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# Life cycle greenhouse-gas emissions from urban area with low impact development (LID)

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**Abstract.** In this study, a comprehensive model developed to estimate greenhouse gas (GHG) emissions from urban area with low impact development (LID) and its integrated management practices (IMPs). The model was applied to the actual urban area in Asan Tangjeong district (ATD) as a case study. A rainwater tank (1200 ton) among various LID IMPs generated the highest amount of GHG emissions ($3.77 \times 10^5$ $kgCO_2eq$) and led to the utmost reducing effect ($1.49 \times 10^3$ $kgCO_2eq$/year). In the urban area with LID IMPs, annually $1.95 \times 104$ $kgCO_2eq$ of avoided GHG emissions were generated by a reducing effect (e.g., tap water substitution and vegetation $CO_2$ absorption) for a payback period of 162 years. A sensitivity analysis was carried out to quantitatively evaluate the significance of the factors on the overall GHG emissions in ATD, and suggested to plant alternative vegetation on LID IMPs.

**Keywords:** greenhouse gas emission; low impact development; green infrastructure; life cycle assessment; reduction effect; sensitivity analysis

## 1. Introduction

Greenhouse gas (GHG) emissions from water infrastructures have been recognized as a severe problem due to their high involvement with the environmental systems (Frijns 2012, Rothausen and Conway 2011). To reduce the emissions from water infrastructures, previous studies have suggested several innovative ways such as a decentralized system for the sustainable water infrastructures (Lienert *et al*. 2006). However, few researchers brought the benefits of the mitigation methods into question whether how much the methods could mitigate the environmental impacts on the ecosystem as well as a human society. To resolve the question, life cycle assessment (LCA) methodology has been widely applied to evaluate the mitigation methods whether they are truly beneficial on the environment or not (Angrill *et al*. 2012, Kyung *et al*. 2013, Lim *et al*. 2010, Lundie *et al*. 2004, Nessi *et al*. 2012, Pasqualino *et al*. 2011).

In recent years, a great deal of effort has been made on the low impact development (LID) and its integrated management practices (IMPs) as an effective decentralized stormwater management system, because it cost-effectively reduces the bulk loading of runoff and environmentally

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promotes infiltration and evaporation within an urban area (USEPA 2009). LID IMPs have been also assessed to verify its mitigation impacts on the environment by estimating GHG emissions (Kim *et al*. 2012, Spatari *et al*. 2011). Under these circumstances, development of a model to estimate GHG emissions from LID IMPs is timely and essential.

The objectives of this study are (1) developing a model to estimate GHG emissions from LID IMPs and assess reducing effects; (2) applying the model to an actual urban area in Asan Tangjeong district (ATD) as a case study to verify its potential for mitigating GHG emissions; (3) suggesting the most effective tactics to mitigate GHG emissions with LID IMPs, based on the significant factors derived from a Monte-Carlo simulation.

## 2. Methodology

### 2.1 Scope of model

A model was developed to quantitatively evaluate the benefits and environmental impacts of LID IMPs on the urban areas. In this study, among various types of LID IMPs, public use facilities such as constructed wetland, lateral infiltration ditch, vegetated swale, infiltration swale, and rainwater harvesting tank were considered. The progresses for the model practically consists of two parts that estimates; (i) GHG emissions of each unit IMP by calculating the amount of materials and fuel consumption; (ii) avoided GHG emissions from each unit IMP and they were summed based on the actual data sets (e.g., units of IMPs, vegetation type, area) of urban planning by assessing the reducing effects such as tap water substitution and vegetation $CO_2$ absorption for IMPs at specific urban areas (Spatari *et al*. 2011, USEPA 2009).

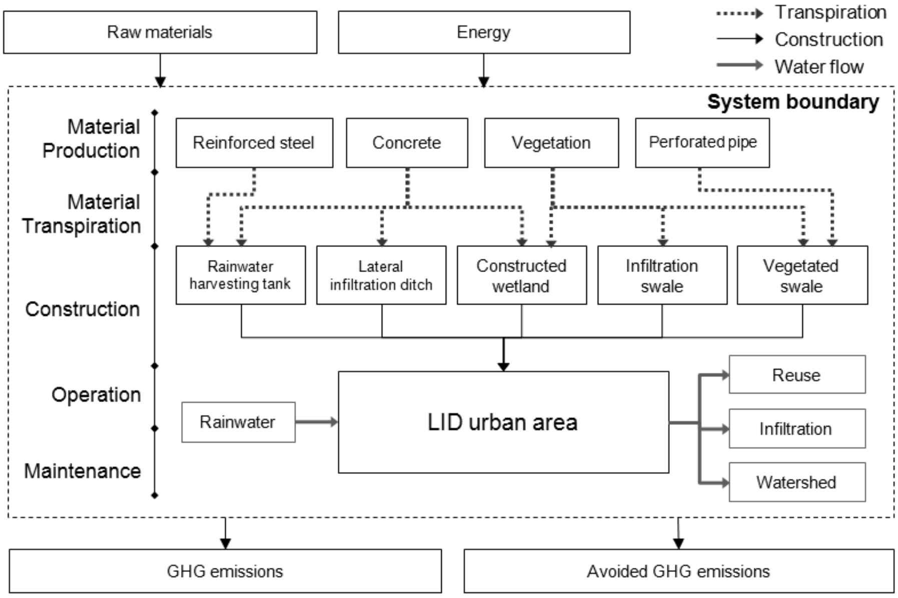

Fig. 1 Schematic diagram of the system boundary

Functional units for estimating GHG emissions of IMPs were defined as unit IMPs. A system boundary included entire life cycle stages from material production to the maintenance as shown in Fig. 1. Each of life cycle stages and GHG emissions sources from the stages are described as followings: (1) material production (MP); GHG emissions due to the consumption of raw materials and manufacturing process; (2) material transportation (MT); GHG emissions during transportation processes (from producers to the construction sites) of the IMPs; (3) construction (CO); GHG emissions due to the site improvement activities and installation of IMPs; (4) operation (OP); GHG emissions by electricity consumption and avoided GHG emissions by reducing effects over years; (5) maintenance (MI); GHG emission due to the maintenance activities including replacement processes based on the lifespans of each IMP.

In this study, to assess the impacts of different types of GHG emissions on the environment, global warming potentials (GWP 100a) characterized by intergovernmental panel on climate change (IPCC 2007) were referred and compared. Acquired results to quantitatively estimate the GHG emissions were expressed in a unit of $CO_2$equivalents (kg$CO_2$eq).

### *2.2 Development of model*

A model to estimate GHG emissions and avoided emissions from life cycle of LID IMPs was developed by a utilizing process based LCA procedure (ISO 1997). Total GHG emissions from each life cycle stage were estimated by following equation and summed as shown in Eq. (1), where $E_{MP}$ = GHG emissions from material production stage [kg$CO_2$eq]; $E_{MT}$ = GHG emissions from material transportation stage [kg$CO_2$eq]; $E_{CO}$ = GHG emissions from construction stage [kg$CO_2$eq]; $E_{OP}$ = GHG emissions from operation stage [kg$CO_2$eq]; $AE_{tapwater}$ = avoided GHG emissions from operation stage [kg$CO_2$eq]; and $AE_{vegetation}$ = avoided GHG emissions from operation stage [kg$CO_2$eq].

$$\text{Total GHG emissions} = E_{MP} + E_{MT} + E_{CO} + \sum\nolimits_{t} (E_{OP} + AE_{tapwater} + AE_{vegetation}) \qquad (1)$$

To estimate GHG emissions for construction of LID IMPs, several equations were developed and shown in Eqs. (2), (3), and (4). The additional equation to calculate annual emissions for the operations is shown in Eq. (5), where $EF_{m(\mathrm{i})}$ = emission factors (EF) of type $i$ raw material [kg$CO_2$eq/kg]; $M_{m(i)}$ = weight of type i raw material [kg]; $EF_{t(j)}$ = EF of transportation type $j$ material ($j$ = ship, road, and railway) [kg$CO_2$eq/kg-km]; $D_{m(i)}$ = transportation distance of type $i$ material [km]; $EF_{e(k)}$= $EF$ of construction equipment type $k$ ($k$= excavator and dump truck) material [kg$CO_2$eq/liter]; $F_{e(k)}$ = fuel consumption of construction equipment using type $k$ material [liter]; $EF_{electricity}$ = EF of electricity consumption [0.558 kg$CO_2$eq/kWh]; $C_{electricity}$ = electricity consumption using a pump [kWh].

$$E_{MP} = \sum\nolimits_{m(i)} \left( EF_{m(i)} \times M_{m(i)} \right) \qquad (2)$$

$$E_{MT} = \sum\nolimits_{m(i)} \sum\nolimits_{t(j)} \left( EF_{t(j)} \times M_{m(i)} \times D_{m(i)} \right) \qquad (3)$$

$$E_{CO} = \sum\nolimits_{m(i)} \sum\nolimits_{e(k)} \left( EF_{e(k)} \times F_{e(k)} \right) \qquad (4)$$

$$\sum\nolimits_{t} E_{OP} = \sum\nolimits_{t} \left( EF_{electricity} \times C_{electricity} \right) \qquad (5)$$

It was reported that mainly used materials for constructing LID IMPs were concrete and reinforced steel (LHI 2011) Permeable soil and crushed stones near the construction sites were used as the filling material in vegetated swales and infiltration swales (LHI 2011). Perforated polyethylene (PE) pipes were buried under the vegetated swales to facilitate runoff of penetrated rainwater (LHI 2011). Vegetation (reed) was planted in constructed wetland, vegetated swale, and infiltration swale and the pumps (40 W single-stage volute, 24.4 kWh/year) were operated to reuse the stored rainwater for toilet flushing or gardening (LHI 2011). Transportation distance was assumed to be 65 km from the producer to the construction sites by 15 ton trucks along the highway in the domestic area. Construction procedures of IMPs were carried out based on the guideline of LID urban planning (LHI 2011) An excavator (backhoe type 0.2 $m^3$) consuming 11.25 liter of diesel per hour was used for 10 or 12 hours for the construction activities such as digging of trenches, material handling, and grading the construction sites. The IMPs made of concrete, reinforced steel, and plastic pipe were replaced based on the expected lifespans of each materials, respectively.

LID IMPs have reducing effects (i.e., tap water substitution and vegetation $CO_2$ absorption) on urban areas by avoiding consumption of tap water and directly absorbing atmospheric $CO_2$. The rainwater harvesting tanks that collect and reuse rainwater can reduce tap water usage, and contribute to the lower GHG emissions from production and distribution processes of tap water. Also vegetation plantation of IMPs for the urban areas absorbs atmospheric $CO_2$ depending on the net ecosystem exchange (NEE) of vegetation, contributing to the lower GHG emissions (Zhou *et al*. 2009) Eqs (6) and (7) were carried out to quantitatively estimate avoided GHG emissions generated by reducing effects where $Q_{RW}$ = average rainwater usage [$m^3$/year]; $EF_{water}$ = $EF$ of tap water production [$kgCO_2/kg$]; $SF$ = conversion factor of substituted tap water; NEE = Net ecosystem exchange of $CO_2$ [$kgCO_2/m^2$-day]; and area = vegetated area on IMPs [$m^2$].

$$\sum\nolimits_t AE_{tapwater} = \sum\nolimits_t \left(Q_{RW} \times EF_{water} + SF\right) \tag{6}$$

$$\sum\nolimits_t AE_{vegetation} = \sum\nolimits_t \left(\mathrm{NEE} \times \mathrm{area}\right) \tag{7}$$

$Q_{RW}$ (37,800 $m^3$/year) was assumed based on the average rainfall (1,227 mm/year) and average usage frequency (9 times/year) (LHI 2011). $SF$ (0.437) was assumed based on the usage of rainwater to the total tap water ratio at the certain area (MoE 2009). NEE of reed (2.719 $kgCO_2/m^2$-year) was referred from the experimental results under the similar environmental conditions (Zhou *et al*. 2009).

## 3. Case study

### *3.1 Asan Tangjeong district* (*ATD*)

ATD was designed by Korea Land and Housing Corporation (LH) to demonstrate LID rainwater management system in urban area. It is located in Cheon-an city, middle of Korea. Its area is 1.7 $km^2$ and the average temperature of the city is 11.8°C (KMA 2013). Fig. 2 demonstrates overview of LID urban planning in ATD. The runoff of rainwater flows into Jangjae stream below Park C.

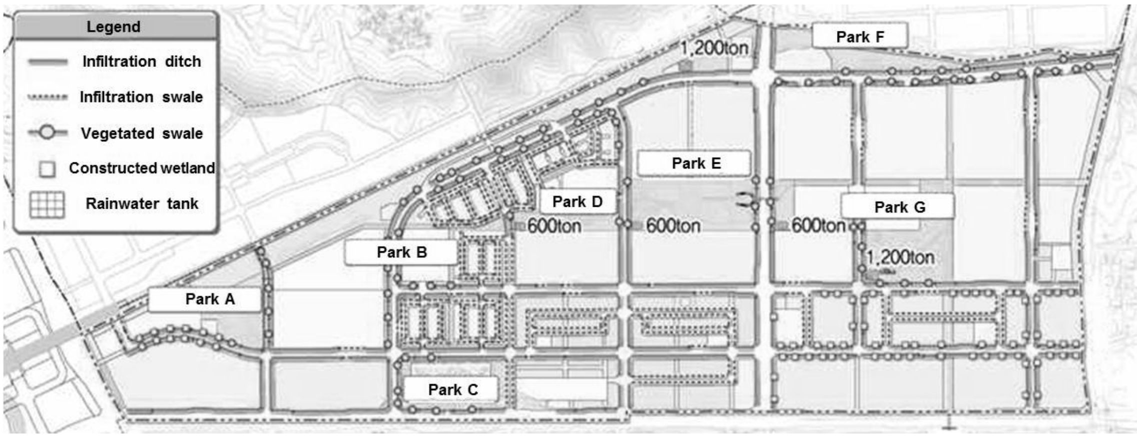

Fig. 2 Overview of LID-applied urban planning in Asan Tangjeong district (ATD)

Table 1 Summary of conventional and LID urban plan in ATD

| Type | | Summary |
|---|---|---|
| Conventional urban plan | *Facility* | 8 water pollution control facilities<br>(gravity powered vortex type, 50 years life span) |
| LID urban plan | *LID IMPs* | 60 constructed wetlands, 463 lateral infiltration ditches, 80 vegetated swales, 845 infiltration swales (800 m perforated pipe), and 5 rainwater harvesting tanks (600 and 1200 ton, $Q_{RW}$ = 37,000 $m^3$/year) |
| | *Vegetation* | Net ecosystem exchange of reed: 2.719 $kgCO_2/m^2$-year |

To assess the effects of LID IMPs on ATD, two urban plans, a conventional urban plan and a LID urban plan were compared. Details of two urban plans are summarized in Table 1. In case of a conventional urban plan, it was assumed that 8 water pollution control facilities (gravity powered vortex type) collect and treat initial runoffs containing non-point pollutants. For a LID urban plan, 60 constructed wetlands, 463 lateral infiltration ditches, 845 infiltration swales with 800 m perforated PVC pipe, 80 vegetated swales, and 5 rainwater harvesting tanks (600 and 1200 ton) were considered.

### 3.2 Data collection

EF used for estimating GHG emissions were gathered from Ecoinvent V2.1 (Ecoinvent 2006) and Korean life cycle inventory database (KEITI 2012). Input factors in modeling such as size, input material consumption, transportation distance, vegetation, construction method and expected lifespans of each LID IMPs were carried out from a construction specification provided by construction company (UB E&C, Seoul) and the LH (LHI 2011). Data of $CO_2$ absorbing vegetation was collected based on the literature (Kim *et al*. 2012, Zhou *et al*. 2009). Data of water substitution was acquired from the technical report published by Korean Ministry of Environment (MoE 2009). Summary of input factors of IMPs is described in Table 2.

Table 2 Summary of input factors of IMPs in ATD

| | Constructed wetland | Lateral infiltration ditch | Vegetated swale | Infiltration swale | Rainwater harvesting tank |
|---|---|---|---|---|---|
| Size | 1.0 × 5.0 $m^2$ | 0.5 × 5.0 $m^2$ | 2.0 × 10.0 $m^2$ | 1.0 × 4.0 $m^2$ | 1200 and 600 ton |
| Input material $^1$ | Concrete 3.8 $m^3$/EA | Concrete 2.3 $m^3$/EA | Crushed stone, permeable soil | Crushed stone, permeable soil | (1200) Concrete 787 $m^3$/EA,<br>Reinforced steel 103,250 kg/EA<br>(600) Concrete 416 $m^3$/EA,<br>Reinforced steel 55,658 kg/EA |
| Transportation distance $^2$ | 65 km | 65 km | 65 km | 65 km | 65 km |
| Construction time $^2$ | 10 hour/EA | 12 hour/EA | 12 hour/EA | 10 hour/EA | 12 and 10 hour/EA |
| Vegetation | Reed | N/A | Reed | Reed | N/A |
| Equipment $^3$ | N/A | N/A | PVC pipe $^4$ (800 m) | N/A | 40 W single-stage volute pump (24.4 kWh/year) |
| Expected Lifespan $^5$ | 50 years | 50 years | 30 years | N/A | 50 years |

Notes: $^1$ Emission factors of input materials was referred from Ecoinvent LCI database (Ecoinvent 2006);
$^2$ Emission factor of transportation and excavator was referred from Korean LCI database (KEITI 2012);
$^3$ A average electricity consumption was calculated based on annual amount of rainwater harvesting;
$^4$ Perforated pipe laid under crushed stone and permeable soil; $^5$80% of deteriorated material is recycled (LHI 2011)

### 3.3 Sensitivity analysis

Sensitivity analysis was implemented using a Monte Carlo simulation to indicate the significance of each factor that affects entire GHG emissions. The Crystal ball (Ver. 11.1), commercially available software was used to simulate each results and analyzed effects of various inputs. Input factors were replaced with uncertain variables based on the probability distribution function which represents the range of values and the likelihood of occurrence. One hundred thousand trials were simulated with a 95% confidence interval.

## 4. Results and discussion

### 4.1 GHG emissions of LID IMPs

GHG emissions and avoided GHG emissions of LID IMPs were estimated and shown in Table 3. Each IMP generated different amount of GHG emissions and avoided GHG emissions depending on their input materials and functions. For unit IMPs installation, rainwater tanks (1200 and 600 ton) generated the highest amount of GHG emissions ($3.77 \times 10^5$ and $2.01 \times 10^5$ kgCO$_2$eq) among those of IMPs. This is due to the high consumption of concrete to construct rainwater harvesting tanks. For the high consumption of concrete, constructed wetland and lateral infiltration

Table 3 GHG emissions and avoided GHG emissions of LID IMPs

| | GHG emissions ($kgCO_2eq$/unit) | | | | Avoided GHG emissions ($kgCO_2eq$/year-unit) | |
|---|---|---|---|---|---|---|
| | MP | MT | CO | OP [3] | TWS [1] | VCA [2] |
| Constructed wetland | 1,013 | 0.06 | 66 | | | 13.6 |
| Lateral infiltration ditch | 613 | 0.03 | 79 | | | |
| Vegetated swale | 1,896 | | 79 | | | 54.4 |
| Infiltration swale | | | 66 | | | 10.9 |
| Rainwater tank (1200 ton) | 375,831 | 1,683 | 66 | 11.2 | 1,493 | |
| Rainwater tank (600 ton) | 200,465 | 907 | 79 | 11.2 | 747 | |

Notes: [1] Reducing effect of tap water substitution;
[2] Reducing effect of vegetation $CO_2$ absorption;
[3] GHG emission per year from operation stages ($kgCO_2eq$/year-unit)

ditch generated $1.07 \times 10^3$ and $6.92 \times 10^2$ $kgCO_2eq$ per unit IMPs, respectively. Infiltration swales required only fossil fuel generated 66 $kgCO_2eq$. Vegetated swale generated $1.97 \times 10^3$ $kgCO_2eq$ as perforated PVC pipes were used, which generated large amount of GHG emissions during its production process (Venkatesh *et al*. 2011). The installed pump annually consumed 24.4 kWh and generated 11.2 $kgCO_2eq$/year to operate rainwater harvesting system.

Highest amount of avoided emissions per unit IMPs were observed from rainwater tanks. 37,800 $m^3$ of rainwater was collected annually and reused for toilet flushing, gardening, and cleaning the parks in ATD. Their avoided emissions of rainwater tanks (1200 and 600 ton) were $1.49 \times 10^3$ and $7.47 \times 10^2$ $kgCO_2eq$ per year, respectively. Moreover, avoided emissions caused by vegetation $CO_2$ absorption of constructed wetlands, infiltration swales, and vegetated swales were 13.6, 54.4, and 10.9 $kgCO_2eq$ per year, respectively. These emissions were dependent on the environmental conditions, vegetation types (Zhou *et al*. 2009), installed area and absorption capacity (Kim *et al*. 2012). It was revealed that the constructed wetland and infiltration swale had limited reducing effects due to their small reed vegetating area ($1 \times 5$ $m^2$, $1 \times 4$ $m^2$) compared to the swale vegetating area ($2 \times 10$ $m^2$).

### 4.2 Cumulative GHG emissions in ATD

Estimated GHG emissions of each IMP installed in ATD and the changes of GHG emissions by time horizon are described in Fig. 3. In the previous section, LID IMPs generated high amount of GHG emissions from the initial installation stages, and offset the emissions by reducing effects over the years.

For 60 units of constructed wetland shown in Fig. 3(a), $6.48 \times 10^4$ $kgCO_2eq$ was initially generated and $8.16 \times 10^2$ $kgCO_2eq$ was annually avoided for the vegetation $CO_2$ absorption effect. In every 50 years, the materials were replaced and GHG emissions were generated periodically. A payback period of constructed wetlands in ATD was 112 years. For 463 units of lateral infiltration ditch shown in Fig. 3(b), relatively high amount of GHG emissions ($3.20 \times 10^5$ $kgCO_2eq$) were generated and the maintenance activities periodically generated GHG emissions over the years without any reducing effect. For 80 units of vegetated swales (Fig. 3(c)) and 845 units of

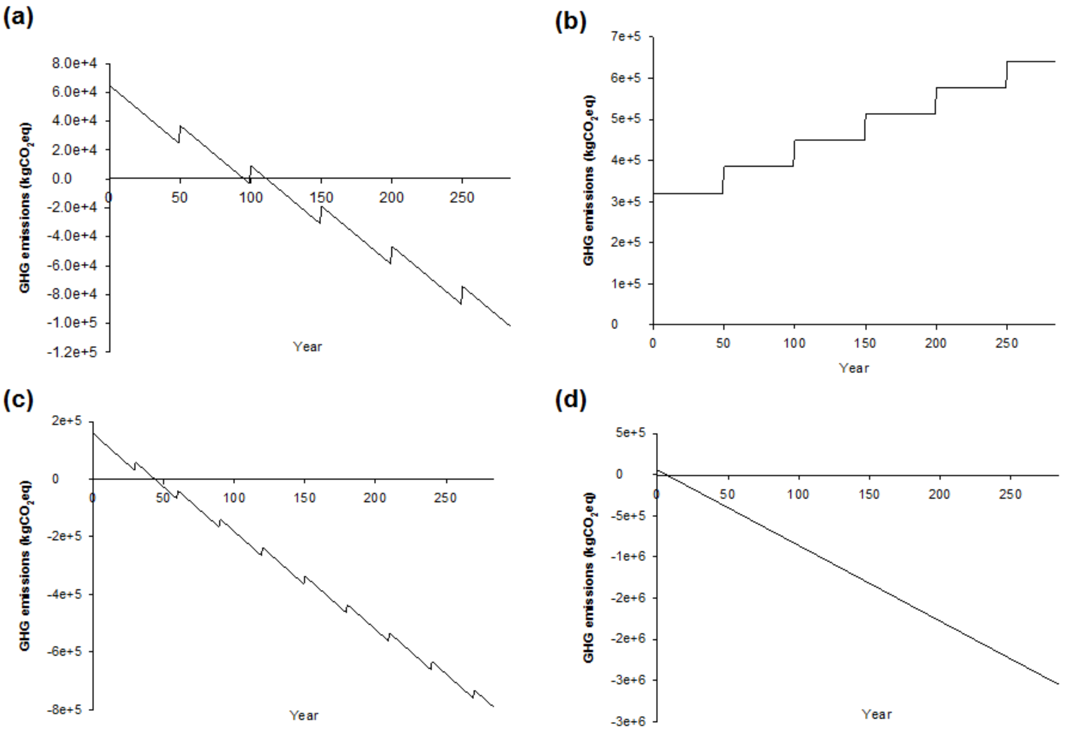

Fig. 3 Cumulative GHG emissions of IMPs: (a) constructed wetland; (b) lateral infiltration ditch; (c) vegetated swale; (d) infiltration swale at ATD; and (e) rainwater tanks (1200 and 600 ton)

infiltration swales (Figure 3 (d)), GHG emissions were $1.58 \times 10^5$ and $5.58 \times 10^4$ kgCO$_2$eq, and annual avoided emissions were $4.35 \times 10^3$ and $9.21 \times 10^3$ kgCO$_2$eq, respectively. In every 30 years, additional GHG was emitted from vegetated swales to maintain and replace perforated pipes under the swales. Their payback periods were 44 and 7 years, respectively.

For 1200 ton (2 units) and 600 ton (3 units) rainwater tanks installed in ATD, Fig. 3(e) shows that GHG emissions were respectively $7.72 \times 10^5$ and $6.18 \times 10^5$ kgCO$_2$eq, covering 75% of total GHG emission. Since the annual avoided emissions ($2.96 \times 10^3$ and $2.21 \times 10^3$ kgCO$_2$eq/year) after tap water substitution were relatively small, rainwater tanks could not offset the GHG emissions and maintenance emissions over the years. These results implies that the rainwater tank constructed for the purpose of public interests (e.g., conservative toilet flush or gardening of parks in ATD) are expected to have a marginal reducing effect. Alternatively, reducing the consumption of concrete referring an environmental-friendly configuration (Angrill *et al.* 2012) and substituting concrete with other alternative materials (BlueScope 2004) should be primarily considered to mitigate GHG emissions.

GHG emissions of constructed wetland, lateral infiltration ditch, and rainwater tanks outweighed their avoided emissions during 100 years. Only vegetated and infiltration swales could alleviate their GHG emissions by their reducing effects. It implies that reducing effect was partial and slow to accrue the payback compared to the material consumption during the installation. Their reducing effects should be improved to be considered as one of the options to mitigate GHG emissions within the urban area. Additionally it is necessary to consider their other advantages such as hydrological improvement in infiltration, water retention, evapotranspiration, and mitigation of urban heat island effect (Spatari *et al*. 2011, USEPA 2009).

### *4.3 Comparison of conventional and LID urban plan in ATD*

Cumulative GHG emissions of conventional and LID urban planning in ATD were compared and described in Fig. 4. Conventional urban planning emitted small amount of GHG ($2.69 \times 10^4$ $kgCO_2eq$) from construction processes of water pollution control facilities (8 units) because the gravity-powered facilities did not consume energy or resources to treat rainwater runoff and maintenance activities which generates negligible amount of GHG emissions. In case of LID urban planning, vegetation $CO_2$ absorption and tap water substitution generated the avoided emissions ($1.95 \times 10^4$ $kgCO_2eq$/year) over years and eventually exceeded GHG emissions ($1.85 \times 10^6$ $kgCO_2eq$) of installation. These results indicates that the cumulative GHG emission of LID urban planning is less than that of conventional one after 160 years, although the initial GHG emission of conventional one was 72 times less than that of LID. The payback period of LID IMPs installed in ATD was 162 years. It implies that LID urban planning can contribute to GHG mitigation only in the long term perspective (> 150 years).

### *4.4 Sensitivity analysis*

Sensitivity analysis was conducted as shown in Table 4 based on the functional year of 162 years identified as payback period of LID IMPs. The most significant factor on overall GHG emissions was NEE, covering 78.4%, due to wide vegetated area of LID IMPs. It indicated that type and area of vegetation have the largest effects on $CO_2$ absorption capacity. The reed vegetated on IMPs in ATD had relatively low NEE (2.72 $kgCO_2/m^2$-year), compared to that of alternative

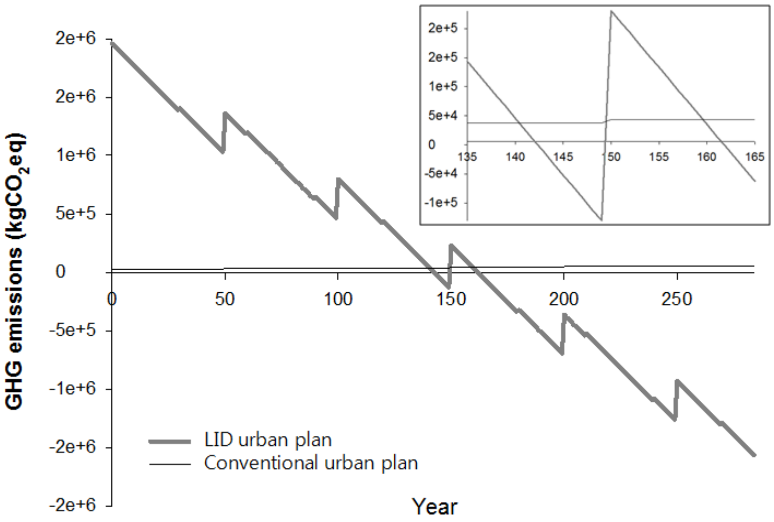

Fig. 4 Cumulative GHG emissions of conventional and LID urban planning in ATD

Table 4 Significant factors influencing cumulative GHG emissions in 162 years in ATD

| | Significant factors (Contribution percentage to variance) |
|---|---|
| GHG emissions | EF of concrete (50.9%), Lifespans (32.6%), EF of reinforced steel (15.3%), EF of PVC pipe (0.9%), and EF of diesel (0.3%) |
| Avoided emissions | NEE (90.5%), Rainwater reuse (7.5%), and EF of Tap water production (2.0%) |
| Overall GHG emissions | NEE (78.4%), Rainwater reuse (7.0%), EF of concrete (6.4%), Lifespan (4.4%), EF of reinforced steel (1.9%), EF of tap water production (1.8%), and other 19 factors (0.1%) |

vegetation such as sedum (sprunum, 3.1 $kgCO_2/m^2$-year), grass (kamtsch aticum, 5.7 $kgCO_2/m^2$-year), and shrub (azalea, 4.9 $kgCO_2/m^2$-year) (Kim *et al*. 2012). This indicated that planting alternative vegetation can effectively reduce GHG emissions over years by improving $CO_2$ absorption capacity. The second significant factor was rainwater reuse capacity (7.0%) which is highly correlated with average annual precipitation. The rainwater reuse capacity of this study was calculated based on weather statistics and assumed reuse rate. The rainwater modeling tool (e.g., Storm Water Management Model) should be utilized later to achieve more detail results with exact value of the reuse capacity than herein (Lee *et al*. 2012). The third significant factor was concrete usage, covering 6.4%. Substituting concrete with plastics for rainwater harvesting tanks (the biggest consumer) can be suggested as practical way to mitigate GHG emission of the tanks (BlueScope 2004). Indeed, plastic rainwater tanks for small volume (< 1 ton) have been widely applied to household rainwater harvesting system (Krishna 2005). Other factors including lifespan (4.4%), EF of reinforced steel (1.9%), EF of tap water production (1.8%), distance for material transportation (< 0.1%), fuel consumption for construction (< 0.1%), and electricity consumption for operation of rainwater tanks (< 0.1%) are relatively negligible.

As a result, regional and climatic characteristics such as average annual precipitation, rainwater runoff, and capacity of rainwater harvesting should be checked and analyzed to maximize their benefits of LID IMPs (Krishna 2005).

## 5. Conclusions

In this study, the model for quantifying GHG emissions and avoided emissions from LID IMPs was developed by applying LCA methodology. Its applicability was demonstrated by applying the model to LID urban area in ATD. The results indicated the avoided emissions caused by tap water substitution and vegetation $CO_2$ absorption effects are annual $2.01 \times 10^4$ $kgCO_2eq$ and its payback period to offset GHG emissions from LID IMPs in ATD is approximately 162 years. The significant factor influencing on overall GHG emissions was identified as NEE (78.4%) by sensitivity analysis. Planting alternative vegetation (e.g., grass or shrub) was suggested as the most effective strategy to reduce the emissions.

This model is the first study to quantify overall GHG emissions and evaluate the environmental benefits of LID IMPs at urban scale. It can be used for urban planner as a powerful tool by providing basic information of GHG emissions and alternative suggestions to design an LID applied area toward being sustainable infrastructures. Finally, it will be connected with models for other water infrastructures and advanced an integrated model to assess entire water system at the city scale in the near future.

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## References

Angrill, S., Farreny, R., Gasol, C.M., Gabarrell, X., Vinolas, B., Josa, A. and Rieradevall, J. (2012), "Environmental analysis of rain water harvesting infrastructures in diffuse and compact urban models of Mediterranean climate", *Int. J. Life Cycle Ass.*, **17**(1), 25-42.

BlueScope (2004), "Rain water tanks – Life cycle analysis", Centre for sustainable technology at the University of Newcastle.

Ecoinvent (2006), "Ecoinvent database in: Inventories", S.c.f.L.-c. (Ed.), Dübendorf, Switzerland.

Frijns, J. (2012), "Towards a common carbon footprint assessment methodology for the water sector", *Water. Environ. J.*, **26**(1), 63-69.

Intergovernmental Panel on Climate Change (2007), "Global Warming Potentials; Contribution of Working Group I to the Fourth Assessment Report of the IPCC", IPCC, South Korea.

International Organization for Standardization (1997), "ISO 14040: Environmental management – Life cycle assessment – Principles and framework", International Organization for Standardization, Geneva, Switzerland.

Kim, J., Hong, T. and Koo, C.W. (2012), "Economic and environmental evaluation model for selecting the optimum design of green roof systems in elementary schools", *Environ. Sci. Technol.*, **46**(15), 8475-8483.

Korea Environmental Industry and Technology Institute (2012), "Korea LCI Database", KEITI, Seoul, Korea.

Korea Meteorological Administration (2013), "Weather statistics in 30 years (1981-2010)", KMA, Seoul, Korea.

Krishna, H.J. (2005), *The Texas Manual on Rainwater Harvesting*, (3rd Edition), Texas Water Development Board, Austin, TX, USA.

Kyung, D., Kim, D., Park, N. and Lee, W. (2013), "Estimation of $CO_2$ emission from water treatment plant – Model development and application", *J. Environ. Manag.*, **131**, 74-81.

Lee, J.M., Hyun, K.H., Choi, J.S., Yoon, Y.J. and Geronimo, F.K.F. (2012), "Flood reduction analysis on watershed of LID design demonstration district using SWMM5", *Desalin. Water. Treat.*, **38**(1-3), 326-332.

LHI (2011), *Guideline of Asan Tangjeong Decentralized Rainwater Management*, Korea Land & Housing Corporation Institution (LHI).

Lienert, J., Monstadt, J. and Truffer, B. (2006), "Future scenarios for a sustainable water sector: A case study from Switzerland", *Environ. Sci. Technol.*, **40**(2), 436-442.

Lim, S.R., Suh, S., Kim, J.H. and Park, H.S. (2010), "Urban water infrastructure optimization to reduce environmental impacts and costs", *J. Environ. Manage.*, **91**(3), 630-637.

Lundie, S., Peters, G.M. and Beavis, P.C. (2004), "Life cycle assessment for sustainable metropolitan water systems planning", *Environ. Sci. Technol.*, **38**(13), 3465-3473.

MoE (2009), "Guidebook for construction and operation of rainwater harvesting tank", Department of Water industry improvement, Seoul, Korea.

Nessi, S., Rigamonti, L. and Grosso, M. (2012), "LCA of waste prevention activities: A case study for drinking water in Italy", *J. Environ. Manag.*, **108**, 73-83.

Pasqualino, J.C., Meneses, M. and Castells, F. (2011), "Life Cycle Assessment of Urban Wastewater Reclamation and Reuse Alternatives", *J. Ind. Ecol.*, **15**(1), 49-63.

Rothausen, S.G.S.A. and Conway, D. (2011), "Greenhouse-gas emissions from energy use in the water sector", *Nature Climate Change*, **1**, 210-219.

Spatari, S., Yu, Z.W. and Montalto, F.A. (2011), "Life cycle implications of urban green infrastructure", *Environ. Pollut.*, **159**(8-9), 2174-2179.

United States Environmental Protection Agency (2009), "Managing wet weather with green infrastructure", USEPA.

Venkatesh, G., Hammervold, J. and Brattebo, H. (2011), "Methodology for determining life-cycle environmental impacts due to material and energy flows in wastewater pipeline networks: A case study of Oslo (Norway)", *Urban Water Journal*, **8**(2), 119-134.

Zhou, L., Zhou, G.S. and Jia, Q.Y. (2009), "Annual cycle of $CO_2$ exchange over a reed (Phragmites australis) wetland in Northeast China", *Aquat. Bot.*, **91**(2), 91-98.

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