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Emergy Based Ecological Assessment of Constructed Wetland for Municipal Wastewater Treatment: Methodology and Application to the Beijing Wetland

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ABSTRACT. This paper improves the traditional emergy method, and presents an ecological assessment for a constructed wetland that is designed for municipal wastewater treatment. The improvement is made by redefining the ecological value of wastewater, using renovated trasformities, and considering the ecological discounting effect. The modified method is applied to assess the Beijing Wetland, a typical constructed wetland in northern China. A parallel monetary based assessment is also carried out to investigate the difference between ecological and economic perspectives. Results show that the Beijing Wetland maintains a positive ecological profit while the discount rate is below 15.58%, and economic deficit will not occur until the discount rate reaches an unusually high level of 41.21%. In the scenario of a yearly discount rate of 5%, the emergy cost to treat one cubic meter of wastewater by the Beijing Wetland is calculated to be 4.53E+10 sej, which is equivalent to 0.01 em$, and is much lower than that by the traditional treatment technology. Moreover, both ecological and economic assessments suggest the application of constructed wetland is profitable and thus should be promoted on a larger scale for municipal use of wastewater treatment if the discount rate does not exceed 15%.

Keywords: ecological assessment, constructed wetland, municipal wastewater treatment, emergy, waste, transformity, discount

1. Introduction

Along with the extensive applications of other methodologies to the field of systems ecology (Wall, 1977; Jørgensen, 1981, 2001; Reini and Valero, 2003; Szargut, 2003; Sciubba and Ulgiati, 2005; Chen and Chen, 2007), the concept of emergy was advanced by Odum (1988, 1996) to evaluate the required work in terms of a certain kind of available energy to generate a product or service. In the past decades, emergy has attracted a significant amount of research, and in turn has greatly expanded the scope of traditional ecological research. Furthermore, it presents a solid background for further studies. To date, the emergy method has been a popular metric for ecological assessment, with various studies to explore algorithms (Bastianoni and Marchettini, 2000; Brown and Buranakarn, 2003; Huang and Chen, 2005; Chen et al., 2010a), to calculate transformities (Odum, 2000; Odum et al., 2000; Brown and Bardi, 2001; Brandt-Williams, 2002; Kangas, 2002), and to apply empirical analyses (Ulgiati et al., 1994; Chen et al., 2006a; Jiang et al., 2007; Yang et al., 2010).

The issue of municipal waste treatment is important for the sustainability of urban development (Li et al., 2008; Azam et al., 2009; Huang et al., 2010). Constructed wetland (CW) attracts intensive interest in emergy studies, since it is one of the most important engineering for ecological waste treatment, in particular for municipal wastewater treatment (USEPA, 2006; Chen and Zeng, 2009; Zeng and Chen, 2009a, b; Zeng et al., 2010). Emergy assessment for CW was carried out for the first time by Howington et al. (1997). Odum and his colleagues made a significant contribution to the CW emergy study via conducting a resource efficiency analysis on a wastewater treatment CW in Mexico (Nelson et al., 2001). According to their results, this artificial ecosystem depends mainly on locally available materials and renewable energy resources and thus is more sustainable in the long-term than conventional sewage treatment technologies. Moreover, with smaller economic cost, CW systems are more affordable in comparison with the conventional package plants and their development should be applied to larger scales. Afterwards, Siracusa and la Rosa (2006) evaluated the use of environmental resources for a projected traditional wastewater treatment plant coupled with a surface flow CW in a Sicilian town, by the means of emergy analysis. Their results show the installlation of the hybrid system is profitable via not only reducing electricity

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consumption but also relieving local environmental impact. In order to compare the resources consumed by CW and by other systems, emergy assessments were also processed by Geber and Björklund (2001), Grönlund et al. (2004), Zuo et al. (2004), and Zhou et al. (2009). Particularly, in one of the latest efforts concentrating on the sustainability of CW engineering, Chen et al. (2009a) carried out a study comparing various waste treatment technologies, in which indicators including emergy yield ratio, emergy load ratio, emergy sustainability index, net economic benefit index, and renewable percentage index were applied.

The aforementioned efforts have enhanced the understanding of CW engineering and provided useful advice for its management. However, we believe the effectiveness of the related studies can further be improved if the following points are addressed appropriately. First, despite that CW is usually designed as an ecological engineering to treat wastewater, the ecological value of wastewater had not yet been properly defined, i.e., it was either neglected or overestimated (Geber and Björklund, 2001; Nelson et al., 2001; Grönlund et al., 2004). Second, using valid transformities adapted to local circumstance is a crucial process for precise and reliable results in emergy study but the lack of an appropriate transformity database lead to a practical obstacle in conventional studies (Zhou, 2008). Third, regarded as a general property of ecological activity (Faber, 2008), the dynamics of time had not been paid sufficient attention to. As a consequence of the above problems, particular ecological characteristics of CW engineering were usually not emphasized and sometimes ignored in previous studies. Therefore a specific emergy based CW assessment scheme with adequate melioration to settle these problems is required for concrete emergy research.

In this paper, a modified ecological assessment scheme for CW is established based on the modified emergy method, in which the ecological value of waste is redefined, the renovated transformity database is adopted, and the ecological discounting effect is taken into account. Driven by the prevalent social concerns, economic assessment is also frequently applied to CW to investigate its environmental cost-benefit issues (Zuo et al., 2004; Yang et al., 2008). The comparison between the ecological assessment which is based on emergy budget, and the economic assessment which is based on monetary budget, is helpful for the selection of most suitable tools in order to satisfy practical requirements. Thereby, the new emergy scheme is applied to a case study of a typical CW, i.e., the Beijing Wetland, with parallel assessment based on monetary budget carried out for further comparison.

2. Methodology

2.1. A Description of Emergy Method

Based on the combination of ecological thermodynamics and systems ecology, the emergy method is put forward to integrate all ecological endowments, i.e., energy, mass, and information, into a unified unit (Odum, 1988, 1996). Considering most territorial processes are driven directly or indirectly by solar energy, different forms of ecological endowments are usually transformed into the solar energy equivalent, i.e., solar joule (sej). In empirical calculation, the emergy value is obtained through multiplying the magnitude of ecological endowment by its transformity, which is the average emergy intensity of the endowment. Analogous to currency used in economics, the concept of embodied currency normalizing the thermodynamic equivalent (sej) by the quantity embodied in one economic unit ($1) of product for a macroeconomic system with unit of embodied dollar (em$) is also advanced to measure the ecological wealth related to social activities (Ton et al., 1998; Odum and Odum, 2003; Brown et al., 2004). The difference between market value and embodied currency value can be applied to reveal in what degree an ecological endowment is misjudged by economic consideration comparing to by ecological consideration.

The ecological assessment process is generally performed as follows. First, an emergy diagram is sketched to depict the system boundary, major components, and input-output flows. Second, an emergy table is built up to account for the related flows illustrated in the aforementioned diagram. Finally, concerned emergy indicators are calculated to assess the ecological characteristics of the concerned system. The detailed algorithm for the process can be referred to in a series of studies and thus is not repeated here (Odum, 1996; Chen and Chen, 2009; Jiang et al., 2008, 2009).

2.2. Modified Emergy Method

In order to address the aforementioned problems of the traditional emergy method, a modified emergy method is introduced in this study via redefining the emergy value of waste, applying renovated trasformities, and considering ecological discounting effect. With the meliorations, the new emergy method is considered to be more adequate than the traditional one in order to assess the ecological characteristics of CW engineering, as well as other systems, in China.

2.2.1. Emergy Value of Waste

It is not trivial to mention that in general emergy transformation process, besides the flows of common goods, undesired ecological endowments are denoted as waste (e.g., wastewater, greenhouse gases, and noise) also frequently appear (Ulgiati and Brown, 2002). As an artificial ecosystem, CW is usually designed to treat wastewater while corresponding greenhouse gases (Matsuhashi et al., 2009; Yoshida and Matsuhashi, 2009) are commonly emitted as a result of the elimination of pollutants (see Figure 1). Consequently, the components of wastes are playing significant roles for CW and their impacts should be included in emergy account in order to assess the ecological characteristics of the artificial ecosystem adequately. Particularly, the ecological effect originated in the waste generated by a system was conceptually denoted as "environmental impact" or "virtual environmental input" in previous studies (Odum, 1996; Chen, 2005, 2006). The two terms indicate the same ecological endowment associated with different system boundary determinations: if the generated waste is emitted from the system, it will deliver an ecological disturbance (environmental impact); if the generated waste is treated within the system, it will require additional ecological input (virtual environmental input) to restore its internal impact on the system. However, the value of neither effect has been concretely assessed in previous studies owing to the inappropriate understanding of waste. In this study, we do, for the first time, take the ecological effects of waste input as well as waste emission of CW engineering into account via redefining the emergy value of waste as illustrated in the following.

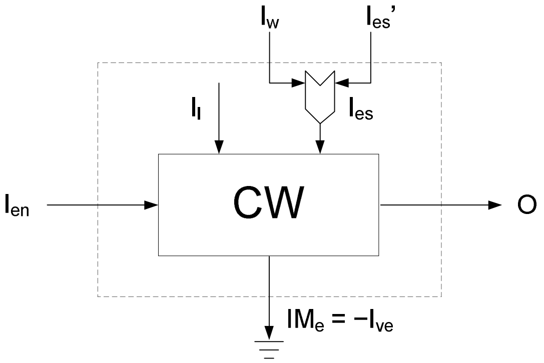

Figure 1. Schematic emergy diagram of a typical CW.

The emergy value of waste was either neglected or determined by the amount of emergy associated with the waste generation process in previous studies (see Geber and Björklund, 2001; Grönlund et al., 2004; Nelson et al., 2001) until Brown and Buranakarn (2003) first applied the required work for waste disposal to reflect its environmental cost. Lately, Chen (2006) further advanced a more explicit proposition to define the ecological value of waste as the negative value of the total work consumed in the course of natural reduction or technical treatment for the waste to reach ecological equilibrium. The treated waste has a null emergy value if it reaches the ecological equilibrium status. However, for most treatment processes, the waste is not treated as reaching ecological equilibrium but as reaching near-equilibrium and thus is considered to be a special ecological endowment of either useful resource or less harmful waste. Based on the above consideration, the emergy value of waste is redefined in this study as the emergy embodied in the treated waste minus the emergy embodied in the treatment process. For example, for the Chinese economy, about 2.30E + 11 sej of emergy is required for technical treatment to purify one cubic meter of municipal wastewater into the criterion for agricultural use, in which 1.58E + 11 sej of emergy is embedded, hence the emergy value of the untreated wastewater is -7.17E + 10 (= 1.58E + 11 - 2.30E + 11) sej. Subsequently, the environmental impact originated in the emitted waste is defined as the ecological value of waste, while the virtual environmental input is determined accordingly as the negative environmental impact.

The concepts of common product (with non-negative emergy value) and waste (with negative emergy value) are connected via the introduction of treated waste as their transition. If the treated waste implies a non-negative emergy value, it is already a favorable ecological resource. If the treated waste implies negative emergy value, further treatment should be processed to recover its ecological impact in order to preserve the equilibrium of environment. It might be weird to notice the negative emergy value of waste since the definition of emergy would guarantee positive outcome for every ecological process (Odum, 1996). However, when we acknowledge the fact that waste itself never appears as the sole output but always as the by-product of a process, the existence of negative emergy value sounds reasonable and does not violate the rigorous emergy definition.

2.2.2. Transformity Database

A commonly encountered challenge in emergy study is the lack of transformities for social products of various kinds adapted to local and recent economy. Despite the emergy transformities for environmental inputs such as sunlight and wind power are relatively constant, the emergy transformities for social products vary across regions and time as a result of the diverse economic structures and technology levels. As a pioneer in emergy study, Odum collaborated with his colleagues and fellows to construct an emergy transformity database (Odum, 1996, 2000; Odum et al., 2000; Brown and Bardi, 2001; Brandt-Williams, 2002; Kangas, 2002;). However, this database generally provides transformities adapted to the world as a whole or the US economy specifically, but those related to other economies are not presented. Furthermore, via using the process chain analysis method, their calculation of transformity was time-consuming and the database covers only a small category of social products, thus transformity of many products have to be estimated very coarsely.

Elaborated on the ecological input-output simulation, Chen and his fellows presented a network modeling to obtain a renovated trasformity database for China (Zhou, 2008; Chen and Chen, 2010; Chen et al., 2010b). The use of the renovated database in this study (when the analyzed case is in China) has two advantages, i.e., concrete validness and good adaptability. On one side, based on the sectoral input-output data, the renovated database provides transformities of different social products in more detailed manner and thus is more valid than tranditional one (Baral and Bakshi, 2010). For example, when using traditional database the transformities of pump and electricity equipment are assumed to be the same (Zhou et al., 2009) since their respective transforities are not available. However, in the renovated database, their transformities are separately presented (Chen and Chen, 2010). On the other side, based on the latest Chinese economic and environmental information, the transformity presented in the renovated database reflects the resource use efficient of China, which is significantly different from that of other countries. For example, the transformity of electricity generated in China in 2007 is 4.70E + 11 sej/kwh according to the input-output database (Chen and Chen, 2010), while that in the US in 1991 from the traditional database is 5.72 sej/kwh (Brown and Bardi, 2001) as a result of the different power generation structures.

2.2.3. Temporal Dimension in Emergy Study

Since value across time is usually not considered to be constant, the present value of future gain or cost is expressed using discounting effect. Even though the discounting effect is commonly calculated in conventional economical studies as well as in some of the other environmental studies (Chen et al., 2009b), it has not been essentially taken into account yet in emergy study for CW. Björklund et al. (2001) were the first to include capital interest in empirical emergy analysis for CW engineering. Their results suggest the dynamics of time has a significant impact on the ecological characteristics of ecosystem. Analogous to other discount studies in environmental economic domains (Costanza et al., 1989; Gren et al., 1995; Kosz, 1996; Gutrich and Hitzhusen, 2004; Ko et al., 2004; Leschine et al., 1997), this study attempts to investigate the discounting effect of CW engineering via applying different ecological discount rates in our emergy account.

2.3. Emergy Indicators for CW

Referring to the emergy method, a series of ecological indicators specified for CW engineering are established while each indicator is specially designed to illustrate particular feature of this ecosystem.

2.3.1. Constructed Wetland Service Cost

Compared to the natural ecosystem, a CW has a large construction cost. Constructed wetland service cost (CWSC) is the expenditure in CW construction and maintenance, which can be evaluated as:

$$CWSC = C_{ei} + C_{li} + C_{vei} \tag{1}$$

where C_{ei}, C_{li}, and C_{vei} are the emergy values of external input, local input, and virtual environmental input, respectively. If the ecological effect of waste is accounted for as a negative CW service (see below), the item of C_{vei} should be eliminated from Formula (1).

2.3.2. Constructed Wetland Service Value

Constructed wetland service value (CWSV) is the value of the ecosystem service obtained from a CW. Since CW is commonly built as an ecological engineering with specific functions to satisfy human needs, it is crucial to evaluate the value provided by overall as well as individual ecosystem service. In the present assessment scheme, CWSV is calculated as:

$$CWSV = \sum_{i=1}^{n} CWSV_i \tag{2}$$

where $CWSV_i$ is the emergy value gained from the i-th category of CW service, and n is the number of category. If the ecological effect engendered by waste emission is categorized as a negative ecosystem service, the overall $CWSV$ should also include the ecological value of environmental impact.

2.3.3. Net Present Value of Constructed Wetland Service

One of the most important indicators affecting decision making is profit, which is usually assessed by weighing total costs against benefits. For the construction of an ecological engineering such as the CW, it is the maximal long term profit that decision maker is looking for, thus possible life cycle profit illustrated by the net present value of constructed wetland service (NPVCWS) is concerned as:

$$NPVCWS = \int_0^l [CWSV_t \times (\frac{1}{1+d})^t - CWSC_t \times (\frac{1}{1+d})^t] dt \tag{3}$$

in which l represents the lifetime of the CW, d represents the discount rate, and $CWSV_t$ and $CWSC_t$ represent the service value and service cost occur in time t. In practical calculation, the analyzed time span is usually set to be one year and Formula (3) can be transformed into:

$$NPVCWS = \sum_{i=1}^{l} [CWSV_i \times (\frac{1}{1+d})^i - CWSC_i \times (\frac{1}{1+d})^i] \tag{4}$$

In this scheme, however, it is vital to emphasize the discounting effect should be applied according to the ecological discount rate specify to emergy study.

3. Case Study

3.1. The Beijing Wetland

As a typical city located in northern China, Beijing has long been suffering from a severe shortage of available water resources and heavy wastewater pollution. The Beijing municipal government has been expediting an exploration on technologies to solve the water problems since the theme "Green Olympics" was put forward for the Beijing Olympics 2008, amongst which CW engineering is of major concern.

As one of the branches of the Great Canal, the Longdao River flows across suburb of Beijing with a daily runoff of 16,000 m^3, and is seriously polluted by the municipal wastewater released from the upstream residential area. To deal with the heavy pollution and make restoration for the Longdao River ecosystem, a pilot CW, the Beijing Wetland, was constructed near the estuary of the river. This pilot CW is located in a latitude and longitude of 40°04' N and 115°34' E in the North Temperate Zone, with corresponding climate type of semi-humid temperate continental monsoon climate and average daily temperature and precipitation of 11.8 °C and 578 mm in 2004 (ISY, 2005).

The construction of the Beijing Wetland system was initiated in mid April, 2004 and completed after one and a half months. Soil as one of the substrate materials was obtained from nearby farmland while most of the other inputs were produced in different places within China. With a length and width of 28 m and 21.5 m respectively, the Beijing Wetland has a vegetated bed of 602 m^2 and a treatment capacity of 200 m^3 per day. The average depth of the wetland basin is 1.55 m with a bottom gra-

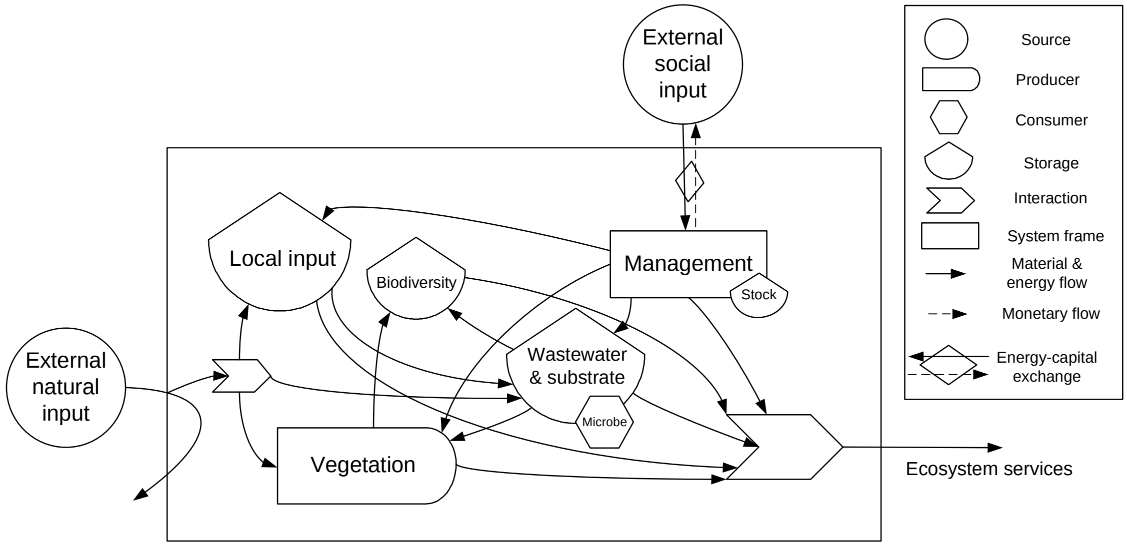

Figure 2. Systems diagram of the Beijing Wetland.

Table 1. Removal Efficiencies of the Beijing Wetland (according to Chen et al., 2008)

Item	BOD$_5$	COD	TSS	TP	NH$_3$-H
Sample Nums	22	45	17	17	18
Influent (mg/l)	47.05	108.00	47.60	5.01	22.90
Effluent (mg/l)	6.00	19.70	7.08	0.06	5.19
Efficiency (%)	87.25	81.76	85.13	98.80	77.34

dient of 0.00714. To avoid possible impact on the flood regulation capability of the Longdao River, the Beijing Wetland is constructed 5 m above the river's ordinary water level. A pre-treatment facility is omitted in this pilot CW but a steel barrier is installed against the entrance of large-size suspended solids. Aeration pipes are also installed to increase oxygen concentration in the wastewater while PE liner is laid at the bottom of the basin to prevent penetration. Three vegetation species, i.e. common reed (*phrugmites australis*), water bamboo (*zizania aquatica*), and cattail (*typha latifolia*) are planted in the wetland and two water pumps with maximum power of 750 W each are equipped to uplift water from the river. The designed lifetime of the Beijing Wetland is 20 years, and the removal efficiencies for different pollutants during its first operating year are listed in Table 1.

3.2. System Structure

The systems structure of the Beijing Wetland is depicted in Figure 2. In this figure, the various environmental sources (such as sunlight, rainfall, and wind) are abstracted as the external natural input, which flows into the CW system with partly return because of sunlight reflection, groundwater penetration, etc. The social products accompanied with monetary exchange (such as linear, pumps, and pipes) are abstracted as the external social input. Besides external inputs, local materials are also used in the Beijing Wetland and thus a corresponding storage is portrayed. Vegetation plays a part of producer and human management as a subsystem to maintain the CW. Sustained by different inputs and the management, two other storages are he biodiversity and the wastewater and substrate. Meanwhile, the ecological effect of the greenhouse gases engendered by the Beijing Wetland is regarded as a negative CW service, hence the environmental impact and/or virtual environmental input (see Figure 1) are not depicted but are still considered.

3.3. Adopted Transformities

The acquisition of appropriate local transformities is a key process for precise emergy account and assessment. As mentioned above, the previous emergy trasformity database does not include all social products. Moreover, due to the shortage of uniform data for local economic and environmental circumstance, transformities have to be collected from studies which do not account for particular local circumstances and thus might induce error in concrete account. Since most of the social inputs for the Beijing Wetland are produced in China, the present study adopted the latest input-output based trasformities for social products (Chen and Chen, 2010) to complement the constant transformities for environmental resources (Odum, 1996). The adopted transformity database has more concrete validness and better adaptability than traditional one (Baral and Bakshi, 2010). Transformities for all the environmental resources and social products used in the Beijing Wetland system are listed in the Appendix, in which the embodied currency intensities as well as market prices are also presented.

Table 2. Emergy and Monetary Accounts for the Beijing Wetland

Note	Item	Raw material	Unit	Emergy account		Monetary account
				Emergy (sej)	Embodied currency (em$)	Currency ($)
Environmental input (/yr)						
1	Sunlight	2.49E+12	J	2.49E+12	1	N/A
2	Wind power	3.65E+08	J	8.94E+11	0	N/A
3	Rain, chemical	1.15E+09	J	5.41E+13	16	N/A
4	Rain, geopotential	2.48E+07	J	7.56E+11	0	N/A
5	Earth cycle	1.14E+09	J	6.61E+13	19	N/A
Linear input (2004)						
6	HDPE linear	9.00E+02	m^2	7.74E+15	2225	2415
Substrate input (2004)						
7	Local materials	3.00E+02	m^3	5.00E+15	1437	2012
8	Organic composts	3.90E+02	m^3	9.45E+15	2717	3805
9	Minerals	1.20E+02	m^3	2.12E+16	6105	1727
10	Other substrates	2.20E+02	m^3	1.25E+16	3580	2415
Vegetation input (2004)						
11	Vegetation	2.85E+04	$	1.47E+16	4219	3476
Machinery input (2004)						
12	Pumps	2.00E+00	unit	1.52E+15	437	366
13	Electronic equipment	1.00E+00	unit	5.59E+14	161	134
Pipes, barrier, and construction input (2004)						
14	PP pipes (110mm)	9.00E+01	m	7.39E+14	212	230
15	PP valves	3.00E+00	unit	5.40E+13	16	17
16	PE pipes (160mm)	4.80E+01	m	5.44E+14	156	170
17	PE valves	1.00E+01	unit	2.58E+14	74	80
18	Steel barrier	1.00E+00	kg	3.03E+12	1	1
19	Bricks and concrete	2.20E+01	m^3	2.49E+15	717	537
Other initial input (2004)						
20	Consultant fee	1.00E+00	Unit	1.00E+16	2883	7195
Operation and maintenance (/yr)						
21	Electricity	6.57E+03	kwh	3.09E+15	888	509
22	Maintenance	7.00E+02	$	1.19E+14	34	85
23	Wage	2.00E+03	$	3.40E+14	98	244
Waste input (/yr)						
24	Wastewater	7.31E+04	m^3	-5.24E+15	-1505	N/A
One-off ecosystem services (2004)						
25	Regulation	1.85E+02	m^3	1.82E+13	5	N/A
26	Wetland surface	6.02E+02	m^2	4.41E+12	1	N/A
One-off ecosystem services (2023)						
27	Recycled minerals	1.20E+02	m^3	2.12E+16	6105	1727
28	Recycled steel barrier	1.00E+00	kg	3.03E+12	1	1
Annual ecosystem services (/yr)						
29	Biomass	3.09E+04	g	6.37E+12	2	N/A
30	Greenhouse gases	-9.15E-01	tCO$_2$eq	-1.04E+15	-300	N/A
31	Oxygen	3.29E-02	ton	1.50E+14	43	N/A
32	Purified water	6.21E+04	m^3	9.80E+15	2816	N/A
33	Water vapor	1.10E+04	ton	1.73E+15	497	N/A
34	Waste disposal	7.31E+04	m^3	N/A	N/A	8018

* N/A stands for not accounted.

3.4. Other Data Sources, Assumptions, and Simplifications

Other relevant data of the Beijing Wetland are obtained from Chen et al. (2008), Chen et al. (2009a), and Zhou et al. (2009), and engineering infrastructures are assumed to be abandoned after their lifetime. Part of the construction materials can be reused, and the recycling of these materials is regarded as a CW service. To facilitate the accounting process, the mineral inputs and steel barrier are assumed completely

Table 3. Emergy and Money Based Assessments for the Beijing Wetland

Item (unit)	Emergy account		Monetary account
	Emergy (sej)	Embodied currency (em$)	Currency ($)
CWSC (construction)	8.68E+16	24940	24579
CWSC (annual)	-1.57E+15	-451	838
CWSC discounted to 2004 (discount rate=0%)	5.54E+16	15924	41335
CWSC discounted to 2004 (discount rate=2%)	6.06E+16	17421	38552
CWSC discounted to 2004 (discount rate=5%)	6.62E+16	19041	35542
CWSC discounted to 2004 (discount rate=10%)	7.21E+16	20718	32425
CWSC discounted to 2004 (discount rate=15%)	7.55E+16	21695	30610
CWSC discounted to 2004 (discount rate=20%)	7.76E+16	22306	29475
CWSC discounted to 2004 (discount rate=50%)	8.21E+16	23588	27091
CWSC discounted to 2004 (discount rate=100%)	8.36E+16	24039	26254
CWSV (construction)	2.26E+13	6	0
CWSV (disposal)	2.12E+16	6106	1727
CWSV (annual)	1.06E+16	3058	8018
CWSV discounted to 2004 (discount rate=0%)	2.34E+17	67272	162081
CWSV discounted to 2004 (discount rate=2%)	1.92E+17	55118	134885
CWSV discounted to 2004 (discount rate=5%)	1.47E+17	42322	105565
CWSV discounted to 2004 (discount rate=10%)	1.03E+17	29552	75342
CWSV discounted to 2004 (discount rate=15%)	7.79E+16	22392	57819
CWSV discounted to 2004 (discount rate=20%)	6.27E+16	18035	46896
CWSV discounted to 2004 (discount rate=50%)	3.19E+16	9180	24046
CWSV discounted to 2004 (discount rate=100%)	2.13E+16	6122	16035
NPVCWS in 2004 (discount rate=0%)	1.79E+17	51348	120746
NPVCWS in 2004 (discount rate=2%)	1.31E+17	37697	96333
NPVCWS in 2004 (discount rate=5%)	8.10E+16	23281	70023
NPVCWS in 2004 (discount rate=10%)	3.07E+16	8833	42917
NPVCWS in 2004 (discount rate=15%)	2.42E+15	696	27209
NPVCWS in 2004 (discount rate=20%)	-1.49E+16	-4271	17422
NPVCWS in 2004 (discount rate=50%)	-5.01E+16	-14409	-3045
NPVCWS in 2004 (discount rate=100%)	-6.23E+16	-17916	-10219
NPVCWS in 2004 (discount rate=15.58%)	0	0	25874
NPVCWS in 2004 (discount rate=41.21%)	-4.49E+16	-12917	0

reusable and other inputs are assumed completely non-reusable while the recycling fee is ignored. Even though the social economic discount rate is commonly estimated to be between 2 and 5% (Conrad, 1999), few studies have been done to determine an ecological discount rate in emergy studies and thus it is usually taken to be zero in empirical accounts (Nelson et al., 2001; Chen et al., 2006b; Zhou et al., 2009). In the present study, we apply different discount rates between 0 and 100% to investigate how the ecological characteristics vary with the discounting effect. The Excel solver function is used to solve for two particular discount rates in order to determine in what situation the emergy or monetary NPVCWS are equal to zero.

4. Results and Discussion

Based on the engineering information and the renovated local transformities, the emergy account with input-output flows of the Beijing Wetland is presented in Table 2. For comparison, parallel account is processed based on monetary account and results are also listed in the same table. Since there is no generally accepted and precise method to evaluate the CWSV of biodiversity, this study adopts the assumption of Chen et al. (2009b) to account it according to the habitat and refugia provision capability in terms of wetland surface (item 26 in Table 2). Grounding on the account table and the assumptions and simplifications presented in Section 3.3, the ecological assessment and parallel economic assessment for the Beijing Wetland are processed and the results are listed in Table 3.

The expenditure for construction is 8.68E + 16 sej, with equivalent of 24,940 em$ which is close to the monetary cost of $24,579. However, the two accounts show opposite operation and maintenance costs as negative ecological value (-1.57E + 15 sej or -451 em$) is obtained in contrast to the positive economic value ($838), which is mainly attributed to the negative emergy intensity but zero market price of wastewater. Comparing to the emergy account, the monetary account neg-

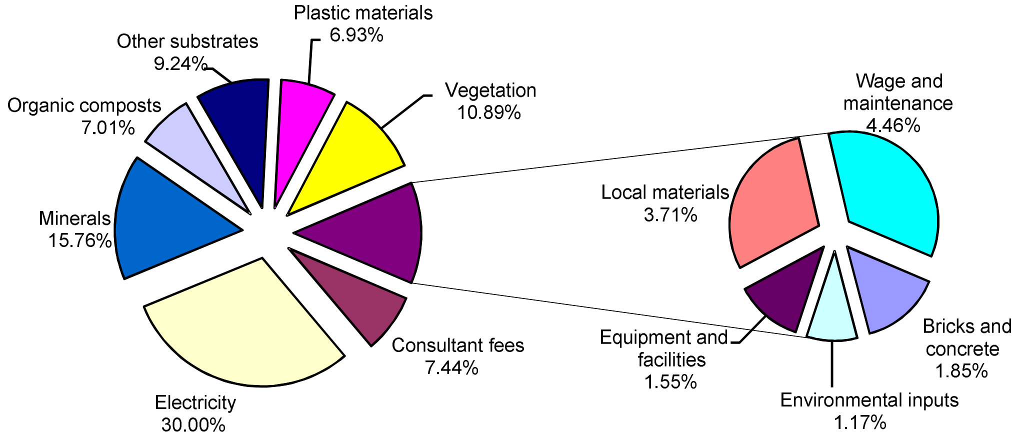

Figure 3. Composition of CWSC based on an ecological discount rate of 5%.

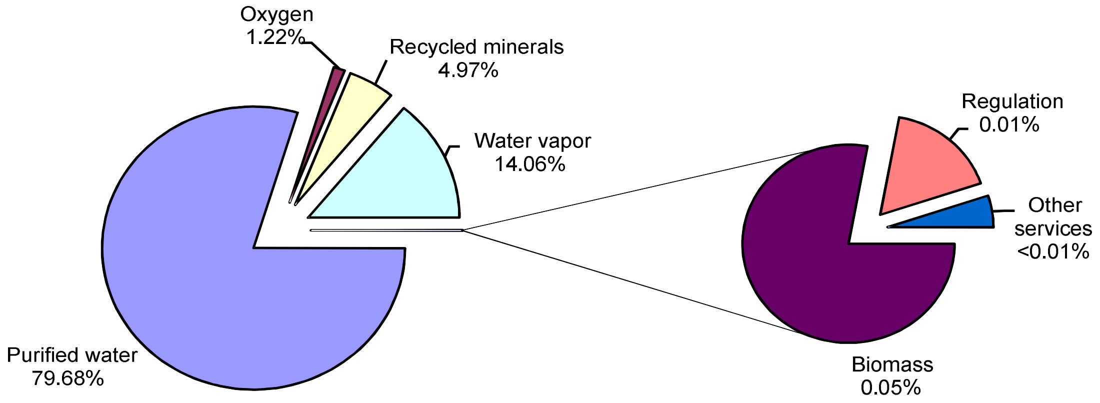

Figure 4. Composition of CWSV based on an ecological discount rate of 5%.

Table 4. Emergy and Monetary Cost for the Beijing Wetland to Treat Waste

CWSC to treat	*Emergy account*		*Monetary account*
	Emergy (sej)	Embodied currency (em$)	Currency ($)
1 m^3 of wastewater	4.53E+10	0.01	0.02
1 kg of BOD$_5$	1.10E+12	0.32	0.59
1 kg of COD	5.14E+11	0.15	0.28
1 kg of TSS	1.12E+12	0.32	0.60
1 kg of TP	9.16E+12	2.63	4.91
1 kg of NH$_3$-N	2.56E+12	0.74	1.37

lects the contributions of environmental input as well as many CW services except that of waste disposal. Meanwhile, the ecological values of minerals and electricity are underestimated by the monetary account while those of human labor (consultant fees and wage) are significantly overestimated. In conclusion, while the emergy methodology takes the externalities (waste) and the value of nature (environmental input) into account to depict the ecological characteristics of CW in an objective ecological perspective, the monetary methodology tends to ignore or underestimate many of the environmental inputs and places an extraordinary weight on the economically scarce endowment in order to represent the subjective willingness of a human being.

Under all presumed scenarios (discount rate between 0 to 100%), emergy CWSC and CWSV are both smaller than monetary ones, and ecological balance (emergy NPVCWS = 0) is obtained when the discount rate is equal to 15.58% but economic profit persists until discount rate reaches 41.21%. Since the economic discount rate is usually considered to be under 5% (Conrad, 1999), the economic assessment suggests that the application of the Beijing Wetland is financially profitable. However, since the emergy based ecological discount rate has not been discussed concretely in previous studies, the ecological profit is difficult to determine. Besides, the emergy NPVCWS is more sensitive than the monetary NPVCWS with low discount rate (when discount rate increases from 0 to 10%, NPVCS will decrease by 82.80 and 62.46% for ecological and economic accounts, respectively). Consequently, unless a more explicit consideration of the ecological discount can be made, the application of the economic assessment on ecological endowments might underestimate the future value of resource and lead to an overdrawing of ecological wealth.

Based on the scenario with a discount rate of 5%, the compositions of emergy CWSC and CWSV for the Beijing Wetland are portrayed in Figure 3 and 4, along with the average costs to treat one unit of wastewater and its particular pollutants listed in Table 4. Electricity (30%) represents the largest ecological cost for the Beijing Wetland, followed by minerals (15.76%) and vegetation (10.89%) when other wetland substrates such as organic composts and local materials also constitute significant fractions of CWSC. Regarding the return, water related services (purified water and water vapor) contribute a dominant fraction of 93.74% for total CWSV. About 4.53E + 10 sej of emergy is required to treat one cubic meter wastewater by the Beijing Wetland, with equivalent of only 0.01 em$, which is significantly lower than the average cost by the traditional treatment technology of 2.30E + 11 sej or 0.07 em$. The ecological costs to treat one kilogram of BOD_5, COD, TSS, TP, and NH_3-H are 1.10E + 12, 5.14E + 11, 1.12E + 12, 9.16E + 12, and 2.56E + 12 sej, respectively. Comparing to the treatment costs of traditional plants (Zhou et al., 2009), results show that CW has comparative advantages in treating TP and NH_3-H and thus is more suitable to be considered for municipal wastewater treatment with large concentrations of nutrient pollutants.

5. Conclusions

The present study aims at a methodological development of emergy and a concrete ecological assessment for real-world constructed wetlands. With regard to the unresolved problems of previous emergy research, a revised emergy method is proposed in this study. Unlike proposals that tend to neglect or overestimate ecological impact brought forward by waste, this method adopts a more reasonable approach and determines the emergy value of waste with regards to the work required to remediate the waste. A modified transformity dataset adjusted with regards to local circumstances is adopted for the present method in order to provide accurate and reliable results. Furthermore, different discount rates are applied to take the dynamics of time into account for the first time, in emergy study. With the above meliorations, the new emergy method modifies the traditional one and provides a more reliable theoretical basis for ecological assessment.

The ecological assessment based on the modified emergy method is applied to a typical wastewater treatment CW, the Beijing Wetland, to measure the natural and social resources consumed in and ecological services provided by this engineering. Electricity and wetland substrates contribute the largest fractions of CWSC while water related services are the predominant sources of CWSV. The Beijing Wetland maintains a positive ecological profit as long as the discount effect is not significant (below 15.58%) and economic deficit will not occur until the discount rate becomes unusually high (above 41.21%). It is important to assert that the value of NPVCWS is sensitive to the value of the discount rate and thus further understanding of the concrete ecological discounting effect should be explored. In fact, there is no general agreement with regards to the discounting effect of ecological factors besides that many scholars acknowledge that a positive ecological discount rate is reasonable (Markandya and Pearce, 1991; Pearce et al., 1989). This study provides a preliminary experiment on the discounting effect but further explorations in both theory and implication are needed.

Besides the emergy based assessment, monetary based assessment is also carried out in this study to investigate the different of ecological and economic perspectives. Compared to the emergy account, the monetary account tends to overweight the annual CWSV values of water related product (waste disposal) but underestimate those of minerals and air compositions, which intuitively tells the relative importance of each components on economic perspective -- the Chinese (especially Beijing) society is facing more urgent and direct pressure from water problems in comparison with other resources and thus tends to emphasize the importance of water. However, the ecological perspective is independent to human willingness and thus provides an objective measure on every ecological endowment. It is momentous to realize both perspectives have their particular audients and usages -- while the former is applied to assess regional interest by the local governor for small scale management, the latter can be applied to determine more general interest by the decision maker for holistic environmental management.

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Appendix

Table A1. Trasformities, Embodied Currency Intensities, and Market Prices for the Environmental Resources and Social Products Used in the Beijing Wetland

Note	*Item*	*Unit*	*Transformity (sej/unit)*	*Embodied currency intensity (em$/unit)*	*Market price ($/unit)*
1	Sunlight	J	1.00E+00	2.87E-13	0.00E+00
2	Wind power	J	2.45E+03	7.04E-10	0.00E+00
3	Rain, chemical	J	4.70E+04	1.35E-08	0.00E+00
4	Rain, geopotential	J	3.05E+04	8.77E-09	0.00E+00
5	Earth cycle	J	5.80E+04	1.67E-08	0.00E+00
6	HDPE linear	m^2	8.60E+12	2.47E+00	2.68E+00
7	Local materials	m^3	1.67E+13	4.79E+00	6.71E+00
8	Organic composts	m^3	2.42E+13	6.97E+00	9.76E+00
9	Minerals	m^3	1.77E+14	5.09E+01	1.44E+01
10	Other substrates	m^3	5.66E+13	1.63E+01	1.10E+01
11	Vegetation	$	5.15E+11	1.48E-01	1.22E-01
12	Pumps	unit	7.61E+14	2.19E+02	1.83E+02
13	Electronic equipment	unit	5.59E+14	1.61E+02	1.34E+02
14	PP pipes (110mm)	m	8.21E+12	2.36E+00	2.56E+00
15	PP valves	unit	1.80E+13	5.17E+00	5.61E+00
16	PE pipes (160mm)	m	1.13E+13	3.26E+00	3.54E+00
17	PE valves	unit	2.58E+13	7.42E+00	8.05E+00
18	Steel barrier	kg	3.03E+12	8.69E-01	6.10E-01
19	Bricks and concrete	m^3	1.13E+14	3.26E+01	2.44E+01
20	Consultant fees	unit	1.00E+16	2.88E+03	7.20E+03
21	Electricity	kwh	4.70E+11	1.35E-01	7.74E-02
22	Maintenance	$	1.70E+11	4.89E-02	1.22E-01
23	Wage	$	1.70E+11	4.89E-02	1.22E-01
24	Wastewater	m^3	-7.17E+10	-2.06E-02	0.00E+00
25	Regulation	m^3	9.83E+10	2.83E-02	0.00E+00
26	Wetland surface	m^2	7.32E+09	2.10E-03	0.00E+00
27	Recycled minerals	m^3	1.77E+14	5.09E+01	1.44E+01
28	Recycled steel barrier	kg	3.03E+12	8.69E-01	6.10E-01
29	Biomass	g	2.06E+08	5.92E-05	0.00E+00
30	Greenhouse gases	tCO$_2$eq	1.14E+15	3.28E+02	0.00E+00
31	Oxygen	ton	4.57E+15	1.31E+03	0.00E+00
32	Purified water	m^3	1.58E+11	4.54E-02	0.00E+00
33	Water vapor	ton	1.58E+11	4.54E-02	0.00E+00
34	Waste disposal	m^3	0.00E+00	0.00E+00	1.10E-01

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