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Energy and GHG accounting for wastewater infrastructure

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ABSTRACT

Ensuring water and energy security and lowering the emissions of Greenhouse Gases (GHGs) are now priority areas for urban planners. However, most studies considered different components of urban wastewater infrastructure in isolation. This paper calculates the total energy and GHG footprints of wastewater infrastructure, including the energy consumption of, and GHG emissions from, the transport and treatment of wastewater, taking Delhi as a case study. The net energy consumed by wastewater infrastructure was conservatively estimated at 0.26 kWh/m^3 ($\sigma = 0.101$ kWh/m^3). Operating the infrastructure claimed 70% of the total energy, and electricity accounted for about 55% of the total energy. Nearly two-third of the total energy was used for treating the wastewater. The infrastructure for transporting wastewater claimed a greater share of the embodied energy of materials. Net GHG emissions from the wastewater infrastructure were estimated at 1.426 kg CO_2-eq/m^3 ($\sigma = 0.41$ kg CO_2-eq/m^3). Fugitive emissions contributed 53% of the total daily GHG emissions. The study revealed a trade-off between energy savings and environmental and GHG implications of wastewater infrastructure. Unlined open drains had lower GHG emissions and negligible energy use but an adverse impact on the environment and public health. Decentralized wastewater infrastructure is energy efficient in terms of the amount of pollutants removed but consumes more energy per unit volume of wastewater treated. Producing energy from the biogas generated in the process lowered the energy and GHG footprints of wastewater infrastructure by 0.10 kWh/m^3 ($\sigma = 0.01$ kWh/m^3) and 0.08 kg CO_2-eq/m^3 ($\sigma = 0.01$ kg CO_2-eq/m^3) respectively.

1. Introduction

Ensuring water and energy security and lowering GHG emissions are important items on the planning agenda of city governments today. There is also growing understanding that the Water–Energy–Carbon (WEC) are interlinked as is evident from the large number of research papers published on the topic in the last five years (Hospido et al., 2008; Préndez and Lara-González, 2008; Foley et al., 2010; Siddiqi and Anadon, 2011; Strokes and Horvath, 2010; Plappally and Lienhard, 2012; Ventkatesh et al., 2014; Cornejo et al., 2013; Lorenzo-Toja et al., 2015; Wang et al., 2015). This interest is also linked to the recognition of the fact that cities consume huge amounts of energy to pump water and to treat wastewater (Plappally and Lienhard, 2012; Rothausen and Conway, 2011). The Urban Water Chain (UWC) has become energy intensive and more traditional sector-specific planning needs to be replaced with integrated multi-sectoral planning.

Earlier studies on the WEC nexus have used various approaches that differ in terms of boundary conditions, the scope of analysis, and methodology. For example, Plappally and Lienhard (2012) and Nair et al. (2014), attempted a meta-analysis of published

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Abbreviations: ASP, activated sludge process; BIOFOR, attached growth biological filtration; BOD, biological oxygen demand; CF, conversion factor; CEA, central electricity authority; CSE, centre of science and environment; CPHEEO, central public health and environment engineering organization; CH_4, methane emission; CO_2, carbon emission; DJB, Delhi Jal Board; EA, extended aeration; E_1, electrical energy; E_d, diesel energy; E_{mt}, embodied energy of construction material; E_{ch}, embodied energy of chemicals; FBR, fluidized bed reactor; G_eGHG, emission from use of electricity; G_dGHG, emission from use of diesel; G_{mt}, emissions embodied in construction materials; G_{ch}, emissions embodied in chemicals; GHG, greenhouse gas; GNCTD, Government of National Capital Territory of Delhi; Gg CO_2-e/day, giga gram carbon dioxide equivalent per day; ISBR, improved sequential batch reactor; IPCC, international panel of climate change; JJ, jhuggi jhopri; kg CO_2-e/m^3, kilogram carbon dioxide equivalent per cubic meter; kg CO_2/kWh, kilogram of carbon dioxide per kilowatt hour energy; kWh/L, kilo watt hour per litre; L/m^3, litre per cubic meter; MLD, million litres per day; MBR, membrane bioreactor; MW, mega watt; MWh/day, megawatt hour per day; NCT, National Capital Territory; N_2O, nitrous oxide emission; OP, oxidation pond; RBD, rate of BOD degradation; R^2, coefficient of co-relation; $\boldsymbol{\sigma}$, standard deviation; SBR, sequential batch reactor; USEPA, United States Environmental Protection Agency; UWC, urban water chain; WWTP, wastewater treatment plant; WWPS, wastewater pumping station; WEC, water-energy-carbon.

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data on the WEC nexus and presented a comprehensive analysis of energy consumption of different components of the UWC, although they limited their analysis only to electrical energy and excluded all other sources of energy including diesel, labour, and resource recovered (biogas). They also excluded carbon and fugitive emissions from the purview of their study. Risch et al. (2015), used Life Cycle Analysis (LCA) of an urban water system to quantify the environmental impact of sewers on the entire system, and Loubet et al. (2014), reviewed 18 LCA case studies to recommend different ways of assessing the environmental impact of urban water systems. Also, Zhang et al. (2010), demonstrated the use of process-based and input–output based LCA in reducing the discharge of secondary effluent. Strokes and Horvath (2010), estimated energy consumption of, and GHG emissions from, the collection, treatment, and discharge of wastewater and also looked into the options to offset energy consumption. Tran et al. (2015), pronounced biogas recovery for production of electricity to offset energy footprint of wastewater infrastrucrture and Hoek et al. (2016), explained such methods for recovery of biogas from sludge. Garcia et al. (2011), estimated the electricity consumption (for operations) of the oxidation ditch process, Activated Sludge Process (ASP), and ASP with lime stabilization. Venkatesh and Brattebø (2011), considered the water and wastewater system (operation and maintenance) to estimate the consumption of electricity and heat. A few studies, such as those by Shahabadi et al. (2010), Siddiqi and Anadon (2011) and Hospido et al. (2008), emphasized the importance of systems analysis for the WEC nexus in their study of carbon emissions. Different models and tools were used in the above-mentioned studies to estimate the energy footprint and GHG emissions from wastewater processing, and the estimates arrived at have also varied, depending on other factors such as the technology used and topography.

The studies reported in the literature have considered various components of the UWC as individual entities to report the energy and carbon footprints of each but have ignored the UWC as a single systems to establish the WEC nexus, which can provide useful information for planning low-carbon and less energy-intensive urban infrastructure. This paper presents the WEC nexus with reference to wastewater infrastructure of a city, includes wastewater transport and treatment, and takes into account the energy consumption and carbon emissions of the materials used in constructing the infrastructure and in its operation. The paper also estimates the contribution of fugitive GHG emissions to total emissions from the system. The data are analysed separately for various regions within a city and for centralized and decentralized systems to understand the factors that influence energy use and GHG emissions.

2. Description of the study area

The region selected for the study is National Capital Territory (NCT) of Delhi, which is located at foothills of Aravalli ranges in India. It has both rural and urban populated areas, variety of economic activities such as agriculture (in peri-urban areas), industrial/service sector, and has distinct variation in provisioning of wastewater infrastructure in various locations of the city. Therefore, it presents an excellent case to capture the influence of various factors on WEC nexus. Wastewater infrastructure of the NCT is managed by Delhi Jal Board (DJB; *jal* means water in *Hindi* and *Sanskrit*), which is an autonomous department of the Government of Delhi. NCT is divided into 12 drainage zones with 35 Wastewater Treatment Plants (WWTPs) (Table 1) (SI 1, Supplementary information), 105 Wastewater Pumping Stations (WWPS), and 13 Common Effluent Treatment Plants. The boundaries of drainage zones are not based on topography; the zones are essentially administrative units. Two drainage zones are new, and work related to transport and treatment infrastructure in these two is yet to be completed.

Table 1
Characteristics of drainage zones in Delhi (DJB, 2014).

Drainage zone	Area (km^2)	Population (million)	Land use	Cumulative discharge in open drains[a] (m^3/day)	No. of WWPS	Total sewer length (km)	Range of sewer diameter (mm)	No. of functional WWTPs	Wastewater generated within the zone (MLD)	Wastewater treatment capacity (MLD)	Actual wastewater treated (MLD)	Treatment method
Shahdara	90.38	3.8	Domestic + Industrial	606 062.2	37	1059	325–1275	9	416	454	343	ASP, FBR, ISBR
Okhla	204.74	3.0	Domestic + Industrial	1 249 359.9	23	1730	250–1600	8	519	665	567	ASP,PC
Keshopur	115.37	2.2	Domestic	–	13	1534	125–1100	3	235	273	235	ASP
Rohini-Rithala	127.80	1.7	Domestic	199 320.5	16	875	125–825	2	360	360	151	ASP,BIOFOR
Coronation Pillar	63.24	1.1	Domestic	414 543.7	9	545	800–1500	3	208	174	47	ASP, OP
Dwarka	61.12	0.8	Domestic	–	1	150	350–750	1	144	76	61	ASP
Najafgarh	263.66	1.4	Domestic	797 282.0	1	313	250–750	1	163	19	6	EA
Nilothi	64.13	1.2	Domestic + Industrial	597 961.5	1	350	250–750	2	170	151	57	ASP, MBR
Narela	120.84	0.6	Domestic	–	1	250	250–750	1	98	57	15	ASP
South Delhi	75.84	0.6	Domestic	–	3	400	325–1100	4	87	58	38	EA, SBR
Outer South Delhi	101.36	0.6	Domestic	–	Work in progress							–
Kanjhwala-Bawana	194.52	0.9	Domestic	–	– do –							–

ASP, activated sludge process; BIOFOR, attached growth biological filtration; EA, extended aeration; ISBR, improved sequential batch reactor; FBR,Fluidized bed reactor; PC, physico-chemical along with attached growth trickling filter; SBR, sequential batch reactor; OP, oxidation pond; MBR, membrane bioreactor.

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