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The environmental sustainability evaluation of an urban tap water treatment plant based on emergy

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ABSTRACT

The resources and environment issues, derived from tap water production, have been widely concerned with fast development of social economy. Based on the characteristics of water supply systems (especially its pollution emissions' impact), this work proposed a set of improved indicator system for evaluating their environmental sustainability. As a case study, a tap water treatment plant, located in Jiangsu Province, China, was investigated using the proposed indicator system. The study results show that (1) purchased nonrenewable input accounts for 50.24% of the total input; therein, thermal power contributes the largest; (2) the unit emergy value of tap water reaches 9.03E11sej/m^3 based on the baseline 12.0E24 Sej/a; (3) the M_n removal needs the largest cost in terms of emergy; (4) the pollution emissions' impact reduces its performances slightly; (5) based on the classic indicator values, it has better economic benefit, lower environmental loading, and higher sustainability level than the similar systems. After some issues' discussions, this work puts forward the related suggestions for further improving its comprehensive performance in the future.

1. Introduction

Tap water is one of strategic resources for social economic development and residents' ordinary life. Therefore, safe and reliable supply of tap water is necessary for the sustainable development of social economy. Tap water treatment plants, as one of important municipal infrastructures in modern society, have been developed fast. The total amount of tap water supply increased by 14.50% from 4.69E10 m^3 in 2000 to 5.37E10 m^3 in 2013 in China, with an annual growth rate of 1.05% in this period (Zhang et al., 2016). The water supply system has contributed to China's social economic development greatly, but the resources and energy consumption derived from this system is also rising quickly. Meanwhile, some indirect and direct pollution from the construction materials production and transportation and the operation of tap water treatment plants should be emphasized under the background of energy-saving and emissions-reduction of this country. All these related resources and environmental issues have been challenging the sustainable development of tap water supply industry, and could further affect the sustainable economic growth of China in the future.

In recent years, the growing demand of resources and energy and the increasingly serious environmental challenges, derived from water supply, have attracted many scholars' interests, and many works have been done to investigate these complex issues from different angles, such as the water-energy nexus (Arent et al., 2014; Santhosh et al., 2014; Okadera et al., 2015; Cherchi et al., 2015; Lubega and Farid, 2014; Gilron, 2014; Vilanova and Balestieri, 2015), the interactions between water supply, population and economy (Barbier and Chaudhry, 2014), the relationships between water supply, energy and environment (Sanjuan-Delmáset al., 2015), the relationships between water supply, economy, energy and environment (Kajenthira et al., 2012; Jung et al., 2014), relationships between water supply and environment (Lattemann and Höpner, 2008), life cycle assessment of water supply scenarios (Bhakar et al., 2015; Lyons et al., 2009; Stokes et al., 2013; Xu et al., 2015), the relationships between water supply and economy (Frone and Frone, 2014), footprint analysis of water supply systems (Wackernagel and Rees, 1996; Wiedmann and Minx, 2008; Zeng et al., 2012), etc. Meanwhile, some researchers have explored how to improve the comprehensive performances of water supply systems, including the water supply availability and energy efficiency (Xu et al., 2015; Tatietse et al., 2000), the energy consumption and energy efficiency (Bolognesi et al., 2014; Cheung et al., 2013), the treatment efficiencies of different purification technologies (Kunikane

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et al., 1995), the interactions between technological developments and new energy sources (Liang and Zhang, 2011), the co-benefits between water and energy saving actions (Bartos and Chester, 2014), water and energy efficiencies (Jiménez-Bello et al., 2015), etc. However, these researches have the following defects, including (1) the isolated perspectives. They only concentrate one or several aspects on the interactions between water supply systems, resources & environment and economy, and this can lead to unilateral conclusions. (2) Ignorance of natural contribution to economic activities. This is not beneficial for resources-saving and environmental protection. (3) Existence of subjectivity to some degree. Some subjective integration methods (such as Weighting and Sorting Method, Analytic Hierarchy Process etc.) are adopted, and then the subjectivity could be introduced in the final conclusions. (4) Neglect of the quality differences between different categories of resources and/or energy sources. This could make the research results deviating from the reality to some degree. In summary, these works cannot represent a holistic picture when discussing ecological sustainability on larger time and spatial scales (Björklund et al., 2001; Zhanget al., 2014). Compared to the aforementioned methods, the emergy analysis (EmA), founded by Odum (Odum, 1988; 1996), can overcome these shortcomings. As a systematic method (Brown and Ulgiati, 2004), EmA incorporates environmental services and human inputs into a common unit of nonmonetary measure (solar energy equivalent joule, sej) through unit emergy values (UEVs); meanwhile, these coefficients can also make differences among different types of inputs. Therefore, this method can evaluate all kinds of natural, artificial and compound systems objectively. With a universal measure of different kinds of resources and energy and money flows, the resource efficiency, environmental impact, sustainability level can be clearly described by a series of emergy-based ratios and indicators, and then the comprehensive performance of the concerned system can be evaluated fully. So it can provide policy-makers with more comprehensive and objective information.

So far, many scholars have also carried out emergy evaluation of water supply systems. Wu and Lv (2009) and Luo et al. (2011) assessed the benefit sharing coefficient of industrial water supply (the ratio of industrial water supply emergy to total industrial production input emergy); Guo et al. (2011) calculated water price of the domestic water based on emergy; Rugani et al. (2011) compared the environmental cost and benefit of the maintenance between a historical Bottini water supply system and a contemporary one in Siena using EmA; Chen et al. (2011) implemented an emergy evaluation of an irrigation improvement project proposed in China; Chen and Chen (2009) carried out an emergy evaluation of the Yellow River basin, and Chen et al. (2014) investigated the contribution of irrigation water and its utilization in three agricultural systems in China using emergy approach. However, these works ignored emissions' impact during the production phrases of raw materials and energy and the operation stage of the water supply systems. Brown and Ulgiati (2010) propose that the emergy value of water resources should be estimated using the sustainability criteria established by European norms in regards to water management; Fonseca et al. (2017) assessed the sustainability levels of water systems through the geo-informatics tool with an emergy accounting approach in order to achieve an integrated management of water resources; Andres (2001) carried out the comparison of the tap water's UEVs of three kinds of water production systems with different water sources in Florida. However, they ignored the related emissions' impact. In recent years, emissions' impacts have been quantified in terms of emergy by some scholars (Vassalloet al., 2009; Chen et al., 2009; Zhou et al., 2009; Arias and Brown, 2009; Zhang et al., 2010; Zhanget al., 2014; Winfrey and Tilley, 2016). In order to fully assess the comprehensive performance of water supply systems, they should be investigated through an improved EmA, which can integrate the related emissions' impacts into the corresponding performance indicators.

This paper aims to evaluate the sustainability level of tap water treatment systems using an improved EmA and the related indicator system through integrating the emissions' impacts. A tap water treatment plant in Jiangyin city of Jiangsu, China, as a case study, was investigated using the proposed methods and indicator system. Its contribution lies in (1) setting up a proper emergy method and the related indicator system for evaluating the performances of water supply systems, (2) providing the unit emergy value of tap water for Chinese emergy related scholars due to few works implemented on this aspect, and (3) giving the corresponding suggestions for the policy-maker of this enterprise.

2. Materials and methods

2.1. Materials

The tap water treatment plant investigated is located in Jiangyin city, located in southern Jiangsu Province, China. This city lies between longitudes 119°59′E -120°34′30″E and between latitudes 31°40′34″N -31°57′36″N, and it belongs to humid north subtropical monsoon climate, with an annual average temperature of 16.7 °C, an annual average precipitation of 1084.1 mm and an annual average wind speed of 2.8 m/s (Available site: http://wenku.baidu.com/view/fdd50645336c1eb91a375dab.html). It covers an area of 986.97 km^2, of which the land area is 811.7 km^2 and the water area is 175.8 km^2, consisting of a downtown and four suburb districts, i.e. the central urban district, Jinagyin east district, Jiangyin west district, Jiangyin southeast district and Jiangyin south district. Its gross domestic product was 46.24 billion US$ in 2015.

The raw water of this water treatment plant comes from the Yangtze River, whose water quality is given in Table 1. It has the total amount of tap water supply of about $1 \times 10^5 m^3/d$, and its investment & operation cost was 3.02E06 US$ per year. It adopts the technology of "Aeration sedimentation + Filtration + Disinfection", composed of "mechanical mixing + folded plate flocculating advection sedimentation tank + V filter" (Fig. 1). The outflow can satisfy the standard for drinking water quality (GB5749-2006). Sludge water from setting tank and dewatered sludge treatment is also treated, as shown in Fig. 2. Dewatered sludge is sent to the local landfill plant. The quantity of pollutants eliminated per year can be estimated, as shown in Table 1. The treatment technology adopted by this plant is the most widely used one in the field of tap water treatment in China. That is to say, the case study investigated can stand for the general technical level of China's tap water plants.

Table 1
The raw water quality, the drinking water quality standard, and the quantity of pollutants eliminated per year for the tap water treatment plant investigated.

Item	Fe (mg/L)	Mn (mg/L)	Al (mg/L)	Petroleum (mg/L)	Total coliform bacteria (mpn/100 mL)	Fecal coliform (mpn/100 mL)	Total number of bacteria (cfu/100 mL)
Influent concentrations	0.76	0.13	0.708	1.61	1238	649	8696
Effluent concentrations[a]	0.30	0.10	0.200	0.05	0	0	100
The quantity of pollutants eliminated (g/a)	1.68E07	0.11E07	1.85E07	5.69E07	–	–	–

[a] Effluent concentrations are considered as the indicator values in the standard for drinking water quality (GB5749-2006). Available site: http://www.moh.gov.cn/zwgkzt/pgw/201212/33644.shtml (accessed 10/10/2016, in Chinese).