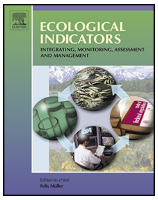
Ecological Indicators 60 (2016) 402–409

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Quantification of the water, energy and carbon footprints of wastewater treatment plants in China considering a water–energy nexus perspective

Yifan Gu[a,1], Ya-nan Dong[b,1], Hongtao Wang[a], Arturo Keller[c], Jin Xu[b], Thomas Chiramba[d], Fengting Li[a,*]

[a] State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, Shanghai 200092, China
[b] College of Environmental Science and Engineering, Tongji University, Shanghai 200092, China
[c] Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, United States
[d] United Nations Environment Programme (UNEP), Nairobi, Kenya

ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form 9 July 2015
Accepted 11 July 2015

Keywords:
Wastewater treatment plants
Water footprint compensation
Energy intensity
Carbon emission
Environment impacts

ABSTRACT

Water and energy are closely connected and both are very important for human development. Wastewater treatment plants (WWTPs) are central to water–energy interactions as they consume energy to remove pollutants and thus reduce the human gray water footprint on the natural water environment. In this work, we quantified energy consumption in 9 different WWTPs in south China, with different treatment processes, objects, and capacities. The energy intensity in most of these WWTPs is in the range of 0.4–0.5 kWh/m^3 in 2014. Footprint methodologies were used in this paper to provide insight into the environmental changes that result from WWTPs. A new indicator "gray water footprint reduction" is proposed based on the notion of gray water footprint to better assess the role of WWTPs in reducing human impacts on water resources. We find that higher capacity and appropriate technology of the WWTPs will result in higher gray water footprint reduction. On average, 6.78 m^3 gray water footprint is reduced when 1 m^3 domestic sewage is treated in WWTPs in China. 13.38 L freshwater are required to produce the 0.4 kWh electrical input needed for treating 1 m^3 domestic wastewater, and 0.23 kg CO_2 is emitted during this process. The wastewater characteristics, treatment technologies as well as management systems have a major impact on the efficiency of energy utilization in reducing gray water footprint via these WWTPs. The additional climate impact associated with wastewater treatment should be considered in China due to the enormous annual wastewater discharge. Policy suggestions are provided based on results in this work and the features of China's energy and water distribution.

1. Introduction

As driving forces and limiting factors for sustainable development, water and energy are key resources for global production and life (Dincer, 2002; Gleick, 1994; Walker et al., 2013). The nexus between water and energy pervades modern economies. These two inextricably intertwined fundamental resources have become a fascinating topic (Hellegers et al., 2008; Jägerskog et al., 2014; Kenway et al., 2011; Perrone et al., 2011; Scott et al., 2011; U.S. Department of Energy, 2014; Water in the west, 2013). Water supply, consumption, transportation and wastewater treatment require various forms of energy (Lazarova et al., 2012; Stokes and Horvath, 2006, 2009), while almost every stage in the energy supply chain needs water (Blackhurst et al., 2010; Dominguez-Faus et al., 2009; Gerbens-Leenes et al., 2009; International Energy Agency, 2012; Rio Carrillo and Frei, 2009). The energy sector is the second largest water user in the world in terms of withdrawals, following irrigation (Hightower and Pierce, 2008). For example, water used in thermoelectric power generation accounted for nearly 49% of total fresh water withdrawals in the United States (Scown et al., 2011). In addition, some large water transfer projects, such as China's South-to-North water diversion project, need enormous energy supply. The water–energy nexus has increasingly become prominent in domestic and international policy discourse and prompted a number of studies to explore managing the

---

* Corresponding author. Tel.: +86 21 65980567.
E-mail address: fengting@tongji.edu.cn (F. Li).

[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.ecolind.2015.07.012
1470-160X/

links between energy and water for a sustainable future (Hardy et al., 2012; Kahrl and Roland-Holst, 2008; Kenney and Wilkinson, 2011; Lofman et al., 2002; Malik, 2002; Siddiqi and Anadon, 2011).

Wastewater treatment plants (WWTP) are a typical case of water–energy interactions. In the WWTP, water quality is improved at the cost of energy consumption. The emission of greenhouse gases from respiration and power consumption in WWTP has caused wide concern (Gori et al., 2011; Stokes and Horvath, 2009). Schnoor pointed out that probably the greatest water story of the 21st century is to treat wastewater through membranes and reverse osmosis for drinking water supplies with significant energy consumption (Schnoor, 2011). In developed countries, wastewater treatment accounts for about 3% of the electrical energy load (Curtis, 2010). It was reported that the high energy costs for wastewater treatment due to aeration requirement in the U.S. cannot be borne by developing countries (Liu et al., 2004). Therefore, the water–energy nexus in wastewater treatment needs further study.

Assessing humanity's "environmental footprint" is one way of reflecting the total human pressure on the planet (Hoekstra and Wiedmann, 2014). Water footprint (WF) (Hoekstra et al., 2011) and energy footprint (EnF) (Wiedmann, 2009) refer to the total freshwater and energy directly and indirectly required to produce a commodity or service. The Water Footprint Network uses energy water footprint to link energy with water, which makes it possible to assess the virtual water consumption through the usage of energy (Hoekstra et al., 2011; Gu et al., 2014b). As a reflection of growing concerns about the increasing pressures of energy and water consumption, there have been an increasing number of studies aimed to systematically quantify the energy–water nexus by using water footprint tool, such as water footprint of biofuels (Dominguez-Faus et al., 2009); bioenergy (Gerbens-Leenes et al., 2009); bio-ethanol (Gerbens-Leenes and Hoekstra, 2012); nonfood biomass fuel (Zhang et al., 2014); and electricity from hydropower (Mekonnen and Hoekstra, 2012). These studies are meaningful and helpful to understand the water–energy nexus and guide policy making. However, there are few studies on the water–energy nexus in WWTPs from the water footprint point of view. The energy used in wastewater treatment also consumes some direct and indirect water withdrawals and results in wastewater discharge. Research by Shao and Chen, 2013 shows that the water footprint of electricity accounts for 57% of the total water footprint for a medium scale WWTP in Beijing, China. These links between water embodied in energy use are considerable but usually not included to assess the efficiency of WWTPs.

In this study, we evaluate the water–energy nexus in WWTPs in south China considering their water and energy footprints to reduce their environmental impacts. We investigate 9 different WWTPs in south China with different treatment techniques, sources (domestic/industrial wastewater) and treatment capacities in 2014. We quantify energy consumption and the virtual water embodied in energy consumed by these WWTPs. A new indicator "gray water footprint reduction" is proposed based on the notion of gray water footprint (GWF) (Hoekstra et al., 2011) to better assess the role of WWTPs in reducing human impacts on water resources. Thus, this study also contributes to the development of footprint methodologies. Our aims are (1) to quantify the water–energy nexus in WWTPs by accounting for the freshwater, energy and carbon footprints as they seek to reduce the GWF; (2) to assess the efficiency of the energy utilization of WWTPs in reducing the GWF; (3) to understand how WWTPs interact with the hydrologic cycle, energy resources and climate; and (4) to make policy suggestions for future WWTP construction in consideration of the energy–water implications.

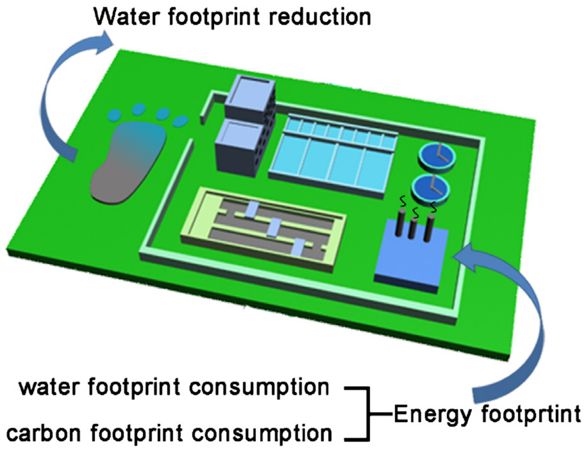


Fig. 1. Input and output footprints of a WWTP.

2. Materials and methods

2.1. *Water footprint compensation and energy efficiency assessment model*

Fig. 1 shows the connections between various footprints of a WWTP based on the water–energy nexus. Every stage in the WWTP needs energy input, such as wastewater collection, physical treatment, chemical treatment, sludge treatment, and discharge. In most WWTPs, electricity is used as the only energy source for pumping and carrying wastewater through pipes, as well as operating most of the equipment. Electricity production needs water withdrawals and causes CO_2 emissions. Thus, there are both WF and carbon footprint (CF) (Wiedmann and Minx, 2008) behind the EnF input, based on a life cycle analysis. GWF refers to pollution and is defined as the volume of freshwater that would be required to dilute the pollutants to meet given natural background concentrations and existing water quality standards (Hoekstra et al., 2011). It assumes that dilution is the only treatment, although in almost all cases this is not the case. The GWF of the region can be reduced via the WWTP, reducing the impact on the environment. Treated WWTP effluent can also be reused for irrigation, industrial purposes, drinking and many other activities, reducing blue water footprint (i.e. groundwater and surface water consumption) to realize water footprint compensation. However, there are trade-offs in water footprint reduction since it can increase EnF and CF.

GWF is a useful metric for comparing effluent water quality when there are multiple pollutants at different concentrations and perhaps different water quality standards due to the sensitive nature of some water bodies in water footprint assessment. Although it refers to a hypothetical dilution volume, GWF is important in the assessment of environmental effects on a water resource. In the existing water footprint methodologies, wastewater treatment can reduce the GWF down to zero when the concentrations of pollutants in the treated effluent are equal to or lower than the water quality standards or the concentrations from the water source (Hoekstra et al., 2011). However, to better reflect the role of WWTPs in reducing the impact on human activities on water resources, a new indicator "water footprint reduction" (ΔGWF) is proposed here. The ΔGWF (in m^3 of freshwater) of a WWTP for a specific period of time is defined as follows:

$$\Delta GWF = MIN\left[\frac{Q_i - B_i}{B_i}\right] \times V$$

where Q_i are the concentrations of main pollutants in the WWTP influent (in mass/volume); B_i are the concentrations of main pollutants i after treatment (in mass/volume) and V is the wastewater