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Estimation of greenhouse gas emissions from sewer pipeline system

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Abstract

Purpose The aim of this study was to estimate the total greenhouse gas (GHG) emissions generated from whole life cycle stages of a sewer pipeline system and suggest the strategies to mitigate GHG emissions from the system.

Methods The process-based life cycle assessment (LCA) with a city-scale inventory database of a sewer pipeline system was conducted. The GHG emissions (direct, indirect, and embodied) generated from a sewer pipeline system in Daejeon Metropolitan City (DMC), South Korea, were estimated for a case study. The potential improvement actions which can mitigate GHG emissions were evaluated through a scenario analysis based on a sensitivity analysis.

Results and discussion The amount of GHG emissions varied with the size (150, 300, 450, 700, and 900 mm) and materials (polyvinyl chloride (PVC), polyethylene (PE), concrete, and cast iron) of the pipeline. Pipes with smaller diameter emitted less GHG, and the concrete pipe generated lower amount of GHG than pipes made from other materials. The case study demonstrated that the operation (OP) stage (3.67×10^4 t CO_2eq year^{-1}, 64.9%) is the most significant for total GHG emissions (5.65×10^4 t CO_2eq year^{-1}) because a huge amount of CH_4 (3.51×10^4 t CO_2eq year^{-1}) can be generated at the stage due to biofilm reaction in the inner surface of pipeline. Mitigation of CH_4 emissions by reducing hydraulic retention time (HRT), optimizing surface area-to-volume (A/V) ratio of pipes, and lowering biofilm reaction during the OP stage could be effective ways to reduce total GHG emissions from the sewer pipeline system. For the rehabilitation of sewer pipeline system in DMC, the use of small diameter pipe, combination of pipe materials, and periodic maintenance activities are suggested as suitable strategies that could mitigate GHG emissions.

Conclusions This study demonstrated the usability and appropriateness of the process-based LCA providing effective GHG mitigation strategies at a city-scale sewer pipeline system. The results obtained from this study could be applied to the development of comprehensive models which can precisely estimate all GHG emissions generated from sewer pipeline and other urban environmental systems.

Keywords GHG emissions · Process-based LCA · Scenario analysis · Sensitivity analysis · Sewer pipeline system

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Nomenclature

DMC	Daejeon Metropolitan City
MP	Material production
MT	Material transportation

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CO	Construction
OP	Operation
MI	Maintenance
EL	End of life
PE	Polyethylene
PVC	Polyvinyl chloride
D150	Pipeline with 150 mm of diameter
D300	Pipeline with 300 mm of diameter
D450	Pipeline with 450 mm of diameter
D700	Pipeline with 700 mm of diameter
D900	Pipeline with 900 mm of diameter
C	Current construction plan (construction with 100% PVC pipe)
P1	plan 1 (construction with 100% PE pipe)
P2	Plan 2 (construction with 100% concrete pipe)
P3	Plan 3 (construction with 50% PVC and 50% PE pipe)
P4	Plan 4 (construction with 50% PVC and 50% concrete pipe)
P5	Plan 5 (construction with 50% PE and 50% concrete pipe)
E_{MP}	GHG emissions from material production stage (kg CO_2eq)
E_{MT}	GHG emissions from material transportation stage (kg CO_2eq)
E_{CO}	GHG emissions from construction stage (kg CO_2eq)
E_{OP}	GHG emissions from operation stage (kg CO_2eq)
E_{MI}	GHG emissions from maintenance stage (kg CO_2eq)
E_{EL}	GHG emissions from end of life stage (kg CO_2eq)
$EF_{m(i)}$	GHG emission factor of raw materials (i: PVC, PE, concrete, cast iron, and other raw materials) (kg CO_2eq kg^{-1})
$M_{m(i)}$	Mass of pipe material (kg)
$EF_{t(j)}$	GHG emission factor for transportation (j: road, ship, and railway) (kg CO_2eq (kg-km)$^{-1}$)
$D_{m(i)}$	Transportation distance of pipe material (km)
$D_{ex,m(i)}$	External diameter of pipeline (mm)
$D_{in,m(i)}$	Internal diameter of pipeline (mm)
$L_{m(i)}$	Length of pipeline (km)
$\rho_{m(i)}$	Density of pipe material (kg m^{-3})
$EF_{e(k)}$	GHG emission factor for construction equipment (k: excavator and dump truck) (kg CO_2eq t^{-1}) or (kg CO_2eq m^{-3})
$Eff_{CO,e(k)}$	Efficiency of construction equipment k (t h^{-1}) or (m^3 h^{-1})
$t_{CO,e(k)}$	Construction hour of equipment for installing 1-m pipeline (h km^{-1})
$EF_{tc(l)}$	GHG emission factor of trench construction materials (l: sand and gravel) (kg CO_2eq kg^{-1})

$M_{tc(l)}$	Mass of trench construction material per kilometer of pipes (kg km^{-1})
$E_{CH4,t}$	Direct CH_4 emissions during conveyance of sewage (kg CO_2eq)
Q	Flow rate of sewage (m^3 year^{-1})
$Rate_b$	Microbial reaction rate by methanogenic biofilm (kg m^{-2} h^{-1})
$A/V_{m(i)}$	Surface area to volume ratio of pipe (m^{-1})
HRT	Hydraulic retention time of the sewage (h)
E_{pump}	GHG emissions from pump stations (kg CO_2eq)
$EF_{electricity}$	GHG emission factor for electric energy generation (kg CO_2eq kWh^{-1})
$C_{electricity}$	Annual electricity consumption (kWh year^{-1})
$ratio_{m(i)}$	Replacement ratio of pipeline
$EF_{d(m)}$	GHG emission factor for disposal treatment (m: incineration, landfill, or recycle) (kg CO_2eq kg^{-1})
$\%_{d(m)}$	Proportion of disposal treatment (%)

1 Introduction

Life cycle assessment (LCA) is a widely known technique to evaluate the environmental impact of a wide spectrum of targets throughout their entire life cycles (ISO 2006). LCA has been successfully used to investigate main environmental impacts of urban water infrastructures such as water and wastewater treatment plants (WTPs and WWTPs), and its results have suggested several options to minimize the impacts (Filion 2008; Hospido et al. 2008; Strutt et al. 2008; Pasqualino et al. 2009; Stokes and Horvath 2009; Lee et al. 2012; Nessi et al. 2012; Kyung et al. 2013, 2015).

Sewer pipeline systems require government-driven investment due to high material and construction costs to cover whole service area (Stokes and Horvath 2010; Zhang et al. 2012) like WTPs and WWTPs. Continuous maintenance cost is also required to run the systems properly and avoid potential system malfunction leading to road subsidence and harmful gas (CH_4 and H_2S) leakage (Yuan et al. 2008; Ana and Bauwens 2010; Risch et al. 2015). In addition, it has been highlighted that massive amounts of greenhouse gas (GHG) such as CO_2, CH_4, and N_2O are generated from sewer pipeline systems due to high consumption of electric energy and materials and biochemical reactions, resulting in a significant contribution to the carbon footprint (CPSA 2011; Venkatesh et al. 2011; Petit-Boix et al. 2015; Risch et al. 2015; Eijo-Río et al. 2015; Morera et al. 2016). Under the circumstances, effective management plans for sewer pipeline system should be set up, based on accurate estimation of GHG emissions.

LCA has been applied to the environmental assessment of sewer pipeline systems to quantitatively estimate the GHG emissions and investigate significant factors affecting the GHG emissions. However, previous studies have been

performed within limited system boundaries. They have usually focused on the estimation of energy consumption for the production of pipe materials and GHG emissions from main life cycle stages (e.g., construction, operation, and maintenance) of sewer pipeline systems. Few studies have considered direct GHG emissions (i.e., formation of CH_4 and N_2O during the movement of sewage through the pipeline and its degradation) and city-scale electric energy consumption during the operation of sewer pipeline systems (Yuan et al. 2008; Foley 2009; Venkatesh et al. 2009, 2011; Listowski et al. 2011; Piratla et al. 2011; Zhang et al. 2012; Petit-Boix et al. 2014, 2016). Therefore, the system boundary of a sewer pipeline system should be extended to include all life cycle stages and consider direct GHG emissions and electric energy consumption at city scale (Gurney et al. 2012).

Hence, the main goal of this study is to estimate GHG emissions from each life cycle stage of a sewer pipeline system within the entire system boundary. In this study, (1) we have applied the process-based LCA with a city-scale inventory database of a sewer pipeline system to a real system for a case study, (2) identified significant factors affecting GHG emissions during each life cycle stage using sensitivity analysis, and (3) suggested the proper strategies that could effectively mitigate GHG emissions from the sewer pipeline system by analyzing promising scenarios.

2 Methodology

2.1 System boundaries

System boundaries (Fig. 1) include the entire life cycle stages of a sewer pipeline system: (1) material production (MP), (2) material transportation (MT), (3) construction (CO), (4) operation (OP), (5) maintenance (MI), and end of life (EL). Three categories of GHG emissions defined in the GHG protocol (scopes 1, 2, and 3) were estimated from each life cycle stage by adopting an inventory database. Scopes 1 and 2 (herein, direct and indirect) emissions are due to CH_4 generation by biofilm reaction from a sewer pipeline system and consumption of electric energy for each life cycle stage, respectively. For the estimation of direct emissions, N_2O generation by biochemical reaction from a sewer pipeline system was excluded from this work, due to the lack of reliable data. Scope 3 (herein, embodied) emissions stem from energy consumption required by all the activities associated with a material production for on-site use. The functional unit was defined as the transport of the sewer generated in a year (m^3 $year^{-1}$). The time horizon of the sewer pipeline system was assumed to be 20 years regardless of pipe materials, based on the expected minimum lifespan of Korean sewer pipeline system (MoE 2007). Emission categories with inventories and methods to estimate GHG emissions from each life cycle stage are summarized in Table 1. The amounts of GHG emissions were expressed in

CO_2 equivalents (kg CO_2eq) by referring its global warming potential (GWP) over a 100-year period (IPCC 2007b).

2.2 Case study: GHG emissions from the sewer pipeline system in DMC

The combined sewer pipeline system in Daejeon Metropolitan City (DMC) was selected for a case study to estimate city-scale GHG emissions with the process-based LCA due to the ease of data access and acquisition. DMC is one of the largest cities in South Korea, and the population and area of DMC are 1.5 million and 539.8 km^2, respectively. Wastewater generated by DMC households is collected and conveyed through the pressurized and gravity sewer pipelines (semi-anaerobic) to two WWTPs treating 900,000 m^3 day^{-1} (Yuseong-gu) and 1000 m^3 day^{-1} (Seo-gu), respectively (Fig. S1, Electronic Supplementary Material). There are seven pump units to convey wastewater (136 × 10^6 m^3 $year^{-1}$) in the sewer pipeline system. The total length of the sewer pipeline is 1940 km, and it is composed of various types of materials (PVC 0.5%, PE 11.2%, concrete 87.3%, and cast iron 0.8%). The rest of 0.2% was not listed in the database and excluded from this work. The size of the pipelines and their proportions in the DMC system are summarized as follows: 150 mm (D150, 2.0%), 300 mm (D300, 29.8%), 450 mm (D450, 34.4%), 700 mm (D700, 25.0%), and 900 mm (D900, 8.8%), and more detailed information is described in Table S1 in the Electronic Supplementary Material (MoE 2011a).

2.2.1 Data inventory

All data, i.e., life cycle inventory of the sewer pipeline system in DMC and GHG emission factors (midpoint impact indicator evaluated in a unit CO_2 equivalent) used to estimate GHG emission at each life cycle stage are specifically demonstrated in Tables 2 and 3. MP stage data was acquired from the specifications of pipe production provided by the manufacturers. Based on the specifications (Table S2, Electronic Supplementary Material), the mass of the pipe products per unit length (kg m^{-1}) were calculated. Data for MT and CO stages were obtained from the construction specification (MoE 2010) and POSCO, one of representative construction corporations (Seoul, South Korea). Data for OP, MI, and EL stages were collected from the national statistics data for sewer pipeline systems (MoE 2011a, 2011b). The GHG emission factors of pipe materials, sand, gravel, manhole, and lorry for transportation were obtained from an inventory database, Ecoinvent Ver. 2.1 (Ecoinvent 2006). The GHG emission factor for electric energy generation (0.5584 kg CO_2eq kWh^{-1}) calculated based on the national statistics data for electric power generation (KEPCO 2011) was used to estimate GHG emissions produced by electric energy consumption (Kyung et al. 2013, 2015).
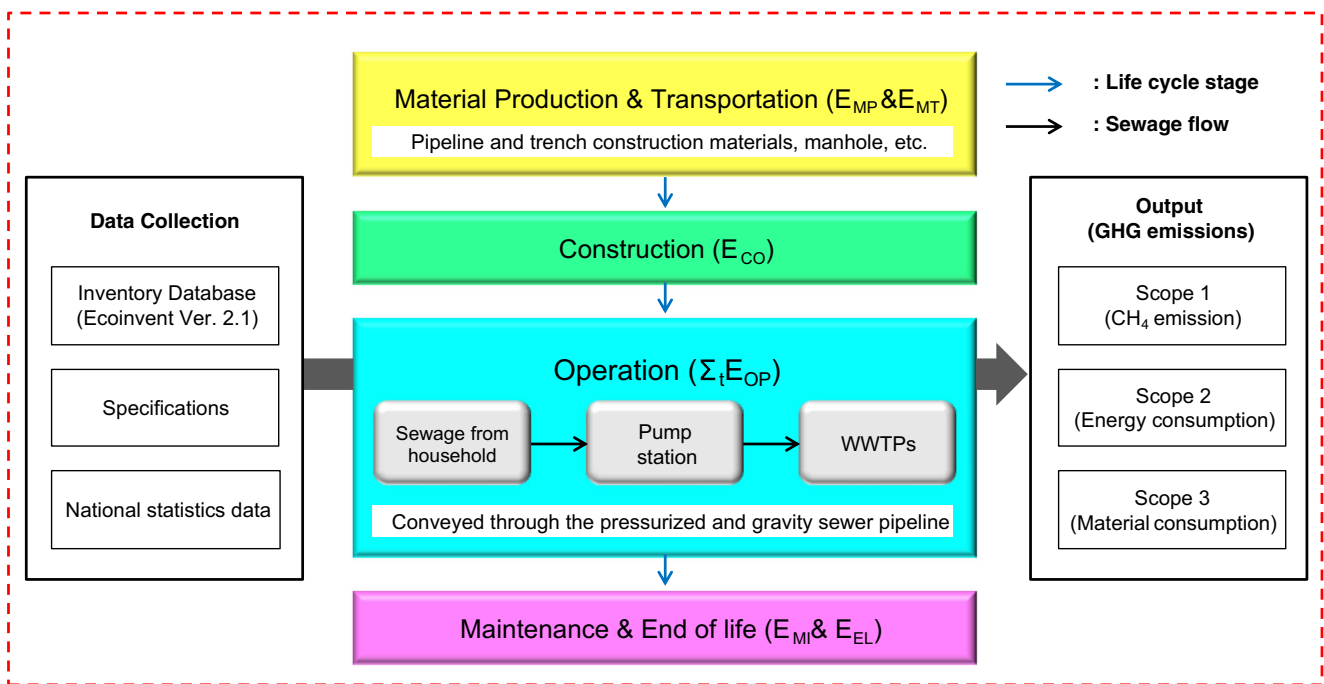
Fig. 1 System boundary for the estimation of GHG emissions from sewer pipeline system

2.2.2 Estimation of GHG emissions at each life cycle stage

In this study, the GHG emissions were calculated through the Intergovernmental Panel on Climate Change (IPCC) method. The total GHG emissions from a sewer pipeline system (E_{Total}) is the summation of those from all life cycle stages (MP, MT, CO, OP, MI, and EL), and it can be expressed as Eq. 1. GHG emissions from the MP, MT, and CO stage (E_{MP}, E_{MT}, and E_{CO}) were estimated based on the actual construction process, i.e., POSCO E&C, Chung-ju sewer pipeline Build-Transfer-Lease (BTL) project. GHG emissions from the OP stage (E_{OP}) were estimated over the time horizon of a sewer pipeline system. GHG emissions from MI and EL stages (E_{MI} and E_{EL}) were calculated by considering replacement ratio of pipeline and manholes.

$$E_{Total} = E_{MP} + E_{MT} + E_{CO} + \sum_t E_{OP} + E_{MI} + E_{EL} \tag{1}$$

The amounts of raw materials consumed to make pipelines ($M_{m(i)}$) were derived from their volume and density (Eq. 2). GHG emissions from the MP stage (E_{MP}) were estimated by multiplying the consumed mass with the emission factor for each raw material ($EF_{m(i)}$) as described in Eq. 3.

$$M_{m(i)} = \left(D^2_{ex,m(i)} - D^2_{in,m(i)}\right) \times \frac{\pi}{4} \times L_{m(i)} \times \rho_{m(i)} \tag{2}$$

$$E_{MP} = \sum_{m(i)} \left(EF_{m(i)} \times M_{m(i)}\right) \tag{3}$$

GHG emissions from the MT stage (E_{MT}) were estimated by Eq. 4. Road transportation (3.5–16 t trunks) was assumed as the main type of transportation rather than other types of

Table 1 Emission categories with inventories and methods to estimate GHG emissions

Stage	Category	Inventory	Method	Data source
MP	Scope 3	Material consumption for pipeline	Process-based LCA	Product specification
	Scope 3	Material consumption for manhole	Process-based LCA	Product specification
	Scope 3	Material consumption for pump station	Process-based LCA	Product specification
MT	Scope 2	Fuel consumption for transporation	Process-based LCA	Personal interview
CO	Scope 2	Fuel consumption for equipment use	Process-based LCA	Personal interview
OP	Scope 1	Methane formation by biofilm reaction	Empirical equation	Foley (2009)
	Scope 2	Electricity consumption for pump stations	Process-based LCA	Sewer statistics
MI	Scope 3	Material consumption for maintanace activities	Process-based LCA	Sewer statistics
EL	Scope 3	Disposal plan for materials	Process-based LCA	Waste statistics

Table 2 Life cycle inventory of the sewer pipeline system in DMC and the variables for the each life cycle stage

Stage	Inventory[a]		Value	Distribution type	Uncertainty characterization[d]
MP	Pipe length (km)	PVC	10	Normal	CV = 20%
		PE	218	Normal	CV = 20%
		Concrete	1695	Normal	CV = 20%
		Cast iron	15	Normal	CV = 20%
	Manhole (unit)		48,980	Normal	CV = 15%
	Pump station (unit)		7		
	Installment ratio (%)	D150	2.0		
		D300	29.8		
		D450	34.4		
		D700	25.1		
		D900	8.7		
MT	Transporation distance (km)		100	Normal	CV = 15%
CO	Excavating (kg km^{-1})		22,000		
	Distance of equipment (km km^{-1})		1		
	Trench construction (kg km^{-1})	Sand	1.92×10^5	Normal	CV = 10%
		Gravel	60,060	Normal	CV = 10%
OP	Electricity consumption for pump stations (MWh year^{-1})[b]		1722	Normal	CV = 20%
	Generated sewage (m^3 year^{-1})		1.36×10^8	Normal	CV = 10%
	Flowrate (m^3 year^{-1})		4.96×10^{-10}	Normal	CV = 10%
	Biofilm reation rate (kg m^{-2} h^{-1})		5.24×10^{-5}	Normal	CV = 15%
MI	Replaced pipe length (km)		23		
	Replaced manhole (unit)		667		
	Pipe replacement ratio		0.199	Normal	CV = 10%
	Manhole replacement ratio		0.271	Normal	CV = 10%
EL	Main disposal treatment[c]	PVC	Incineration		
		PE	Incineration		
		Concrete	Recycling		
		Cast iron	Landfill		
		Manhole	Landfill		

[a] The inventory was prepared based on sewer statistics (MoE 2011a)

[b] Details in electric energy consumption at pump stations are demonstrated in Table S3 (DDI 2008)

[c] Disposal plan includes 18% recycle and 82% incineration for both PVC and PE pipe, 99% recycle and 1% incineration for concrete pipe, and 44% recycle and 56% landfill for both cast iron pipe and manhole (MoE 2011b)

[d] The coefficient of variation (CV) was determined by previous statistics data from the sewer pipeline system in DMC

vehicles, such as ship and railway. The transportation distance was determined based on the actual distance between a pipe material manufacturer and a construction site:

$$E_{MT} = \sum_{m(i)} \sum_{t(j)} \left(EF_{t(j)} \times M_{m(i)} \times D_{m(i)} \right) \qquad (4)$$

GHG emissions from the CO stage (E_{CO}) were estimated based on the fuel consumption of construction equipment used for excavating and filling the ground, installing sewer pipes, and hardening the construction (Eq. 5). It was assumed that sand and compacted soil (i.e., gravel) were used for trench construction regardless of the pipe material and the depth of the trench.

$$E_{CO} = \sum_{m(i)} \sum_{e(k)} \left(EF_{e(k)} \times t_{CO,e(k)} \times Eff_{CO,e(k)} \times L_{m(i)} \right)$$
$$+ \sum_{m(i)} \sum_{tc(l)} \left(EF_{tc(l)} \times M_{tc(l)} \times L_{m(i)} \right) \qquad (5)$$

GHG emissions from the OP stage (E_{OP}) over the time horizon are the summation of direct GHG emission by biochemical reaction (CH_4) and indirect GHG emission by electric energy consumption of pump stations (Table S3, Electronic Supplementary Material) (Eq. 6). Some advanced mathematical modeling tool (e.g., SeweX) can characterize the in-sewer physical, chemical, and biological processes and make it possible to predict both spatial and temporal variation of CH_4 and other parameters (H_2S, N_2, and N_2O). To

Table 3 GHG emission factors for raw materials and energy consumption

	Value	Unit	Reference
Concrete	0.4828	kg CO_2eq kg^{-1}	Ecoinvent (lightweight concrete block)
PVC	3.2335	kg CO_2eq kg^{-1}	Industry data 2.0 (PVC pipe E)
PE	2.4815	kg CO_2eq kg^{-1}	Industry data 2.0 (HDPE pipes E)
Cast iron	1.4787	kg CO_2eq kg^{-1}	Ecoinvent (cast iron)
Sand	0.0024	kg CO_2eq kg^{-1}	Ecoinvent (sand)
Gravel	0.0044	kg CO_2eq kg^{-1}	Ecoinvent (gravel, crushed)
Manhole	228.96	kg CO_2eq EA^{-1}	Ecoinvent (cast iron), Industry data 2.0 (PVC calendared sheet E)
Pump station	159,864	kg CO_2eq EA^{-1}	Ecoinvent (pump station)
Transportation	0.257	kg CO_2eq·(t km)$^{-1}$	Ecoinvent (transport, lorry 3.5–16 t, fleet average)
Excavator	0.002	kg CO_2eq kg^{-1}	ELCD (excavator, technology mix)
Electricity	0.5584	kg CO_2eq kWh^{-1}	KEPCO (2011)
Disposal, concrete	1.1347	kg CO_2eq kg^{-1}	Ecoinvent (disposal, concrete)
Disposal, PVC	5.1088	kg CO_2eq kg^{-1}	Ecoinvent (disposal, PVC)
Disposal, PE	4.5982	kg CO_2eq kg^{-1}	Ecoinvent (disposal, PE)
Disposal, cast iron	1.4831	kg CO_2eq kg^{-1}	Ecoinvent (disposal, cast iron)
Disposal, manhole	195	kg CO_2eq EA^{-1}	Ecoinvent (disposal, building, bulk iron)

estimate the CH_4 emission with the model, the key parameters such as physical properties (pipe length, diameter, and slope), hydraulic properties (velocity and flow rate of wastewater), and wastewater characteristics (organic matter concentrations in wastewater, pH, and temperature) are needed. However, due to the lack of those data, the CH_4 emission was empirically estimated in the present study (Eq. 7). Hydraulic retention time (HRT) and surface area to volume ratio ($A/V_{m(i)}$) were obtained from specifications of pipeline. Microbial reaction rate ($Rate_b$) was estimated by empirical field data in a city (Foley 2009). To estimate the GHG emissions from pump operation, the electric energy consumed at pump stations ($C_{electricity}$) were multiplied with the GHG emission factor for electric energy generation ($EF_{electricity}$) as shown in Eq. 8.

$$\sum_t E_{OP} = \sum_t \left(E_{CH_4} + E_{pump} \right) \quad (6)$$

$$E_{CH_4} = \sum_{m(i)} \left(Rate_b \times \frac{A}{V_{m(i)}} \times HRT \times Q \right) \quad (7)$$

$$E_{pump} = EF_{electricity} \times C_{electricity} \quad (8)$$

GHG emissions from the MI stage (E_{MI}) were calculated based on replacement ratio of pipeline and manholes (Eq. 9). The replacement ratio is described by the length of replaced pipeline and the amount of replaced manholes within the time horizon, and it was obtained by averaging past 10-year replacement data (Table S4, Electronic Supplementary Material). The removal of sediments accumulated in the pipeline was not included due to lack of data reported. However, its exclusion was not expected to underestimate the GHG emissions from the MI stage. GHG emissions from the EL

stage (E_{EL}) are highly correlated to the proportion of disposal treatment and the material replacement ratio (Eq. 10) because deteriorated pipeline and manholes should be disintegrated and treated:

$$E_{MI} = ratio_{m(i)} \times (E_{MP} + E_{MT} + E_{CO}) \quad (9)$$

$$E_{EL} = \sum_{m(i)} \sum_{d(m)} \left(EF_{d(m)} \times \%_{d(m)} \times ratio_{m(i)} \times M_{m(i)} \right) \quad (10)$$

3 Results and discussion

3.1 GHG emission factors of pipe materials with different diameters

The GHG emission factors (EF_{EST}: kg CO_2eq m^{-1}) of pipe materials (PVC, PE, concrete, and cast iron pipes) with different diameters (D150, D300, D450, D700, and D900) (Table 4) were calculated by using the data of raw materials (Table 3) and developed equations for the estimation of GHG emissions at MP stage (Eqs. 2 and 3). PVC pipes with diameters of 700 and 900 mm and a concrete pipe with a diameter of 150 mm were excluded because they were commercially unavailable.

Pipes with larger diameter showed higher EF_{EST} values because they consumed greater amounts of raw materials for pipe production resulting in higher embodied emissions, which is the greatest share in the life cycle (see details in Table S5, Electronic Supplementary Material). The increase in the EF_{EST} value with increased diameter varied depending on the pipe material. The EF_{EST} values of cast iron, concrete,

Table 4 The GHG emission factors of pipe materials with different diameters

Diameter (mm)	Emission factor, EF_{EST} (kg CO_2eq m^{-1})			
	PVC	PE	Concrete	Cast iron
150	83.7	73.6	N/A[a]	96.6
300	131.9	122.7	106.8	173.6
450	159.4	215.0	167.9	263.3
700	N/A[a]	432.8	311.4	466.2
900	N/A[a]	670.5	453.3	679.1

[a] PVC pipe with diameters larger than 700 mm and concrete pipe with diameters smaller than 150 mm are not commercially available

and PE pipe increased by 6.4, 4.2, and 5.5 times, respectively, when the pipe diameter was changed from 300 to 900 mm. The EF_{EST} values of the four pipe materials with the same diameter were different because different amount of energy was consumed in the MP stage due to the different characteristics of the raw materials. The result also corresponds to previous study reporting that plastic-made pipes (e.g., PE) are not competitive among large pipes because they are made of oil derivatives (Petit-Boix et al. 2014). Using concrete pipe resulted in the lowest EF_{EST} values among the four types of pipes with any diameter, except 450 mm. This is because the embodied GHG emissions of concrete per unit mass (0.48 kg CO_2eq kg^{-1}) are relatively lower than those of PVC (3.23 kg CO_2eq kg^{-1}), PE (2.48 kg CO_2eq kg^{-1}), and cast iron (1.48 kg CO_2eq kg^{-1}), although the mass of concrete pipe per unit length (kg m^{-1}) is heavier than that of other material pipe (Table S2, Electronic Supplementary Material). This indicates that the use of concrete pipeline could potentially reduce the GHG emissions from sewer pipeline systems. The decision on the selection of pipe materials has been commonly made by significant factors (cost, quality, longevity, etc.). Based on the result, the environmental factor for the mitigation of GHG emission should be also considered for a proper decision on the best selection of pipe materials. Previous studies also have shown that the EF_{EST} of concrete pipe was the smallest among various types of materials. However, the values of a Norwegian study (37.4 kg CO_2eq kg^{-1}) and a British study (31.0 kg CO_2eq kg^{-1}) were approximately three times smaller than those observed in the present study (Table S6, Electronic Supplementary Material) (CPSA 2011; Venkatesh et al. 2009). The reason for this difference is assumed to be the expanded system boundary; this work considered operation, maintenance, and end of life stages. Additionally, the emissions were estimated with novel emission factors and different database for life cycle inventory in this work.

3.2 GHG emissions from sewer pipeline system in DMC

The total GHG emissions from the sewer pipeline system in DMC were estimated with the life cycle inventory of sewer pipeline system in DMC (Table 2) and developed equations based on the reference GHG emission factors (Table 3) and EF_{EST} of pipe materials with different diameters (Table 4). Estimated GHG emissions from each life cycle stage (time horizon of the model = 20 years) in DMC and its contribution to the total GHG emissions are shown in Fig. 2a. The results indicate that the OP is the main GHG emission stage of the sewer pipeline system in DMC. GHG emissions via bio-chemical reaction (direct) and those from pump stations (indirect) were generated from the OP stage (3.67×10^4 t CO_2eq $year^{-1}$), covering 64.9% of the total GHG emissions (Fig. 2b). This is mainly due to the continuous CH_4 generation inside the sewer pipeline (3.51×10^4 t CO_2eq $year^{-1}$) and electric energy consumption for running pump stations (0.16×10^4 t CO_2eq $year^{-1}$) over 20 years, while other stages (MP, MT, and CO) emitted GHG once when pipelines were installed. Direct CH_4 emissions generated by biofilm reaction in the inner pipeline accounted for 95.6% of total GHG emissions at the OP stage; however, its significance has been overlooked before. Therefore, managing the direct CH_4 emission by reducing the biofilm and controlling hydraulic retention time (HRT) is necessary to effectively reduce the total GHG emissions from the sewer pipeline system in DMC.

The second largest GHG emissions occurred in the MP stage (9.10×10^3 t CO_2eq $year^{-1}$), occupying 16.1% of the total GHG emissions. This is because considerable amounts of raw materials and energy were consumed during the manufacturing process of pipes and manholes. The GHG emissions from the MP stage in the DMC sewer pipeline system are presented in Fig. 2c. Concrete pipe (D300, D450, D700, and D900) contributed the largest portion of GHG emissions (83.8%) in this stage because 87.4% of the pipeline (1676 km) installed in DMC is made of concrete. The installation rates of concrete pipes with D300, D450, D700, and D900 were 22.9, 31.7, 24.1, and 8.6%, respectively (Table S1, Electronic Supplementary Material). The GHG emissions from using concrete pipe with a 700-mm diameter (3.27×10^3 t CO_2eq $year^{-1}$) was the highest, occupying 35.8% of total emissions, despite its relatively small installment rate (24.1%). This is because pipes having larger diameter (D700 and D900) consumed more raw materials, which can lead to the generation of greater amounts of embodied GHG emissions during pipe production, as explained in the previous section. The results indicate that the amounts of embodied GHG emissions in the MP stage are highly dependent on the pipe diameter and installment ratio. This implies that the predicting the future demands and optimizing the pipe diameter and installment ratio during construction and/or replacement stages of the sewer pipeline system could effectively reduce embodied GHG emissions as well as cost from the MP stage. Additionally, improvement of manufacturing processes (e.g., extraction and injection molding) that consume intensive energy could be a solution to reduce GHG emissions from the MP stage (Carolin and Boonen 2011).
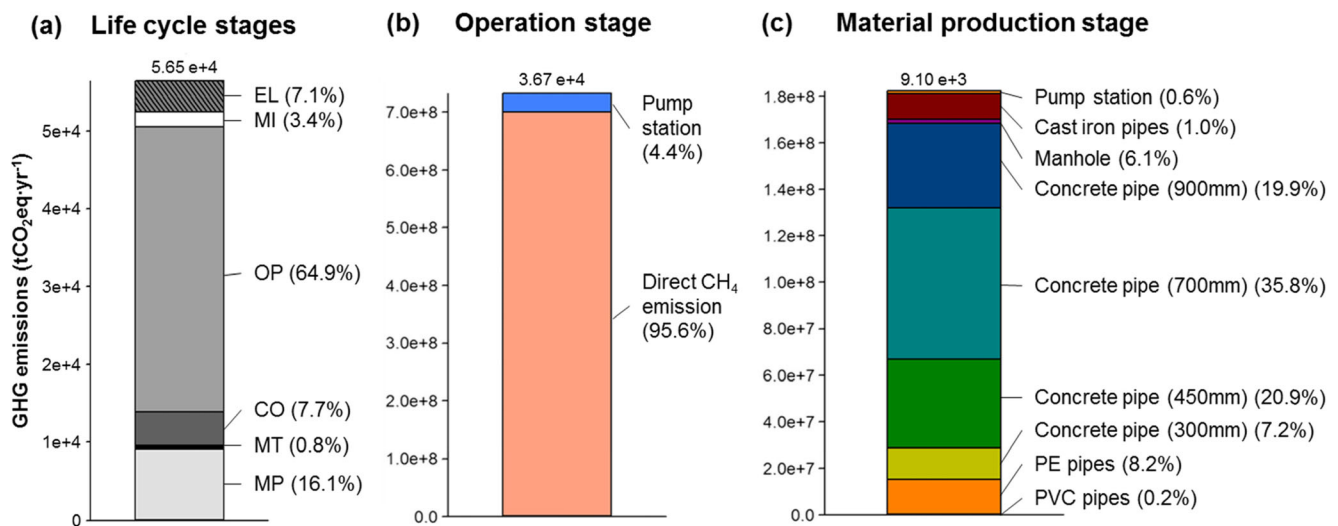
Fig. 2 GHG emissions from the **a** entire life cycle stages, **b** operation stage, and **c** material production stage

The third largest source of GHG emission in the DMC sewer pipeline system was the CO stage, contributing 7.7% of total GHG emissions. The emissions during the construction process are mainly due to the fuel combustion of excavators, which occupies 87% of the GHG emissions from the stage. Alternative construction methods such as trench-less technology may reduce energy consumption (Rehan and Knight 2007) by decreasing amount of excavation. The fourth and fifth largest sources were the EL (4.01×10^3 t CO_2eq year^{-1}) and MI stages (1.92×10^3 t CO_2eq year^{-1}). Since these emissions are related to the rehabilitation of the sewer pipeline system over a period of 20 years, these could be successfully reduced by (1) enhancing the lifespans of pipes and manholes, (2) improving the recycling ratio of deteriorated pipes, and (3) conducting periodic maintenance. The GHG emission from the MT stage took the smallest portion (0.8%) of total emissions at the transportation distance of 100 km.

The results presented are quite different compared to a previous study representing that the construction phase of the sewer infrastructure (e.g., onsite civil works) is the biggest contributor to climate change (Risch et al. 2015). This is probably due to the relatively simple inventory for civil work compared to the previous work. This study only considered excavating (fuel consumption), distance of equipment, and trench construction, while the previous study included more activities (e.g., pipes bedding with concrete and aggregates, civil works to build the sewer on site including machine construction, and road rehabilitation) for the estimation of GHG emissions. Another reason for this difference might be derived from the different operation of sewers and effect of direct GHG emissions. It has been reported that the operation of sewers highly depends on the type of city such as urban form, tradition, and climate (Petit-Boix et al. 2015). Moreover, the amounts of direct GHG emissions generated from sewers are significantly related with various physicochemical factors like

sewer components, temperature, flow rate, and pipeline designs (Foley 2009; Eijo-Río et al. 2015). Therefore, the largest contributor to GHG emissions would be changed during the whole life cycle stages of sewer pipeline system.

In this work, the amount of direct CH_4 emission (3.51×10^4 t CO_2eq year^{-1}) is greater than those of embodied (1.51×10^4 t CO_2eq year^{-1}) and indirect emissions (6.35×10^3 t CO_2eq year^{-1}) in the DMC sewer pipeline system. CH_4 emissions from unmanaged pipelines would possibly cause environmental disasters such as global warming and climate change because the GWP of CH_4 is 21 times higher than that of CO_2 over a 100-year period (IPCC 2007a). This implies that management of CH_4 emissions is the most effective way to reduce GHG emissions from the sewer pipeline system in DMC. Reducing sewage HRT for the discharging from households to WWTPs and optimizing A/V ratio of pipes would reduce the CH_4 emissions because the CH_4 formation rate is proportional to the sewage HRT and the A/V ratio of the pipes. Regular maintenance to prevent the formation of a biofilm layer inside the sewer pipeline also significantly reduces the CH_4 emissions. Furthermore, CH_4 gas collected from the sewer pipeline system can be used as an alternative energy source (Yuan et al. 2008). If the CH_4 gas generated from sewage pipeline systems in DMC is properly collected and used as an energy source instead of natural gas, it is expected that the economic value of CH_4 reuse could exceed $601,125 as a certified emission reduction (CER) unit with $27.07·(t CO_2)$^{-1}$, average price in EU emission trading system (CCC 2009).

3.3 Scenario analysis

The scenario analysis was carried out to determine suitable strategies that could effectively mitigate GHG emissions during the rehabilitation of 228 km of sewer pipeline system in DMC. A procedure for scenario analysis can be summarized

below: (1) sensitivity analysis to identify the significant factors affecting GHG emissions at each life cycle stage, (2) development of realistic scenarios reflecting the variation of the most significant factor in each life cycle stage (Hojer et al. 2008), and (3) comparison of the scenarios by estimating GHG reductions depending on the suggested strategies.

3.3.1 Sensitivity analysis

The factors used for the sensitivity analysis could be set up in different ways according to a variety of conditions and scenarios. The variables for the each life cycle stage and their ranges are listed in Table 2. A Monte Carlo simulation scheme provided by commercial software, Crystal Ball (Ver. 11.1), was used to analyze probabilistic data with defined probability distributions of variables (Table 2) and 100,000 trials were simulated with a 95% confidence interval. The coefficient of variation were determined by previous statistics data from the sewer pipeline system in DMC, and uncertainty assessments were conducted with defined normal distributions of variables to avoid negative random values of emissions during the simulation. The effect of variables on GHG emissions was evaluated by changing the variables in the selected ranges and observing the consequences.

According to the sensitivity analysis results (Table S7, Electronic Supplementary Material), the material of pipeline (70.6%) was the most significant factor for GHG emission in the MP stage. The most influential factor in the OP stage was the diameter of pipeline (59.8%), and biofilm reaction rate (19%) followed as the second significant factor. Regarding the CO stage, it was most strongly influenced by EF of excavator (71.7%). The pipe replacement ratio was the influential factor for GHG emissions in the EL (62.9%) and MI (32.2%) stage. The transportation distance directly influencing the GHG emission from the transportation of pipe materials was the most crucial factor affecting GHG emissions in the MT (99.2%) and MI (40.2%) stages.

3.3.2 Development of realistic scenarios

Four promising scenarios (scenarios A–D in Table 5) were developed based on the results from sensitivity analysis at each life cycle stage and future master plans for the sewer pipeline system in DMC (i.e., rehabilitation of 228 km of pipeline). In scenario A, we considered different combinations of material (P1–P5) for new installation and compared the results with current construction plan (C). In this scenario, pipe materials most frequently used in DMC (PVC, PE, and concrete) were only considered to estimate GHG emissions. In scenario B, increasing of the lifespan of pipelines was considered. We assumed that replacement ratio of new pipeline would be decreased by 15.0% compared with current situation (0.199). The increase of pipe lifespan would be possible by

improving pipe durability using a multilayer pipe technology (Carolin and Boonen 2011) and conducting proper maintenance and repair activities with a real-time monitoring system such as CCTV (Rolfe-Dickinson 2010). In scenario C, construction of new pipeline with different diameters (D150, D300, D450, D700, and D900) was considered because the sewer pipeline of DMC is currently oversized. Finally, the reduction of biofilm reaction rate was considered in scenario D. We assumed that the biofilm reaction rate of new pipeline would be reduced by 5.0% compared with current condition (5.24×10^{-5}). This would be possible according to the maintenance activities such as cleaning and dredging of inner pipeline.

3.3.3 Comparison of the scenarios

Scenario A showed that the lowest amount of GHG (6.41×10^3 t CO_2eq year^{-1}) was emitted with P4 (Fig. S2, Electronic Supplementary Material). The total GHG emissions from the sewer pipeline system would be reduced by 0.52×10^3 t CO_2eq year^{-1}, if the current plan (C: 100% PVC pipe) is changed to P4 (combination of 50% PVC and 50% concrete pipes). This result is mainly due to the decrease of embodied and direct emissions. Construction of a sewer pipeline system with 100% concrete pipe, having the lowest EF (P2), cannot be a better option compared to P4 or P5 (combination of PE and concrete pipe) to mitigate GHG emissions. This result is mainly due to the frequent use of small diameter PVC and PE pipes (< D300), compared to the use of concrete pipe. P1 (100% PE pipe) and P3 (combination of 50% PVC and 50% PE pipes) were the worst scenarios for the highest level of GHG emissions because of the high EFs of PE and PVC. Scenario B showed that 1.66% of total GHG emissions (0.11×10^3 t CO_2eq year^{-1}) can be reduced by increasing the lifespan of pipe material (Table S8, Electronic Supplementary Material). GHG emissions from the overall, MP, and OP stages under new pipeline construction (228 km) with D150, D300, D450, D700, and D900 pipes are summarized in Table S9 (Electronic Supplementary Material). Scenario C showed that GHG emissions were reduced by using pipelines with smaller diameter. The difference between the amounts of GHG emitted by D150 and D900 was equivalent to 1.29×10^3 t CO_2eq year^{-1}. Scenario D showed that 4.96% of total GHG emissions (0.26×10^3 t CO_2eq year^{-1}) can be reduced by decreasing the biofilm reaction rate (Table S10, Electronic Supplementary Material).

3.3.4 Strategies to mitigate GHG emissions from sewer pipeline system in DMC

Based on the scenario analysis results, we can suggest effective strategies to minimize GHG emissions from each life

Table 5 Four promising scenarios for reducing GHG emissions from sewer pipeline system in DMC

Scenario	Scenario details
A	228 km of pipes would be replaced by different combination of materials (C^a, P1[b], P2[c], P3[d], P4[e], and P5[f])
B	Replacement ratio of 228 km of pipes would be decreased by 15.0% with the improvement of pipe durability, proper maintenance, and repair activities
C	228 km of pipes would be constructed with different diameters of pipes (D150, D300, D450, D700, and D900)
D	Biofilm reaction rate of 228 km of pipes would be reduced by 5.0% according to the maintenance activities such as cleaning and dredging of inner pipeline

[a] C (current plan: construction with 100% PVC pipe)

[b] P1 (100% PE pipe)

[c] P2 (100% concrete pipe)

[d] P3 (50% PVC and 50% PE pipes)

[e] P4 (50% PVC and 50% concrete pipes)

[f] P5 (50% PE and 50% concrete)

cycle stage. As a long-term approach to obtain a sustainable sewer pipeline system, small diameter (<D300) pipe that reduces CH_4 emission could be used for the replacement of an older pipeline system (scenario C). A combination of PVC and concrete pipes can also be an option to significantly reduce GHG emissions (scenario A). On the other hand, improving the lifespans of pipe materials (scenario B) is not suggested as effective strategy due to the inefficient GHG reduction compared to other scenarios. As a short-term approach to manage current sewer pipelines, periodic maintenance activities (scenario D), such as frequent cleaning and dredging of the inner pipeline are highly recommended to reduce GHG emissions. The activities can effectively eliminate the biofilm causing a huge amount of direct CH_4 emission.

4 Conclusions

The process-based LCA was adopted to quantitatively estimate GHG emissions from whole life cycle stages of the combined sewer pipeline system in DMC as a case study. Based on the scenario analysis results, proper strategies to reduce GHG emissions from sewer pipeline systems in DMC have been suggested. The results showed that direct CH_4 emission was the greatest contributor, generating 62.1% of the total GHG emissions at city scale. Considering the N_2O emissions not measured in this work, the portion of direct emissions on the total GHG emissions would be much greater because the GWP of N_2O is 298 times higher than that of CO_2. Additionally, the seasonal changes in rainfall and temperature and their effects on the emissions were not considered in this work. It is clear that these emissions are extremely important in the life cycle, but there is a lot of uncertainty. The

development of comprehensive models that can accurately predict the direct emissions generated from sewers should be achieved.

Nonetheless, our present work considers various environmental factors such as pipe specification, regional features of a pipeline system, biochemical reaction, and time horizon. It can provide detailed and proper methods to estimate GHG emissions from each life cycle stage within the system boundaries. In addition, strategies to minimize GHG emissions were identified through systematic and analytic processes, such as Monte Carlo simulation and scenario analysis with extensive city-scale inventory data. Finally, it can be applied to various environmental systems (e.g., WTPs, WWTPs, power plants, incineration systems, etc.) and sewer pipeline systems in other cities by simple modification of equations and factors. The method and sensitivity analysis protocol developed in this study may be extended to all urban environmental systems. Therefore, an integrated estimation model covering the whole environmental systems at city scale can be developed and applied to establish sustainable urban environments in the near future.

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