Sustainable Cities and Society 23 (2016) 37–49

Contents lists available at ScienceDirect

Sustainable Cities and Society

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

Complementary life cycle assessment of wastewater treatment plants: An integrated approach to comprehensive upstream and downstream impact assessments and its extension to building-level wastewater generation

Marc Morrison*, Ravi S. Srinivasan, Robert Ries

M.E. Rinker, Sr. School of Building Construction Management, College of Design, Construction and Planning, University of Florida, Gainesville, FL, USA

ARTICLE INFO

Article history:
Received 17 March 2015
Received in revised form
11 November 2015
Accepted 18 February 2016
Available online 22 February 2016

Keywords:
Wastewater treatment plant
Wastewater management
Life cycle assessment
EIO-LCA
Eco-LCA
Emergy

ABSTRACT

Typical life cycle assessment (LCA) studies of Wastewater Treatment Plants (WWTP) too often focus exclusively on either upstream or downstream impacts while failing to connect this to a scale appropriate for integration in building assessments. A solution to this problem would offer a framework of tools to map the full scope of WWTP impacts, both upstream and downstream, in an integrated manner yet can be valid on an individual building level. This will allow for the capture of an aspect of the building use phase that is often neglected in the assessment process. The integrated approach discussed in this paper is unique in that it uses existing LCA methods to evaluate upstream and downstream impacts in a novel and complementary fashion. Upstream impacts are determined using three methods, namely: Economic Input–Output LCA (EIO-LCA), Ecologically-based LCA (Eco-LCA), and emergy analysis. Downstream impacts are captured through the application of U.S. Environmental Protection Agency calculations and a process-based method for land application of sludge waste products. Furthermore, this paper discusses the results that were extended to assess wastewater impacts on the scale of a specific building to complete the impact assessment from a previous study by the authors (Srinivasan et al. (2014). *Building and Environment, 79*, 151). The goal of this work is to develop a method to account for the upstream and downstream life cycle impacts of wastewater treatment at the plant and individual building level.

1. Background

Wastewater treatment has become a standard practice in developed nations and a key aspiration of developing countries. Not only does wastewater treatment assure the continued utility of ecosystems, water scarcity makes it a pragmatic necessity. It has been found that low stream flow conditions can lead to de-facto wastewater reuse rates in drinking water treatment plants of up to 20% (Rice, Wutich, & Westerhoff, 2013). This demonstrates why the effective treatment of wastewater is such a necessity. The steps used in the wastewater treatment process often differ from plant to plant based on water composition or plant location but they are composed of 6 steps; pre-treatment (physical process), primary treatment (physical and mechanical treatment), secondary treatment (biological treatment under aerobic-anaerobic-anoxic conditions), tertiary treatment (physical/chemical), sludge treatment, and sludge disposal (UNEP, 2016). These steps accelerate the natural processes by which water is purified. The primary types Wastewater Treatment Plants (WWTPs) can be roughly divided into two categories: biological and physical/chemical WWTPs. Biological WWTPs are the preferred type. Physical/chemical plants have many variations in design but this is typically manifested in the different kinds of chemicals they choose for coagulation, flocculation, and sedimentation of wastewater for physical removal. These systems are cheaper than their biological counterparts because they rely physical processes such as sedimentation and filtration.

Urban planners attempt to pinpoint the impact of built environments on natural environments in order to mitigate the detrimental effects seen with rapid urban growth. A tool in this paradigm is the life cycle assessment (LCA), which evaluates the impact of a defined system on the environment. Life cycle assessments of WWTPs gauge their impacts on a range of environmental issues. LCAs analyze the environmental implications of product systems and services, where emissions and resource inputs during production, distribution, use, and disposal of a product are the scope of the assessment (Odum, 1996). Due to increased oversight, WWTPs

* Corresponding author. Tel.: +1 954 839 0960; fax: +1 352 392 9606.
E-mail address: Morrma@ufl.edu (M. Morrison).

http://dx.doi.org/10.1016/j.scs.2016.02.013
2210-6707/

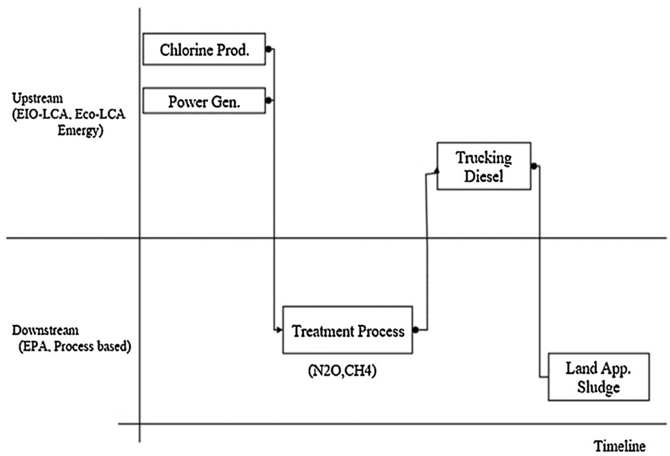

Fig. 1. Timeline graph showing WWTP's upstream and downstream impacts.

and other pollution control facilities are regulated and required to produce effluent within particular parameters and therefore monitor flow and emission data throughout operation periods, closing many data gaps that can occur in other types of facilities (Yoshida, Clavreul, Scheutz, & Christensen, 2014).

2. Theory

Different life cycle inventory methods can be employed for assessing WWTPs including process- and economic sector-based approaches. Two sector-based approaches are Economic Input–Output (EIO-LCA) (Yoshida et al., 2014) and Ecological-based LCA (Eco-LCA) (OSU, 2009–2012). These methods focus on the upstream emissions in the provision of a good or service, but EIO-LCA does not include the external (solar) energy in these products and services. A method that incorporates estimates of the solar energy embodied in goods and services is known as emergy analysis (Odum, 1996). Besides these LCA methods, emissions due to treatment process can be estimated using US Environmental Protection Agency (US EPA) Methodology, and transportation related to sludge for land application using emergy analysis. Furthermore, these LCA methods can be broadly classified based on the context of time when such impacts to the environment occur in the life cycle of WWTPs, i.e., (a) upstream and (b) downstream impacts. This can be better explained using a timeline graph that shows the upstream and downstream impacts of a case study WWTP at the University of Florida (UF) campus, Fig. 1. Upstream impacts are considered chlorine production, power generation, and trucking operation. Downstream impacts include the treatment process and off gassing from treatment waste products.

In the life cycle of this WWTP, the wastewater undergoes pre-treatment where machines either separate out or grind any debris or grease in the wastewater. This debris is then deposited in a dumpster and trucks are later used to haul this solid waste to a landfill. Return activated sludge is then pumped and mechanically mixed with the wastewater; electricity is used in this process for the pumping sludge, powering the mixing equipment, and operating the plant control systems. The wastewater moves into anaerobic tanks where it is retained and subjected to changes in oxygen level allowing for the dilution and digestion of the inherent nitrogen and phosphorous in the wastewater via microorganisms. Wastewater then goes through a process of filtration, where sludge is separated out and returned to the anaerobic digester or wasted from the system for dewatering and subsequent land application. This effluent water is considered treated but it must go through tertiary disinfection treatment before it reaches discharge standards. This disinfection process is done through the addition of liquid chlorine that diffuses through the water killing most virulent and bacterial organisms. Only after wastewater has gone through all these steps is it deemed acceptable for injection into groundwater wells or for use in landscape irrigation. In this example, the upstream impacts can be assessed by EIO-LCA, Eco-LCA, and emergy methods, while the downstream impacts can be assessed using US EPA methodology for Greenhouse Gas (GHG) emissions and emergy methods.

Although several works of research exist in assessing WWTPs, a complementary approach using existing methods to estimate the total environmental impact, simultaneously upstream and downstream, is largely missing. Prior to the discussion of this complementary approach, a literature review of the LCA methods and their application to WWTPs is discussed in this section. While LCA methods organized using upstream and downstream impacts are discussed in the following Section 2.1, the subsequent Section 2.2 provides a detailed literature review of existing work in LCAs of WWTPs.

2.1. LCA methods used for assessing upstream and downstream impacts

2.1.1. Upstream impacts

2.1.1.1. EIO-LCA. EIO-LCA calculates the material and energy resources used for the production of a product or provision of a service and estimates the environmental impact of the related emissions (CMUGDI, 2008). This is done through analysis of inter-industry activity rates related to the provision of a product or service, addressing traditional shortfalls of process based LCA which often neglect this complex aspect of inventory modeling. Inter-industry monetary transactions along with pollution discharge and nonrenewable resource consumption data from industry sectors allow the emissions resulting from the interaction of system components to be determined (Hendricksen, Horvath, & Joshi, 1997).

2.1.1.2. Eco-LCA [Chlorine production, power generation, and trucking operation]. Eco-LCA aims to give a comprehensive description of a system in relation to the ecosystem services and embodied energy needed to form the raw input materials. Eco-LCA integrates thermodynamics, economic valuation through the use of EIO-LCA as a foundation, and aspects of other conventional life cycle assessment methods (Zhang, Singh, & Bakshi, 2010). Data is aggregated based on three thermodynamic schemes, i.e., Energy, I Energy, I + E Exergy, Energy in this method includes renewable and non-renewable energetic sources including fossil fuels, sunlight and wind; I Energy is the Industrial Cumulative Exergy Consumption including material and energy resources extracted from nature and consumed in industrial activities; and I + E Exergy is Ecological Cumulative Exergy Consumption which extends I Exergy by also accounting for the exergy consumed within ecosystems (RTI EPA, 2010).

2.1.1.3. Emergy analysis. Emergy analysis is a means of assessing the amount of work by nature as well as humans in the production of a product or provision of a service. In this way the method is able to represent both the environmental and economic values in a standardized unit of measure (Odum, 1996). This analysis can be applied at various scales ranging from specific locations such as a forest to entire regions or countries.

2.1.2. Downstream impacts

2.1.2.1. US EPA greenhouse gas emission estimation. The equations used in the estimation of CH_4, N_2O, and CO_2 are from the 2010 EPA publication "Greenhouse Gas Emissions Estimation Methodologies for Biogenic Emissions from Selected Source Categories: