Energ. Ecol. Environ. (2018) 3(1):48–68
https://doi.org/10.1007/s40974-017-0066-7

ORIGINAL ARTICLE

Life-cycle atmospheric emissions and energy use of the collection phase of a typical Indian sewerage system

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Received: 1 January 2017 / Revised: 5 March 2017 / Accepted: 13 April 2017 / Published online: 18 July 2017

Abstract Considerable number of Indian and international studies has focused on the environmental implications of sewage treatment plants. However, not many studies have taken up a comprehensive assessment of the collection phase of the Indian sewage systems. The aim of the present study is to carry out an integrated life-cycle assessment for the collection phase of an Indian wastewater treatment system. The paper develops in the form of a case study for Begusarai sewerage project and attempts to estimate life-cycle air pollution, greenhouse gas emissions and energy consumption for the collection phase of the project. The work consists of developing a life-cycle inventory for pipelines, manholes, pumps and transportation facilities in a typical collection phase, by making use of existing activity data and emission factors from secondary literature (see graphical abstract). Further, the normalized factors for different environmental damage categories are incorporated within the developed inventory to estimate overall life-cycle damage. Initially, the major components for each damage category are identified. For instance, side walls of manholes are major contributors towards $PM_{2.5}$ emissions while pumping stations are major energy consumers and CO_2 emitters. High resource consumption is identified as the major damage category, compared to atmospheric emissions. As larger quantities of water need to be treated owing to increasing water use in the country, a discussion on water–energy nexus is required to estimate the implications of sewage systems.

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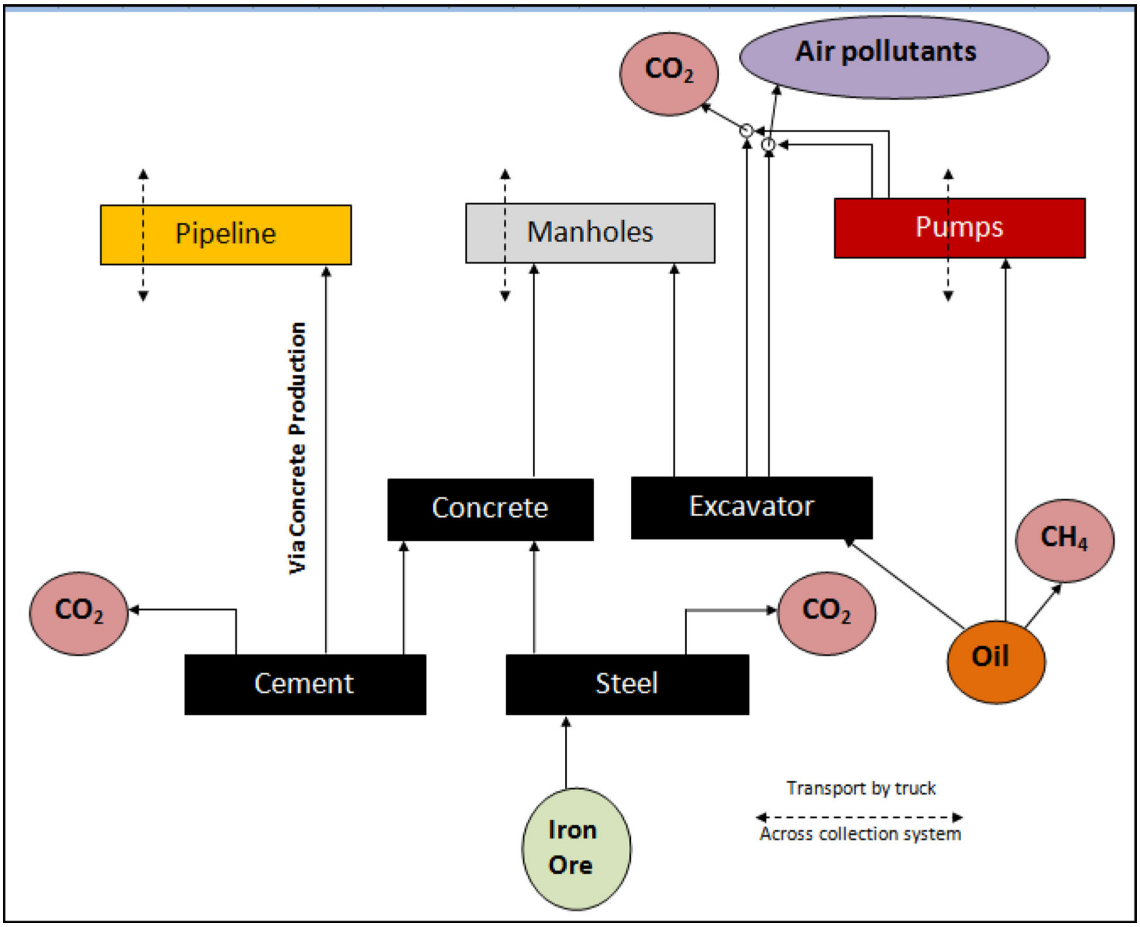
Graphical Abstract



1 Introduction

1.1 Context

India is the second most populous country in the world with an estimated population of 1.32 billion. Various models project the population rise to 1.5–2.5 billion by 2050 (Sathaye and Shukla 2013). Recent population dynamics have seen a strong urbanization trend, with urban population registering a growth of 32.2% during the past decade (CPCB 2013). The all-India water requirement for the year 2010 was 813 BCM of which ~85% is used for irrigation purposes. However, due to urban expansion and development of the economy, higher amounts of water are anticipated to be consumed by the industry (increment of five times during 2010–2050) and energy sector (increment of 26 times during the said period; CPCB 2009). Also, the domestic demand is expected to increase by 40%, i.e. from 41 to 55 BCM (KPMG 2010). Domestic wastewater from urban areas is also likely to increase to the tune of 132,253 MLD by 2051, resulting in high sewage generation (Kapshe et al. 2013).

Table 1 lists the wastewater generation projections from 2009 to 2051 by various sources. The increasing magnitude of sewage generation poses problems in its disposal and treatment. Due to the environmental concerns (air, land and water pollution), the sewage generated is subjected to various treatment facilities via sewage treatment plants (STPs). The entire chain of sewage treatment involves substantial energy usage and atmospheric emissions. The collection of wastewater, for instance, requires fuel oil for excavation for manholes, operation of pumps and use of maintenance trucks.

Treatment also involves energy usage for operation of multiple units of treatment plants, emissions from organic degradation and sludge treatment. Sewage disposal is the fifth-largest source of GHG emissions in India (Garg et al. 2006). Globally, they are the seventh-largest contributors to methane (CH_4) and nitrous oxide (N_2O) emissions (Dong 2012). The wastewater system contributes to direct and indirect energy consumption, which has been a source of important research in the recent years. Several Excel-based models such as Water–Energy Simulator

Table 1 Wastewater generation estimates for the period 2009–2051

Source	Wastewater generation for Urban Settlements (in MLD)		
	2009/2011	2021	2051
CPCB (2009)	38,000	–	
Kamyotra and Bhardwaj (2011)	38,254	–	120,000
Kapshe et al. (2013)	45,617	59,048	132,253

(WESim),[1] Water–Energy Sustainability Tool (WEST)[2] and Wastewater–Energy Sustainability Tool (WWEST)[2] have surfaced to understand the water–energy dynamics of such systems. Multiple techniques have also been proposed to reuse and recycle the treated wastewater to reduce the environmental, energy and cost implications of such systems. Thus, a quantitative analysis of the energy requirements of processes involved and the subsequent emissions obtained from various facilities is imperative to understand the environmental impacts of wastewater infrastructure and operation.

1.2 Objectives and scopes

This paper aims at carrying out an integrated life-cycle assessment (LCA) for the collection phase of an Indian wastewater system. The paper develops in the form of a case study for Begusarai sewerage project and attempts to estimate life-cycle air pollution, greenhouse gas emissions and energy consumption for the collection phase of the project. The work consists of developing a life-cycle inventory for pipelines, manholes, pumps and transportation facilities in a typical collection phase, by making use of existing activity data and emission factors from secondary literature. This has been followed by carrying out sensitivity analysis for various parameters based on efficiency of pumping stations and variation of materials for manhole constructions and determining the effect of such variations on different social perspectives. Further, the paper discusses the implications of the present work on improving the design of wastewater collection systems.

Collection systems are an integral part of the overall wastewater cycle. However, treatment and disposal phases also contribute significantly to the total energy usage and atmospheric emissions of the wastewater treatment life-cycle. This analysis lies beyond the scope of this paper and can be addressed subsequently. Also, the system boundaries of the collection phases have been restricted to include components that contribute considerably to the resource consumption and environmental footprints. The manufacturing of raw materials and equipment, maintenance and reuse and recycle of waste have not been taken into account in the study definition area. It is hoped that the results obtained in this study can be incorporated into a more extensive study on the entirety of wastewater system including the preceding and consequent activities.

1.3 Organization of the paper

This paper applies LCA to determine the environmental impacts in the wastewater collection phase in Indian sewerage system and discusses its implications. Section 2 provides an overview of India's water and wastewater scenario. It presents an extensive literature survey of national and international studies on LCA for wastewater systems along with the current situation of the Indian sewerage system. Section 3 delineates the methodology used for carrying out the current study. It describes the system boundaries and the preparation of inventory using secondary literature for various components of the wastewater cycle. In addition, it also discusses the importance of various perspectives and the normalization, weighting and damage calculations used for the LCA technique. The net life-cycle outputs and sensitivity analysis have been detailed in Sect. 4. In this section, the contribution of each component in the system towards net life-cycle outputs in terms of energy consumption (Sect. 4.2), air pollution (Sect. 4.3) and climate change (Sect. 4.4) and finally normalized results (Sect. 4.5) have been discussed. In Sect. 4.6, we also discuss the effect of enhanced efficiency of pumping stations and change of materials in manhole construction to the net life-cycle outputs. Finally, Sect. 4.7 discusses the importance of the present study and the implications of the work towards improvement of wastewater system design and a culmination to water–energy nexus.

2 Brief literature review

2.1 Water and wastewater in India: present and future

India has the largest water footprint in the world, contributing to 13% of the world water usage. However, on a

[1] Developed by the Pacific Institute and Dr. Bob Wilkinson, with support from the WateReuse Research Foundation, the California Energy Commission and the Canadian Mortgage and Housing Corporation.

[2] Developed by Dr. Jennifer Stokes and Prof. Arpad Horvath, University of California at Berkeley Department of Civil and Environmental Engineering, with funding from the California Energy Commission Public-Interest Energy Research (PIER) programme.

per capita basis, India has a lower footprint than most of the developed and developing countries, with a per capita usage less than 21% of the global average (Hoekstra and Chapagain 2007). The gross per capita availability is projected to decline by ~38% by 2050, as compared to 2001 levels due to rising population, shrinking groundwater resources and increased water contamination (Gupta and Deshpande 2004). Haddeland et al. (2014) have also indicated human impacts on the hydrological cycle which have complex interrelations with the climatic change processes. It is estimated that groundwater depletion due to climate change will be most pronounced in countries such as India and China (Taylor et al. 2013). In view of the above, the Government of India initiated National Water Mission in 2011, with the following goals:

- Formulating a comprehensive water database in public domain and assessment of the impact of climate change on water resource.
- Promotion of citizen and state actions for water conservation, augmentation and preservation.
- Focused attention on vulnerable areas including over-exploited areas.
- Increasing water use efficiency by 20%, and
- Promotion of basin-level integrated water resources management.

The utilizable water resources in the country are 1086 BCM, of which around 64% are surface water and the rest are ground water resources (Verma and Phansalkar 2007). Future predictions suggest that India will become water-stressed[3] by 2020 (FICCI 2011). It has also been projected that the water demand will rise by 22 and 32% by 2025 and 2050, respectively (Amarasinghe et al. 2007). Currently, more than 80% of the water resources are utilized by the agricultural sector, whereas that used by the industries is less than 10%. The latter is bound to increase, since the developed economies have an average industrial water consumption of more than 50%. Ranade and Bhandari (2014a) predict the growth in industrial water demand to about 18% by 2050. As large amount of water will be used by industries and urban settlements, the wastewater generation is also projected to rise. The urban population constitutes nearly 32% of the total population of the country, generating municipal wastewater of about 38,000 MLD. The sewerage network is utilized by 10% of the population in rural areas and by 67% in urban settlements (IPCC 2007). The maximum concentration of municipal sewage generation is found in the states of Maharashtra (~27%), followed by Uttar Pradesh (~11%) and Delhi (~10%) (CPCB 2013). Despite construction of large number of WWTPs in the country, about 74% of the domestic wastewater and 41% of the industrial wastewater remain untreated (Ranade and Bhandari 2014b).

2.2 Review of major international and Indian studies on the collection phase

LCA has evolved as a standard methodology to analyse the environmental burdens associated with any product, processes and/or services. The technique successfully quantifies the impacts of all stages of product, service and processes by adopting a cradle-to-grave approach. LCA-based studies on wastewater treatment can be cited dated back to 1990s. These have evaluated environmental and societal impacts of wastewater treatment (WWT) but only taking treatment and disposal phases into consideration (Emmerson et al. 1995; Roeleveld et al. 1997). Wastewater treatment plants (WWTPs), an end-of-pipe technology, remain a common (sometimes the sole) element of the system definition that is evaluated for their sustainability and performance (Yoshida et al. 2014; Meneses et al. 2015; Rodriguez-Garcia et al. 2014). The end-of-life stages such as dismantling of the infrastructure and recycling are usually not included in the system boundary in most of the studies (Risch et al. 2015). In a review carried out by Corominas et al. (2013), only 18 studies out of 45 reviewed took the collection phase as a part of the system boundary, while carrying out LCA for the entire wastewater system. Risch et al. (2015) confirm that sewer system (collection phase) contributes significantly (~64%) to the overall impacts of urban wastewater systems. The work reviews nearly twenty studies that have included sewer systems in the system boundaries for conducting LCA on wastewater systems. Table 2 complements the review by Risch et al. (2015) by listing the variable approaches and inventory taken up for analysing sewer systems. Most of the literature for Indian context has focused mainly on the treatment phase, and little or no mention of the collection phase has been made. Nevertheless, this phase also contributes to a significant amount of energy usage and emission sources as stated in earlier references. Therefore, a life-cycle analysis of collection phase of typical Indian sewerage system is necessary to get a complete view of the environmental impacts of the wastewater cycle.

2.3 Indian sewerage system: the current scenario

Sewerage and water sanitation systems have gradually developed in India. Inadequate sanitation and sewage facilities in India were reported to cause economic losses of the order of US$ 53.8 billion for the year 2006 (WSP-SA 2010). The current fleet of India STPs is composed of 816

[3] Water availability of <1700 m^3/person/year is considered as a 'water-stressed' country and that of <1000 m^3/person/year is considered as a 'water-scarce' country (Gupta and Deshpande 2004).

Table 2 Literature review of various LCA methodologies implemented on wastewater systems

Reference	Region	Boundaries	Methodology/inventory	Outputs/conclusions/remarks
International studies of sewer appurtenances of wastewater systems				
Vahidi et al. (2015)	Hypothetical city (200,000 inhabitants)	Production, transportation, installation and maintenance of pipelines	ISO Standard 14040 (ISO 2006) + Ecoinvent database	Production phase of pipelines has maximum impact PVC pipes preferable
Petit-Boix et al. (2014)	Spain	Production, installation and construction and demolition phases of pipelines, pumps and manholes	ISO Standard 14040 (ISO 2006) + CML 2 baseline 2000 method version 2.05	Contribution to impact categories: pipes (48–85%), manholes (13–43%), inspection chamber (2–9%) and pumps (<2%)
		Comparison of different materials and diameters of pipelines	Ecoinvent 2.2 + SimaPro 7.2.0	Concrete pipes are preferable
Slagstad and Brattebø (2014)	Norway	Entire water and wastewater system	ISO Standard 14040 (ISO 2006) + ReCiPe 2008 (Ecoindicator 99 and CML handbook)	Sewerage network (pipelines and wastewater pumps) contributed 28% of the total impact
			SimaPro version 7.3.2 + Ecoinvent database	These contribute mostly to particulate matter formation and freshwater eutrophication categories
Amores et al. (2013)	Spain	Water abstraction, water treatment, distribution, sewerage and wastewater treatment phases	ISO Standard 14040 and 14044	Environmental impacts of 35.2% for distribution network and 20.5% for collection pumping
			Ecoinvent version 2.1 database + CML2001	Sewerage contributed 0.5–5% to various impact categories for the combined system
De Sousa et al. (2012)	USA	Construction, operation and maintenance of sewer system and WWTP	Hybrid of process-based and economic input–output (EIO) LCA	Transportation, cement manufacturing and concrete contributed maximum to the construction phase
			ISO Standard 14044; SimaPro 7.1 + Ecoinvent version 2 + US input–output	
Kim et al. (2012)	Korea	Construction of Sewer pipes and manholes	ISO Standard 14040 Korea life-cycle inventory + Ecoinvent (2006)	Contribution to emissions: material production (49.3%), operation (30.7%) and end-of-life (16.9%) for PVC
Venkatesh and Brattebø (2011)	Norway	Operation and maintenance phase of urban water and wastewater network	SimaPro 7.1.5 + CML 2001 guidelines	Sewage pumping and pipelines accounted for 1.25 and 0.97%, respectively, to total environmental impact
Roux et al. (2010)	Hypothetical city (1000 inhabitants)	Sewer network and treatment phases	ISO Standard 14040 and 14044 CML 2001 + Ecoindicator 99	Sewer network contributes to more than 50% for almost all the impact categories
Stokes and Hovarth (2010)	USA	Collection, treatment and disposal phases with construction, operation and maintenance, material production and delivery	Wastewater–Energy Sustainability Tool (WWEST) Combination of process-based and economic input–output LCA	Collection phase contributed to ~11% of energy consumption and 36% of total GHG emissions
Venkatesh et al. (2009)	Norway	Pipelines	SimaPro (PRé Consultants 2008) + Ecoinvent database (Swiss Centre for Life Cycle Inventories 2008) + CML2 2000 guidelines	Construction phase amounts to 80% of the total GHG emissions for pipelines Concrete pipelines are preferable

Table 2 continued

Reference	Region	Boundaries	Methodology/inventory	Outputs/conclusions/remarks
Indian studies on wastewater systems				
Singh et al. (2016a)	India	Mainline treatment technologies and supporting facilities	Survey of 50 Indian STPs and 14 sewage treatment options	Average electrical consumption of large-scale STPs is 0.11 kWh/m^3 with 70% contributed by secondary treatment
			Use of formulae from secondary literature to estimate energy consumption and carbon emissions	Average energy intensity for Indian STPs is 0.4–4.87 kWh/m^3
Kalbar et al. (2016)	India	Operation and maintenance phases of 4 treatment methods	ISO standard 14040 + CML 2002 baseline Scenario-based multiple attributes decision-making (MADM) approach	Develops a tool to evaluate the suitability of a particular treatment method for India, based on land requirement, energy consumption and environmental impacts.
Flores Rosell (2015)	Nagpur, India	Pumping stations, storage tanks, manholes and constructed wetlands	SimaPro version 8 + Ecoinvent 3 database + CML 1S baseline (2015)	Operation phase contributed to 37–62% of total impact Wastewater reuse reduced total impact to 24–54%
Kalbar et al. (2012)	Hypothetical city (1,00,000 inhabitants)	Construction, operation and maintenance phase of a Sequencing Batch Reactor (SBR) plants	ISO standard 14040 + CML 2002 guidelines	Total energy consumption was found to be 28.21 kWh/year, operational phase had a share of 99.97% Construction phase contributed to 1% of the net environmental impact
Miller (2011)	Hyderabad, India	Pipeline and pumps, constructed wetland and sludge treatment and disposal phase (reuse)	ISO standard 14040	Energy use of 0.7 kWh/gal and GHG emissions of 1 g-CO_2 equivalent/gal

units with a total treatment capacity of approximately 23,300 MLD (CPCB 2015). Of the total installed capacity, about 64% of the units are operational and the rest are either in dormant condition or are under construction. This has built up a capacity gap of ~27,000 MLD between the generated and treated sewage. Therefore, emphasis is being put on setting up new STPs and planning of sewerage networks, under the 11th 5-year plan initiated by the Government of India. This targeted at 100% coverage of urban sewerage system and rural sanitation by 2012.

Under the National Urban Sanitation Policy scheme (NUSP 2008), decentralized wastewater management system (DWMS) with new pipe materials for sewer construction, treatment and non-conventional sewers has been proposed. The wastewater generated is generally assumed to be 80% of the total water supplied to a particular area (MoEFCC 2007). For the newly commissioned plants, a design period of thirty years is adopted for sewer system and all its components and 15 years for the pumping machinery and STPs (MoUD 2015). The construction material used for all the units is preferably reinforced concrete following the standards IS: 456 and IS: 12330. Table 3 lists the norms prescribed by Central Public Health and Environmental Engineering Organization (CPHEEO 2015) to be followed while designing a typical sewer network in India.

Based on these standards, several sewerage projects have been proposed and are under construction across the country. Table 4 summarizes few such projects with their specifications.

It can be noted that the sewage generated per kilometre of the sewerage network for Mumbai is nearly four times as compared to Delhi and Bangalore which have similar magnitudes of sewage generation. This can be attributed to the high population density of 19,652/km^2 for Mumbai as opposed to 11,320 and 4381/km^2 in case of Delhi and Bangalore, respectively (Census 2011). The layout for sewerage network also depends on the availability of the land and the topography of the region. This is evident from the fact that there is an intensive sewerage network without the presence of any pumping stations in Bangalore as compared to Mumbai, where the sewage is transported by an intensive network of pumping stations. The land requirements for various treatment technologies vary from 0.002 to 0.01 km^2/MLD. For the optimization of land area, the multi-tier STPs with common walls for sewage holding structures have been proposed by the Ministry of Urban Development (MoUD 2015). With the problem of increasing water scarcity and unavailability of adequate supply of water for irrigation purposes, the ministry has advised the reused of treated sewage for farm forestry,

Table 3 Specifications and standards to be followed for different components of sewer system (CPHEEO 2015)

Component	Specification (per unit)	Standards
Pipeline		
Precast concrete	Length: 2 m for diameter <250 mm	IS: 458
	Length: 2.5 m for diameter >250 mm	
Vitrified clay	Length: 600 mm, 750 mm, 900 mm	IS: 651
	Diameter: 100–600 mm	
Plastic (PVC and HDPE)	Length: 5–6 m	IS: 4685, IS: 4984
	Diameter: 75–400 mm	
Ductile iron	Length: 4–6 m	IS: 8329, IS: 15155
	Diameter: 80–2000 mm	
Manhole	Depth: 0.9–14 m	Manual on Sewerage and Sewage Treatment Systems (MoUD 2015)
	Diameter: 900–1800 mm	
	Maximum manhole spacing: 30 m	
Sewage pumping stations and pumping mains	Minimum number of pumps: 3	Manual on Sewerage and Sewage Treatment Systems (MoUD 2015)
	Minimum diameter: 150 mm	
	Efficiency: 0.65–0.85	
Transportation trucks	Sewage handling capacity: 2000–12,000 L (for rural areas: 200–2000 L)	NUSP (2008)

Table 4 Sewerage projects across the country

City/town	State	Sewage generated (MLD)	Sewerage network (km)	Sewage generated per km	Pumping stations (#)	Source
Begusarai	Bihar	25	105	0.24	2	NGRBA (2010a, b)
Sahibganj	Jharkhand	12	54	0.22	7	UDD (2010)
Chandigarh[a]	Chandigarh	197	742	0.27	–	CDPC (2004)
Bangalore[a]	Karnataka	1400	6800	0.21	–	BWSSB (2016)
Delhi	Delhi	2574	7000	0.37	11	DJB (2016)
Nashik	Maharashtra	230	1745	0.13	16	NMC (2011)
Mumbai	Maharashtra	2600	1500	1.73	52	MCDP (2004)
Panaji	Goa	13	40	0.33	8	PWD, Govt. of Goa
Salt Lake	West Bengal	8	18	0.44	1	KMC (2016)
Lucknow	Uttar Pradesh	490	5072	0.10	5	LMC (2015)

[a] Pumping stations are not required as the topography provides with a natural system of drainage

horticulture and in industries (non-human contact cooling towers).

3 Methodology

3.1 System definition

The wastewater life-cycle constitutes of three distinct phases, i.e. collection phase, treatment phase and disposal phase (Fig. 1). The collection phase includes the unit processes involved for collecting the wastewater from different point sources and transporting it to the treatment plants, and forms the area of interest for this study.

The collection phase comprises of three basic components viz. the sewer network (consisting of pipeline and manholes), pumping stations and transportation facilities. The sewer network comprises of a network of pipelines with manholes (inspection chambers) at regular intervals. Pumping stations or lift stations are located at intermediate

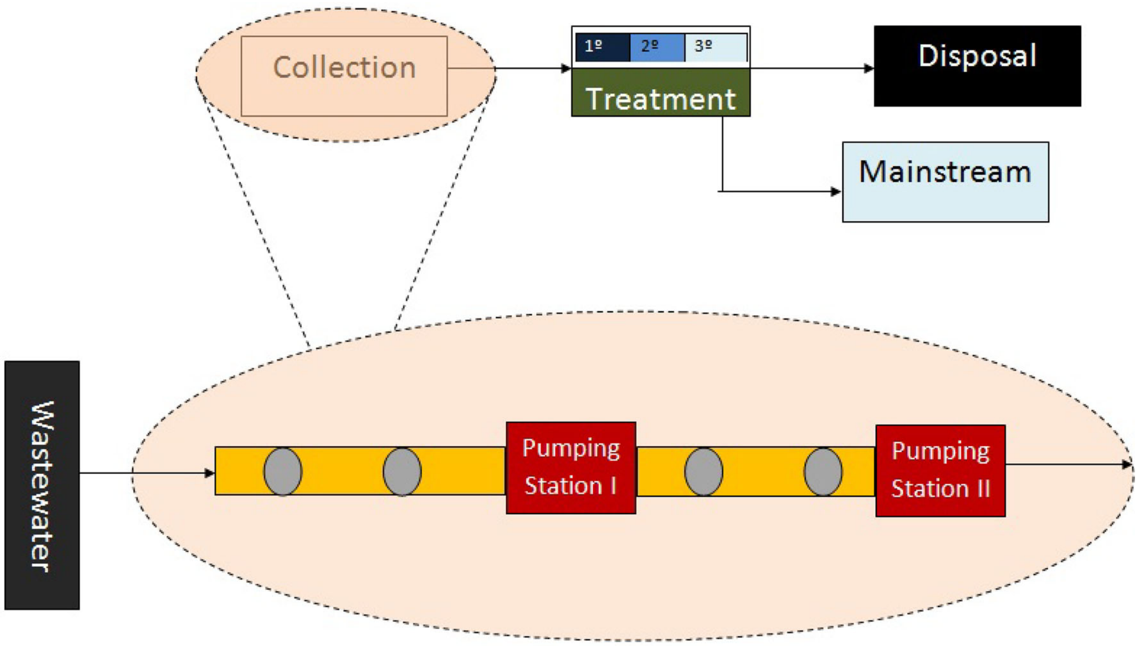


Fig. 1 Schematic diagram of the wastewater life cycle

locations to deliver the sewage to higher elevations for further transport by pipelines via gravity flow. Transportation [using Heavy Earth Moving and Mining (HEMM), trucks and cars] occurs along all the processes of the collection phase. It is used for transporting sewage as well as for commuting purposes by the officials for operation and maintenance of different units. The system life-cycle is depicted in Fig. 2.

3.2 Inventory preparation

For the present study, we select a typical Indian sewerage project, viz. Begusarai sewerage project under the National Ganga River Basin Authority of India (NGRBA) in Bihar. The project was proposed by the Bihar Urban Development Agency under the Urban Development and Housing Department, Government of Bihar, in the year 2010. The sewerage project aims at serving a population of 117,516 and is spread over an area of 7.51 km^2. The inventory for each component is discussed in details in the following subsections.

3.2.1 Pipeline

The pipelines used in the sewer network are of diameter 150–1100 mm with the lengths depicted in Fig. 3. This profile helps us to calculate the amount of material used.

The proposed project uses concrete pipes due to their durability, low corrosion rate and widespread availability at cheaper costs. According to this, thickness for various diameters is assumed as shown in Table 5 (IS: 458). The parameters for pipeline construction are shown in Table 6.

The average density for light graded concrete ranges from 1800 to 2200 kg/m^3 and that for heavy graded concrete is 2200–2500 kg/m^3 (Panasyuk et al. 2014). By inspection of several sewerage projects around the country, we assume heavy graded concrete. Ma et al. (2016) have carried out an inventory analysis to evaluate the GHG emissions from concrete pavement construction using similar concrete characteristics. Accordingly, we assume the energy required for 1 m^3 of concrete produced to be 2 kWh.

3.2.2 Manholes

The construction of a manhole involves three basic steps, i.e. excavation of soil, construction of beds and side walls and construction of cover. Manholes should be constructed at every change in alignment, gradient or diameter, at the head of all sewers and branches and at every junction of two or more sewers with a maximum distance of 30 m between consecutive manholes (IS: 4111). Lewinski (2015) have indicated that circular manholes are preferable with regard to stress. The depth of the manhole is chosen as 4.5 m. As per the manhole depth, the prescribed nominal diameter of the manholes is 1.5 m (CPHEEO 2015). Corresponding to the manhole depth, the thickness of the side walls for circular manhole is two brick lengths. The length

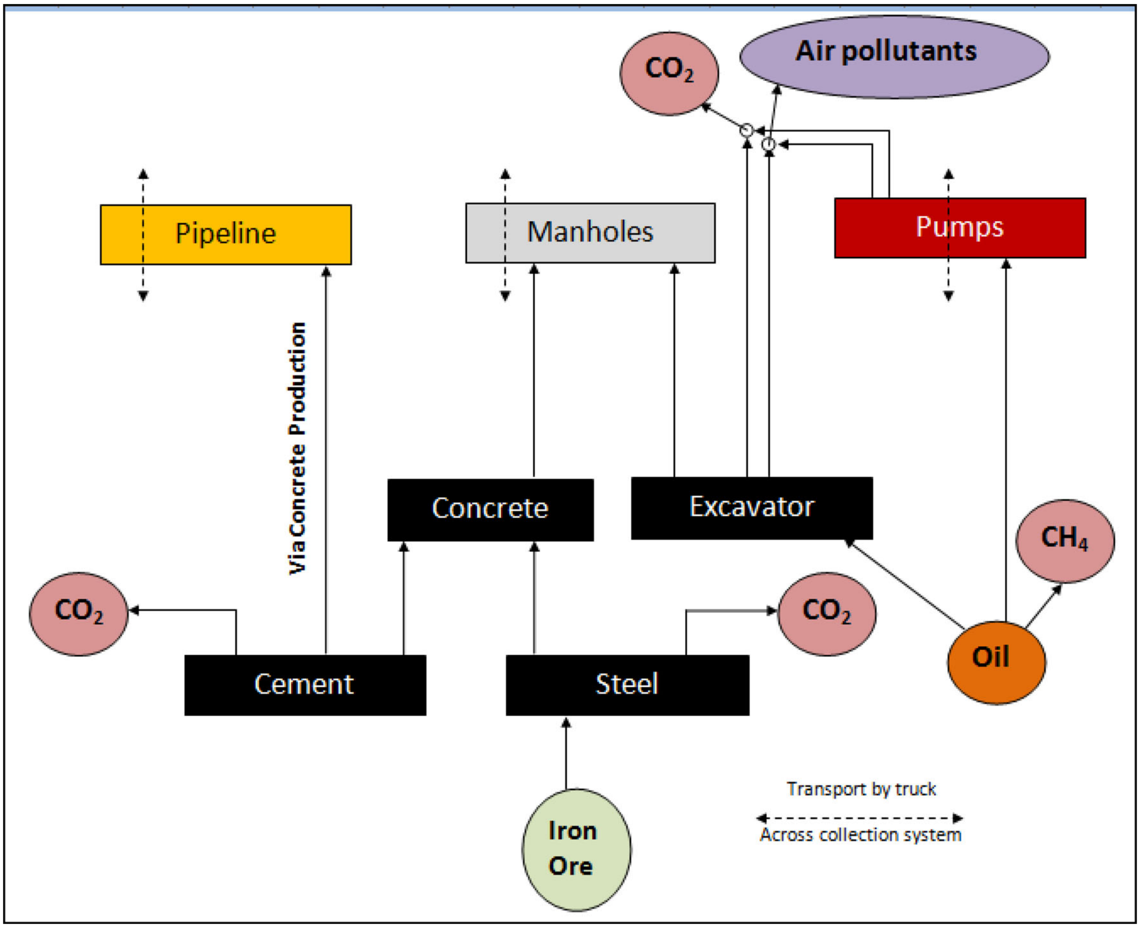


Fig. 2 System framework for the study

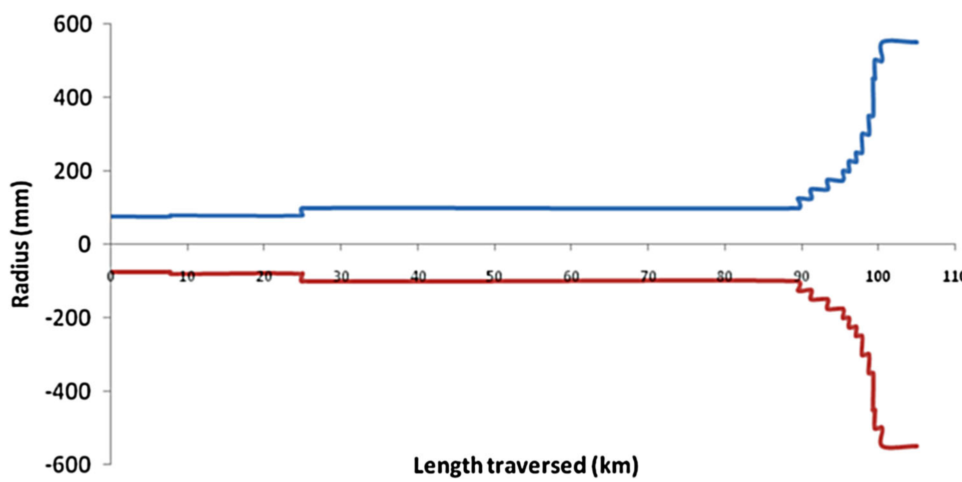


Fig. 3 Length profile of the sewerage collection pipeline

of brick is 190 mm as per IS: 1077 standards along with 10 mm of mortar. The standard also specifies the bed thickness to be 300 mm for manhole depths >2.30 m. As regards to the manhole covers, concrete structures are heavy, and hence, cast iron has been assumed as the material for construction of covers. Based on strength considerations, we assume medium-duty MD-10 grey cast iron (FG 150) (IS: 1726). The opening of the cover is taken to be 500 mm, which is the maximum for circular manholes of the grade.

The specific energy for concrete production is taken from Table 5. The specific power consumption for cast-

Table 5 Parameters for pipeline network. *Source*: Compiled by author from various sources

Parameter	Unit	Value
Length	m	104,949
Material		Precast concrete
Diameter	mm	Variable (see Table 5; Fig. 4)
Concrete density	kg/m^3	2200
Thickness	mm	Variable (see Table 5)
Energy consumed	kWh/m^3	2

iron foundries in India was found to be 620 kWh/t (Arasu and Rogers 2009). For excavation purpose, we assume medium-sized excavators having fuel consumption of 0.1941 l/m^3 (Trani et al. 2016). The parameters for construction of manholes used for the above project are listed in Table 7.

3.2.3 Transportation

For transportation purposes, two types of vehicles are proposed: Heavy-duty truck (HDT) and light-duty vehicle (LDV). Stokes and Horvath (2010) have assumed truck usage of 10 km/year and LDV usage of 1.5 km/year for each metre of pipeline. The fuel characteristics are assumed from Sadavarte and Venkataraman (2014). The details for transportation are shown in Table 8.

3.2.4 Pumping station

The sewerage project uses two pumping stations using diesel pumps. The fuel characteristics are same as those assumed in Table 9. Considering pumping station I, we find that Kirloskar SVI NW4+ is a suitable pump for the desired needs. This pump has a specific fuel consumption of 185 g/hp-h. For the second station, Kirloskar KS8B 3503 pump is selected with the specific fuel consumption assumed to be proportional to the capacity of the pump.

Table 10 lists the emission characteristics of each material/component used in the study. For excavator, the emission characteristic is assumed to be similar to that of the truck and for pumps it is assumed to be that of the diesel generators. In India, about 50% of cement production is done using dry kiln technology (Taylor et al. 2006). Therefore, we have also assumed emission characteristics of dry kiln type technology.

3.3 Normalization and weighting based on cultural theory

The perception of environmental impacts varies from individual to individual. The Ecoindicator model (EI99) categorizes individuals into three archetypes of perspectives, i.e. Egalitarian, Hierarchist and Individualist, based on fundamental differences in attitude towards resources and environmental impacts (Thompson et al. 1990; Hofstetter 1998). The category chosen determines the normalization results and the weightage of different damage categories to the LCA. Table 11 includes some of the main differences between the three categories. The impact of cultural theory on the LCA of the collection phase has been discussed in detail in Sects. 4.5 and 4.6.1.

The normalization and weighting factors, for the three perspectives, i.e. Egalitarian, Hierarchist and Individualist, for Indian scenario were obtained from Singh et al. (2016b) and EI99 methodology (Table 12).

Table 6 Variation of pipe thickness and external diameter with nominal diameter. *Source*: Compiled by author from various sources

Nominal diameter (mm)	Minimum thickness (mm)	External diameter (mm)	Length (m)	Volume (m^3)
150	25	200	7761	106.67
160	25	210	17,133	248.94
200	25	250	64,564	1140.94
250	25	300	1802	38.92
300	30	360	2051	63.78
350	35	420	1996	84.49
400	35	470	893	42.71
450	35	520	853	45.48
500	40	580	756	51.30
600	40	680	921	74.07
700	45	790	505	53.18
900	55	1010	313	51.64
1000	60	1120	966	193.01
1100	65	1230	4435	1055.07

Table 7 Parameters for manholes. *Source*: Compiled by author from various sources

Parameter	Unit	Value
Number of manholes		3498
Shape		Circular
Manhole spacing	M	30
Depth	M	4.5
Material for wall		Concrete
Nominal diameter	M	1.5
Cement density	kg/m^3	3150
Thickness of the side walls	mm	400
Material for bed		Concrete
External diameter	M	2.3
Thickness of the bed	mm	300
Material for cover		Cast iron
Cast-iron density	kg/m^3	7050
External diameter of cover	mm	590
Thickness of the cover	mm	12
Depth of the cover	mm	20
Fuel consumption of the excavator	l/m^3	0.1941
Specific energy consumption for construction of side walls	kWh/tonne	89
Specific energy consumption for construction of cover	kWh/tonne	620

Table 8 Details for transportation. *Source*: Compiled by author from various sources

Parameter	Unit	Value
HDT usage	km/year	1,049,490
LDV usage	km/year	157,423.5
Fuel		Diesel
Calorific value of fuel	kCal/kg	10,350
Density of fuel	tonne/kl	0.8263
HDT fuel usage[a]	km/l	5
LDV fuel usage[a]	km/l	13

[a] Assumed based on inspection of data of various types of vehicles

The final damage factors are used to compute the EIC. These are listed in Table 13.

3.4 Calculation of damage

Final environmental impact of collection (EIC) is obtained using the following equation (Singh et al. 2016b),

$$\mathrm{EIC} = b_{\mathrm{f}} m_f + \sum b_{\mathrm{e}} m_{\mathrm{e}},$$

where b_{f} represents the normalized factor for energy usage, b_{e} stands for the normalized factor for each pollutant (both from Table 13) while m_f denotes the energy consumption

Table 9 Inventory for pumping stations. *Source*: Compiled by author from various sources

Parameter	Unit	Value
Number of pumping stations (PS)		2
Number of pumps		4 (operational) + 1 (standby) For each pumping station
Flow rate of PS I	m^3/h	92.28
Flow rate of PS II	m^3/h	359.23
Sewage input to PS I	MLD	4.9
Sewage input to PS II	MLD	21.1
Pump capacity for PS I	kW	6
Pump capacity for PS II	kW	25.4
Specific fuel consumption for PS I	g/hp-h	185

Table 10 Emissions factors for different materials

Component	Unit	$PM_{2.5}$	SO_2	NO_x	CO	CO_2	NMVOC	CH_4	N_2O
Concrete production[a]	kg/m^3	1.68	1.41	0.155	0.113	38.7	0.004	0.01	0.12
Heavy-duty truck[b]	g/km	0.2	1.42	6.3	3.6	515.2	4.43	0.09	–
Light-duty vehicle[b]	g/km	0.2	0.029	1.28	5.1	60.3	2.385	0.18	–
Diesel pump[c]	g/kg	0.89	20	59.17	15.72	3186	1.51	0.15	0.03
Cast-iron production[d]	g/kg	53	5	4.23	3.3	2210	0.06	0.14	0.02

[a] Ma et al. (2016) for CH_4, CO_2, N_2O; For $PM_{2.5}$, SO_2, NO_x, CO,NMVOC, emission factor is varied in ratio proportional to that for cement (USEPA 1995) with respect to CO_2 emission factor

[b] Ramachandra (2009) for $PM_{2.5}$, SO_2, NO_x, CO, CH_4, CO_2; Goel and Guttikunda (2015) for NMVOC

[c] Sadavarte and Venkataraman (2014)

[d] Sadavarte and Venkataraman (2014) for $PM_{2.5}$, SO_2, NO_x, CO, CH_4, NMVOC; Shi et al. (2015) for CO_2

Table 11 Objective comparison of the thinking characteristics of Egalitarian, Hierarchist and Individualist perspectives (Thompson et al. 1990; Hofstetter 1998)

Predictions	Archetypes		
	Egalitarian	Individualist	Hierarchist
Criteria	Argument	Experience	Evidence
Management style	Preventive	Adaptive	Control
Distribution	Parity	Priority	Proportionality
Perception of time	Long term dominates short term	Short term dominates long term	Balanced distinction between short and long terms
Intergeneration responsibility	Present < future	Present > future	Present = future
View of resources	Depleting	Abundance	Scarce
Perception of needs and resources	Can manage needs, but not resources	Can manage needs and resources	Can manage resources, but not needs
Energy future	Low growth (radical change now)	Business as usual	Middle of the road (technical fix)
Attitude to nature	Attentive	Laissez-faire	Regulatory
Attitude towards humans	Construct Egalitarian Society	Channel rather than change	Restrict behaviour
Attitude towards resources	Need reducing strategy	Manage needs and Resources	Increase resources
Perception (myth) of nature	Nature ephemeral	Nature benign	Nature perverse/tolerant
Perception of human nature	Born good, malleable	Self seeking	Sinful
Attitude towards risk	Risk aversive	Risk seeking	Risk accepting

Table 12 Normalization and weighting factors for various impact categories. *Source*: Singh et al. (2016b)

Category	Normalization Factor			Weighting Factor		
	Egalitarian	Hierarchist	Individualist	Egalitarian	Hierarchist	Individualist
Human health	4.50×10^{-3}	4.45×10^{-3}	2.23×10^{-3}	300	400	550
Ecosystem quality	4.50×10^{3}	4.50×10^{3}	2.84×10^{3}	500	400	250
Resources	1.03×10^{3}	8.21×10^{2}	8.22×10^{1}	200	200	200

Table 13 Damage factors (b) obtained after normalization and weighting for various perspectives and impact categories. *Source*: Author's estimates

Component	Category[a]	Egalitarian	Hierarchist	Individualist
$PM_{2.5}$	RI	46.67	62.92	125.78
SO_2	RI	3.64	4.91	9.62
SO_2	AE	1.16×10^{-2}	9.25×10^{-2}	9.16×10^{-2}
NO_x	RI	5.94	7.97	2.93×10^{-1}
NO_x	AE	6.35×10^{-1}	0.51	0.50
CO	RI	0.05	0.066	0.18
CH_4	CC	0.29	0.39	1.085
CO_2	CC	1.4×10^{-2}	1.89×10^{-2}	4.93×10^{-2}
NMVOC	RO	0.08	0.11	0.29
N_2O	CC	4.6	6.20	16.52
Energy usage (kgoe)	Re	0.68	1.47	0

[a] *RI* respiratory inorganic, *AE* acidification and eutrophication, *CC* climate change, *RO* respiratory organic, *Re* resources

(in kgoe) of the plant and m_e stands for emission of a particular pollutant in the plant inventory (from Table 12).

4 Results and discussion

4.1 Net life-cycle outputs

Table 14 shows the material requirements for the collection phase of plant studied.

The fuel consumption for HDTs is approximately 17 times than LDV in transportation phase. This is due to the higher mileage and lower vehicle usage for LDVs. For pumping stations, the fuel consumption for PS II is 20 times greater than PS I, because of higher flow rate and power capacity for pumps in PS II. The total fuel consumed annually for operation of pumping stations is three times higher than the transportation unit. The concrete required for manhole construction is 13 times greater than that required for construction of pipelines. This is so as to maintain the integrity of structures for manholes, to protect contamination of groundwater and to prevent entry of external materials into the sewage system.

The results of Table 14 coupled with the emission factors and specific energy requirements lead to total life-cycle outputs for the entire design period (30 years) of the sewerage project (see Fig. 4; Table 15).

Table 14 Material required for collection phase of Begusarai sewerage project. *Source*: Author's estimates

Parameter	Unit	Value
Pipeline		
Concrete required	m^3	3250
Transportation		
HDT fuel consumption	L/year	209,898
LDV fuel consumption	L/year	12,109
Pumping Station		
Fuel consumption for PS I	L/year	34,914
Fuel consumption for PS II	L/year	692,132
Manhole		
Soil excavated	m^3	27,819
Excavator fuel consumption	L	5400
Concrete required for walls	m^3	37,586
Concrete required for bed	m^3	4360
Cast iron required	m^3	19

4.2 Energy consumption

Pumping stations and transportation units collectively contribute to more than 99% of the total energy consumption for the entire sewerage project. This is attributed to the constant requirement of diesel combustion by these units. This is in line with the finding of (Risch et al. 2015; Barjoveanu et al. 2014) who have indicated a dominance of the operation stage of the collection system to energy consumption. Diesel pumps used in pumping stations result in approximately 76% of the total life-cycle energy usage. The brake specific fuel consumption for 6 hp pump is around 185 g/hp-h. A reduction in this requirement will be helpful since India possesses low petroleum reserves. Electric pumps (having power capacity of $\sim$3 hp) can be used in pumping stations as a replacement to diesel pumps for sewerage systems where the net wastewater generation is low. Renewable sources of energy such as renewable electricity can also be explored for reducing the dependence on carbon-based fuels (Pensini et al. 2014). Hybrid energy systems (HSPs) have become more prevalent to facilitate the efficient utilization of renewable resources (Qi et al. 2014). The transportation units consume a total of

Table 15 Life-cycle outputs of the collection phase. *Source*: Author's estimates

		$PM_{2.5}$ (tonne)	SO_2 (tonne)	NO_x (tonne)	CO (tonne)	CO_2 (tonne)	NMVOC (tonne)	CH_4 (tonne)	N_2O (tonne)	Energy (GJ)
Pipeline		5.461	4.583	0.504	0.367	125.785	0.013	0.032	0.390	23.401
HDT	A	6.297	44.708	198.353	113.344	16,220.920	139.477	2.834	–	225,104
LDV	B	0.944	0.137	6.045	24.086	284.7791	11.263	0.850	–	12,987
Transportation	A + B	7.241	44.845	204.398	137.430	16,505.70	150.740	3.684	–	238,091
Pumping station		16.040	360.454	1066.406	283.317	57,420.45	27.214	2.703	0.541	779,718
Excavator	C	0.162	1.150	5.103	2.916	417.287	3.588	0.073	–	5790.86
Side walls	D	63.145	52.997	5.826	4.247	1454.601	0.15	0.376	4.51	270.623
Manhole cover	E	7.147	0.674	0.571	0.445	298.032	0.008	0.019	0.003	300.998
Bed	F	7.325	6.148	0.676	0.493	168.746	0.017	0.044	0.523	31.395
Manhole	C + D + E + F	77.780	60.970	12.175	8.101	2338.666	3.764	0.511	5.036	6393.87
Total		106.52	470.852	1283.483	429.216	76,390.6	181.732	6.931	5.967	1,024,226

222 kl of diesel per year resulting in about 23% of energy consumption.

4.3 Air pollution

The contribution to particulate matter pollution is dominated by the manhole unit (~73%). The construction of side walls leads to 81% of these emissions within the manhole. This is due to the larger concrete requirement of walls, which are required for their integrity. Although transportation and pumping stations are the most energy-intensive units, their relative contribution to particulate matter emissions is considerably lower. This can be attributed to the use of petroleum-based fuels (diesel) for operation of these units, which have a lower $PM_{2.5}$ emission factor than coal-based industries.

Due to higher rate of fuel combustion, pumping stations produce maximum amount of SO_2 (~76.5%) and NO_x

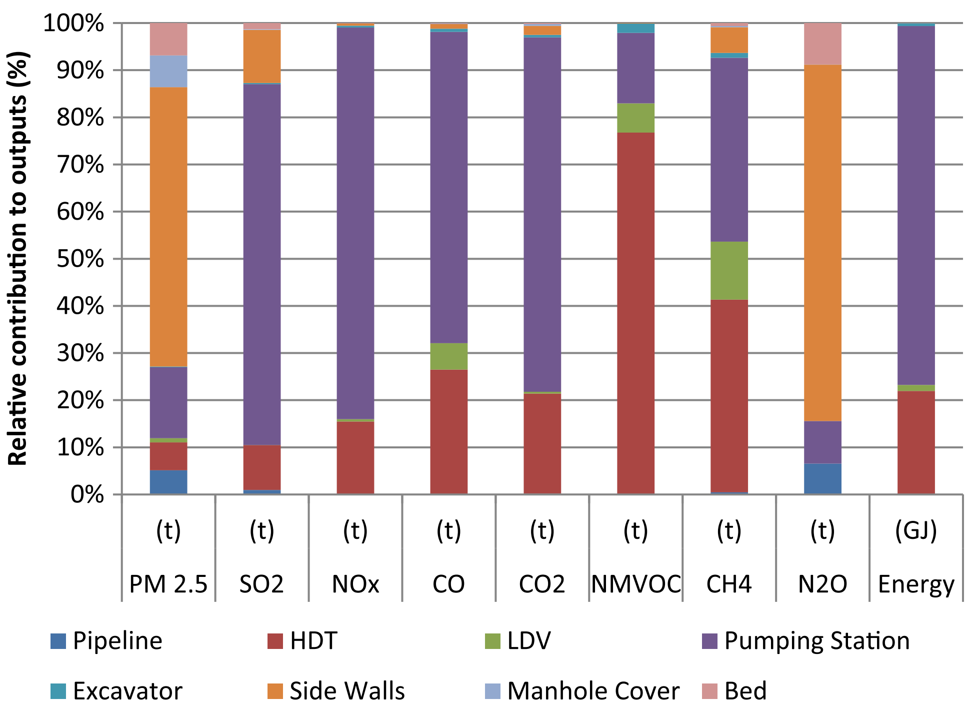


Fig. 4 Contribution of each component to the life-cycle output for collection phase

(83.1%) for the entire life cycle. These gases are hazardous for human health. India is the second-highest emitter of SO_2 after China (Lu et al. 2013), and numerous initiatives have focused towards lower SO_2 emissions. Therefore, low NO_x and SO_2 solutions such as use of selective catalytic reduction and low-sulphur content fuels can significantly help in reducing these emissions. The sewer network (construction phase) has impacts only on particulate matter and N_2O emissions. Transportation units contribute to over 80% of NMVOC emissions. This may be due to poor efficiency of heavy-duty vehicles. Similar trends are exhibited by these units for CO emissions, due to incomplete fuel combustion.

4.4 Climate change

The cumulative GHG emissions are calculated to be 78,166 t-CO_2 eq/year. The operational sewage treatment capacity for India is approximately 22,700 MLD (CPCB 2015). This results in annual production of about 71 Tg-CO_2 eq/year of GHG emissions from collection phase of sewerage systems. There may be considerable uncertainty in this amount, but the associated avenues are well known. A better understanding of the usage of maintenance trucks in this phase can lead to substantial uncertainty reduction. General understanding on our part indicates that the actual value would be lower than the aforementioned one. Further, these emissions are already a part of India's national GHG inventory from the fuel combustion sector (Sharma et al. 2011).

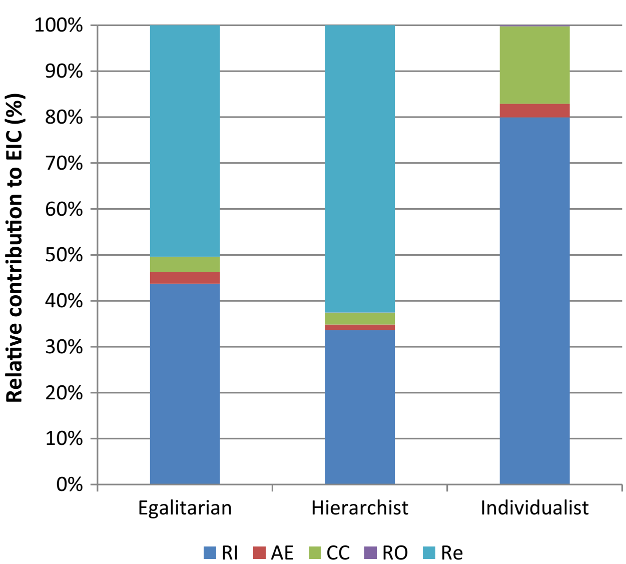


Fig. 5 Categorywise contribution to EIC in various perspectives. Stacks appear in the same vertical order as in the data table. *RI* respiratory inorganic, *AE* acidification and eutrophication, *CC* climate change, *RO* respiratory organic, *Re* resources

The global warming potential GWP of CH_4 has increased from 25 to 28 (IPCC 2007). This is bound to increase if the methane removal from atmosphere decreases. This also serves as a precursor for increasing environmental impact of ozone depletion category. Although GWP of N_2O has decreased significantly from 298 to 265, the effect is less pronounced due to lower amount of N_2O emissions from the collection phase units. Operation phase contributes to over 80% of the CH_4 emissions and 97% of CO_2 emissions. This is mainly due to flaring and venting during petroleum extraction.

4.5 Normalized results

The environmental impacts due to energy use and atmospheric emissions are made comparable by the method of normalization and weighting. The effect of these damage categories is studied for various perspectives that represent the various types of people in a society. The categorywise contribution to various damage categories for various perspectives is shown in Fig. 5.

Of the three perspectives, Individualists do not consider resource depletion as a problem due to long-term perspective, and therefore, the contribution of resource category (Re) is zero and respiratory inorganic (RI) category has the maximum impact, contributing nearly 80% to the EIC. , while for the remaining two perspectives, resource category has maximum impact on EIC. The resource category contributes to over 50 and 62% in Egalitarian and Hierarchist perspective, respectively. The Egalitarian perspective pushes for alternative energy sources, whereas Hierarchists do not prefer substitution of resources. Water and wastewater systems are energy-intensive but emit relatively lower amount of atmospheric emissions. The higher need felt by these perspectives for resources category has put emphasis on developing variety of water–energy models such as WESim and WWEST models. An important debate surrounding this area is that of the water–energy nexus, i.e. an increase in the amount of water treatment requirements will lead to less water scarcity but higher energy scarcity, and vice versa. Therefore, improvement in technologies should focus at reduction in energy requirement of water collection per unit amount of water treated.

The Re category is followed by RI category with 43.7 and 33.65% of the overall impact in Egalitarian and Hierarchist perspectives, respectively. The impact of respiratory organic (RO) category is almost negligible (<1%) in all the three perspectives. Acidification and eutrophication (AE) category does not significantly affect the EIC, with <3% impact for all the perspectives. Damage by climate change (CC) category can be noticeably seen in Individualist perspective (~17%) but not for Egalitarians (3.35%) and Hierarchists (2.6%).

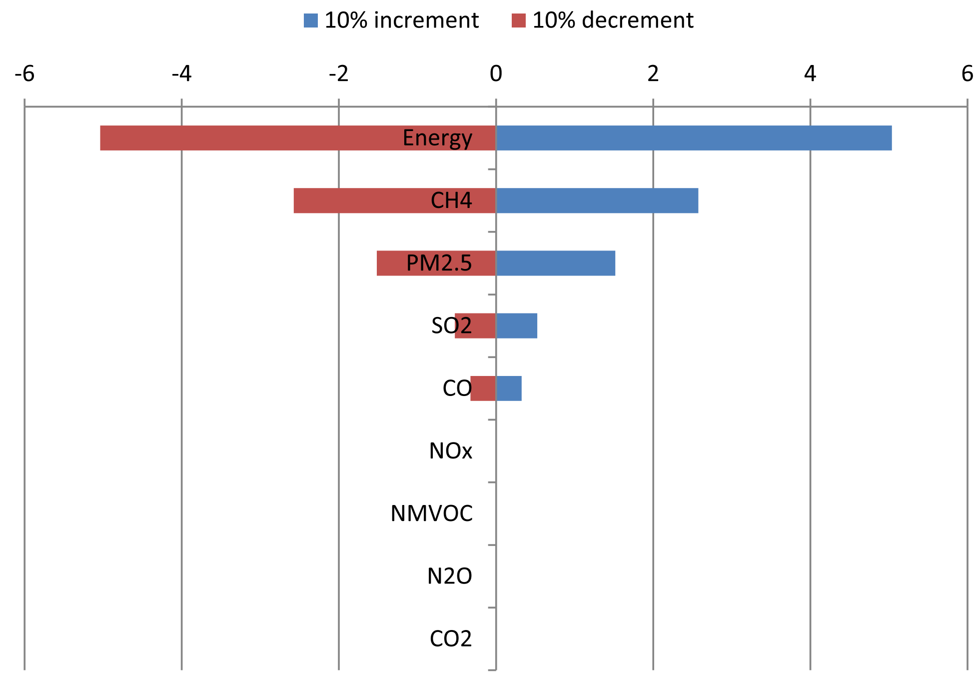


Fig. 6 Percentage deviation in EIC due to % change in 'b' of particular component for Egalitarian perspective

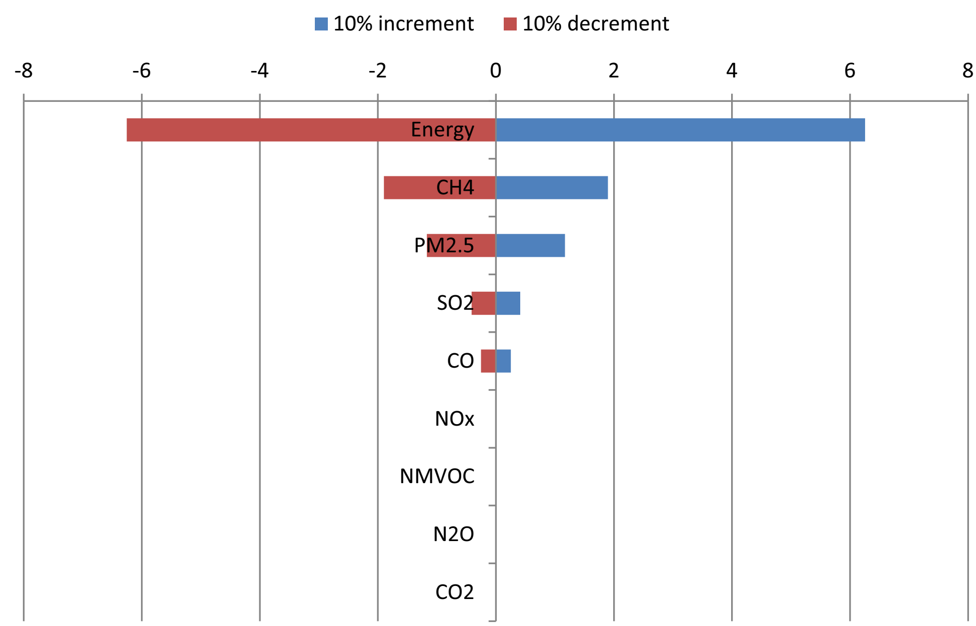


Fig. 7 Percentage deviation in EIC due to % change in 'b' of particular component for Hierarchist perspective

4.6 Sensitivity analysis

4.6.1 Sensitivity analysis for impact categories

Figures 6, 7 and 8 show the percentage deviation in EIC due to 10% increment and decrement in particular component (*b*) for various perspectives. This is obtained by varying a particular component and keeping all other parameters constant and then determining the change in EIC.

$$\text{Deviation in EIC}(\%) = \frac{\text{EIC}_{\text{new}} - \text{EIC}_{\text{base}}}{\text{EIC}_{\text{base}}} \times 100\%,$$

where EIC_{new} denotes the total EIC obtained after 10% change in a particular damage category and EIC_{base} denotes the total EIC without any changes.

For Egalitarians and Hierarchists, the variation of EIC with change in damage categories is almost similar. The maximum impact is due to energy (resources category $\sim$5 and 6%, respectively) and minimum is due to CO_2 (climate change category <0.001% for both). But for Individualists,

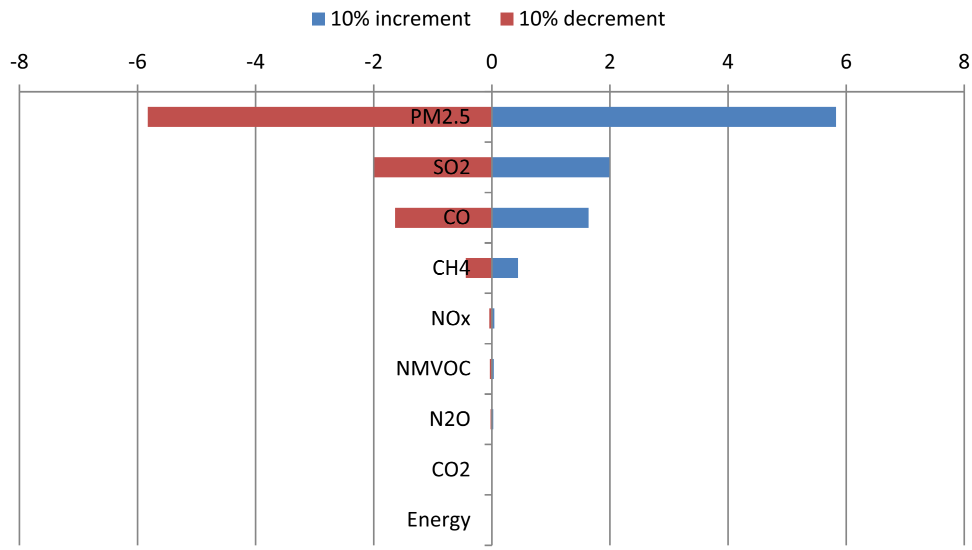


Fig. 8 Percentage deviation in EIC due to % change in 'b' of particular component for Individualist perspective

Table 16 Unitwise contribution to EIC for various perspectives. *Source*: Author's estimates

	Egalitarian	Hierarchist	Individualist
Pipeline	278,846.466	376,420.862	744,468.500
HDT	5,634,518.098	10,511,052.12	2,247,128.59
LDV	300,001.648	574,457.991	147,492.044
Pumping stations	22,468,261.51	40,257,017.45	9,265,377.068
Excavator	144,949.251	270,399.191	57,807.891
Side walls	3,224,637.311	4,353,007.488	8,609,185.32
Manhole cover	348,845.384	474,144.692	920,836.664
Bed	374,086.214	504,987.053	998,741.016
Total	32,774,145.88	57,321,486.85	22,991,037.09

maximum variation is due to $PM_{2.5}$ (respiratory inorganic ~6%) and least is due to energy (resource category 0%) and CO_2 (climate change category <0.01%). For Individualists, energy and associated resource depletion is not a major concern, because of their short-time perspective. Therefore, the impact of resource category is taken to be zero, and a business-as-usual attitude is advocated by them. Similar is the case for climate change category, which has long-term consequences, and in case of Individualists, these parameters do not contribute much to the variation of EIC. This is not the case for the other two perspectives, where long-term effects are more focused on. Therefore, energy and climate change affecting parameters have greater impact on EIC for Egalitarians and Hierarchists. Effect of CH_4 is more prominent in Egalitarian (2.6%) and Hierarchist (1.9%) perspectives, whereas it contributes to merely 0.5% for Individualist perspective. The respiratory organic category does not contribute significantly to EIC. The variation in EIC due to acidification and eutrophication category varies nearly 0.6% for Egalitarians and Hierarchists and about 2% for Individualists for 10% change in SO_2 and NO_x. Apart from studying the effect of various damage categories to EIC for various perspectives, it is prudent to analyse the impact of various components of collection phase studied on the total EIC (Table 16).

The contribution to EIC is maximum by pumping stations in all the three perspectives, contributing to 68.5% for Egalitarians, ~70% for Hierarchists and 40.3% for Individualists. This is followed by usage of HDTs in Egalitarian (17%) and Hierarchist (18.3%) perspective, whereas construction of side walls (37.5%) for Individualist perspective. The excavator contributes the least to EIC in all the three perspectives (<0.5%). The EIC is dominated by operation and maintenance phases for Egalitarians and Hierarchists, whereas both construction and operation phases contribute evenly to EIC in Individualist perspective. Manhole unit represents nearly 46% of the total EIC in case of Individualists, whereas about 10% of EIC for the other two perspectives. The sensitivity analysis of individual units is discussed in the subsequent sections.

Fig. 9 Percentage variation of EIC with 10% decrease in BSFC for various perspectives

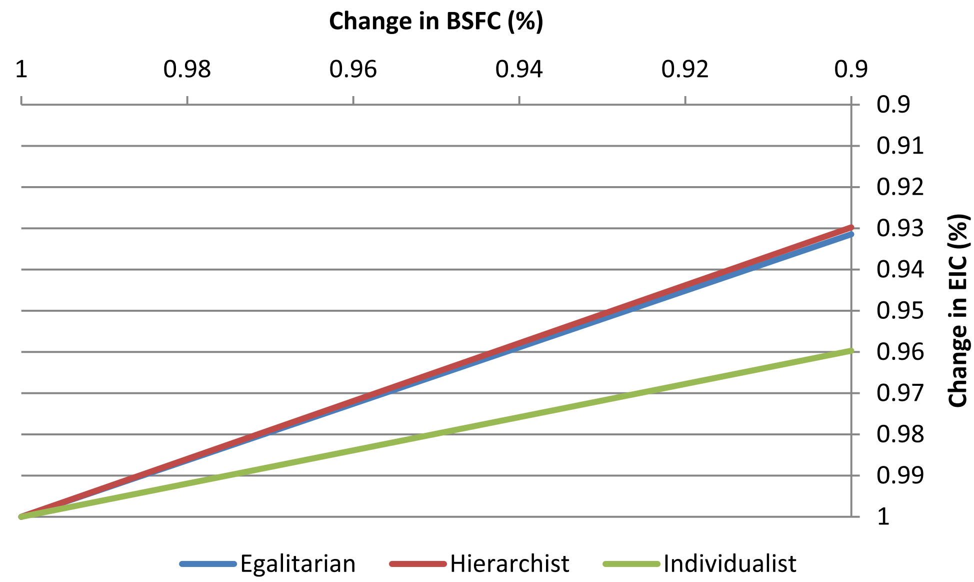


Table 17 Emission factors and total emissions due to brick masonry used for manholes. *Source*: Author's estimates

	$PM_{2.5}$	SO_2	NO_x	CO	CO_2
Emission factor (g/brick)[a]	6.8	4.6	4.7	90	520
Emissions (tonnes)	185.34	125.38	2453.04	14,173.12	128.10
% change with respect to use of concrete	66.69	211.98	1970.28	51,751.80	873.08

[a] *Source*: Guttikunda et al. (2013)

4.6.2 *Improved efficiency of pumping stations*

Pumping stations are the most energy-intensive unit and contribute significantly to atmospheric emissions. For the pumps taken into consideration, the most important parameter affecting the fuel usage is the brake specific fuel consumption (BSFC). Assuming a reduction of 10% in BSFC of the pumps used, we analyse the variation of EIC. With the decrease in BSFC, diesel consumed per MLD of sewage pumped reduces, and thus, the energy requirements for operation of pumps will decrease (Fig. 9). The EIC reduces to approximately 93% for Egalitarian and Hierarchist perspective, and up to 96% for Individualists.

4.6.3 *Variation of manhole materials*

Clay bricks are one of the common materials used for infrastructure construction in India (Kumbhar et al. 2014). For the current study, nearly 272.5 million bricks are required for construction of side walls and bed. Table 17 lists the life-cycle emissions due to use of clay bricks for manhole construction. Also a comparison has been presented with concrete as the construction material, which is used in the current study.

The fuel used for brick production is essentially coal (nearly 20 tonnes/million bricks). With a calorific value of 0.022 GJ/kg (Guttikunda et al. 2013), total energy consumption amounts to 11,926.4 GJ. This is nearly 400 times the energy consumed when the material used in concrete.

4.7 Implications for sustainable design and water–energy nexus

The net life-cycle outputs indicate that manhole unit is the major contributor towards atmospheric emissions. This is mainly from the concrete used in construction of side walls. Use of concrete as raw material for manholes is environmentally friendlier than the commonly used clay bricks (Sect. 4.6.3). However, for further reduction in emissions, low-carbon concrete can be preferred for manhole construction. This can be achieved by using different cement mix for concrete manufacturing which can result in about 4.6–24% reduction in CO_2 emissions (Kim et al. 2013; Limbachiya et al. 2014). Concrete production also involves non-value adding activities which contribute to an increase in the carbon emissions. Wu et al. (2013) list out these activities and suggest the use of green building material and adoption of better guidance practices to achieve low-carbon installations in concrete manufacturing units. For more radical reductions in CO_2 emissions from concrete production, CO_2 capture processes may also be thought of in the cement sector (Li et al. 2013).

Pumping stations and transportation unit have the largest share in the total energy consumption and GHG emissions. We have assumed the use of diesel as the primary fuel for operation of HDT and LDV and also excavators. Under low-carbon scenario with 2° policy, electric vehicles will play an important role in the Indian transport sector and will contribute appreciably to mitigation of emissions (Shukla et al. 2014). Increasing the fuel efficiency and fuel quality standards in these units will also add to reduction in energy usage and emissions. Use of renewable energy for power production is an effective way of decreasing the environmental impacts from pumping stations. Pumping stations running on photo-voltaic (PV) motor pumps have been incorporated in various irrigation and water supply facilities. The normalized cost of energy and life-cycle costs for PV pumping stations is 61 and 30% lesser than diesel pumping stations (Chandel et al. 2015; Gherbi et al. 2017). These can be thus be used in wastewater systems for sustainable design of collection phase units.

Increasing population, stricter water quality norms and rising energy prices and concerns regarding climate change pose risks of increased energy usage and costs for wastewater systems. Energy consumed at various stages of the collection phase of sewerage system is closely associated with water resources. A considerable amount of water is used in concrete production, operation of pumping stations and extraction of fuels for transportation segment. In the face of growing need for wastewater treatment for cleaner water resources, utilization of water resources at various stages of wastewater cycle must be carefully planned to avoid potential water crisis. Furthermore, the stringent water quality norms for disposal of wastewater to water bodies have led to adopting water-intensive treatment techniques. This necessitates the evaluation of water–energy nexus in wastewater system. The reuse phase such as production of energy from secondary/tertiary treatment by-products such as sludge and methane must be given emphasis so as to recover a part of the expended energy. This can help to reduce the net energy requirements, thereby reducing the water requirement.

5 Conclusion

This paper presents a case study of a typical Indian sewerage network to carry out life-cycle assessment of wastewater supply systems. The total energy requirements and atmospheric emissions from the major units of collection phase have been calculated based on real-time data, and its effect on different societal perspectives has been studied. This is the first Indian study to carry out a detailed analysis of the collection phase of wastewater life cycle and quantify the environmental impact of various damage categories using EIC, to the best of our knowledge.

The net life-cycle outputs are dominated by the operation and maintenance units of the collection phases. In all the three perspectives, energy consumption has maximum impact on the overall EIC, and major source of impact is the intermediate pumping of wastewater. Sensitivity analysis carried on in pumping station units shows that increasing the efficiency of pumps will curb their environmental impacts considerably. Also, local topography and proper networking of pipelines are important criteria to be taken into account for designing the overall sewerage system.

In order to estimate the overall environmental effects of the sewerage system, treatment and disposal phases should also be taken into account. Various studies have indicated that the treatment units contribute significantly to the energy usage as well as methane emissions. Apart from the construction of various units, renovation and modernization at regular intervals also considerably affect the environmental assessment of the sewerage system (Morera et al. 2016). Therefore, these factors can be coupled together to provide a more improved evaluation of the environmental impacts of Indian sewerage system.

Acknowledgements The first author would like Prof. S.S. Mahapatra and Udayan Singh, NIT Rourkela, for their continuous support and guidance throughout the work. We also thank the three anonymous reviewers for their valuable suggestions.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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