saved
Volume = [(700 $m^3\cdot Mu^{-1}$) – (585 $m^3\cdot Mu^{-1}$)] × (900 Mu) / (1 yr) (The annual irrigation water quotas for rice are in typical dry years)
= 1.04×10^5 $m^3\cdot yr^{-1}$
Energy (J) = (1.04×10^5 $m^3\cdot yr^{-1}$) × (1.0×10^6 $g\cdot m^{-3}$) × (4.92 $J\cdot g^{-1}$)
= 5.09×10^{11} $J\cdot yr^{-1}$
Required emergy (sej) = 4.45×10^{17} $sej\cdot yr^{-1}$ (assumed the same as No.33 in Table 1)
Transformity = (4.45×10^{17} $sej\cdot yr^{-1}$) / (5.09×10^{11} $J\cdot yr^{-1}$)
= 8.73×10^5 $sej\cdot yr^{-1}$