Can constructed wetlands be more land efficient than centralized wastewater treatment systems? A case study based on direct and indirect land use

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Abstract

Compared with centralized wastewater treatment systems, constructed wetlands are generally regarded as not suitable for wide deployment due to the comparatively larger direct land area. Much of the traditional thinking is based on an onsite perspective, while the offsite information is left out. By a comparative case study with systems accounting of both onsite and offsite land use, this study questioned the traditional picture and found that constructed wetlands can be more land use efficient than centralized wastewater treatment systems. On a unit of wastewater treated basis, the land use induced by a typical constructed wetland in China is revealed to be less than half of that by the case of a centralized wastewater treatment plant or a hybrid system. On a unit removal basis for biological oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solid (TSS) and ammonia-nitrogen (NH_3-N), the land use induced by a constructed wetland is only around 61%, 67%, 73% and 64% of that by a centralized wastewater treatment system, respectively. Meanwhile, the indirect effect is demonstrated to be significant for these three systems: this magnitude

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amounts to three times the direct land occupation for a constructed wetland, and one order of magnitude higher of that for the a centralized wastewater treatment system. By a scenario analysis for China in 2017, it is preliminarily estimated that over two billion square meters of land use could be reduced if all the centralized wastewater treatment systems are replaced by constructed wetlands. The outcome may serve a benchmark and offers a new way of thinking for management of wastewater treatment systems.

Keywords: Constructed wetland; wastewater treatment; land use; systems process analysis

1. Introduction

Wastewater treatment plays a crucial role in the construction and development of cities. Historically, as cities grew and natural wetlands failed to treat increased wastewater, the new cities' industrial technologies evolved using tanks, pumps and chemicals to solve the problem. Because city land is valuable, the processing sites, even including the large surface area of the tanks, was constricted to be more like an industrial factory than a spread-out, natural wetlands. Only later was there a move to attempt to plan and construct wetlands as a solution to city wastewater. This paper analyses the differences between centralized wastewater treatment systems (WTSs) and constructed wetlands (CWs).

CWs are artificial engineered systems and designed in a way similar to natural wetlands for treating municipal wastewater. Physical, chemical and biological synergies of substrate, plants and microorganisms serve for treatment of organic, inorganic as well as excess nutrient contaminants when the wastewater goes through CWs in a controlled way through manual design and supervision (Eifert, 1999; Wang and Chen, 2016, 2017; Wang and Zeng, 2019; Wengrzynek, 1991).

CWs were used experimentally in Germany early in 1952 to treat domestic wastewater in rural areas (Seidel, 1955). Soon afterwards, in 1960s the full-scale engineered wetland system came into use for the first time and thereafter rapidly spread to the rest of the world. In 1972, the United States witnessed the birth of the first domestic constructed wetland (CW) built at Vermontville, Michigan (Brown, 1994). In subsequent years, other nations and regions also witnessed the appearance of such kind of CW systems ranging from pilot-scale projects in Portugal (Amaral et al., 2013) to an increasing quantity of commercial-scale CW projects in Italy (Masi et al., 2017), France (Pálfy et al., 2017) and the United States (Tao et al., 2014). As for China characterized with a rapid progress of urbanization and industrialization in recent decades, the CW has also been highlighted as a promising alternative to cope with the over-consumption and degradation of water resources, especially in suburb areas of small- and medium-size cities. The first reed bed wetland in China was launched by Tianjin Environmental Protection Research Institute in 1987 (Liu, 2017). Later in 1990, Bainikeng Constructed Wetland, the first full-scale CW project in medium-scale municipalities in China for wastewater treatment and located at Shenzhen Special Economic Zone, appeared. By 2015 there were at least 791 CWs for urban and rural wastewater treatment in China (Li, 2018).

Compared with centralized WTSs, CWs have many advantages in terms of strong feasibility of technology implementation, little secondary pollution and environmental impacts, low costs of management during construction and operation, representing landscape elements thus providing social values. Furthermore, these factors are of great significance in terms of hydrology, biogeochemistry and the maintenance of biological habitats and food webs (Richardson, 1994; Vymazal, 2005). According to the 13th Five-Year Plan for the

Construction of Urban Wastewater Treatment and Recycling Facilities jointly formulated by the National Development and Reform Commission (NDRC) and the Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD), it is suggested that priority should be given to the wastewater treatment schemes (such as CWs) with large water yield, feasible technology, low comprehensive cost, significant economic and social benefits to provide reclaimed water for industry, green irrigation and urban miscellaneous use. What deserves our attention is that it has been continuously pointed out in existing works that CWs are more advantageous in rural areas with low population density, while typical centralized WTSs are more suitable for cities with high population density, mainly due to the large onsite area required for CWs projects (Kivaisi, 2001; Lu et al., 2016; Merlin et al., 2002; Otterpohl et al., 2004; Parkinson and Tayler, 2003; Wu et al., 2011; Ye and Li, 2009).

A major obstacle to the wide deployment of CWs is that the direct land occupation of CWs is much larger than that of centralized WTSs. However, an onsite perspective usually includes only the onsite information but fails to incorporate the offsite information, namely the land use indirectly required by construction, operation, and maintenance of the wetland system. For instance, a CW needs a number of inputs such as substrates, plants and pipes, the production of which will directly and indirectly induce a certain amount of land use. In other words, extra land use is induced in upstream processes to provide the material, machinery and service inputs required by the CW. Just as noted by Lave et al. (1995), the indirect effects could be significant, which may sometimes surpass the direct resource use or emissions. As previously mentioned, CW bears a resemblance to natural wetland system and resorts to physical, chemical and biological synergies of soil, plants and microorganisms to treat wastewater. While for the centralized wastewater treatment system (WTS), it is a purely artificial system and requires lots of external inputs, such as the chemical compounds, machinery, corresponding building works and service inputs, to deal with the contaminants. As a result, the indirect impact on land use of centralized WTSs may be much more significant than that of CWs. Consequently, to give an objective comparison of the centralized wastewater systems and CWs in terms of land use, attention should be paid not only to direct land occupation during the treatment process, but also the land use induced for the production of energy and materials as well as other inputs to reflect the overall land use induced in the different stages.

Academic efforts have been made to compare the environmental impact induced by CWs and that by centralized WTSs based on a life cycle approach. Through solar emergy analysis, Zhou et al., (2009) revealed that CWs were environment-benign and less emergy-intensive despite the relatively low ecological waste removal efficiency compared with the centralized WTSs. This study was inspired by the Odum H.T. and Mitsch W.J. investigation of the embodied energy and solar equivalents of materials used to construct wetlands (Nelson et al., 2001; Mitsch 1975; Mitsch, 2003). Pan et al. (2011), for instance, estimated the life cycle greenhouse gas (GHG) emissions for a CW and three centralized WTSs and concluded that the vertical subsurface flow CW was an effective option for GHG emissions mitigation in the wastewater sector. Similarly, Garfi et al. (2017) adopted a life cycle approach to compare the environmental impact of three alternatives for wastewater treatment and found that the CWs rather than non-nature-based ones were the most environmentally friendly options. De Feo and Ferrara (2017) pointed out that the CW system was the best environmental choice after considering three different LCA impact assessment methods and 81 comparative cases were considered. According to Chen et al. (2011), a CW is shown to be remarkably less carbon intensive than a typical centralized WTS when including the emissions induced by the inputs in the construction and operation stages. Shao et al. (2013) revealed that energy required for treating a unit of wastewater in a CW is much lower than treating it in a centralized WTS. Han et al. (2016) used process-based analysis to track the land use of a CW in China. Nevertheless, to our knowledge, few attempts on comparing the performances of CWs and centralized WTSs in terms of land use via a systems perspective have been made so far.

In this study, a new way of thinking is provided to understand the land use of a CW by taking full account of the inputs during the construction and operation stages. A CW is compared with a centralized WTS and a hybrid system to explore which alternative for wastewater treatment is superior in terms of land conservation. Scenario analysis has also been conducted to show the potential impacts by the wide deployment of CWs, with policy implications enunciated.

2. Method and materials

2.1. Systems process analysis

Process analysis is a widely used approach for calculating the resources use to produce all types of goods or services. It is appreciated for being capable of tracing the production chain of a product or technology in detail. The downside is that process analysis is time-consuming and may involve an infinite number of steps for the tracing, which have to be truncated after several steps. Generally, the tracing terminates after one or two steps and only the major inputs are taken into consideration. Thus, the process analysis is likely to be influenced by truncation errors and uncertainties associated with the subjective definitions of systems boundaries (Suh, 2009; Treloar, 1997).

Given this, Bullard et al. (1978) for the first time proposed the systems process analysis to calculate the resource use induced by atypical products or technologies, which combines the process analysis and resource intensity derived from systems input-output analysis. The systems input-output analysis was firstly proposed by Bullard and Herendeen (1973) and then further developed by Chen and his colleagues for calculating resource use (Chen et al., 2019; Guo et al., 2019) and environmental emissions (Chen and Chen, 2011; Mi et al., 2016; Zhang and Chen, 2010; Zhang et al., 2018). It is able to depict the interwoven relationships between economic sectors and has been used to help mitigate the truncation error involved in process analysis. The process analysis traces the production chain to a certain level at which the sub-inputs could be treated as typical products as categories in the input-output table. In this way, the aggregation errors that may be induced by the homogeneity assumption inherent to input-output tables could be avoided. The systems input-output analysis allows us to obtain the intensity database that details the resource use induced in the whole production chain to manufacture per unit of the sectoral output, which suitably mitigate the truncation errors associated with process analysis. By now, the systems process analysis has been widely extended to account for life cycle resource use and emissions induced by coal-fired power plants (Wu et al., 2018, 2019), renewable energy systems (Chen et al., 2011b, 2011c), building clusters (Chen et al., 2011; Li et al., 2019) and WTSs (Chen et al., 2011a; Shao et al., 2013).

It is worth noting that there are also some attempts trying to combine process analysis and intensities derived from environmental-extended input-output analysis. The environmental-extended input-output analysis assigns the resource use or emissions to final demand by means of the Leontief inverse matrix (Leontief, 1970). Therefore, the corresponding intensity is only defined for final products (namely products used as final demand) instead of intermediate products. For systems input-output analysis, it gives an objective evaluation of the resource use induced directly and indirectly to yield the sectoral output, regardless of whether the products are for intermediate or final use. For most production systems, the required items are intermediate inputs to support the producing processes. Therefore, using intensity database obtained from systems input-output database is justified.

2.2. Case description

Three WTSs are compared in this study, all of which are located in Beijing and have a designed lifetime of 20 years. The Longdao River Constructed Wetland (LRCW), which is located in the upper reaches of Longdao River and Wenyu River in Shunyi District of Beijing, was built in 2004 and put into use in the same year (Chen et al., 2008). It has a daily household wastewater treatment capacity of 200 m^3 with an onsite land area of 900 m^2 (adjacent to 21,700 m^2 set aside for constructed wetland vegetation). The electricity consumption during the designed lifetime is 131,490 kWh (Table 1). According to the original engineering data of the LRCW, the main inputs of the project include wetland plants, ten kinds of substrate, water conservancy and power auxiliary equipment.

A typical centralized WTS is represented by a cyclic activated sludge system (CASS) (Zhang, 2002) which is researched in this study in order to compare the land use of a CW.

With coverage of 1,008 m^2 onsite land area, daily treatment capacity of the CASS is 1,700 m^3 and estimated electricity use is 396,807.6 kWh/year. As an additional comparison, a hybrid wastewater treatment system (HS), occupying an onsite area of 15,215 m^2, is included in this study. The original engineering data are available in Zhou (2008). It treats 5,600 m^3 wastewater every day and has an electricity consumption of 964,260 kWh/year (Table 1).

The inflow and outflow samples in different seasons for the three systems were collected. Meanwhile, the raw wastewater being treated by any one of these three systems is greywater, in other words, wastewater generated from households or buildings not including toilet water. Details on sample collection and determination are presented in Zhou (2010). Removal efficiency (concentration-based) of five-day biological oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solid (TSS), and ammonia-nitrogen (NH_3-N) for these three systems are displayed in Table 1. The quality of effluent meets the requirements of Article 50 of the Law on Prevention and Control of Water Pollution (MEP, 2018).

Table 1
Technical parameters for the three wastewater treatment systems

Item	LRCW	HS	CASS
Onsite land area (m^2)	900	15,215	1,008
Designed lifetime (year)	20	20	20
Daily treatment capacity of household wastewater (m^3/day)	200	5600	1700
Electricity use during the designed lifetime (kWh/year)	6,574.5	964,260.0	396,807.6
Removal efficiency of BOD_5 (%)	87.25±2.45	85.94±2.07	78.57±2.06
Removal efficiency of COD (%)	81.76±3.15	83.53±2.81	72.22±2.45
Removal efficiency of TSS (%)	85.13±5.13	84.17±2.69	81.25±2.05
Removal efficiency of NH_3-N (%)	77.34±5.54	82.86±4.28	83.33±2.73

Note: 22, 45, 17 and 18 repetitions of the sampling at different times for BOD_5, COD, TSS and NH_3-N determination respectively. LRCW means Longdao River Constructed Wetland; HS means hybrid wastewater treatment system; and CASS means cyclic activated sludge system.

2.3. Accounting steps

The systems accounting for land use induced by three different kinds of wastewater treatment systemWTSs follows the steps below.

I. List the input items of the investigated system (complete inventory of materials, equipment and electric inputs of the construction and operation phases). Input items are quantified in monetary units. It is worth noting that the most important monetary input during the operation stage is electricity, while the material and other inputs are negligible, according to calculations by Shao et al., (2013).

II. Select an appropriate land use intensity database. The input-output table is updated periodically every few years. Economic classifications are quite flexible in different years. China's input-output table in 2002 contains a 42-sector classification; the table for 2007 divides the economy into 135 economic sectors. Therefore, it is critical to select a proper land use database that best fits the WTSs under investigation, since the land use intensity database reflected in input-output analysis varies greatly in different years. As the constructed wetland is built and put into use in 2004, the land use intensity database that corresponds to the 135-sector input-output table for China economy in 2007 is used. This is because of the fact that the supply chains of the constructed CW in Beijing may involve also other provinces and cities in China, due to the unprecedented expansion of urbanization. The country has grown into an integrated economic network and the cross-division of production chain has been formed, which has smeared out the industrial boundaries between the provinces and cities. Especially, Beijing has for long been a highly heterotrophic city relying on material, energy and service inputs from the rest of the country. The methodological details and calculating procedures are presented in Chen and Han (2015).

III. Identify the corresponding economic sector for each input item. The relevant land use intensity is tracked for each input item.

IV. The monetary expenditure of each input is multiplied by its corresponding land use intensity. The land use for plant infrastructure is the summation of the land used for each input item, which is formulated as:

$$TLU = \sum_i LU_i = \sum_i (LI_i \times MC_i),$$

where, *TLU* represents the total land use induced; LU_i represents the embodied land use of the i-th input item; LI_i represents the land use intensity of the i-th input item; *MCi* represents the monetary cost of the i-th input item.

3. Results and discussions

3.1. Inventory of the construction stage and land use induced

For LRCW, vegetation is the biggest contributor. Then local organic substrate (composed of soil, fly ash, peat, bauxite, bentonite and so on) follows and electricity comes third (Table 2). Table 3 shows that a total amount of 2.05E+06 m^2 land use is required by the construction stage of HS, with electricity accounting for more than 50%. However, vegetation and local organic substrate are shown to occupy only 4.59% and 0.08% of the total (Table 3). Among all the input items of the CASS in the construction stage, the contribution by vegetation and local organic substrate is almost zero. Electricity as the biggest contributor, accounting for 67.89% of the total land use (Table 4).

Table 2

Inventory for the land use by the construction stage of the LRCW

Item	**Sector code**	**Sector contents**	**Embodied land use intensity (m^2/yuan)**	**Embodied land use (m^2)**	**Fraction (%)**
Geotextile	49	Manufacture of plastic	1.37E-01	2.72E+03	5.35
Local organic	5	Services in support of agriculture	2.77E-01	1.32E+04	26.05

substrate					
Mineral substrate	10	Mining and processing of nonmetal ores and other ores	1.32E-01	1.86E+03	3.67
Other substrate	52	Manufacture of brick, stone and other building materials	1.33E-01	2.64E+03	5.20
Vegetation	1	Farming	7.60E-01	2.17E+04	42.63
Pump	67	Manufacture of pump, valve and similar machinery	1.04E-01	3.13E+02	0.62
Electric control	78	Manufacture of equipment for power transmission and distribution and control	1.13E-01	1.24E+02	0.24
Pipe and valve	49	Manufacture of plastic	1.37E-01	5.59E+02	1.10
Steel grille	63	Manufacture of metal products	1.48E-01	7.40E-01	0.00
Bricks and cement	50	Manufacture of cement, lime and plaster	1.23E-01	5.43E+02	1.07
Electricity	92	Production and supply of electric power and heat power	8.57E-02	7.15E+03	14.07
Total land requirement				5.08E+04	100.00

As stated in existing studies, numerous works only focused on the operation of the wastewater treatment equipment (Zang et al., 2015). In addition to the operation stage, this study, however, gives full consideration to the construction stage by a comprehensive inclusion of the related inputs, including transportation pipeline, such as feeders, water collection system, and watershed diversion structures.

Table 3
Inventory for the land use by the construction stage of the HS

Item	**Sector code**	**Sector contents**	**Embodied land use intensity (m^2/yuan)**	**Embodied land use (m^2)**	**Fraction (%)**
ABFT					
Aeration tank and sedimentation tank					
Excavate, backfill, grave cushion	10	Mining and processing of nonmetal ores and other ores	1.32E-01	2.09E+04	1.01
Stone wall, soleplate and step	95	Construction	1.73E-01	5.76E+04	2.80
Concrete	51	Manufacture of products of cement and plaster	1.19E-01	1.52E+03	0.07
Reinforced bar	59	Rolling of steel	9.35E-02	3.89E+02	0.02
Stainless steel railing	63	Manufacture of metal products	1.48E-01	1.05E+04	0.51
Polyethylene board	49	Manufacture of plastic	1.37E-01	3.34E+03	0.16
Abft tank					
Excavate and backfill	10	Mining and processing of nonmetal ores and other ores	1.32E-01	3.68E+03	0.18
Concrete	51	Manufacture of products of cement and plaster	1.19E-01	6.49E+04	3.16
Reinforced bar	59	Rolling of steel	9.35E-02	2.17E+04	1.06
Stainless steel railing, lander	63	Manufacture of metal products	1.48E-01	1.54E+04	0.76
Equipment and material					

Aeration tank and sedimentation tank					
Aeration machine	72	Manufacture of other special purpose machinery	1.17E-01	1.65E+04	0.80
Steel griller	63	Manufacture of metal products	1.48E-01	1.10E+03	0.05
Pump and valve	67	Manufacture of pump, valve and similar machinery	1.04E-01	6.71E+03	0.33
Connecting hose	49	Manufacture of plastic	1.37E-01	5.20E+02	0.03
Electromagnetic flowmeter	88	Manufacture of measuring instruments	1.15E-01	1.93E+03	0.09
Embedded steel plate	59	Rolling of steel	9.35E-02	8.45E+01	0.00
Blower room					
Blower	68	Manufacture of other general purpose machinery	1.10E-01	1.01E+04	0.49
Electric control and power system	78	Manufacture of equipment for power transmission and distribution and control	1.13E-01	1.88E+04	0.91
Abft tank					
Biological carrier	43	Manufacture of synthetic materials	1.00E-01	1.55E+05	7.56
Aeration hose, casing and elbow	49	Manufacture of plastic	1.37E-01	9.70E+03	0.47
Intercept net, perforated sludge discharge pipe, air duct, stainless steel griller	63	Manufacture of metal products	1.48E-01	3.33E+04	1.62
Butterfly valve	67	Manufacture of pump, valve and similar machinery	1.04E-01	7.67E+03	0.37
Steel bracket	59	Rolling of steel	9.35E-02	4.95E+03	0.24
Enzyme	44	Manufacture of special chemical products	4.46E-01	1.61E+05	7.84
Embedded steel plate	59	Rolling of steel	9.35E-02	1.15E+03	0.06
Tube settler sedimentation					
Tube	49	Manufacture of plastic	1.37E-01	1.25E+04	0.61
Steel bracket and plate	59	Rolling of steel	9.35E-02	7.29E+02	0.04
Stainless steel overflow weir	63	Manufacture of metal products	1.48E-01	8.59E+02	0.04
Rubber	48	Manufacture of rubber	1.49E+00	4.77E+02	0.02
Pipes					
Sump pump					
ABFT valve well	95	Construction	1.73E-01	7.83E+02	0.04
Elbow and tee joint	49	Manufacture of plastic	1.37E-01	7.09E+02	0.03
Constructed wetland					
Construction					
Concrete	51	Manufacture of products of cement and plaster	1.19E-01	2.95E+04	1.44
Non-woven fabrics	28	Manufacture of textile products	2.72E-01	7.23E+03	0.35
Brick	52	Manufacture of brick, stone and other building materials	1.33E-01	2.61E+04	1.27
Polyethylene board, waterproof carpet	49	Manufacture of plastic	1.37E-01	3.11E+04	1.52
Excavate and backfill	10	Mining and processing of nonmetal ores and other ores	1.32E-01	1.10E+04	0.54
Equipment and material					
Pipe and accessory	49	Manufacture of plastic	1.37E-01	5.53E+03	0.27
Valve	67	Manufacture of pump, valve and similar machinery	1.04E-01	2.32E+03	0.11

Substrate					
Mineral substrate	10	Mining and processing of nonmetal ores and other ores	1.32E-01	1.48E+05	7.19
Local organic substrate	1	Farming	7.60E-01	1.73E+03	0.08
Vegetation					
Acorus calamus, reed, cyperus rotundus	1	Farming	7.60E-01	9.43E+04	4.59
Pipes					
Valve well	95	Construction	1.73E-01	5.47E+03	0.27
Elbow and tee joint	49	Manufacture of plastic	1.37E-01	1.11E+03	0.05
Electricity	92	Production and supply of electric power and heat power	8.57E-02	1.05E+06	50.93
Total land requirement				2.05E+06	100.00

For LRCW, the contribution of vegetation and local substrates to the total land use by the construction stage is significantly higher than that of the other two systems. While for CASS, the contribution of vegetation and local substrates to the total land use by the construction stage is marginally negligible. As witnessed, all the substrates used in the construction stage of this CW are mainly excavated nearby, and some are even from immediate local sources, such as the soil and the sand. Moreover, a CW requires minimal onsite civil engineering work. In comparison, CASS requires a tremendous number of expensive and land-intensive inputs from domestic heavy industry sectors, resulting the high amount of land use induced in the construction stages. Therefore, compared with LRCW, CASS indirectly induces a much larger amount of land use in the construction stage, which is generally neglected in existing studies and policy packages. This might also well support the argument that CW system for wastewater treatment as one of the most important applications of ecological engineering, can provide the optimal wastewater treatment scheme with low capital cost and resource consumption, and finally realize the beneficial saving of natural resources (Zhang et al., 2009).

Table 4
Inventory for the land use by the construction stage of the CASS

Item	**Sector code**	**Sector contents**	**Embodied land use intensity (m^2/yuan)**	**Embodied land use (m^2)**	**Fraction (%)**
Pump	67	Manufacture of pump, valve and similar machinery	1.04E-01	3.74E+03	0.59
Steel grille	63	Manufacture of metal products	1.48E-01	1.48E+03	0.23
Equipment	72	Manufacture of other special purpose machinery	1.17E-01	4.53E+04	7.13
Electric control	78	Manufacture of equipment for power transmission and distribution and control	1.13E-01	1.13E+04	1.78
Pipe and accessory	49	Manufacture of plastic	1.37E-01	1.37E+04	2.16
Basin, room and shaft	95	Construction	1.73E-01	1.28E+05	20.22
Electricity	92	Production and supply of electric power and heat power	8.57E-02	4.31E+05	67.89
Total land requirement				6.35E+05	100.00

3.2. Total land use induced by construction and operation stages

The component profiles of land use induced by the construction and operation stage of the three WTSs are shown in Figure 1. As can be observed, for all these three types of WTSs, the land use induced by the construction stage is larger than that of the operation stage. This is primarily due to the fact that the monetary cost for the material and machinery inputs in the construction stage is quite high. Meanwhile, the inputs required in the operation stage (mainly electric power) are relatively much less land-intensive compared with various land-intensive inputs in the construction stage, mainly the materials and equipment from the heavy manufacturing industries. The results obtained in this paper differ from other former research projects focusing on energy use, which revealed that the energy use induced by the operation stage is much greater than that of the construction stage for WTSs (Ko et al., 2004; Lundin et al., 2000; Shao et al., 2013; Zhang et al., 2010). This can be attributed to the fact that electricity as the most important input in the operation stage of WTS is quite energy-intensive but not land-intensive as compared to the inputs in the construction stage. As shown in this study, electricity, which belongs to Sector 92 (Production and supply of electric power and heat power) in the input-output table for the economy, requires a tremendous amount of energy-intensive inputs (such as fossil fuel inputs, heavy machinery in terms of boilers, turbines and generators, and services in terms of transportation and construction) from other sectors to yield the electricity output.

Furthermore, the operation phase for CASS takes up a greater share than that for LRCW, while the proportion for construction phase is smaller than that of CW, as illustrated in Fig. 1. This is mainly due to the vast electricity required for lifting, transporting, mixing, stirring, and dehydrating during the operation stage of centralized wastewater treatment plants, compared to CWs. Meanwhile, the capital investment of vegetation and local substrates in the construction stage of LRCW is 12.61% and 21.11% of the total capital investment, respectively; in contrast, this share for HS has decreased, and this share for CASS is zero.

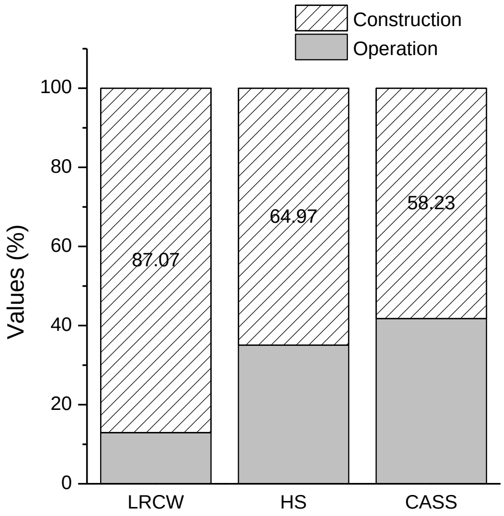

Fig. 1. The proportion of embodied land in the construction and operation stages of different wastewater treatment systems

3.3. Comparison with direct land occupation

In this study, it is calculated that LRCW, HS and CASS respectively induce a total amount of 5.83E+04, 3.16E+06 and 1.09E+06 m^2 land use during their construction and operation stages, with direct land occupation of 1.80E+04, 3.04E+05 and 2.02E+04 m^2 during the lifetime. The indirect land use, defined as the land use induced, is revealed as in magnitude 3.24, 4.33 and 53.95 times as large as direct land occupation for LRCW, HS and CASS, respectively (Fig. 2). It is proved that indirect land use by the production of required energy, materials and machinery inputs should be taken into account to give an overall reflection of the life cycle land use of WTSs. This finding is consistent with extensive studies on indirect land use on different scales. For instance, Yu et al. (2013) pointed out that land use attributed to "unusual" sectors, including machinery, construction and services, accounts for massive land use. Meanwhile, according to Wu et al. (2018b), indirect arable land use induced by internationally traded products is in magnitude up to 40% of the total arable land exploited. As seen, the results obtained in this study are in good accordance with previous studies and have demonstrated the remarkable land use induced by plant infrastructure and operation that has been traditionally ignored.

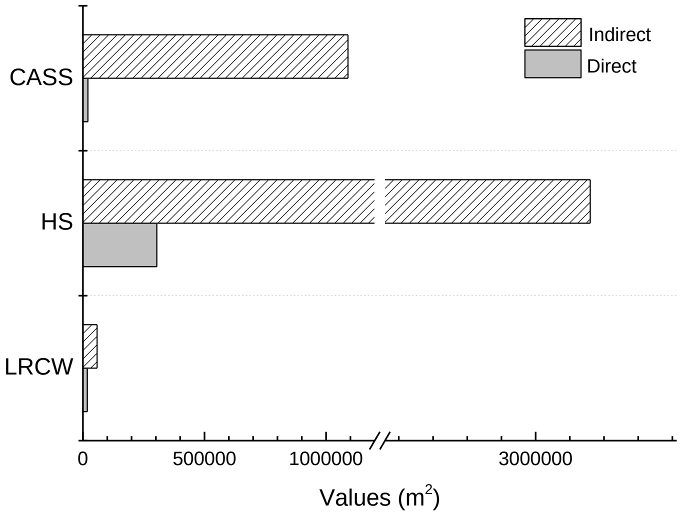

Fig. 2. Direct land occupation and indirect land use of different wastewater treatment systems

during the twenty-year lifetime

3.4. Induced land use by type

Among the different land types, the proportion of agricultural land is much higher than that of non-agricultural land (Fig. 3a, 4a and 5a). Generally speaking, the agriculture land resources enter into the economy through the agriculture sector and support the production of agriculture products. Within the economy depicted by input-output table, the agricultural products will come into the second and tertiary industries as intermediate inputs, which means that the use of agricultural land is supportive for not only the production of agricultural products but also all other products along the value chain due to the interconnected linkages between economic sectors. Therefore, though the products by second or tertiary industry may not directly require agriculture land, they may indirectly induce a large amount of land use in upstream processes. This could provide a new perspective for future policy decisions by reminding us to fully consider the agricultural land use induced by each project. The results suggest that it is essential to take full account of the interlinkage between different sectors and improve the existing policy framework in order to relieve the increasing pressure of wastewater treatment on different kinds of land use.

Another point that can be concluded from Figure 3b, 4b and 5b is that the non-agriculture (including transportation, residential, water conservancy facility and industrial land), especially industrial land use induced by LRCW is much less than those by HS and CASS. For HS and CASS, massive industrial inputs, including associated building products, electricity and machinery, are required in the construction activities, which induce a great deal of industrial land use in the supply chains.

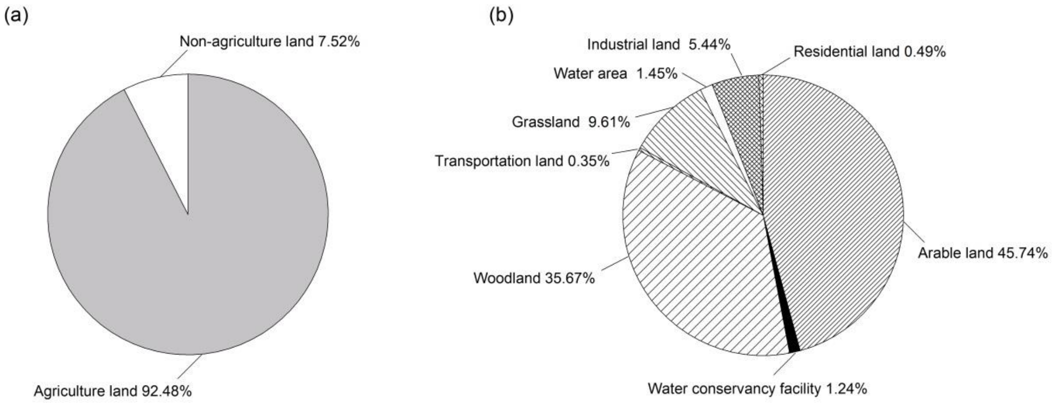

Fig. 3. (a) Proportion of agriculture and non-agriculture land; (b) Land use by type for LRCW

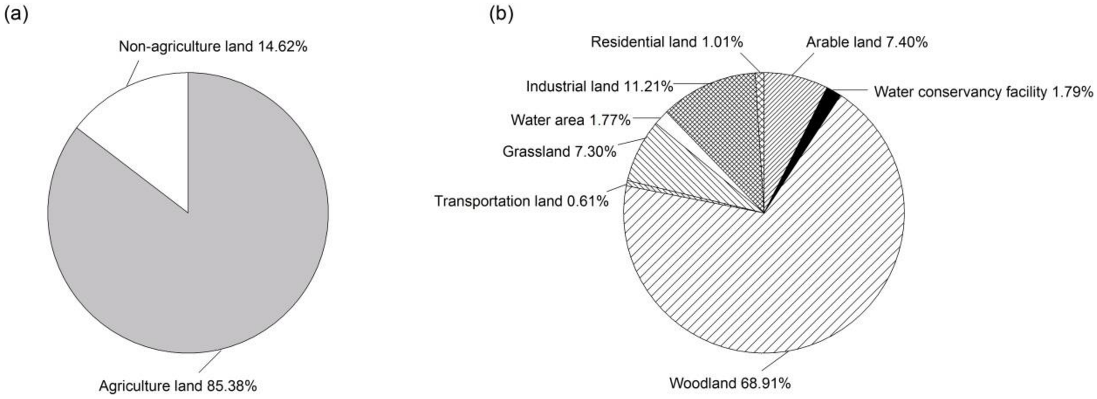

Fig. 4. (a) Proportions of agriculture and non-agriculture land; (b) Land use by type for HS

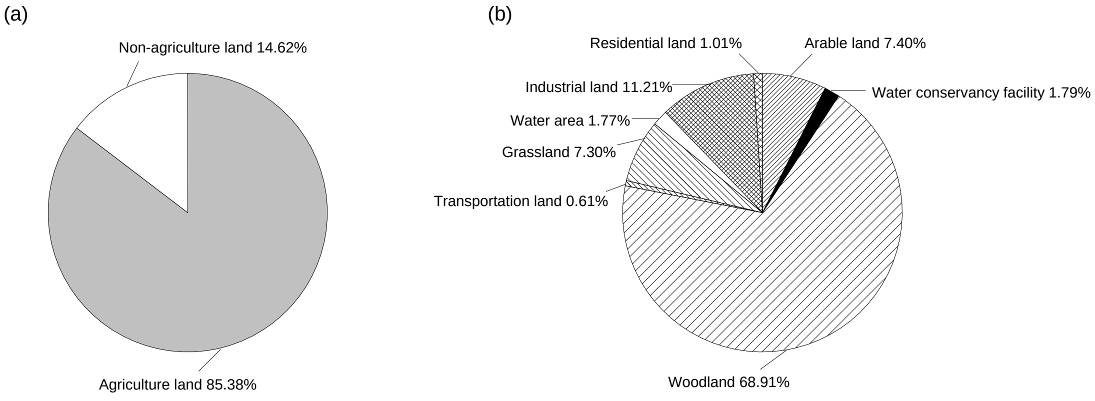

Fig. 5. (a) Proportions of agriculture and non-agriculture land; (b) Land use by type for CASS

3.5. Land use required for treating per m^3 wastewater and removing per kg BOD_5, COD, TSS and NH_3-N

Among the three kinds of WTSs, a surprising finding is that the land use required for treating per m^3 wastewater of this CW is significantly smaller than that of the centralized and hybrid WTS, as seen in Fig. 6a. Meanwhile, the land use required for removing per kg BOD_5, COD, TSS, and NH_3-N of the LRCW is 60.95%, 66.97%, 72.97% and 64.21% of that of the CASS, respectively (Fig. 6b). By removing per kg of BOD_5, COD, TSS, and NH_3-N, CW saves 33.98%, 27.46%, 20.96% and 30.45% of induced agricultural land and 68.66%, 65.56%, 62.48%, 66.98% of induced non-agricultural land than the centralized WTS. According to the results, it is found that the ecological engineering of the CWs is remarkably less land-use-intensive than the centralized WTS.

This is contrary to our previous belief that centralized WTSs are more land-conservative than CWs. From an onsite perspective, a CW uses more onsite land area than a centralized WTS and is more suited to be deployed in suburb areas. From a systems perspective, however, the indirect land use is in magnitude much higher than the direct land occupation and a CW is revealed to have an obvious advantage over a traditional WTS in terms of land use. CWs are designed in a way similar to natural wetlands and make use of physical, chemical and biological synergies of soil, plants and microorganisms to deal with the contaminants in wastewater, which requires a small number of material and other inputs in the construction and operation stages. In contrast, centralized WTSs require a lot of external inputs, which could induce much more land use in the upstream processes compared to CWs. Just as previously noted, once the land is exploited for economic uses, the land use keeps circulated in the economic network via the supply chain and support the production of all commodities in the economy. Therefore, though many industrial products require not too much land use in the production processes, the land use induced to support the input items may be significant. Even for the service inputs that direct require little land use, they may also be land intensive. The large amount of land use induced by the massive input items of centralized WTS demonstrates that it may not be land-conservative as generally believed. Meanwhile, as described by Millennium Ecosystem Assessment (MEA), people could directly obtain benefits from ecosystems (MEA, 2005). CWs as planned and managed semi-natural systems are used in wastewater treatment to capture the value from ecosystem by effectively mimicking processes normally performed by conventional, gray infrastructure technologies, which is much more ecological friendly and land-conservative than the anthropogenic production system.

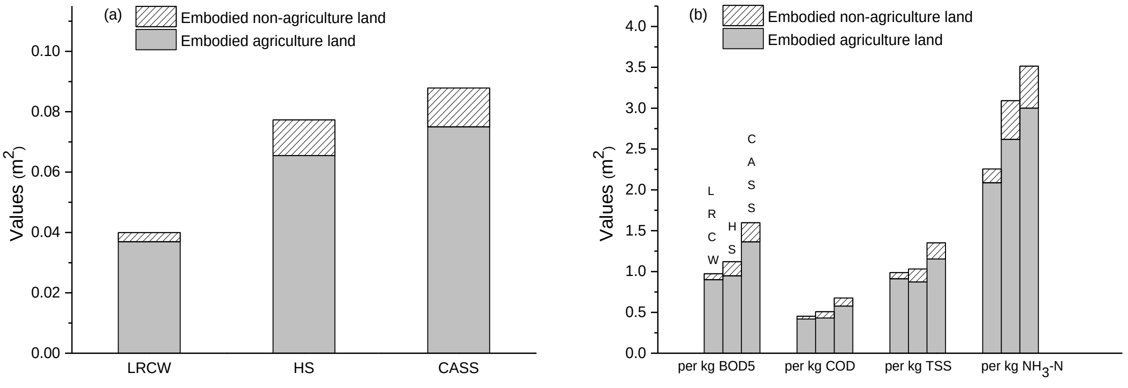

Fig. 6. Land use required for treating per m^3 wastewater and removing per kg BOD$_5$, COD, TSS and NH$_3$-N

3.6. Scenario analysis and implications

The total amount of urban wastewater discharged and treated in China has kept increasing year by year since 2004 (Fig. 7). The capacity and efficiency for wastewater treatment are improving which may be due to the continuous enhancement of public awareness of environmental protection and improvement of special wastewater treatment technology as well as the associated legal system. However, China is still faced with the concern of the continuously growing wastewater discharge along with rapid urbanization.

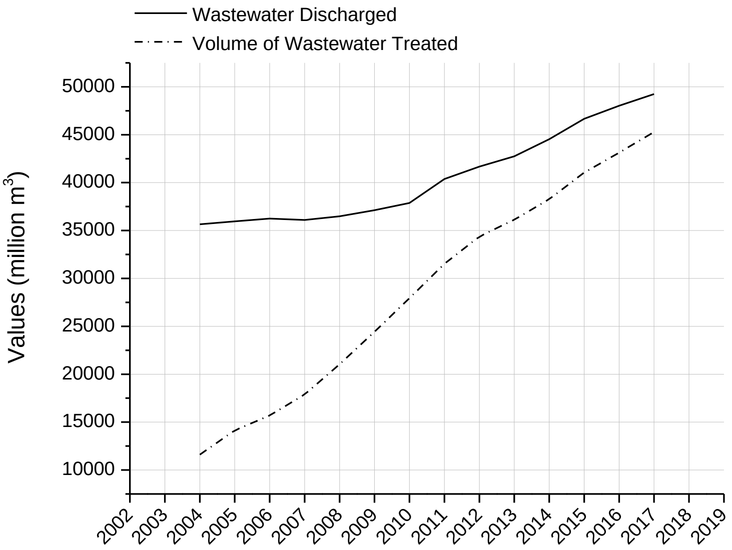

Fig. 7. The volume of urban wastewater discharged and treated 2004-2017 in China

By the end of December 2017, a total number of 2,209 urban centralized wastewater treatment plants (excluding township and industries wastewater treatment plants) had been built in cities in China, with a wastewater treatment capacity of 157.43 million m^3 per day, according to China Environmental Statistics Yearbook (CSP, 2018). The amounts of wastewater discharged and treated in Chinese cities in the year of 2017 are both presented in Figure 8.

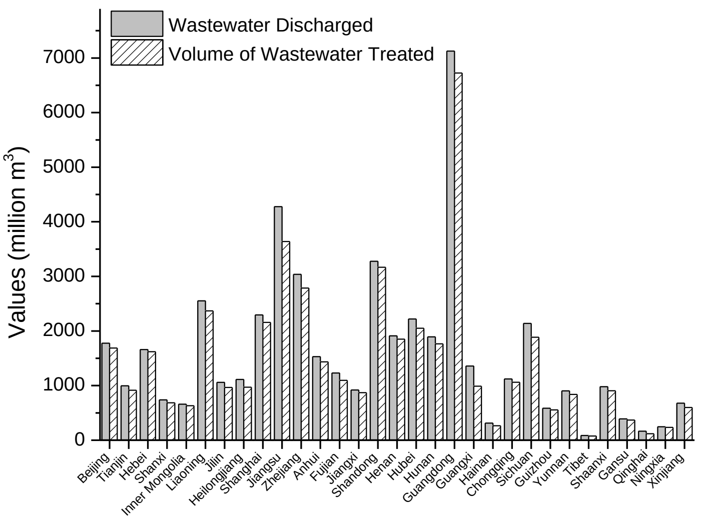

Fig. 8. The amount of wastewater discharged and treated in Chinese cities in 2017

According to the above calculations, the CW utilizes 0.05 m^2 less than the centralized WTS when one m^3 wastewater is treated. Therefore, it can be preliminarily estimated that if all urban centralized WTSs in 2017 are replaced by CWs, an enormous amount of land use induced (about 2.17 billion m^2) could be reduced.

If the Chinese urban WTSs are replaced by CWs, the amount of land saved by each province and land saved per capita by each province in 2017 are illustrated in Fig. 9. Meanwhile, it is necessary to note that since the physical boundaries between the provinces and cities have been gradually smeared out as mentioned previously and the cross-division of production chain has been formed, a system that physically situates in a city/provinces may need energy, material and equipment inputs from the rest of the country. Therefore, land use intensity for China economy instead of that for regional economy was used to give preliminary estimation. Such preliminary scenario analysis could provide a basis for making of provincial wastewater treatment policies.

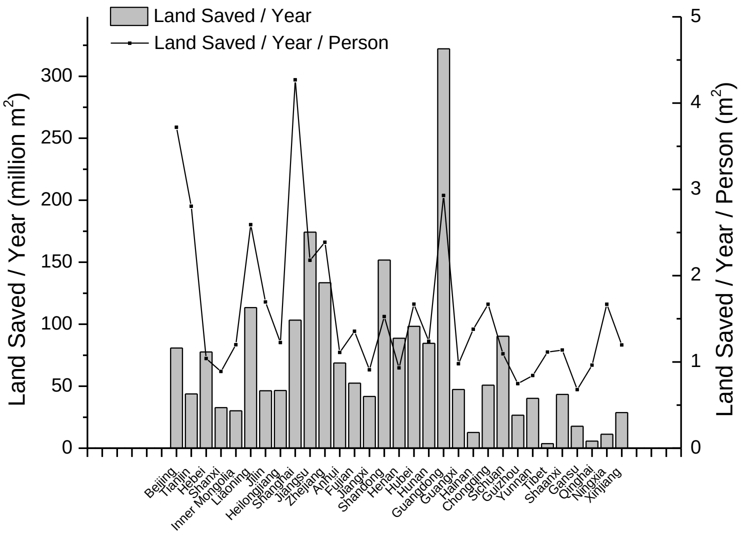

Fig. 9. The total and per-capita land use saved per year

Previous studies have shown that CW wastewater treatment plants have less impact on the environment than centralized wastewater treatment plants (Austin and Nivala, 2009). It has also been reported that CW wastewater treatment plants are less energy-intensive (Shao et al., 2013) and carbon-intensive (Chen et al., 2011a) than the centralized ones. Furthermore, it is generally accepted that CWs have many ecological benefits over the centralized wastewater treatment plants, such as biodiversity maintaining and carbon sequestration (Shaharuddin et al., 2013). In addition to the benefits reported above, CWs are delivering cultural services in the form of educational tours.

What has been discussed above has supported the argument that a CW is more favorable when compared with a centralized WTS. Given the advantages of CWs in treating wastewater, Chinese government has carried out a series of policy incentives for the development of CWs. In 2000, the Chinese government promulgated the technical policy on Urban Wastewater Treatment and Pollution Prevention, which emphasizes that the prevention and control of secondary pollution should be given due attention in urban wastewater treatment. It also advocates the use of reclaimed water in agricultural irrigation, green irrigation, ecological restoration and industrial cooling. In order to standardize the construction, operation, maintenance and management of CW wastewater treatment projects in China, the set of standards, Technical Specification of Constructed Wetlands for Wastewater Treatment Engineering, has been enacted and implemented since 2011. The standing committee of the National People’s Congress of the People’s Republic of China further amended the law on Prevention and Control of Water Pollution in 2018, with special emphasis on building CWs in line with local conditions to improve the carrying capacity of environmental resources in river basins.

A similarity inherent in these policy packages is that although ecological advantages of CWs are acknowledged, while much anxiety has been given to the hypothetical threat that expansion of CWs deployment may increase great pressures on the availability of land resources. Therefore, the promotion of CWs in urban area is greatly hindered due to the large onsite area required. This study revealed that, despite the superficial observation that centralized WTSs require less onsite area than CWs, the wide deployment of WTSs in cities may induce a much greater quantity of land use in upstream processes, which may cast more pressure on the available land resources. In context of the limited availability of land resources, the system accounting revealed that substantial land use could be reduced if centralized WTSs are replaced by CWs. This provides a systems view for the refinement of the existing land planning and wastewater treatment policies.

4. Concluding remarks

A typical CW in Beijing as an ecological project to treat wastewater is studied, supported by a comprehensive inventory of inputs and the land use intensity database. Parallel calculations are carried out for two systems for comparison: one is a hybrid system of centralized WTS and CW, and another one is a typical centralized WTS. According to the results of assessment, indirect land use is much larger than onsite land occupation for these three WTSs. Therefore, the importance of indirect land use cannot be ignored in the overall land assessment. Moreover, land use in the construction phase, which is usually overlooked, exceeds that in the operational phase for these three WTSs. The key finding of this study is that total land use required for treating per unit wastewater of CWs is smaller than that of centralized WTSs. Thus, CWs are more likely to help achieve the goal of land conservation than centralized WTSs, which goes beyond the conventional belief that CWs are land-intensive and not suitable for promotion in urbanized areas. The outcome of this study could provide a benchmark for future studies and a reference for policy enactment.

Acknowledgements

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