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# Systems ecological accounting for wastewater treatment engineering: Method, indicator and application

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ABSTRACT

Wastewater treatment facility is vital for sustainable urban development. In the course of removing contaminants and discharging ready-for-reuse water, wastewater treatment consumes resources and triggers environmental emission during its lifetime. A comprehensive framework to analyze the embodied ecological elements as natural resources and environmental emissions of wastewater treatment is presented in this work. The systems method as a combination of process and input–output analyses is applied and a set of indicators are accordingly devised. Two representative ecological elements, i.e., greenhouse gases emissions and solar emergy of alternative wastewater treatment systems, i.e., a traditional activated sludge wastewater treatment plant and a constructed wetland have been taken into consideration. For each ecological element, five indicators have been calculated and compared to assess the impact on climate change and resources utilizing style of the case systems. The framework raised in this paper is fully supportive for optimal decision-making among different wastewater treatment technologies, and could be transplanted to be applied to systems ecological accounting for other production systems.



## 1. Introduction

Wastewater treatment is of vital significance for a modern city. While wastewater treatment plays an irreplaceable role in pollutants removal and ready-for-reuse water supply, it also consumes resources and releases environmental emissions during the construction and operation processes. Abundant studies have been carried out to analyze the environmental implications of wastewater treatment (Chen et al., 2011b, 2012, 2010b; Emmerson et al., 1995; Fuchs et al., 2011; Shao and Chen, 2013; Wu and Chen, 2014). Given the background of the worldwide energy crisis in 1970s, the direct energy consumption associated with wastewater treatment process has initially been accounted (Smith, 1973). Latter, the direct greenhouse gas emission of wastewater treatment has also arrested extensive attention (Czepiel et al., 1993, 1995). Taken into account the dual roles of a constructed wetland as a wastewater treatment technology and a more or less anthropogenic ecosystem, its impact on climate change has attracted even more interests (Maltais-Landry et al., 2009; Søvik and Kløve, 2007; Teiter and Mander, 2005). These studies cover solely the direct in-site environmental impacts of wastewater treatment. However, as a matter of fact, more resources uses and environmental emissions have been initiated by wastewater treatment in its supply chain via products and services purchase.

Life cycle assessment (LCA) is widely recognized as a tool to analyze the environmental impacts of a given service or product throughout its lifecycle. It has gained momentum to assess various environmental impacts of wastewater treatment and carry out comparison studies between different treatment technologies ever since its proposal, especial the tradition chemical wastewater treatment plants and new technologies such as constructed wetland. These works either trace the exact quantity of a specific resources use or environmental emission, for instance, embodied energy, greenhouse gas emission, or emergy of a wastewater treatment system (Chen et al., 2009a; Emmerson et al., 1995; Ko et al., 2004; Lundin et al., 2000; Tillman et al., 1998; Zhou et al., 2009), or evaluate the final environmental impact, such as carcinogen, eco-toxicity, acidification, and eutrophication of wastewater treatment by means of damage assessment (Fuchs

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et al., 2011; Gallego et al., 2008; Renou et al., 2008). They have greatly enlarged our knowledge of wastewater treatment, but they still have some shortcomings.

With regard to the method, most of these studies based on process analysis have suffered from truncation errors. The process analysis is to trace each stage of a product or service's production processes to individually analyze the resources use or environmental emission of each input. But these traces have to be truncated after a few stages because it is time-consuming, infinite and sometimes the tracing might even fall into a loop (Bullard et al., 1978; Treloar, 1997). The ignored upstream inputs would trigger unavoidable truncation errors. Current process analysis based studies adopt the intensities data of a specific product or service contributed by others to simplify the accounting. But such treatment has instigated more problems. The adoption of intensities for other countries or various years is not rare in related studies. Due to the diverse technical efficiencies, the same products from two economic communities have different intensities. As a matter of fact, even the same products produced by the same economic community at different time do not have the same intensity due to the distinct economic structures. Moreover, the intensities are not consistent since their accounting backgrounds and frameworks differ greatly from each other. Therefore, the consistency could hardly be maintained in the analyses of different products performed by different researchers in different economic and social backgrounds.

The input–output analysis is a network modeling approach based on the economic input–output table. Since it can provide consistent and unified intensity data for all products and services within the economy, the hybrid method as a combination of process analysis and input–output analysis has been contributed to avoid the truncation error of the process analysis (Bullard et al., 1978). This has found wide applications in assessing the environmental impacts of wastewater treatment (Chen et al., 2011b,c, 2010b; Shao and Chen, 2013; Shao et al., 2013b; Zhang et al., 2010) as well as other production systems (Chen et al., 2011a; Han et al., 2013; Meng et al., 2014; Shao et al., 2014). But till now, these studies are scattered and each study has only accounted a single specific environmental impact of wastewater treatment. A comprehensive and unified ecological accounting framework of wastewater treatment is lacking.

Regarding each resources or emission as one kind of ecological element (or endowment for resources), the embodied ecological element means the total use of ecological element by an ecological economic system as induced by a concerned activity (Chen, 2011; Zhou, 2008). In systems ecological accounting, the embodied ecological element intensity is principally defined as the marginal ecological cost as the change in the total amount of ecological element input that arises when the quantity produced has an increment by unit (Chen et al., 2011a, 2013; Zhou, 2008). That means it is the ecological cost of producing one more unit of a good. In general terms, marginal ecological cost at each level of production includes any additional costs required to produce the next unit. The same definition is adopted in this study with full consideration of the sum of the direct and indirect ecological element as the embodied element of a wastewater treatment system. The ecological elements can be either natural resources, such as fossil energy, water resources, land, mineral, and integrated measure as emergy and exergy or environmental emission, such as carbon and pollutant.

This work is to provide a comprehensive unified framework and corresponding indicators to account the ecological elements (unless otherwise stated, the ecological element refers to the embodied ecological element hereafter) of wastewater treatment. The systems method as a combination of process and input–output analyses is applied. On the basis of concrete inputs inventories and appropriate embodied element intensity databases, two case studies are carried out to account the greenhouse gas emission and solar emergy for a traditional activated sludge wastewater treatment system and a constructed wetland as ecological engineering.

## 2. Methodology

### 2.1. Hybrid method

Both the process analysis and input–output analysis (IOA) have been performed for the embodied ecological element calculation of a target product or service in ecological accounting studies. Though the process analysis can offer us detailed information, it is labor intensive and suffers from the truncation errors (Bullard et al., 1978; Treloar, 1997). The economic input–output tables based IOA (Leontief, 1936, 1970) has been extended to calculate the embodied ecological element intensities of the produced goods and services within an economic system. It utilizes the statistics and organizes matrices of all the intermediate inputs into goods and services of the whole economic network, making it capable of overcoming the truncation errors brought about by process analysis (Miller and Blair, 2009). However, the IOA can only give an average quantity of ecological element embodied in the wastewater treatment industry, which is not detailed enough to elaborate the ecological implication of a specific wastewater treatment system.

Given that, the hybrid approach combining the process analysis and the IOA has been proposed. It is taken root as an accurate, complete, quick and widely applicable tool (Bullard et al., 1978; Joshi, 1999; Suh and Huppes, 2005). It enables us to account the ecological element of a wastewater treatment system as a microsystem embedded in the macro-economy by tracing the indirect fluxes originated outside the process boundary with average sectoral intensities provided by proper IOA. As a consequence, the hybrid approach is utilized to account the ecological elements of wastewater treatment in this work.

### 2.2. Accounting framework

The procedure for the systems ecological accounting of a wastewater treatment system is illustrated below:

#### 2.2.1. Inventory compilation

Building a concrete and detailed inputs inventory based on the process analysis is the first and fundamental step in ecological accounting for a wastewater treatment system. A representative inventory with reference to the daily practice of wastewater treatment is presented in Table 1. The major input flows have been categorized as environmental input and economic input. The environmental input includes various natural resources flowing into the wastewater treatment system, such as sunlight, rainfall, and wind. The economic input is social product accompanied with monetary exchange, such as steel, pumps, and pipes. Some inputs of the inventory may be uncommon in a traditional wastewater treatment system, for instance, the substrate and plant. But they are the main components of a constructed wetland as ecological wastewater treatment engineering. The labor and service have also been listed in the inventory since they also partially impact on environment in the supply chain. The inventory only lists a part of the most typical inputs of a wastewater treatment system. It can be more detailed in a practical accounting.

#### 2.2.2. Embodied ecological element intensity database selection

The embodied ecological element intensity is defined as the amount of some kind of natural resources and environmental emissions embodied in a unit product or service. The embodied ecological element intensities of different natural resources are calculated according to the biophysical costs to generate one unit of