Embodied water accounting and renewability assessment for ecological wastewater treatment

Ling Shao, G.Q. Chen

School of Humanities and Economic Management, China University of Geosciences, Beijing 100083, China
Key Laboratory of Carrying Capacity Assessment for Resource and Environment, Ministry of Land and Resource, Beijing 100083, China
Laboratory of Anthropogenic Systems Ecology (LASE), College of Engineering, Peking University, Beijing 100871, China
NAAM Group, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia

Abstract

For water accounting of wastewater treatment, existing studies focused on either direct water loss caused by evaporation/evapotranspiration by natural process or indirect water cost induced by economic inputs. As an extension of our previous work (Shao and Chen, 2013), both the direct and indirect water losses as embodied water are accounted for in the present study. A set of improved indicators have also been devised to assess the efficiency and renewability of wastewater treatment. After accounting and analyzing the embodied water of a pilot constructed wetland wastewater treatment system as an ecological engineering in Beijing, a comparison has been carried out between the case system and a traditional wastewater treatment plant based on the proposed indicators. The traditional wastewater treatment technology is illustrated however superior to the ecological way in terms of water use context. The present framework is capable of providing clear guidance for prioritizing options of wastewater treatment technologies by evaluating water trade-off, beyond the usual practice on treatment efficiencies and quality standards in effluents.

1. Introduction

A constructed wetland is ecologically typical in integrating biological, physical and chemical processes to treat wastewater. It is widely embraced as a promising technology owing to its low cost, simple maintenance, favorable environmental appearance and little secondary pollution, compared with conventional chemical wastewater treatment plants (Chen et al., 2009, 2011b, 2008; Shao et al., 2014b, 2013; Shao and Chen, 2015; Wu et al., 2015). A constructed wetland can play a remarkable role in both the cycling of water as a fundamental economic resource and the evapotranspiration of water as an essential climate buffering medium. The water cost assessment of a constructed wetland is therefore of interest in the background of accelerated water resource scarcity and climate change.

Owing to the continued concerns on water loss of the soil or water surface to atmosphere since decades ago, evapotranspiration of a constructed wetland, with surface comprised of open water and plants, has been intensively investigated (Kantawanichkul et al., 2009; Sarmento et al., 2012). Several techniques based on lysimeter techniques and micrometeorological methods were developed to measure evapotranspiration of a constructed wetland system. However, limited by the complex surface characteristics and defects of the measure methods, direct measurement of evapotranspiration is usually hard to be performed (Drexler et al., 2004). The dilemma has led to the evolution of some empirical estimation methods. These methods, represented by the Penman-Monteith formula, need to be calibrated before application in accordance with the local meteorological and hydraulic conditions, such as the temperature, the wind speed and the plant species. The results are not guaranteed and may produce conflicting results (Campbell and Williamson, 1997).

Existing studies on evapotranspiration have contributed a lot in assessing the water budget of a constructed wetland. However, while the direct water loss through water surface to atmosphere
the natural implication of a constructed wetland) is concerned, the virtual water involved in the social product inputs (human society implication of a constructed wetland) is undeservedly neglected. The inputs such as substrates, plants and pipes consumed water resources in their productions, and their virtual water contents should be included in the water accounting of a constructed wetland. That is, not only direct water loss, but also indirect water consumption should be taken into account to reflect the real overall water cost of a constructed wetland.

The total water cost as the direct water loss plus the water consumption embodied in the production of all the intermediate economic inputs as supplied by the economy (indirect water) is referred to as the embodied water in this paper. The embodied water assessment of a constructed wetland wastewater treatment system is set as the primary aim of this work. The direct water cost of a constructed wetland can be measured in field or estimated by empirical method, as aforementioned. As for the indirect water cost of a constructed wetland, a hybrid method as a combination of process analysis and input–output analysis integrating the goods and remediating the drawbacks of both methods is applied (Bullard et al., 1978). The method was initially devised to calculate the embodied energy under the circumstance of energy crisis in the 1970s, which was then intensively employed to assess various environmental impacts of all sorts of production systems, e.g., the greenhouse gas emission and embodied water of a building, a constructed wetland and a renewable energy system (Chen et al., 2011a,b; Gao et al., 2012; Meng et al., 2014; Shao et al., 2014a,b, 2013).

Wastewater treatment is regarded as the sole technology to renew water resources. Since it has consumed water resources in its supply chain like any other product or system, the efficiency and renewability assessment of wastewater treatment focusing input–output ratio of water resources is likely to be a key issue in water resources management and water environment improvement. On the basis of embodied water accounting, a set of indicators are devised to assess the efficiency and renewability of constructed wetland wastewater treatment.

As most previous works only concerned water loss associated with natural processes, the originality of this study lies in the discussion of the first ever combination of natural water circulation and social water recycling issues of wastewater treatment. For accounting the embodied water of a constructed wetland wastewater treatment system and assessing its efficiency and renewability, the rest of this paper is organized as follows: Section 2 describes the framework and indicators for embodied water assessment of a constructed wetland; the embodied water of a constructed wetland is assessed in Section 3 with detailed results discussed in Section 4; and finally, the conclusions are drawn in Section 5.

2. Methods

2.1. Framework of embodied water accounting for a constructed wetland wastewater treatment system

Both physical and virtual water flows of a constructed wetland wastewater treatment system are shown in Fig. 1. The dashed box outlines the systems boundary of this study. And the present work aims at systematically accounting the life-cycle anthropogenic water cost as embodied water of a constructed wetland wastewater treatment system.

The anthropogenic water cost of a constructed wetland can be divided into two categories. One is the direct water (DW) loss caused by evapotranspiration as natural processes. The water content of biomass, such as the plant and fish, also serves a direct water loss source. In this study it is not accounted due to its meager contribution to the total embodied water. Meanwhile, the water loss caused by percolation is not included, either, given that anti-seepage measure is usually undertaken to prevent soil from being polluted in constructed wetland. The other, often overlooked in previous literatures, is the indirect water (IW) cost initiated by the products inputs. It can be calculated as the sum of total water cost during the production of each input, i.e., the embodied water of related products.

Therefore, the whole embodied water (EW) of a constructed wetland is the sum of the direct water sources related to evapotranspiration and indirect water embodied in the supply chain of products inputs:

$$EW = DW + IW$$

The direct water as the evapotranspiration of a constructed wetland, which has been intensively studied, can either be measured or calculated from empirical methods. The estimation of indirect water as embodied water of inputs (EWI), however, is relatively subjective and complex.

In context of global economic integration, the production of each product is highly interdependent and requires various inputs from heterogeneous economic systems worldwide. To evaluate the indirect water of an individual constructed wetland wastewater treatment system, which is commonly treated as a micro-system in the macro-economy, the indirect fluxes from outside the process boundary can be well traced by averaged sectoral intensities provided by proper input–output analysis of the economy. Based on the hybrid method as a combination of process analysis and input–output analysis, the procedure of indirect water accounting for a constructed wetland is described as follows.

(1) Itemize all the products required in the lifecycle of a constructed wetland to form the inputs inventory.

Founding on process analysis, the first step seeks to characterize the features of the targeted constructed wetland through determining the quantity of all inputs. The embodied water intensity, i.e., the embodied water or virtual water required to produce one unit product is usually in monetary unit as a result of economic input–output analysis. Therefore the monetary cost ($C_j$) of the $j$th input should be listed in the inventory.

(2) Choose an appropriate embodied water intensity database for all inputs.

The embodied water intensity database originating from input–output analysis is applied to trace the previous water consumption of a product. It could efficiently avoid the truncation error of process analysis when tracing all processes linked to a constructed wetland in the economic network. The economic input–output table is regularly updated by local statistics department. Previous works have carried out embodied water input–output analysis for different economic systems, in which a whole set of embodied water intensity data for all products within the economy have been presented.

Due to diverse technical efficiencies or economic structures, the same products produced in different years or different economic systems are coupled with different virtual water contents. Therefore the following two factors are suggested as the guidelines to choose a reliable database. First, the based year of the input–output table should be synchronized with the year when the target system was constructed. Second, the based country or territory of input–output table should be the place where the target system was located. If more than one database could meet
these premises, then the more detailed one, i.e., the database with more sectors or more kinds of goods is preferred.

(3) Identify the corresponding production sector for each item in the inventory.

The intensities are usually listed sector by sector in the database. Once the database is determined, the corresponding embodied water intensity \( I_j \) of each input can be derived from the database promptly.

(4) Multiply each input’s monetary cost by its embodied water intensity to give the embodied water (EWI) of each input, then the total indirect water (IW) of a constructed wetland is readily obtained as

\[
IW = \sum_{j=1}^{n} EWI_j = \sum_{j=1}^{n} (C_j \times I_j)
\]

2.2. Related indices based on embodied water accounting of a constructed wetland

In order to illustrate the efficiency and renewability of a constructed wetland wastewater treatment system, a series of indicators based on embodied water analysis are necessary. Our previous work has contributed three indicators as NW (net water), WROI (water return on investment) and WIWP (water investment in water purified) to reveal the efficiency as well as renewability of a wastewater treatment system in parallel with corresponding indicators in net energy analysis for energy supply and renewable energy systems (Shao and Chen, 2013). As an extension of our previous work, this paper improves the indicators. Definitions and algorithms are presented in Table 1. By unifying the indicators, the results of different wastewater treatment systems can provide clear guidance for prioritizing options of wastewater treatment technologies, especially choice between traditional chemical wastewater treatment system and ecological wastewater treatment engineering.

Although the definitions resemble those in the former study, some changes have been made to clarify their meanings. Firstly, the connotation of water required to purify the wastewater, i.e., the embodied water of the case system, has been enlarged. Both direct water, caused by evapotranspiration, and indirect water, induced by social products input have been taken into account in this study. The former study only paid attention to the indirect water.

Secondly, a new indicator of NWIWP is defined as the ratio of the total nonrenewable water required, i.e., water resources consumption that cannot be utilized by others, to the water purified by the system to assess the renewability of wastewater treatment in this paper. This and the former indicator (WIWP) are both devised in parallel with the indicator of NEIED in renewable energy field (Shao and Chen, 2013). Proposed by Chen et al. (2011c), NEIED is defined as the ratio of nonrenewable energy investment to energy delivered in order to address how much nonrenewable energy instead of inclusive energy is consumed to produce a presumed renewable energy. In this regard this new indicator seems more related to NEIED and is more appropriate to reveal the true contribution of wastewater treatment to renew water resources.

The direct water, i.e., evaporation or evapotranspiration of a wastewater treatment system can be renewed by natural processes and reused by human without cost. But the indirect water, i.e., water resources consumed during the production of various social products input, cannot be utilized by other products before being treated. Given this, the direct water is classified as the renewable water resource and the indirect water is non-renewable water resource.

3. Case study

3.1. Case description

Accompanied by the fast growing population and accelerating urbanization, the shortage of available water resources and heavy

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The embodied water indices of a constructed wetland wastewater treatment system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
<td>Index</td>
</tr>
<tr>
<td>Efficiency</td>
<td>NW (net water)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>WROI (water return on investment)</td>
</tr>
<tr>
<td>Renewability</td>
<td>NWIWP (non-renewable water investment in water purified)</td>
</tr>
</tbody>
</table>
water pollution become critical problems holding back the sustainable development of Beijing. A number of initiative moves have been taken by the local government to promote water resources reservation and water pollution control. As ecological engineering, constructed wetland wastewater treatment has become a good choice for Beijing as it can not only purify wastewater, but also provide citizens with a wealth of ecosystem services. Under the theme of “Green Olympics, Green Beijing”, a pilot constructed wetland has been constructed in a suburb of Shunyi District, Beijing to deal with the heavy pollution caused by nearby municipal domestic wastewater and make restoration for local ecosystem in 2004 (Chen et al., 2008; Zhou, 2004). It was located near the estuary of the Longdao River, and therefore was named Longdao River constructed wetland (LRCW). A vegetated vertical subsurface-flow bed was used to purify the wastewater, with a coverage of 602 m².

Fig. 2 shows the diagram of the LRCW. The height of the system was 5 m higher than the river’s ordinary water level to avoid flooding. The wastewater was extracted to the wetland by a pump at first, and then forced into the bed and filtered by the delicately devised substrates (soil, sand, wood turf, organic compost, gravel, pine bark, active sludge, iron slag, dolomite and limestone) as well as the developed root system of plants, i.e., common reed (Phragmites australis), water bamboo (Zizania aquatica) and cattail (Typha latifolia). The gradient of the bottom has been set as 0.00714 to facilitate the wastewater flow. At last the treated water drained back into the river. A steel barrier was installed in the entrance of the inlet zone as a pretreatment facility to get rid of large-size suspended solids. The geotextile liner has been laid at the bottom of the bed to prevent penetration and a few aeration pipes have been devised at the top of the bed to increase oxygen concentration in treatment processes.

The LRCW was designed with a lifetime of 20 years and a capacity of 200 m³ per day. All the economic products required in the treatment processes.

### 3.2. The embodied water of the case system

As aforementioned in Section 2, the embodied water of a constructed wetland consists of direct and indirect water. As available field experimental data is lacking, the results from other studies have been applied to estimate the direct water for the case system. Considering that the climatic condition and surface field condition are two key factors affecting evapotranspiration, the averaged evapotranspiration data of 0.27 mm/(m² d) measured by Li et al. (2014) based on a two-year field measurement for a constructed wetland in Beijing has been adopted to estimate the direct water. The direct water is calculated as 1186.54 m³.

As for the indirect water, the hybrid method has been employed to trace the total historical water use of related products inputs. Since the case system is constructed domestically in 2004, the embodied water intensity databases corresponding to the Chinese economy in 2005 and 2007 contributed by Chen and his colleagues are optional (Chen and Chen, 2010; Chen et al., 2010). Although the database for Chinese economy in 2005 is closer to 2004, the economic input—output table for Chinese economy in 2005 is an informal one and has less industrial sectors, which bears lower resolution than that in 2007. Therefore, the embodied water intensity database obtained for the Chinese economy of 2007 with 135 industrial sectors is applied in this study (Chen and Chen, 2010).

The water usage was originally divided into four categories as agricultural water, industrial water, domestic water and municipal ecological protection water in China Statistical Yearbook. Chen and Chen (2010) have simplified the assortment by categorizing the water resources as agricultural water (with reference to agricultural water only) and industrial water (with reference to industrial water, domestic water, and municipal ecological protection water) in their work. Both embodied agricultural and industrial water intensities have been provided in their database, which can be

---

### Table 2

<table>
<thead>
<tr>
<th>Stage</th>
<th>Item</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>Local organic substrate</td>
<td>690</td>
<td>m³</td>
</tr>
<tr>
<td></td>
<td>Mineral substrate</td>
<td>120</td>
<td>m³</td>
</tr>
<tr>
<td></td>
<td>Other substrate</td>
<td>220</td>
<td>m³</td>
</tr>
<tr>
<td></td>
<td>Geotextile</td>
<td>900</td>
<td>m³</td>
</tr>
<tr>
<td></td>
<td>Vegetation</td>
<td>28,500</td>
<td>Yuan</td>
</tr>
<tr>
<td></td>
<td>Pump</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electric control</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PP pipe</td>
<td>90</td>
<td>m</td>
</tr>
<tr>
<td></td>
<td>PE pipe</td>
<td>48</td>
<td>m</td>
</tr>
<tr>
<td></td>
<td>PE valve</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel griller</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bricks and cement</td>
<td>22</td>
<td>m³</td>
</tr>
<tr>
<td></td>
<td>Tap water</td>
<td>1350</td>
<td>m³</td>
</tr>
</tbody>
</table>

### Operation

<table>
<thead>
<tr>
<th>Stage</th>
<th>Item</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
<td>Electricity</td>
<td>0.75</td>
<td>kW</td>
</tr>
</tbody>
</table>

---

*a All results without time unit refer to the whole lifetime of the case system.

*b The water consumption data prescribed by the Beijing authority as 1.5 m³/m² construction area is adopted to estimate the tap water input during the construction of the case system. Multiplying by the construction area of 900 m², the tap water input of the LRCW is calculated as 1350 m³.

---

Fig. 2. The diagram of LRCW.
applied to trace the historical agricultural and industrial water use of each product input of the case system.

By turning to the compilation instruction of economic input–output table of Chinese economy in 2007, the corresponding sector as well as the embodied water intensity of each product input in the inventory can be promptly determined (see Table 3). The indirect water of the LRCW can be then calculated. The Producer Price Indices of Industrial Products (PPI) of China have been referred to convert the construction cost of construction year-based (2004) into 2007-based.

3.3. The components of embodied water of the case system

The components of the indirect water of the case system are shown in Fig. 3. The wetland plants, namely vegetation, are the largest indirect water sources, together with substrates sharing more than one-half of the total indirect water, making it the second largest contributor. According to the embodied water theory, the embodied water of tap water is the total marginal water cost induced by the tap water supply rather than its direct water content. The embodied water of tap water input (4911 m$^3$) is about 3.64 times larger than its real water content (1350 m$^3$).

The only product input during the operation stage of the case system is electricity, which shares only about 7% of the total indirect water. From the results, it can be known that the application of cheap vegetation and substrate or mineral substrate without distorting the function could contribute a lot to reducing the water resources consumption of a constructed wetland. In the meanwhile, although the prevailing water conservation policy only pays attention to direct water use, it could also benefit embodied water reduction due to the high value of tap water’s embodied water intensity.

The contrast between the two categories of embodied water during the construction and the operation stages is illustrated in Fig. 4, outlining the balance of direct water in terms of evapotranspiration and indirect water in terms of embodied agricultural water and industrial water for the case system. The indirect water is over ten times larger than the direct water, which has fully illustrated the significance of embodied water accounting.

During the construction stage, embodied agricultural and industrial water contribute almost equally to the total embodied water, while the contribution of evapotranspiration is negligible. However, during the operation stage, evapotranspiration (57.03%) and embodied industrial water (37.32%) are much larger than embodied agricultural water (5.65%). This is mainly because the wetland plant as a main input during the construction stage has consumed vast amount of irrigation agricultural water in its growth. Meanwhile, evapotranspiration continually accumulates during the long run of the case system as time goes on.

Although electricity is the only indirect water source during operation stage and seems not to consume any agricultural water during its production, the agricultural water still occupies a certain proportion in the result. This elaborates the invisible water nexus between different industries, which has been completely and successfully captured by input–output analysis in the present work. However, most of the existing studies only focused on water cost of crops or livestock farming as agricultural products. Given that the extent and complexity of cooperation increase, the study on addressing the water nexus between different industries should be highlighted.

4. Discussions

4.1. The efficiency and renewability assessment based on embodied water accounting of the case system

With references to the definitions in Section 2.2, the NW and WROI of the case system are respectively calculated as 1.45E+06 m$^3$ in its whole lifetime and 1.01E+02 m$^3$ purified water/m$^3$ invested water. The case system, evaluated by the water input–output benefit, proves to be with a high efficiency (with input output ratio larger than 100). Wastewater treatment can hence be considered as a sustainable approach to ensuring the society with purified water.

Water resources can either be renewed through natural processes or purified by manmade wastewater treatment. But as suggested in this work, a wastewater treatment system has its own

| Table 3 | The indirect water accounting of the case system. |
|---|---|---|---|---|
| Item | Sector code | Sector contents | Embodied water intensities (m$^3$/1E+04 Chinese Yuan) | Embodied water (m$^3$) |
| | | | Agricultural | Industrial | Total | Agricultural | Industrial | Total |
| Geotextile | 49 | Manufacture of plastic | 2.89E+01 | 8.95E+01 | 1.18E+02 | 6.22E+01 | 1.93E+02 | 2.55E+02 |
| Local organic substrate | 5 | Services in support of agriculture | 2.13E+02 | 7.57E+01 | 2.89E+02 | 1.13E+03 | 4.02E+02 | 5.15E+03 |
| Mineral substrate | 10 | Mining and processing of nonmetal ores and other ores | 2.07E+01 | 7.66E+01 | 9.73E+01 | 3.39E+01 | 1.25E+02 | 1.59E+02 |
| Other substrate | 52 | Manufacture of brick, stone and other building materials | 2.22E+01 | 8.61E+01 | 1.08E+02 | 4.55E+01 | 1.76E+02 | 2.22E+02 |
| Vegetation | 1 | Farming | 1.62E+03 | 2.73E+01 | 1.65E+03 | 5.14E+03 | 8.67E+01 | 5.23E+03 |
| Pump | 67 | Manufacture of pump, valve and similar machinery | 1.81E+01 | 5.91E+01 | 7.72E+01 | 5.64E+00 | 1.84E+01 | 2.41E+01 |
| Electric control | 78 | Manufacture of equipments for power transmission and distribution and control | 2.21E+01 | 6.98E+01 | 9.19E+01 | 2.79E+00 | 8.82E+00 | 1.16E+01 |
| Pipe and valve | 49 | Manufacture of plastic | 2.89E+01 | 8.95E+01 | 1.18E+02 | 1.28E+01 | 3.97E+01 | 5.25E+01 |
| Steel griller | 63 | Manufacture of metal products | 2.13E+01 | 8.56E+01 | 1.07E+02 | 1.15E+02 | 4.61E+02 | 5.76E+02 |
| Bricks and cement | 50 | Manufacture of cement, lime and plaster | 2.28E+01 | 8.09E+01 | 1.04E+02 | 1.04E+01 | 3.68E+01 | 4.72E+01 |
| Tap water | 94 | Production and distribution of water | 1.46E+01 | 9.31E+01 | 1.96E+04 | 3.66E+00 | 4.89E+03 | 4.91E+03 |
| Electricity | 92 | Production and supply of electric power and heat power | 1.41E+01 | 1.95E+04 | 1.07E+02 | 1.18E+02 | 7.76E+02 | 8.94E+02 |
| Total | | | 6.57E+03 | 6.75E+03 | 1.33E+04 |
embodied water cost, and its renewability index cannot be 100%. The NWIWP has been devised to assess the renewability of wastewater treatment. From the definition, it is evident that NWIWP < 1 means that more water resources are renewed than nonrenewable water resources invested, while NWIWP > 1 means that more nonrenewable water resources are consumed than water resources renewed. The NWIWP of the case system is calculated as $9.13 \times 10^3$ m$^3$ freshwater/m$^3$ purified water, showing that the case system has renewed much more water resources than nonrenewable water resources it consumed. This means wastewater treatment is equipped with a high efficiency in renewing water resources. This conclusion is in accordance with that of the former study (Shao and Chen, 2013).

4.2. The comparison between this study and a former work

Our previous work has for the first time accounted embodied water of a typical traditional wastewater treatment system, i.e., a Cyclic Activated Sludge System (CASS) in Beijing (Shao and Chen, 2013), and two indicators as WROI and WIWO have been devised to assess the efficiency and renewability of wastewater treatment. The present study has advantages over the previous one in the following aspects. On one hand, apart from the indirect water brought by the social products inputs, the direct water caused by evapotranspiration has also been taken into account. On the other hand, the renewability index, one of the most fundamental properties of a wastewater treatment system, is defined as the ratio of the total nonrenewable water required, i.e., indirect water, to the water purified. The reason lies in that the direct water as the evaporation or evapotranspiration of wastewater treatment can be reused by other production systems without any cost, which can be regarded as renewable water resources.

In order to compare the two systems, namely a traditional wastewater treatment system and an ecological wastewater treatment system, the embodied water of the case system in the former study is re-calculated here. The plant utilizes a cyclic activated sludge system (CASS) to treat wastewater. Based on the same algorithm, its indirect water, i.e., the total embodied water in the former study (the former study only concerned the indirect water) is unchanged, which was estimated as $1.64 \times 10^3$ m$^3$ freshwater. Similarly, as no field experimental data is available for the CASS, we have to turn to other sources to estimate the direct water. Unlike the constructed wetland that is covered by vegetation, the CASS sustained by electricity and machines only involves evaporation process. Derived from the experimental data in Munavalli and Saler (2009), the average evaporation rate is set at about 3 mm/(m$^2$ d) for the CASS. The direct water of the CASS is calculated as 15,240.5 m$^3$ water resources during its lifetime. The indirect water of the CASS turns out to be about 10 times larger than the direct water. For the constructed wetland system in this work, the ratio of indirect water to direct water is about 11. This demonstrates that the indirect water induced by various social products inputs is the main source of water cost of a wastewater treatment system, whether a traditional wastewater treatment plant or a constructed wetland as ecological wastewater treatment.

The improved and redefined indicators as WROI and NWIWP presented in this study have also been applied to the CASS as traditional wastewater treatment in the former study, whose values are calculated as $2.93 \times 10^2$ m$^3$ purified water/m$^3$ invested water and $3.12 \times 10^3$ m$^3$ freshwater/m$^3$ purified water, respectively. The CASS is revealed as more efficient (with a higher water resource return) and more renewable (with a lower non-renewable water resources cost) than the LRCW (see Table 4). The traditional engineered wastewater treatment technology is shown superior to the ecological wastewater treatment system as costing less water resources in renewing one unit water resources. However, as the treatment capacity of the traditional system (7200 m$^3$/day) is much larger than that of the pilot constructed wetland (200 m$^3$/day) in this study, the scale effect may also contribute to the advantage of the CASS.
4.3. The implication of this study

The water resources accounting has attracted more and more attention recent years. Several similar but differentiated theories, e.g., water footprint, embodied water, virtual water and embedded water, concerning different aspects of water resources or against different research backgrounds have been developed by different scholars. The related studies can be divided into two groups with reference to different scopes and diverse needs.

Represented by water footprint theory contributed by Hoekstra and his group, the first kind of studies focuses on consumptive water use of products or services, especially agricultural products (Lenzen et al., 2013; Liu et al., 2009; Zhang et al., 2012; Zhao and Chen, 2014; Zhao et al., 2014). Consumptive water use refers to water that after use is no longer available for other purposes, for example, the water vaporized (Mekonnen and Hoekstra, 2010). Apart from the accounting of gray water as a complementary measure to evaluate the volume of freshwater that is required to assimilate the already generated pollutants, Hoekstra and Mekonnen (2012) have estimated the green water footprint (consumptive use of rainwater) and blue water footprint (consumptive use of ground and surface water) of all nations around the world. Water footprint theory emphasizing consumptive water use focuses on natural water circulation change caused by human activity, laying a solid foundation for us to evaluate anthropogenic environmental impacts.

Differing from the above-mentioned studies, the remaining studies keep their eyes on the total volume of water use, considering that most available statistic data of countries and regions only provide the total amount of water use. The total water use-based study aiming at water resources consumed or withdrawn by various economic activity or human being has paid more attention to water recycling associated with product trade or industry cooperation, which can be used to trace the transition of water resources in human society (Fang and Chen, 2015; Fang et al., 2014; Guan and Hubacek, 2007; Guan et al., 2014; Zhao et al., 2015, 2010). Among all these studies, embodied water theory contributed by Chen and his group as a part of a systems embodied element accounting framework has been applied in this work to account the indirect water induced by various social economic products. By concerning original water withdrawal of a product or a service against the background of complex industrial structure, the embodied water theory has efficiently avoided the possible double counting in input–output modeling of water resources (Chen and Chen, 2010; Chen et al., 2012; Shao, 2014).

Taking constructed wetland ecological engineering as a good carrier, the present work has concerned both direct water caused by evapotranspiration as part of natural water circulation and indirect water induced by social product inputs as part of human society water transition. It can be viewed as a novel combination of the aforementioned works. Therefore the study can be a good model for exploring the complex interaction between natural circulation and human society. In the meantime, wastewater treatment itself is a key component and sole technology for human society to renew water resources, making the combination practical and meaningful for the present work.

5. Conclusions

Water resources accounting has been a hotspot for academic researches these years. Considering that wastewater treatment is the sole technology to remove pollutant and is of great significance for water reuse, the lifecycle water resource cost of constructed wetland wastewater treatment has been investigated in this work. Differing from previous studies, both direct water loss caused by evapotranspiration and indirect water cost induced by various products inputs have been covered. A hybrid method integrating process analysis and input–output analysis has been employed to trace the indirect water cost embodied in the supply chain of a constructed wetland. The accounting framework has been fully elaborated. In order to assess the efficiency and renewability of wastewater treatment, a couple of improved indicators have been delicately devised by referring to our former efforts and recent developments in renewable energy field.

A pilot constructed wetland in Beijing has been chosen as a case system. The indirect water is calculated to be over ten times larger than the direct water. The embodied water in the operation stage is about 6 times larger than that in the construction stage. The crux of embodied water accounting has been fully indicated. Among all indirect water sources of the case system, vegetation in terms of plants has ranked the first, which together with the three kinds of substrates have accounted for more than one-half of the total indirect water.

Our previous work has carried out water footprint assessment for a traditional wastewater treatment plant. The improved indicators as WROI and NWIWP have been applied to both case systems in these two works to carry out a comparison study. The result suggests that both systems are coupled with high efficiency and renewability in treating and renewing wastewater, while the traditional wastewater treatment technology is superior to the ecological one. Therefore the traditional technology should be of priority to save and renew as much water as possible.

The proposed procedure and indicators can provide clear guidance for designing water saving strategies as well as prioritizing options of wastewater treatment technologies. It can also be easily transplanted to account the lifecycle water resources cost and assess the efficiency of various production systems, especial water system such as tap water plant and seawater desalination plant. Since constructed wetland can be considered as a good carrier involving both natural water circulation and social water recycling, this work is also a good example to illustrate the complex interaction between natural process and human society.

Acknowledgments

This work is supported by the State Key Program for Basic Research of China (973 Program, No. 2011CB403402), the Fundamental Research Funds for the Central Universities (Grant No. 2652015151) and the National Natural Science Foundation of China (Grant No. 11272012).

References


