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Estimation of greenhouse gas emissions from an underground wastewater treatment plant

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Abstract. Wastewater treatment plants (WWTPs) have been recognized as one of the significant greenhouse gas (GHG) generators, due to the complex biochemical reaction and huge consumption of energy and materials. Recently, WWTPs have been built underground and they will be confronted with the challenges of mitigating GHG emissions and improving the quality of treated wastewater. Here, we focus on estimating GHG emissions to set up effective management plans for a WWTP built underground. First, we apply the process-based life cycle assessment (LCA) with an inventory database of the underground WWTP for a case study. Then, we identify significant factors affecting GHG emissions during service life using sensitivity analysis and suggest the proper tactics that could properly reduce GHG emissions from the WWTP.

Keywords: greenhouse gas emissions; underground wastewater treatment plant; life cycle assessment

1. Introduction

Water and energy are closely linked because huge amounts of energy are required to treat and distribute water for human use while water is essential resource to produce energy (DOE, 2014, Pan *et al.* 2018). Recently, the development of advanced water technologies (e.g., green water infrastructure, energy-efficient water treatment, waste management, etc.) are emerging issues to achieve sustainable water-energy nexus (Pan *et al.* 2018).

Life Cycle Assessment (LCA) is a widely known technique that assesses and quantifies the environmental loads and impacts associated with a product or process throughout their entire life cycle (ISO 2006). This identifies the data for all energy, raw materials, by-products and environmental pollutants within the established system boundary. LCA has been successfully used to investigate main environmental impacts of water infrastructures such as water and wastewater treatment plants (WTPs and WWTPs), and its results have suggested several options to minimize the impacts (Lee *et al*. 2012, Nessi *et al*. 2012, Kyung *et al*. 2018).

WWTPs have been recognized as one of the significant GHG emission sources due to their generation of the three primary GHGs such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Corominas *et al.* 2012, Yerushalmi *et al.* 2013). WWTPs produce both direct and indirect GHGs due to biochemical reaction and consumption of energy and materials during their life cycle (Bani Shahabadi *et al.* 2009, Kyung *et al.* 2015). Because of the strict regulation by international climate change prevention protocols such as Paris Agreement, WWTPs will be confronted with the challenges of mitigating their GHG emissions. Therefore, the GHG emissions from WWTPs should be accurately estimated and need to be reduced by effective management plans.

In recent times, WWTPs haven been built underground (MOE, 2017). This is because underground construction of WWTPs could minimize visual disturbances and generation of secondary hazardous pollutants such as odor. This also could stabilize the treatment efficiency due to prevention of slowing down of microbial activity at temperature below 10°C in cold weather. In addition, the upper part of WWTPs could be used as waterfront parks, sports complexes, and cultural spaces through the efficient land use and it changes awareness of people towards eco-friendly facilities.

LCA has been applied to the environmental assessment of WWTPs to quantitatively estimate the GHG emissions and investigate significant factors affecting the GHG emissions. However, previous studies have usually focused on the WWTPs constructed on the ground. Some researchers have dealt with design and removal efficiency of underground WWTP, while GHG emissions were not deeply considered due to its different construction and operation method (Kuokkanen *et al.* 2017, Tang *et al.* 2018). Hence, the main goal of this study is to estimate GHG emissions from an underground WWTP within the system boundary and suggest proper tactics to minimize GHG emissions and enhance the sustainability of the system.

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2. Methodology

2.1 Functional unit and system boundary

The purpose of this study is to estimate the GHG emissions generated from a WWTP built underground and investigate proper solutions to reduce them. Therefore, the functional unit of this study is set up as a WWTP in South Korea that deals with 122,000 m^3/d of wastewater. The construction and operation stages were established as system boundary to quantitatively estimate the GHG associated with the WWTP. In addition, the life cycle of the WWTP was set as 45 years, which is the ordinary life of civil engineering structures. It was assumed that equipment such as pipes and pumps is replaced twice during the life cycle since they have a duration of about 15 years. Activities occurring in the disposal stage were excluded from this study, due to data uncertainty. Data of material and energy consumption were taken from the specification of the WWTP. Data on actual inflow and water quality during the operation stage were difficult to use and could not be applied. However, it is expected that the amount of GHG emission related with energy consumption is highly accurate, because the equipment capacity described in the detailed design report was used.

2.2 Data inventory

The construction stages were divided into basic construction (BC), pretreatment and flow control tanks (PF), bio-reactors, sludge treatment, and reuse (BSR) facilities.

The operation stages were classified as sedimentation basin (SB), flow control tanks (FCT), bio-reactors and blowing (BB), chemical supply (CS), reclaimed wastewater treatment (RWT), sludge treatment (ST), deodorization (D), and ventilation (V). The materials and electricity consumed at each process are shown in Table 1.

2.3 Estimation of GHG emissions

In the construction stage, the amount of cement, sand, gravel, rebar, cast iron, steel tool special (STS) and steel piping (SPP) used in the construction was considered. Table 2 shows the emissions factors used at the construction stage. The emission factors of materials were referenced by the Ministry of Environment (MOE), national life cycle inventory database (LCI DB) and Eco-invent DB. The MOE data was preferentially used, due to the consideration of domestic situation. Foreign DB such as Eco-invent was used when no appropriate data were available.

$$E_{const} = \sum_{m(i)} \left(EF_{m(i)} \times M_{m(i)}\right) \quad (1)$$

The total GHG emissions from an operation stage is the summation of those from electricity and chemical consumption for wastewater treatment and on-site CH_4 and N_2O emissions during the processes. Table 3 shows the emissions factors used at the operation stage. The emission factors for electricity and poly-aluminium chloride (PAC) consumption were obtained from Korea Power Exchange (KPX) and National LCI DB, respectively. In case of those for sodium hypochlorite (NaOCl) and polymer were acquired from Eco-invent, due to the lack of national data. BOD removal was used as a contaminant source for CH_4, as TN removal was for N_2O. The emission factors of on-site CH_4 and N_2O were obtained from field operation data. CH_4 and N_2O emissions were converted to CO_2 equivalent emissions (CO_2 eq) by multiplying their global warming potential (GWP, CH_4: 21 and N_2O: 310), and then added to estimate total on-site GHG emissions.

Table 1 Consumption of materials and energy in the WWTP

Stages		Materials and Energy	Consumption	Unit
Construction	BC	Cement	43	kg
		Sand	5,247	m^3
		Gravel	87	
		Rebar	4	kg
	PF	Cement	6,385	
		Sand	9,412	m^3
		Gravel	11,812	
		Rebar	2,313	kg
		Cast iron	319	
		STS	34	
		SPP	11	
	BSR	Cement	17,629	kg
		Sand	24,244	m^3
		Gravel	30,309	
		Rebar	5,448	kg
		Cast iron	100	
		STS	216	
		SPP	88	
Operation	SB	Electricity	391,207	kWh
	FCT		3,289,818	
	BB		30,775,997	
	CS	Electricity	15,294	kWh
		PAC	903.8	kg
		NaOCl	146.11	
		Polymer	90.17	
	RWT	Electricity	3,294,282	kWh
	ST		1,581,866	
	D		1,258,279	
	V		11,418,660	

$$E_{oper} = E_{elect} + E_{chem} + E_{CH4} + E_{N2O} \quad (2)$$

$$E_{elect} = \sum_i \left(E_{unit\ process,i} \times EF_{elect}\right) \quad (3)$$

$$E_{chem} = \sum_i \left(M_{chem,i} \times EF_{chem}\right) \quad (4)$$

$$E_{CH4} = EF_{CH4} \times BOD\ removal \times 21 \quad (5)$$

$$E_{N2O} = EF_{N2O} \times TN\ removal \times 310 \quad (6)$$

Table 2 Emission factors at the construction stage

Category	Emission factor		Reference
	Unit	Value	
Cement		0.944	
Sand	$kgCO_2$ eq/m^3	3.87	MOE
Gravel		11.3	
Cast iron		1.631	Eco-invent
Rebar	$kgCO_2$ eq/kg	0.3405	National LCI DB
STS		3.23	MOE
SPP		2.34	

Table 3 Emission factors at the operation stage

Category	Emission factor		Reference
	Unit	Value	
Electricity	$kgCO_2$ eq/kWh	0.4958	KPX
PAC		0.871	National LCI DB
NaOCl	$kgCO_2$ eq/kg	0.6341	Eco-invent
Polymer		2.5748	
On-site CH_4	$kgCH_4$/kgBOD	0.0071	Field operation data
On-site N_2O	kgN_2O/kgTN	0.0012	

2.4 Sensitivity analysis and uncertainty evaluation

Sensitivity analysis was implemented to determine the most influential factors affecting GHG emissions during the life cycle of the WWTP. A Monte-Carlo simulation scheme provided by commercial software, Crystal Ball (Ver. 11.1), was employed to perform the sensitivity analysis. The average daily wastewater inflow of the WWTP was set as an average value for the sensitivity analysis, while the daily maximum inflow of the WWTP were used for LCA. It was assumed that the data variation is fitted by normal distribution, and its mean value was calculated. Standard deviation was estimated by assuming 10% of the mean value.

3. Results and discussion

As a result of evaluating GHG emissions generated during the life cycle of the WWTP, the operating stage accounts for the most of GHG emissions (99.9%). This is because construction is completed only one time during its life cycle, while operations are carried out over 45 years of continuous use of energy and materials.

3.1 GHG emission at construction stage

Fig. 1 illustrates the GHG emissions at the construction stage. Construction of bio-reactors, sludge treatment facilities, and reuse facilities (BSR) accounted for 69.6% (456.45 ton CO_2 eq) of the total emissions at the construction stage. This is because larger amount of materials is consumed at the BSR process compared to the basic construction (BC) and construction of pre-treatment facilities and flow control tanks (PF). As a result, GHG emissions from BSR were approximately 2.6 and 21 times higher than that of PF and BC, respectively.

The major GHG source associated with the construction of BSR and PF is the use of gravel, which contributes to 75.1% of GHG emissions (BSR: 342.5 tonCO_2 eq; PF: 133.5 tonCO_2 eq). This is due to the huge consumption of gravel and its higher emission factor than other materials. On the other hand, GHG emissions related to rebar, cast iron, and pipes were negligible. The material with the greatest impact (95.2%, 20.3 $kgCO_2$ eq) on GHG emissions during the BC appeared as sand. This is because the amount of sand used for BC is enormous compared to other materials.

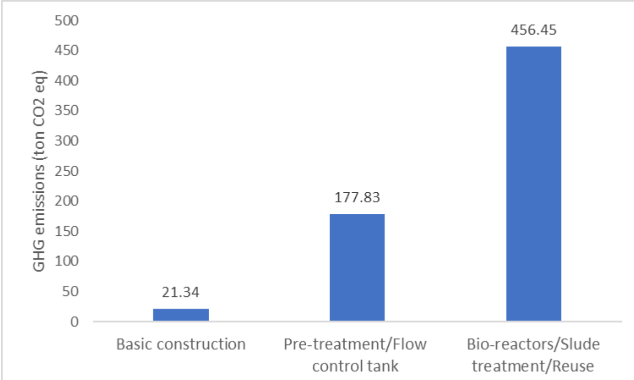

Fig. 1 GHG emissions at the construction stage

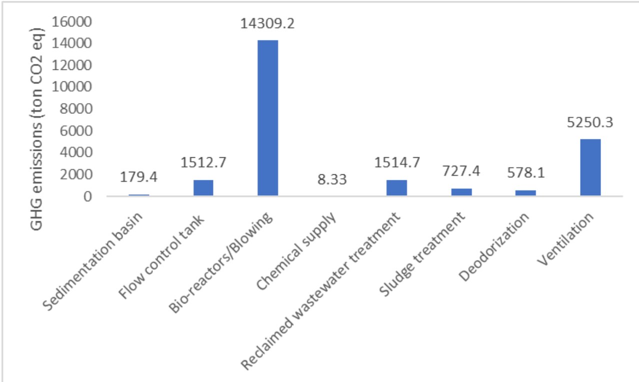

Fig. 2 GHG emissions at the operation stage

3.2 GHG emission at operation stage

Fig. 2 shows the GHG emissions at the operation stage. Unit processes that have the greatest impact on GHG emissions during the operation stage were found to be bio-reactors and blowing facilities (BB, 59.2%) and ventilation facilities (V, 21.9%). The large amount of GHG emissions were emitted from BB because primary sedimentation basin (SB) was not installed to lower the cost during the construction of underground WWTP. Due to the lack of the SB, the amount of air used to oxidize organic pollutants is increased, thus increasing GHG emissions. Membrane Bio-Reactor (MBR) process has the advantage of reducing construction cost because it uses filtration membrane without SB. However, blowers and cleaning processes are additionally required to supply air and prevent contamination of membrane. The WWTP was installed underground unlike general WWTPs constructed on ground. Therefore, the GHG emissions were very high, due to the increase of electricity consumption used for ventilation system.

Membrane blowers (30.0%), aerobic blowers (25.6%), and internal return pumps (25.0%) were the most influencing equipment on GHG emissions related to BB. Membrane blowers are used to supply oxygen for microorganism and air to prevent membrane contamination. The bubble size of the supplying air is larger than that generally used in biological process so that oxygen transfer efficiency is declined. This requires more supplying air than a typical bio-reactor, and the use of more electricity increases GHG emissions. In case of internal return pumps, GHG emissions can be reduced by optimizing the process, according to the loading of incoming nitrogen required for denitrification. Significant amounts of GHG are emitted from the use of electrical energy required for the operation of ventilation facilities (V). Regarding the system of V, supplying fan (50.3%) and exhausting fan (49.7%) were identified as the main sources of GHG emissions. The equipment that have the greatest impact on GHG emissions related to reclaimed wastewater treatment facilities (RWT) are pumps (47.9%), air compressors (19.9%) and ozone generators (17.3%). RWT needs long distance transportation to supply environmental water, and this leads to high amounts of GHG emissions due to pump operation. The inflow pump (43.9%) and the flow control tank blower (39.9%) were found to have a significant impact on GHG emissions among the flow control tank (FCT) related equipment. In the WWTP, the FCT is equipped in the basement deeper than the inlet pumping station of the general WWTPs. This can reduce electricity consumption by lowing the pump head of pumping station to collect and transport the wastewater. However, in the absence of the primary sedimentation basin, it is essential to increase the storage capacity of flow control tank and maintain the residence time longer to keep the bio-reactor load constant. Under the circumstance, larger amount of air must be supplied to prevent sedimentation of suspended solids (SS) and odor from anaerobic conditions. Therefore, GHG emissions relatively increase compared to general WWTPs. Among the sludge treatment facilities (ST), the equipment with a large influence on GHG emissions were surplus sludge storage blowers (30.5%) and dehydrators (27.3%). The primary sedimentation sludge is not generated in the WWTP because there is no primary sedimentation basin, whereas surplus sludge is generated in the bio-reactor. Therefore, the use of blowers increases and other types of GHGs can be emitted. The high concentration deodorizer (41.8%) and low concentration deodorizer (26.5%) were found to have a significant effect on GHG emissions among the equipment related to the deodorization facilities (D). The agitator showed the most significant effect on GHG emissions among the equipment related to the grit chamber. In case of chemical supply facilities (CS), the PAC pump use to supply PCA 24 hours has the largest impact on GHG emissions (79.6%).

Table 4 Comparison of GHG emissions

Author	Capacity (m^3/d)	Method	Life cycle (year)	GHG emissions ($kgCO_2$ eq/m^3)
This study	122,000	MBR	45	0.87
Park & Hwang	100,000	BNR	40	0.21
Zhang *et al.*	150,000	Activated Sludge	20	0.0075
Godin *et al.*	251,700	Aerobic Lagoon	-	0.0051
Shin	150,000	Activated Sludge	-	0.13

3.3 Comparison of GHG emission with other WWTPs

In order to evaluate the level of GHG emissions at the WWTP, the GHG emissions were compared with other existing WWTPs (Table 4). The GHG emissions of the WWTP were 0.87 $kgCO_2$ eq/m^3, much higher than other WWTPs. This is because the use of electric energy is very large due to the increase of (1) required air supply for bio-reactors, (2) amount of internal transfer for the denitrification process, and (3) ventilation according to the underground location. In the Biological Nutrient Removal (BNR) process, the amount of GHG emissions is much higher than that of the standard activated sludge process since the air supply is increased during nitrification.

3.4 Tactics to reduce GHG emissions from the WWTP

Sensitivity analysis was performed to identify the most significant factor affecting the GHG emissions in the WWTP. As a result, the use of electric energy in membrane blower and aerobic blower was the most. It is expected that the total GHG emissions can be effectively reduced by optimizing the operation of the blower. In addition, huge amount of electrical energy was consumed during the operation of the internal return pump used for denitrification reaction. Therefore, a method to minimize the energy consumption due to the operation of the internal return pump should be prepared, by optimizing the nitrification of the aerobic tank and the denitrification of the anoxic tank. In addition, a lot of electric energy is consumed in the use of supplying and exhausting fans for ventilation because of the underground construction of WWTP. Thus, the system should be improved and supplemented to minimize the ventilation space in the future.

4. Conclusions

The process-based LCA was adopted to quantitatively estimate GHG emissions from whole life cycle stages (construction and operation) of the underground WWTP in South Korea as a case study. The results showed that operation stage accounted for 99.9% of the GHG emissions during the lifecycle. The main processes that produce the greatest amount of GHG (81.0% of total emissions) were bio-reactors and ventilation. The GHG emission of the WWTP was 0.87 kgCO_2e/m^3, higher than other WWTPs constructed on the ground. This is mainly due to the increase of electric energy consumption for air supply (bio-reactor and MBR) without primary sedimentation, internal transport for the denitrification, and ventilation for system installed in underground. In order to minimize GHG emissions, optimization of design and operation should be achieved soon. A variety of WWTPs have been built and operated under different operating conditions to remove carbonaceous matter and nutrients from wastewater. Optimal types and operating conditions of WWTPs can be changed depending on different environmental scenarios. The LCA approaches could be applied to classify low-carbon emission and high-removal efficiency methods. Moreover, the boundaries can be further extended to other environmental and industrial sectors to estimate total GHG emissions. This could lead to the development of novel green and sustainable urban environmental infrastructures providing more efficient removals of contaminants, as well as lower GHG emissions.

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