Impact of GHG mitigation measures in sanitation service chains: focusing on septic tanks and sewers

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ABSTRACT

Sanitation service chains (SSC) in many cities in low- and middle-income countries are complex and comprise poorly managed on-site and centralized technologies that emit greenhouse gases (GHG). In this study, we aimed to estimate the impact of GHG mitigation measures along SSCs and account for the interdependencies of SSC components with respect to GHG emissions. Using an SSC in Hanoi, we employed a mass balance approach, empirical emission equations, and a carbon footprint estimation model to estimate GHG emissions by component at baseline and four mitigation scenarios. At baseline, the SSC emitted 3,698–5,147 ton CO_2e/year, with CH_4 accounting for 78–85% of the total emissions. Infrequently emptied septic tanks accounted for 44–60% of the total emissions, followed by poorly maintained sewers (23–32%) and a wastewater treatment plant (WWTP, 17–24%). Scenario comparison showed that removing septic tanks alongside sewer improvement led to 15–24% lower GHG emissions compared to frequent septic tank emptying with sewer improvements, despite a slight increase in the N_2O emissions at the WWTP. Therefore, if not removed, septic tanks will remain an important source of GHG emissions even after a centralized sanitation is established. However, their removal may pose significant social challenges.

KEYWORDS: septic tanks, GHG estimation, urban wastewater management, GHG mitigation; sanitation service chains

SYNOPSIS: Poorly managed septic tanks and sewers constitute a major source of GHG emissions along sanitation service chains. Removing septic tanks and improving sewers are key CH_4 emission mitigation measures.

Introduction

Globally, the sanitation sector constitutes a potential source of greenhouse gas (GHG) emissions.[1] In urban areas, sanitation service chains (SSCs) include a wide range of technologies and can be categorized under four functional components, namely, (i) containment (e.g., pit latrines and septic tanks), (ii) emptying and transportation (e.g., vacuum trucks and sewers), (iii) treatment (e.g., wastewater or fecal sludge treatment plants), and (iv) end-use and disposal (e.g., fertilizer production, landfilling, and discharge into the environment).[2] The technologies associated with these different SSC components vary by city, and in low- and middle-income countries (LMIC) most especially,[2–4] SSCs often consist of a combination of complex on-site/pretreatment systems and centralized sanitation systems with sewer networks.

Each SSC component can be a potential source of GHG emissions, particularly when the SSC is poorly maintained. For example, with respect to containment components, septic tanks with long emptying intervals tend to emit more CH_4 than those with shorter emptying intervals.[5] Similarly, in emptying and transportation component, poorly maintained gravity sewers could be a source of CH_4 emissions due to stagnant wastewater.[6,7] Furthermore, during a periods of high flow, sewers can also be a source of N_2O emissions.[8] Notably, CH_4 and N_2O have, respectively, 28 and 273 times higher global warming potentials (GWP) than that of CO_2 over a 100-year timescale.[9] Wastewater treatment plants (WWTPs) and fecal sludge treatment plants (FSTPs) constitute potential sources of CH_4, N_2O, and CO_2, even when properly operated, owing to their associated biochemical reactions and energy-intensive nature.[10–14]

In most previous studies on GHG emissions from SSCs, the focus has been on emissions related to individual SSC components. Recently, the first study aimed at estimating city-scale GHG emissions by considering all SSC components was conducted in Kampala, Uganda.[15] However, to the best of our knowledge, the GHG emission reduction potentials of different mitigation measures along SSCs have not yet been studied in detail. An effective strategy for mitigating GHG emissions is to improve the current state of SSCs via adequate management and maintenance by optimizing operational conditions or restructuring SSC components. However, examining the GHG emission mitigation impacts of different measures, particularly from an integrated-system perspective, remains challenging given that a change/improvement in a component affects subsequent downstream components.

For example, shortening the emptying intervals of septic tanks could reduce CH_4 emissions but could also lead to higher GHG emissions from the increased frequency of transportation by vacuum trucks and the higher operational demands on FSTPs to handle the larger volumes of emptied fecal sludge. Accordingly, the impact of emptying and transportation using vacuum trucks and treatment at FSTPs must be considered. Furthermore, shortening septic tank emptying interval could also affect the quality of septic tanks effluents, thereby influencing emissions from subsequent components, such as sewers and WWTP. As a result, mitigating GHG emissions from a single component of an SSC can lead to changes in GHG emissions for downstream components, and hence, alter overall emissions. To examine the overall effects of mitigation measures along SSCs, it is necessary to estimate changes in emissions from each upstream and downstream component, taking their interdependencies into account.

Therefore, in this study, we aimed to estimate the impact of GHG mitigation measures along SSCs and account for the interdependencies of the SSCs components with respect to GHG emission. Specifically, we investigated different scenarios based on a typical case study from an LMIC, the Truc Bach sewerage and drainage area in Hanoi City, Vietnam. First, we estimated the current state of GHG emission in this study area. Thereafter, we estimated GHG emission under four potential mitigation scenarios based on the following measures: frequent emptying of septic tanks, removal of septic tanks, and/or improving sewer conditions. These mitigation measures were selected not only to identify the most effective mitigation strategy for the selected sewerage and drainage area, but also to provide reference information that can be employed to mitigate GHG emissions under similar settings in other countries.

Materials and methods

Study area

The study area was selected based on the following criteria: (i) the SSC comprises all SSC components; (ii) the SSC is representative of SSCs in LMIC, in terms of management and component conditions; and (iii) accessibility and availability of data including septic tank GHG emissions, wastewater characteristics (e.g., blackwater and graywater, fecal sludge, WWTP influent), WWTP configuration, and the proportion of wastewater collected and transferred from each component of the SSC (Table S1-2). The sewerage and drainage area that complied the most to these criteria was the Truc Bach drainage area in urban Hanoi, Vietnam (Figure S1-1).

In Hanoi, 88% of households rely on septic tanks,[16] with an average emptying interval of 10.2 years.[17] Typically, these septic tanks receive only blackwater and consist of two or three compartments.[18] Effluent from these septic tanks is discharged into sewers or open drains, while graywater from households is often directly discharged into combined gravity sewers or open drains.[19]

The Truc Bach sewerage and drainage area, which has a population of 15,700[16] and covers 0.55 km^2,[20] has one WWTP, the Truc Bach WWTP, with a treatment capacity of 2,500 m^3/d. With this capacity, the WWTP accommodates wastewater from Truc Bach and nearby areas. The FSTP for the study area is the Cau Dzien FSTP (i.e., Hanoi URENCO 4), with a design capacity of 300 m^3/d. All fecal sludge treated at this FSTP originates from public toilets,[16] while that from household septic tanks is emptied using vacuum trucks and directly discharged into the environment without treatment.[21]

Data analysis

System boundary and input data

We defined the system boundary for GHG emissions along the SSC in our study area as shown in Figure 1. Based on the system boundary, we included emissions from: (i) containment (i.e., septic tanks), (ii) emptying and transportation (i.e., vacuum trucks and sewers), and (iii) treatment (i.e., WWTP and FSTP). End-use and disposal-related emissions, including those from the environment, were considered to be outside the scope of this study. Further, we focused only on wastewater generated from households, while stormwater and wastewater from other types of facilities (e.g., restaurants, hotels, and public toilets) were not included in the dataset.

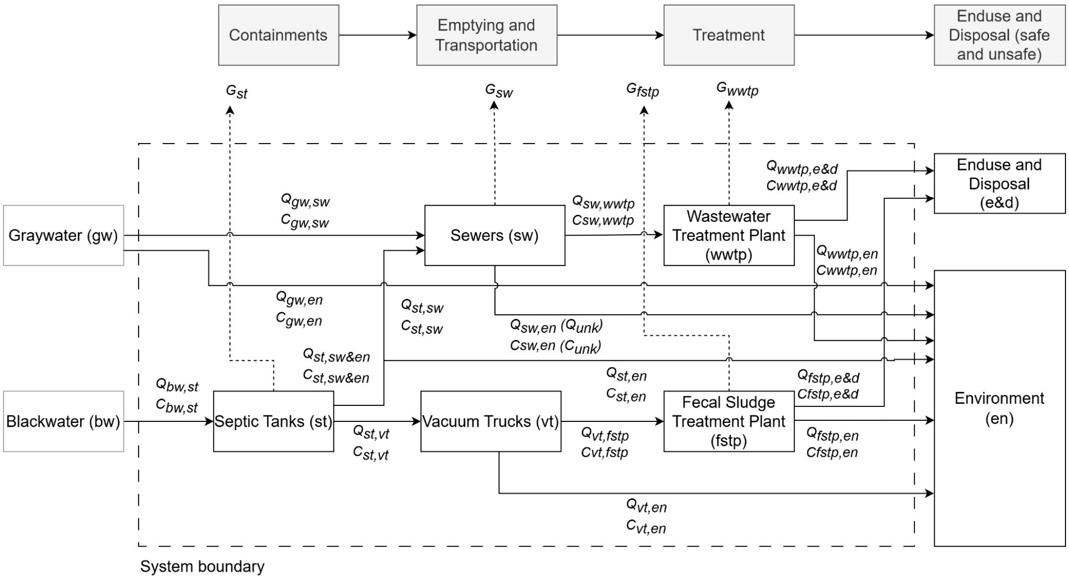

Figure 1. Diagram showing the flow rates (*Q*) and chemical oxygen demand (COD) concentrations (*C*) of the sanitation service chain (SSC), including the system boundary. $Q_{i,j}$ denotes the flow rate from component *i* to *j*. $C_{i,j}$ denotes the change in COD concentration from component *i* to *j*. G_i denotes gases emitted from component *i*.

Wastewater flow rate (*Q*) and COD load (*L*) were calculated for each component using the mass balance approach (Eq. (1) and (2)). The descriptions and equations used to calculate all the parameters required to estimate *Q* and *L* are listed in Table S1-1. The estimation of *Q* and *L* using the measured and reported parameters listed in Table S1-2 were based on the system boundary. The mass balance results for the SSC are shown in Figure S1-2.

$$\sum Q_{in,i} - \sum Q_{out,i} = 0 \quad (1)$$

$$\sum L_{in,i} - \sum L_{out,i} = 0 \quad (2)$$

where Q represents wastewater flow rate (m^3/d) and L represents COD load (kg COD/d) obtained by multiplying Q (m^3/d) by the COD concentration (C) (g/m^3).

In this study, data on the quality and quantity of wastewater discharged directly from sewers into the environment, including leakage data, were lacking. Therefore, during performing mass balance calculations for sewers, we subtracted the flow rates and COD loads entering the sewers from those transferred to the WWTP. The value thus obtained was referred to as the unknown flow rate (Q_{unk}). Thereafter, unknown concentrations (C_{unk}) were calculated based on the obtained Q_{unk}. Hence, the unknown COD load, representing the remaining COD loads after subtracting the COD load of wastewater from sewers transferred to the WWTP ($L_{sw,wwtp}$), was determined as $L_{unk} = Q_{unk} \times C_{unk}$ as shown in Eq. (3). Further details are provided in Section S2.

$$L_{unk} = L_{st,sw} + L_{gw,sw} - L_{sw,wwtp} \quad (3)$$

Additionally, following the guidelines of the Intergovernmental Panel on Climate Change (IPCC), we assumed that in sewers, 50% of COD decomposes through biological processes (Δ_{sw}), resulting in the generation of CH_4.[7,22] We used Sankey diagrams[23] to separately present the percentages of Q and L along the SSC to provide an overview of the current state of wastewater and COD mass streams.

GHG emission estimation

GHGs from SSC, including CH_4, N_2O, and CO_2 were categorized under three emission scopes as follows: Scope 1, direct emissions from the decomposition processes of wastewater, e.g., CH_4 and N_2O emissions from biological processes; Scope 2, indirect emissions from electricity use; and Scope 3, indirect emissions associated with consumables and other activities, e.g., fuel consumption and chemical manufacturing. Notably, CO_2 emissions from the decomposition of organic compounds were excluded from the estimation given that they are considered entirely biogenic and would eventually cycle back into the atmosphere.[7,24] The emission types, categorized according by scope and according to GHG type (CH_4, N_2O, or CO_2) are listed in Table S1-3.

GHG emissions from septic tanks

To estimate emissions from septic tanks, we used the equation proposed by Moonkawin et al. for CH_4 emissions from septic tanks with long sludge emptying intervals:[5]

$$EF_{CH4-st1} = mT_{st} + b \tag{4}$$

where $EF_{\text{CH4-st1}}$ represents the emission factor of CH_4 for the 1st compartment of septic tanks (g CH_4/(cap·d)), T_{st} represents the septic tank emptying interval (year), b represents the vertical intercept (3.83), and m represents slope (0.622).

Owing to the inaccessibility of the 2nd and 3rd compartments, we estimated the GHG emissions based on two approximations: (i) 2nd and 3rd compartments have the same rate of CH_4 production as the 1st compartment (i.e., maximum septic tank emissions) and (ii) 2nd and 3rd compartments cause no additional emissions (i.e., minimum septic tank emissions). All results related to GHG emissions from septic tanks are presented as ranges, minimum–maximum values. Further, given that N_2O production in septic tanks in Hanoi can be considered negligible,[18] only CH_4 emission was considered. Further details regarding this estimation are provided in Section S3.

GHG emissions from sewers

Given the unavailability of direct measurement data for GHG emissions from sewers in the study area, we used the methane correction factor (MCF) recommended by the IPCC to estimate CH_4 emissions from sewers with stagnant wastewater in warm climates, as shown in Eq. (5).[22]

$$E_{CH4-sw} = C_{sw-in} \times B_0 \times MCF_{sw} \times GWP_{CH4} \times 365 \times 10^{-3} \qquad (5)$$

where E_{CH4-sw} represents CH_4 emissions from sewers (tonCO_2e/year); C_{sw-in} represents the COD load entering sewers (kg COD/d), and GWP_{CH4} represents the GWP of CH_4.

The estimation involved the COD loads entering the sewers, *MCF*, and the IPCC's theoretical CH_4-producing capacity (B_0). Notably, *MCF* refers to the fraction of COD used for CH_4 production and B_0 represents CH_4 production per unit COD (kg CH_4/kg COD). The default *MCF* (MCF_{sw}: 0.5) and B_0 (0.25 kg CH_4/kg COD) for sewers were applied to estimate CH_4 emission.

N_2O emissions were estimated using the emission factor derived from N_2O emissions for gravity sewers by Short et al. (2014),[8] as shown in Eq. (6).

$$E_{N2O-sw} = EF_{N2O-sw} \times N_{pop} \times GWP_{N2O} \times 10^{-6} \quad (6)$$

where $E_{N2O\text{-}sw}$ represents N_2O emission for sewers (tonCO_2e/year); $EF_{N2O\text{-}sw}$ represents the N_2O emission factor for gravity sewers (g N_2O/(cap·year)), and GWP_{N2O} represents the GWP of N_2O.

GHG emissions from vacuum trucks

GHG emissions resulting from fecal sludge transportation using vacuum trucks were estimated based on emissions related to fuel consumption by the diesel vacuum trucks that are used to transport fecal sludge from the center of the Truc Bach drainage area to the FSTP or to disposal sites in the case of direct discharge without treatment. This trip was considered a round trip, and to estimate the associated emissions, the emission factors of CO_2, CH_4, and N_2O, and the total number of trips required to empty all the septic tanks within a given emptying interval were taken into account. The equations used in this regard are provided in Section S4.

GHG emissions from WWTPs

Wastewater treatment processes

To estimate GHG emissions from the WWTP, where wastewater from the Truc Bach sewerage and drainage area is treated, we input the flow rate, based on mass balance, to the configuration of the Truc Bach WWTP. The WWTP utilizes an anaerobic–anoxic–oxic (A2O) process, which removes COD, nitrogen, and phosphorus from the wastewater (Figure S5-1). The effluent of the WWTP is discharged into the Truc Bach lake, while the produced sludge is disposed of at a landfill located 41 km from the sewerage and drainage area. The GHG emissions associated with the transportation of sludge were estimated based on the same estimation approach as was applied for vacuum trucks. However, the dewatered sludge was assumed to be handled by a 2-ton truck. The emission factors employed are listed in Tables S1-2.

Model simulation

We employed the *Mantis3lib* carbon footprint estimation model[25] to estimate GHG emissions from the WWTP. The WWTP was simulated under steady state, with constant inflow using the GPS-X 8.5 software (HATCH).[25] The model input data included the flow rate of the influent reaching the WWTP ($Q_{sw,wwtp}$) obtained via mass balance, measured influent characteristic as reported by Watanabe,[26] and the WWTP's configuration and equipment (Tables S5-1 and S5-2). Scope 1 emissions were estimated through a plant-wide simulation using carbon, nitrogen, and phosphorus removal, integrating anaerobic digestion processes (i.e., ASM2d[27] and UCTADM1[28]), a four-step N_2O production model,[29] and N_2O production by autotrophic bacteria.[30,31] Scope 2 emissions were estimated based on electricity use according to regional electricity-related emissions in Vietnam, and Scope 3 emissions were estimated based on the chemical consumption at the WWTP. The equations and parameters used to estimate emissions under Scopes 2 and 3 are presented in Section S5.3.

GHG emissions from FSTP

Figure S6-1 outlines the different processes associated with the Cau Dzien FSTP with a design capacity is 300 m^3/d.[32] Given that fecal sludge from household septic tanks is currently not transported to this FSTP, GHG emissions from this FSTP were not included in the baseline scenario.[32] However, Hanoi city plans to upgrade the FSTP to receive fecal sludge from households and employ sludge dewatering and anoxic-oxic activated sludge technologies.[32]

Further details on the future upgraded FSTP, including the estimations of the associated GHG emissions are provided in Section Scenario development (Scenario A*).

After estimating the GHG emissions associated with all the SSC components, the carbon mass balance of each component was verified using field data. The COD to total organic carbon (TOC) ratio of the influent of the septic tanks was applied to convert the COD into TOC for carbon balance. For septic tanks, mass balance was performed under two conditions: (i) the maximum GHG emission scenario and (ii) the minimum GHG emission scenario. The carbon mass balance results for each component are presented in Section S7.

Scenario development

First, we established a baseline scenario for GHG emissions along the current SSC and thereafter, explored four different mitigation scenarios to reduce GHG emissions based on improvements in the SSC (Table 1). Details on the different scenarios are provided in Table 1 and Table S8-1. Any point not mentioned was not subject to change and thus remained the same as in the baseline scenario.

Table 1. Potential GHG emission mitigation measures for different scenarios.

No.	Scenario	Potential mitigation measures
1	Baseline (current state)	-
2	Scenario A	Emptying septic tanks once a year
3	Scenario B	Removing or bypassing septic tanks
4	Scenario A*	Emptying septic tanks once a year; Improving sewer connections and conditions; Treating all wastewater that is transported to the WWTP; No direct discharge; Treatment of all fecal sludge that is transported to the FSTP
5	Scenario B*	Removing septic tanks; Improving sewer connections and conditions; Treating all wastewater at the WWTP; No direct discharge

Mitigation scenarios focusing on septic tanks

Scenario A

In Hanoi, it is recommended to empty septic tanks every 1–3 years, depending on the size of the septic tank.[33] This emptying interval is within the globally recommended range of 1–5 years.[34,35] Therefore, we changed the average emptying interval from 10.2 years at baseline to 1 year (i.e., emptying once a year) under Scenario A to assess the GHG emission reduction potential of frequent septic tank emptying. This change in emptying frequency affected the emission factor of septic tanks (EF_{st}), COD of septic tank effluent ($C_{st\text{-}eff}$), and COD of fecal sludge ($C_{st\text{-}fs}$), based on the empirical equations of septic tank performance and GHG emissions (Section S8.2).[5] Accordingly, the COD loads and GHG emissions of individual components changed, as calculated using the same methods that were applied at baseline. Similar to baseline, some of the fecal sludge collected during septic tank emptying was not treated at the FSTP, but was directly discharged into the environment.

Scenario B

We hypothesized that removing or bypassing septic tanks can significantly reduce overall GHG emissions along the SSC. Thus, emissions from septic tanks as well as those from associated components, e.g., those related to fecal sludge transportation using vacuum trucks and treatment at FSTP, would become zero. In this scenario, blackwater is discharged directly into sewers. Accordingly, the COD of wastewater transferred from sewers to the WWTP ($C_{sw\text{-}wwtp}$) and from sewers to the environment ($C_{sw\text{-}en}$) were estimated. Thereafter, the GHG emissions for each component were re-estimated.

Mitigation scenarios focusing on septic tanks and sewers

Scenario A*

This scenario builds on Scenario A by further modifying sewer conditions and fecal sludge treatment capacity to ensure that 100% of septic tank effluents and graywater are collected and transported to the WWTP, and 100% of emptied fecal sludge is transported to and treated at the future upgraded FSTP. These modifications resulted in the following changes to the estimation inputs: (i) as the sewer was assumed to be clean and wastewater flow was fast, CH_4 and N_2O emissions from sewers were assumed to be negligible according to IPCC guidelines,[22] (ii) all fecal sludge was treated at the future upgraded FSTP, which employs sludge dewatering and aerobic wastewater treatment; thus, emissions from the FSTP were estimated based on IPCC guidelines for aerobic treatment processes,[22] and (iii) dewatered sludge is transported to a landfill using a 2-ton truck. As a result, the processes associated with the upgraded plant (Figure S6-2) were integrated into the GHG emissions estimation model for the FSTP and using CH_4 and N_2O emission factors for aerobic treatment, following the IPCC guidelines. The estimation details are presented in Section S6.2.

Scenario B*

A fully centralized SSC with 100% sewer coverage is developed, assuming no leakages and the removal of all septic tanks. Further, to estimate the influent characteristics of the wastewater reaching the WWTP, we assumed that flow in the sewers is fast and that the sewers are clean, allowing negligible changes in wastewater characteristics within the sewers until they reached the WWTP. Under this assumption, CH_4 and N_2O emissions from the sewers were considered negligible, following IPCC guidelines.[22]

Scenarios A* and B*, which further extend the mitigation measures of Scenarios A and B, aim to accomplish 100% wastewater and fecal sludge collection and treatment. These two advanced scenarios enable the exploration of GHG emissions and reduction potential when sewer connections and conditions are improved and all wastewater generated in the sewerage and drainage area is treated properly before discharge into the environment. Conversely, in Scenarios A and B, a portion of the wastewater and emptied sludge was discharged into the environment without proper treatment. This untreated discharge falls outside the system boundary, and its associated emissions are not considered within the boundary. Therefore, the results of scenarios A* and B* can only be compared to each other, not to other scenarios (i.e., baseline, Scenarios A and B).

Results and discussion

Wastewater flow along the SSC

The distribution of household wastewaters (blackwater, graywater, and sludge) along the SSC is shown in Figure S9-1. Blackwater and graywater constituted 17% and 83%, respectively, of the wastewater generated in the SSC. Only 18% of total wastewater was treated properly at the WWTP, while 82% was discharged into the environment after passing through septic tanks and/or sewers. The percentage of wastewater that was appropriately treated at the WWTP in this study area seems realistic considering wastewater management in LMIC, as it is similar to the values reported in previous studies conducted in other parts of Asia, e.g., Hue, Vietnam (23%),[36] Thailand (24–27%),[37,38] India (27%),[37] Bangladesh (16%),[37] and Iran (22%).[37]Of all the wastewaters generated in Hanoi, 21% was not treated at any level before discharge into the environment.

Due to the absence of data on leakage, infiltration, exfiltration, and sewer connections, we referred to the net flow rate of those wastewater as unknown wastewater. The unknown wastewater of 52% was estimated to have leaked out from sewers into the environment without treatment. This high loss may be attributed to the effects of exfiltration[36] or to the fact that sewers are still being constructed to drain wastewater and not to transport it to the WWTP.

Additionally, in Hanoi, the average emptying interval of septic tanks was 10.2 years.[17] Thus, the fecal sludge collected by vacuum trucks was equivalent to 0.1% of the total generated wastewater. Further, this fecal sludge was not transported to the FSTP but directly discharged into the environment.

COD mass flow along the SSC

The COD flowing through each SSC component, expressed as a percentage of the total COD load generated from blackwater and graywater, is presented in Figure 2. From this figure, it is evident that graywater constituted the main COD source (67%), whereas blackwater comprised 33% of the total generated COD in the sewerage and drainage area. After passing through septic tanks, only one-third of COD passed through the sewers, the remaining COD was decomposed in septic tanks, transported with fecal sludge, and directly discharged to the environment without secondary treatment. Further, only 7% of the total COD was transported to and treated at the WWTP. This low percentage of treated COD could be attributed to: (i) the low proportion of wastewater that was transported to the WWTP,[26] (ii) low COD concentrations of wastewater after passing through sewers affected by infiltration, and (iii) a high level of COD degradation in poorly maintained sewers.[22,26] According to IPCC guidelines, COD degradation in poorly maintained sewers can be as high as 50% of the COD reaching the sewer.[22] Therefore, unknown COD, i.e., COD discharged from sewers into the environment, was estimated to account for 24% of the total COD. This substantial portion of unknown COD could potentially cause water pollution and additional GHG emissions following environmental processes.

These findings highlight the severe challenges associated with wastewater management, particularly with respect to effective transport and treatment of wastewater and emptied fecal sludge. Furthermore, the high proportion of untreated wastewater suggests the need to improve

SSCs by enhancing sewer connections and conditions, monitoring leakage, and ensuring effective fecal sludge management to prevent water pollution and untraceable GHG emissions.

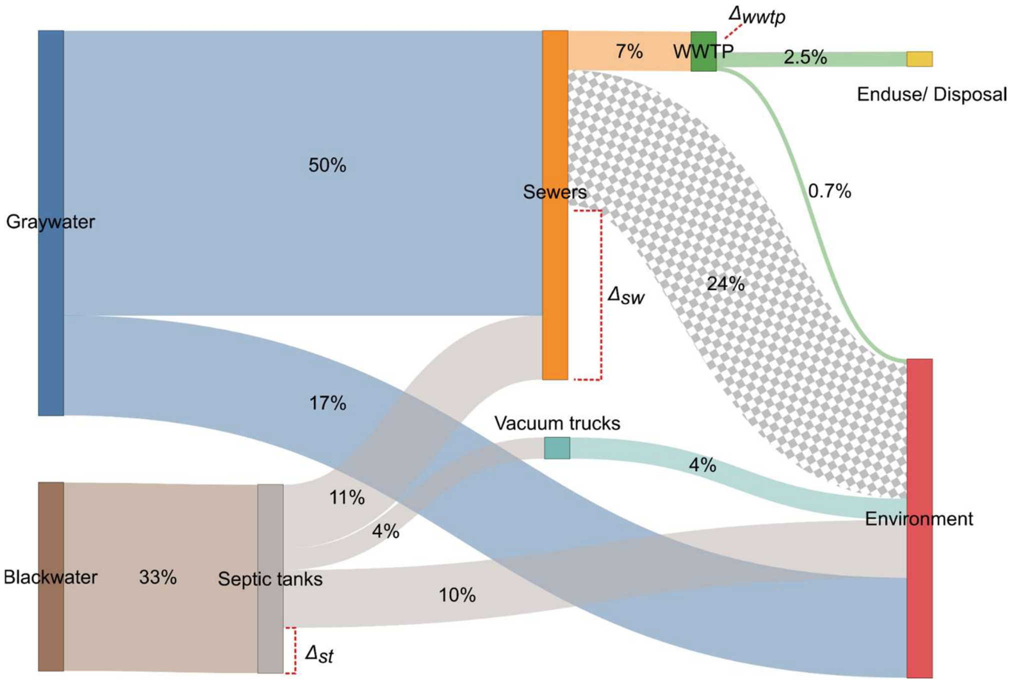

Figure 2. COD mass flow in Hanoi, Vietnam. The percentage flow is expressed in relation to the total COD generated from blackwater and graywater in the SSC.

Estimation of GHG emissions along the SSC

Baseline

GHG emission estimation

At baseline, the estimated GHG emissions for the entire SSC varied between 3,698–5,147 ton CO_2e/year (minimum–maximum GHG emissions, respectively) depending on the assumptions of the emissions from the 2nd and 3rd septic tank compartments as described in Section GHG emissions from septic tanks. In addition, it is evident that the primary contributors to GHG emissions were septic tanks (44–60%), followed by sewers (23–32%), WWTP (17–24%), and vacuum trucks (0.06–0.1%) Figure 3.

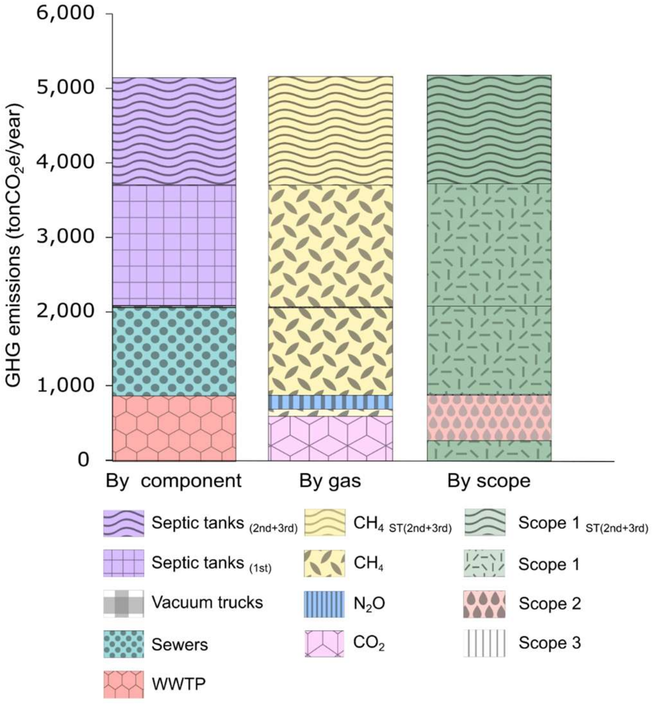

Figure 3. Baseline GHG emissions along the SSC categorized by component, GHG type, and scope of emission.

Categorization based on GHG type showed that CH_4 accounted for 78–85% of the total GHG emissions, and of the total CH_4 emissions, 56–71% originated from septic tanks, while 27–40% originated from sewers. The contribution of CO_2 was 12–16%, whereas that of N_2O was only 4–5%. Furthermore, both CO_2 and N_2O primarily originated from the WWTP. A similar finding has been reported for GHG emissions in Kampala, with CH_4 being the predominant GHG type (81%), followed by CO_2 (14%) and N_2O (6%).[15] Additionally, GHG emissions were analyzed based on each of the three emission scopes. The results obtained showed dominance for Scope 1 emissions relative to Scopes 2 and 3 emissions. Specifically, Scope 1 accounted for 83–88% of the total GHG emissions, while Scopes 2 and 3 accounted for only 12–17% and 0.08–0.1% of the total emissions, respectively. Scope 1 emissions primarily originated from septic tanks (53–68%), sewers (26–38%), and WWTP (6–9%). Conversely, Scope 2 emissions only originated from the WWTP, whereas Scope 3 emissions mainly originated from transportation (97%). Details in this regard are provided in Table S9-1.

Comparison of GHG emissions and key mitigation strategies

Considering the current state, total GHG emissions per capita varied in the range of 236–328 kg CO_2e/(cap·year), similar to the value reported for Kampala, Uganda, i.e., 316 kg CO_2e/(cap·year), when it did not include emissions into the environment as well as those related to end-use and disposal.[15] The total GHG emissions in this study were higher than emissions from only centralized WWTPs reported in previous studies by a factor of 5–10. For example, the values obtained for China and Greece were 37–58[39] and 61 kg CO_2e/(cap·year),[11] respectively. The origin of this difference can be attributed to CH_4 emissions owing to anaerobic processes in septic tanks and poorly maintained gravity sewers. In particular, septic tanks with long emptying intervals could emit large amounts of GHGs owing to a high level of organic matter accumulation under anaerobic conditions.[18] It has also been reported that inadequately maintained or poorly designed gravity sewers constitute a potential source of CH_4 due to wastewater stagnation, which promotes anaerobic conditions.[6,22,40] While GHG emissions for individual SSC components have been studied, our estimation facilitates the comparison of emissions across various components, GHG types, and scopes. Notably, our results indicated that septic tanks were the primary contributors to GHG emissions along SSCs, followed gravity sewers. Long septic tank emptying intervals as well as sewers with inadequate gravity are common in LMIC. Therefore, septic tanks and gravity sewers could be major emission sources along urban SSCs in areas with similar settings. Additionally, this suggests that mitigation efforts should focus on the reduction of septic tanks and sewers due to their substantial contribution to the total GHG emissions at the current state.

Mitigation scenarios focusing on septic tanks

Scenario A

Under Scenario A, reductions in CH_4 emissions from septic tanks were estimated by shortening septic tank emptying interval from 10.2 years to 1 year. Thus, the re-estimated COD concentration in fecal sludge in the first compartment of the septic tanks with a 1-year emptying interval was 2,860 g/m^3, approximately six-fold lower than the baseline concentration of 16,397 g/m^3. The lower COD concentrations in the fecal sludge resulted from a lower level of organic accumulation in the septic tanks, owing to more frequent emptying.

The GHG emissions under this scenario are shown in Figure 4. The total GHG emissions were 2,570–3,204 ton CO_2e/year, equivalent to 31–38% of the baseline emissions. Septic tanks and sewers remained the major contributors to overall GHG emissions (28–42% and 33–41%, respectively). Therefore, with only the change in the septic tank emptying interval, GHG emissions decreased by 56% relative to the baseline value. Emissions from vacuum trucks increased by 920%, even though still comparably small (1.1–1.3% of the total emissions), despite a 10-fold increase in emptying frequency. Therefore, shortening emptying intervals could be a straightforward first measure to reducing overall GHG emissions given that its implementation does not require any transformation of existing built components.

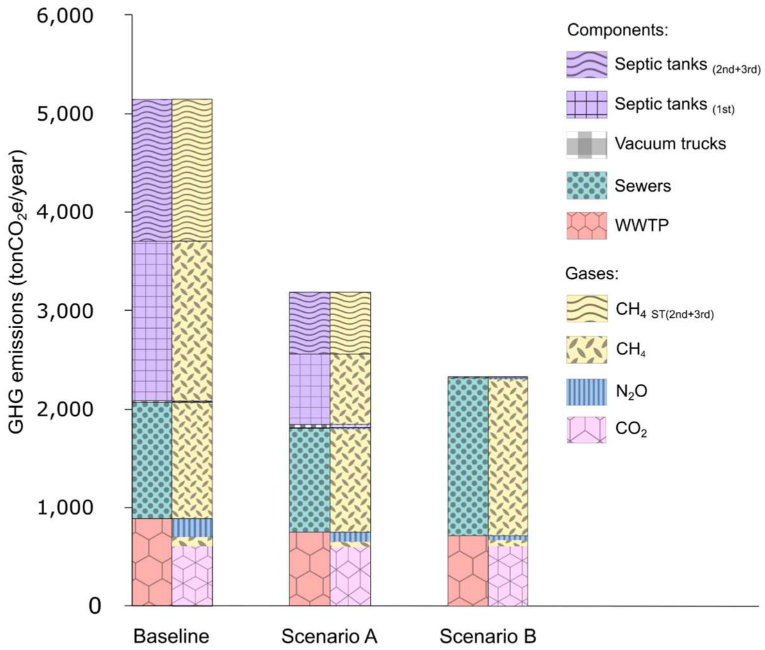

Figure 4. Comparison of GHG emissions along the SSC between baseline and two mitigation scenarios (Scenarios A and B). The GHG missions under each scenario are shown according to SSC component (left bar) and GHG type (right bar), with the GHGs further categorized according to each component.

CH_4 was still identified as the dominant GHG, accounting for 71–77% of the total emissions, followed by CO_2 at 20–25%, and N_2O at 3–4%. The emitted CH_4 primarily originated from sewers (43–58%) and septic tanks (39–55%). In terms of emission scope, Scope 1 emissions accounted for 75–80% of the overall emissions, while Scopes 2 and 3 emissions accounted for 19–24% and 5%, respectively. Further data in this regard are presented in Table S9-2. Additionally, these findings indicated that septic tanks and sewers remained the primary contributors to GHG emissions along the SSC even after shortening septic tank emptying interval.

Scenario B

Under Scenario B, septic tanks were assumed to be either removed or bypassed; thus, all blackwater was directly discharged into the sewers. Accordingly, GHG emissions from septic tanks as well as those associated with transportation by vacuum trucks and treatment at the FSTP were not considered. The estimated GHG emission under Scenario B was 2,319 ton CO_2e/year, equivalent to a 37–55% reduction from the baseline value (Figure 5). The main contributors to this emission were sewers (68%), WWTP (31%). CH_4 emission remained predominant (72%) considering the three GHGs, whereas CO_2 and N_2O emissions were 26% and 2%, respectively. Similar to Scenario A, Scope 1 emissions accounted for the largest proportion (73%) of GHG emissions, followed by Scope 2 emissions (26%), whereas Scope 3 emissions were relatively small (0.05%). Additional data are presented in Table S9-3.

Comparing GHG emissions between Scenarios A and B showed that impact of removing septic tanks under Scenario B was higher than that of frequent septic tank emptying under Scenario A, with the difference in GHG emission reduction between the two scenarios reaching 10–28%. By removing or bypassing septic tanks and allowing wastewater to be directly discharged into sewers, a substantial reduction in emissions could be achieved owing to the elimination of septic tank-related emissions. However, a large amount of CH_4 was still emitted from the sewer given that the sewer conditions were not sufficiently improved or maintained to prevent wastewater stagnation, indicating that mitigation measures should focus on reducing GHG emissions from sewers.

Mitigation scenarios focusing on septic tanks and sewers

Scenario A*

Under Scenario A*, all emptied fecal sludge was transported and treated at the FSTP, and all septic tank effluents and graywater were collected through improved sewers and treated at the WWTP. The estimated total GHG emissions varied in the range of 5,008–5,642 ton CO_2e/year (Figure 5). The main contributors to GHG emission were WWTP (74–83%) and septic tanks (14–24%), while contributions from vacuum trucks and FSTP were 0.6–0.7% and 1.8–2.0%, respectively. It should be noted that the major gas emitted in Scenario A* was different from those observed at baseline and in Scenarios A and B. Specifically, under Scenario A*, the main GHG emitted was N_2O (57–64%), followed by CO_2 (19–22%) and CH_4 (14–24%). In terms of emission scope, Scope 1 emissions showed predominance (78–80%), whereas Scope 2 and 3 emissions accounted for 18–20% and only 2–3% of the total GHG emissions. Additional data in this regard are presented in Table S9-4.

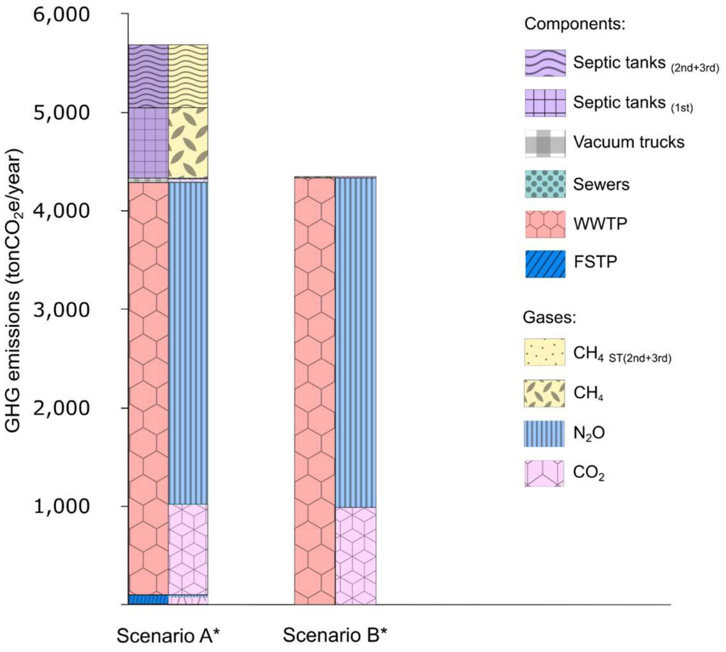

Figure 5. Comparison of GHG emissions between two mitigation scenarios: Scenario A* and Scenario B*. GHG missions under each scenario are shown by component (left bar) and GHG type (right bar), with the GHGs further categorized to align with each component.

Scenario B*

Under Scenario B, characterized as a purely centralized system, the majority of GHG emissions originated from the WWTP (4,278 ton CO_2e/year) as shown in Figure 5. N_2O was the predominant GHG (77%), whereas the contributions of CO_2 and CH_4 were 23% and 0.01%, respectively. Further, Scope 1 emissions accounted for 77% of the total emissions, followed by Scope 2 emission at 23%, and Scope 3 emissions at 0.3%. Additionally, N_2O from Scope 1 originating from WWTP bioreactors was the primary contributor to the total GHG emissions. A similar finding was reported by Gruber et al. for three Swiss municipal WWTPs.[41]

Reportedly, GHG emissions from WWTPs vary depending on the operating conditions of the WWTP. Therefore, altering plant operating conditions could be an effective strategy for reducing GHG emissions.[42,43] Further data are shown in Tables S9-5.

A comparison of Scenarios A* and B*, the GHG emissions of Scenario B* was slightly increased at WWTP due to the increase of N_2O emissions. Additionally, the total GHG emissions under Scenario B* were 15–24% lower than that under Scenario A* due to the elimination of septic tanks related emissions. This observation indicated that to maximize reductions in GHG emissions, it is necessary to remove or bypass septic tanks. Such a measure was also recommended for the urban community sewer network in China, where septic tanks are in use.[44] Septic tanks in the SSC can be important contributors to total GHG emissions. However, removing or bypassing them poses a substantial challenge in the selected sewerage and drainage area given that they are often located under houses, hence their removal requires extensive construction work.

Key implications

Overall, this study highlights the potential mitigation measures to reduce GHG emissions from SSCs accounting for interdependencies of SSCs components, based on the improvement of current operational conditions and the structural changes of SSC components. While strong assumptions were made for the selected study area, addressing them with a wide range of parameters allowed the results to be generalizable. Therefore, the obtained results can apply to any SSC that includes a combination of septic tanks, sewers, and centralized WWTP. Nevertheless, future research should focus on field measurements to refine emission factors, particularly for septic tanks, sewers, and the environment (e.g., soil and water environments), ensuring more reliable data for policy and infrastructure planning. Additionally, quantitative studies, taking into account embedded emissions as well as financial aspects, would be of great significance.

In this study, we also successfully quantified changes in GHG emission along the SSC by considering how emissions related to downstream components respond to changes in upstream elements. In many urban areas in LMIC, septic tanks were introduced before the development of sewerage systems, and flush toilets are widely used. Our results indicated that removing/bypassing septic tanks is effective for reducing GHG emissions only if this strategy does not impose an excessive burden on the local society. In Hanoi, the removal of septic tanks, which have been in use for a decade may result in a considerable burden and present a significant regulatory and social challenge. Given this limitation, a more practical and implementable measure for mitigating GHGs emissions from urban sanitation services would be frequent septic tank emptying through effective fecal sludge collection followed by treatment, and resource use or safe disposal. Alternatively, it may be possible to consider different measures, such as the collection and utilization of CH_4 from households or cluster septic tanks. Further, in areas where sanitation services do not fully cover all urban areas, even though city-wide inclusive sanitation is being emphasized, achieving comprehensive sanitation services through centralized WWTPs only remains challenging. Therefore, on-site or non-sewered sanitation will continue to play a crucial role in urban sanitation. Regardless, further efforts are required to develop technologies that can be employed to effectively mitigate GHG emissions from any SSC that incorporates on-site or non-sewered sanitation.

Supporting Information

Mass balance; Estimation of GHG emissions from sewers; Estimation of CH4 emission from septic tanks; Estimation of GHG emissions from vacuum trucks; Estimation of GHG emissions from WWTP; Estimation of GHG emissions from FSTP; Mass balance at each component (baseline); Scenario development; Detailed GHG emissions along the SSC in all scenarios (PDF)

Author contributions

JM: Conceptualization, Data Collection, Methodology, Writing-original draft, Writing-review & editing, Data analysis and Interpretation, Visualization; MYS: Conceptualization, Methodology, Writing-original draft, Writing-review & editing, Data Analysis and Interpretation, Visualization; VAN, ANP: Data collection, Writing-review & editing; SF, SE: Writing-review & editing, Supervision; HY: Funding acquisition (software), Supervision, Writing-review & editing; HH: Conceptualization, Writing-original draft, Methodology, Funding acquisition, Data Interpretation, Writing-review & editing, Supervision. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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Abbreviations

A2O, anaerobic–anoxic–oxic; B_0, maximum methane-producing capacity; COD, chemical oxygen demand; FSTP, fecal sludge treatment plant; GHG, greenhouse gas; GWP, global warming potential; IPCC, Intergovernmental Panel on Climate Change; LMIC, low- and middle-income countries; MCF, methane correction factor; SSC, sanitation service chain; TOC, total organic carbon; WWTP, wastewater treatment plant

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Supporting information

(SI)

Impact of GHG mitigation measures in sanitation service chains: focusing on septic tanks and sewers

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S1 Mass balance

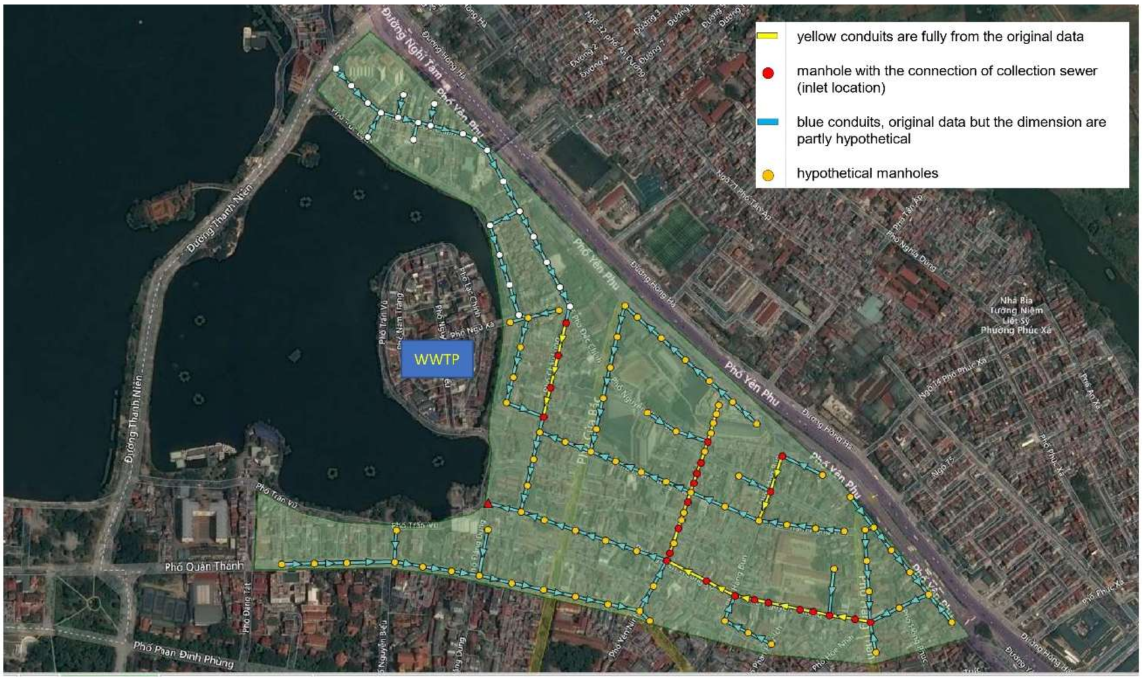

Figure S1–1 Truc Bach sewerage and drainage area obtained from Hanoi Sewerage and Drainage Company (HSDC)

Table S1-1 Description for Q and COD flow balances along the sanitation service chain

Component	**Symbol**	**Description**	**Equation**	**Unit**
Septic tanks (st)	$Q_{st,vt}$	Flow rate of fecal sludge emptied from septic tanks to vacuum trucks	$Q_{st,vt} = N_{st,emp} \times S_r$	m^3/d
	$Q_{st,sw\&en}$	Flow rate of effluent from septic tanks to sewers and environments	$Q_{st,sw\&en} = Q_{bw} - Q_{st,vt}$	m^3/d
	$Q_{st,sw}$	Flow rate of effluent from septic tanks to sewers	$Q_{st,sw} = Q_{st,sw\&en} \times P_{st,sw}$	m^3/d
	$Q_{st,en}$	Flow rate of effluent from septic tanks to environments	$Q_{st,en} = Q_{st,sw\&en} - Q_{st,sw}$	m^3/d
	$C_{st,vt}$	COD of fecal sludge emptied from septic tanks to vacuum trucks	$C_{st,vt} = C_{st\text{-}fs}$	g/m^3
	$C_{st,sw}$	COD of effluent from septic tanks to sewers	$C_{st,sw} = C_{st\text{-}eff}$	g/m^3
	$C_{st,en}$	COD of effluent from septic tanks to environments	$C_{st,en} = C_{st\text{-}eff}$	g/m^3
Vacuum trucks (vt)	$Q_{vt,fstp}$	Flow rate of fecal sludge emptied by vacuum trucks and transported to FSTP	$Q_{vt,fstp} = Q_{st,vt} \times P_{vt,fstp}$	m^3/d
	$Q_{vt,en}$	Flow rate of fecal sludge emptied by vacuum trucks and discharged to environments	$Q_{vt,en} = Q_{st,vt} - Q_{vt,fstp}$	m^3/d
	$C_{vt,fstp}$	COD conc. of fecal sludge emptied by vacuum trucks and transported to FSTP	$C_{vt,fstp} = C_{st,vt}$	g/m^3
	$C_{vt,en}$	COD conc. of fecal sludge emptied by vacuum trucks and discharged to environments	$C_{vt,en} = C_{st,vt}$	g/m^3
Fecal sludge treatment plant (fstp)	$Q_{fstp,e\&d}$	Flow rate of treated fecal sludge from FSTP to end-use and disposal	$Q_{fstp,e\&d} = Q_{vt,fstp} \times P_{fstp,e\&d}$	m^3/d
	$Q_{fstp,en}$	Flow rate of treated fecal sludge from FSTP to environments	$Qf_{stp,en} = Q_{vt,fstp} - Q_{fstp,e\&d}$	m^3/d
	$C_{fstp,e\&d}$	COD conc. of wastewater from FSTP to end-use and disposal	$C_{fstp,e/d} = C_{vt,fstp} \times R_{fstp}$	g/m^3
Sewer (sw)	$Q_{gw,sw}$	Flow rate of graywater discharged to sewers	$Q_{gw,sw} = Q_{gw} \times N_{pop} \times 10^{-3} \times P_{gw,sw}$	m^3/d
	$Q_{gw,en}$	Flow rate of graywater discharged to environments	$Q_{gw,en} = Q_{gw} \times N_{pop} \times 10^{-3} \times (1-P_{gw,sw})$	m^3/d
	$Q_{sw,wwtp}$	Flow rate of wastewater from sewers transferred to WWTP	$Q_{sw,wwtp} = (Q_{st,sw} + Q_{gw,sw}) \times P_{sw,wwtp}$	m^3/d
	Q_{unk}	Flow rate of unknown wastewater not transferred to WWTP	$Q_{unk} = Q_{st,sw} + Q_{gw,sw} - Q_{sw,wwtp}$	m^3/d
	$C_{gw,sw}$	COD conc. of graywater discharged into sewers	$C_{gw,sw} = C_{gw}$	g/m^3
	$C_{sw,wwtp}$	COD conc. of wastewater discharged from sewers to WWTP	$C_{sw,wwtp} = C_{wwtp\text{-}inf}$	g/m^3
	C_{unk}^{*}	COD conc. of unknown wastewater not transferred to WWTP	$C_{unk} = L_{unk}/Q_{unk} \times 1000$	g/m^3
Wastewater treatment plant (wwtp)	$Q_{wwtp\text{-}e\&d}$	Flow rate of sludge from WWTP to end-use and disposal	estimated by GPS-X	m^3/d
	$Q_{wwtp\text{-}en}$	Flow rate of treated wastewater from WWTP to environments	estimated by GPS-X	m^3/d
	$C_{wwtp\text{-}e\&d}$	COD conc. of sludge from WWTP to end-use and disposal	estimated by GPS-X	g/m^3
	$C_{wwtp\text{-}en}$	COD conc. of treated wastewater from WWTP to environments	estimated by GPS-X	g/m^3

*See detailed explanation in section S2

Table S1-2 Input parameters for wastewater flow rate, COD loads, and GHG emissions estimation

Symbol	**Description**	**Value**	**Unit**	**Sources**
B_0	Maximum CH_4 producing capacity	0.25	kg CH_4/kg COD	IPCC 2019[1]
C_{bw}	COD conc. of blackwater	1245	g/m^3	Moonkawin et al., 2023; Huynh et al., 2021[2,3]
C_{st-eff}	COD conc. of effluent of septic tanks	813	g/m^3	Moonkawin et al., 2023; Huynh et al., 2022[2,3]
C_{gw}	COD conc. of graywater	533	g/m^3	Huynh et al., 2020 (*n*=3)[4]
$C_{wwtp-inf}$	COD conc. of influent of WWTP	244.5	g/m^3	Watanabe 2018[5]
C_{st-fs}	COD conc. of fecal sludge in septic tanks	16397	g/m^3	Moonkawin et al., 2023; Huynh et al., 2021[2,3]
D	Distance from the drainage area to FSTP (round trip)	26	km/trip	OpenStreetMap 2023[6]
D_{disp}	Distance from the drainage area to Nam Son waste treatment facilities (round trip)	82	km/trip	Nguyen, 2025[7]
D_{env}	Distance from the drainage area to open dumping at the environment (round trip)	22	km/trip	Nguyen, 2025
$EF_{CH4,vt}$	Emission factor of methane (diesel)	0.00000317	kg CH_4/km	US EPA 2014[8]
$EF_{CH4,2ttt}$	Emission factor of methane of a 2-ton truck	0.0000076	kgCH_4/km	Nakamura et al., 2014[10]
$EF_{CH4,sw}$	Emission factor of methane from sewers	1.63	g N_2O/(cap·year)	Short et al., 2014[9]
$EF_{CO2,vt}$	Emission factor of carbon dioxide (diesel)	2.697	kg CO_2/L	US EPA 2014[8]
$EF_{CO2,2tt}$	Emission factor of carbon dioxide of a 2-ton truck	2.6	kg CO_2/L	Nakamura et al., 2014[10]
$EF_{N2O,vt}$	Emission factor of nitrous oxide (diesel)	0.00000298	kg N_2O/km	US EPA 2014[8]
$EF_{N2O,2ttt}$	Emission factor of nitrous oxide of a 2-ton truck	0.000014	kg N_2O/km	Nakamura et al., 2014[10]
FC_{2tt}	Fuel consumption of a 2-ton truck	7	km/L	Nakamura et al., 2014[10]
FC_{vt}	Fuel consumption of a diesel vacuum truck	5.5	km/L	Nakamura et al., 2014[10]
GWP_{CH4}	Global warming potential of methane	28	-	IPCC 2023[11]
GWP_{N2O}	Global warming potential of nitrous oxide	273	-	IPCC 2023[11]
MCF_{fstp}	Methane correction factor at FSTP, indicating a fraction of COD converted into CH_4 in FSTP	0.2	-	IPCC 2019[1]
MCF_{sw}	Methane correction factor at sewers, indicating a fraction of COD converted into CH_4 in sewers	0.5	-	IPCC 2019[1]
N_{pop}	Population	15700	person	Brandes et al., 2016[12]
$N_{st-area}$	Number of septic tanks in the study area	3140	septic tank	$N_{pop} / N_{user/st}$
N_{st-emp}	Number of septic tanks to be emptied (rounded-up number)	1	septic tank/d	$N_{st-area} / (T_{st} \times 365)$
$N_{user/st}$	Number of users per septic tank	5	Person/tank	Pham 2014 (*n*=46)[13]
$P_{fstp,e\&d}$	Proportion of treated fecal sludge to end-use and/or disposal	1.00	-	Brandes et al., 2016[12]
$P_{gw,sw}$	Proportion of graywater discharged into sewers	0.74	-	Watanabe 2018[5]
$P_{st,sw}$	Proportion of septic tanks connected to sewers	0.53	-	Watanabe 2018[5]
$P_{sw,wwtp}$	Proportion of wastewater collected by sewers and transferred to WWTP	0.26	-	Watanabe 2018[5]
$P_{t,st}$	Proportion of toilets connected to septic tanks	1.00	-	Watanabe 2018[5]
$P_{vt,fstp}$	Proportion of fecal sludge emptied by vacuum trucks and transported to FSTP	0.04	-	The World Bank 2013[14]

Symbol	**Description**	**Value**	**Unit**	**Sources**
Q_{bw}	Flow rate of blackwater per capita	25.3	L/(person·d)	Huynh et al., 2020 (n=15)[4]
Q_{gw}	Flow rate of graywater per capita	120.7	L/(person·d)	Pham 2014 (n=80)[13]
R_{fstp}	Fraction of COD removal of stabilization ponds	0.53		Saqqar & Pescod, 1995[15]
T_{st}	Average emptying interval of septic tanks	10.2	year	Pham 2014 (n=46)[13]
V_{2tt}	Two-ton truck capacity	2		Nakamura et al., 2014[10]
$V_{fs\text{-}emp}$	Volume of fecal sludge emptied per time	3.4	m^3/septic tank	Pham 2014 (n=46)[13]
V_{vt}	Vacuum truck capacity	3.6	m^3	Nakamura et al., 2014[10]

Table S1-3 The emission types, categorized according by scope and GHG type (CH_4, N_2O, or CO_2)

Scope	**Category**	**Included in this study**
Scope 1 (Direct emissions)	CO_2 from aerobic, anoxic, and anaerobic processes (biogenic)	✗
	CH_4 from anaerobic digestion, uncontrolled sludge degradation	✓
	N_2O from nitrification and denitrification in biological treatment	✓
Scope 2 (Indirect emissions from purchased energy)	Electricity use for pumping, blower energy (aeration), mixing, other treatment processes	✓
Scope 3 (Other indirect emissions)	Chemical production (manufacturing)	✓
	Miscellaneous energy (fuel for sludge transport)	✓
	Material replacement, labor activities, infrastructure emissions (construction, maintenance, and embodied carbon), etc.	✗

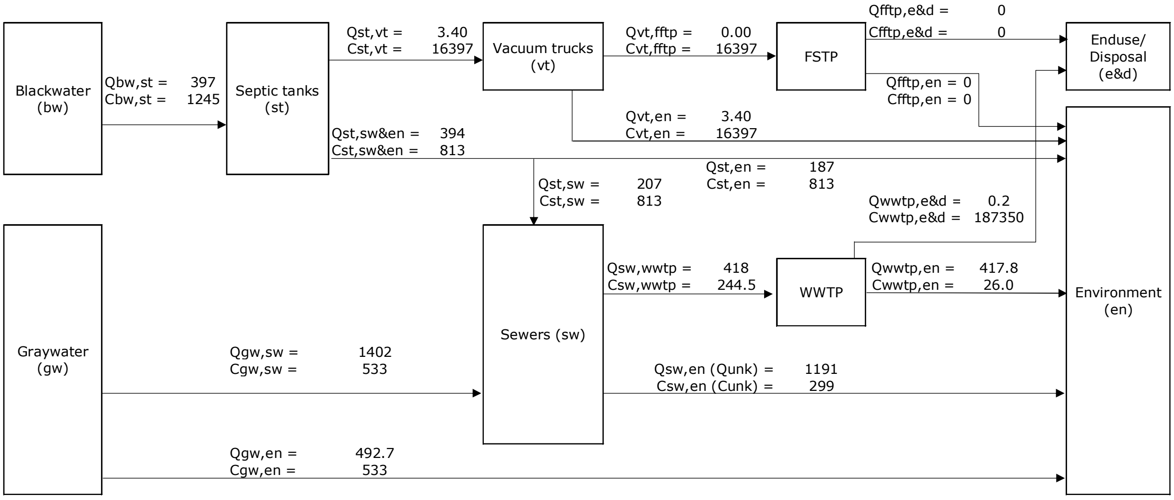

Figure S1–2 Mass balance diagram for baseline

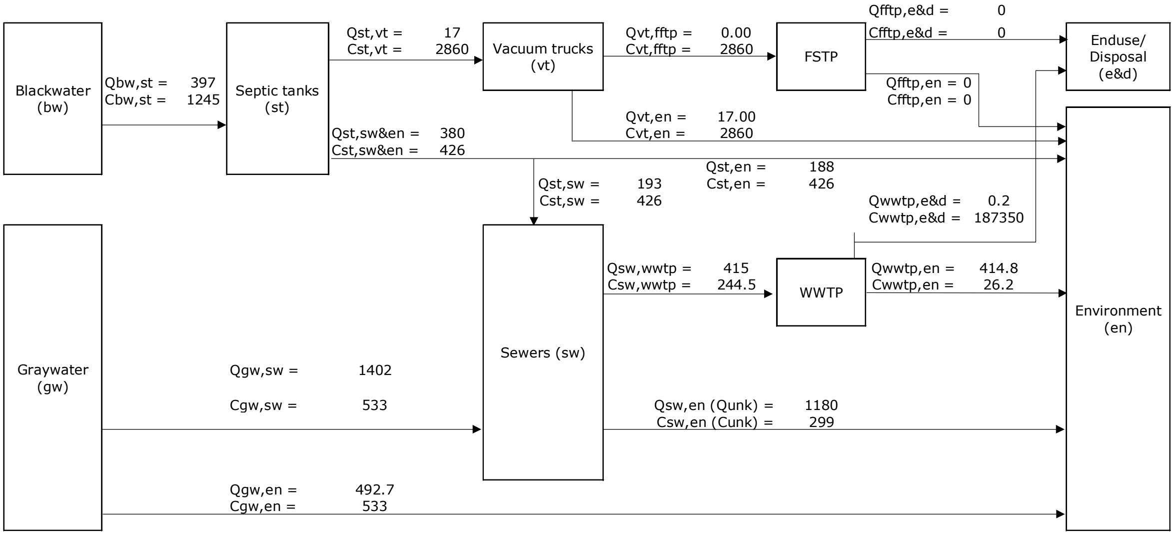

Figure S1–3 Mass balance diagram for scenario A

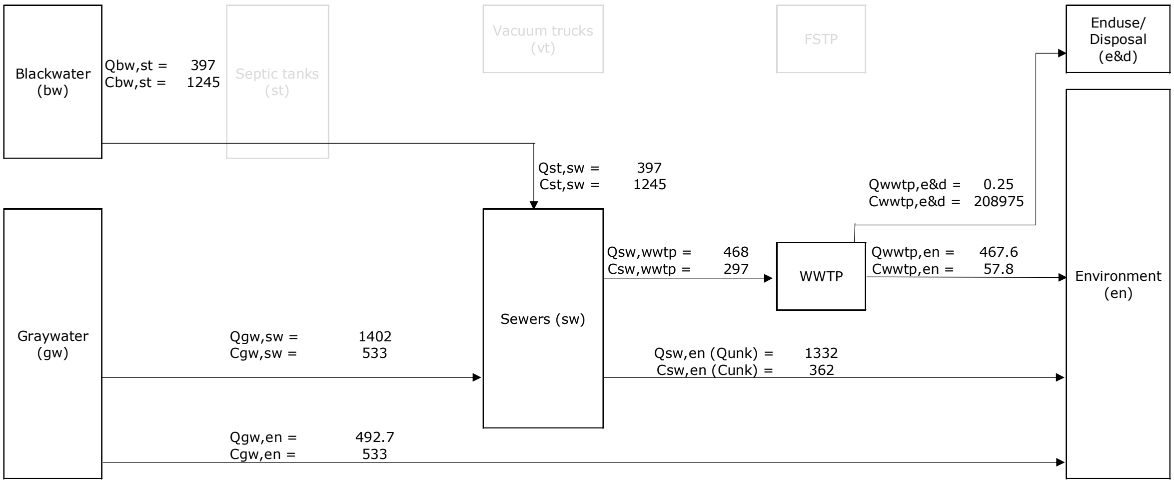

Figure S1–4 Mass balance diagram for scenario B

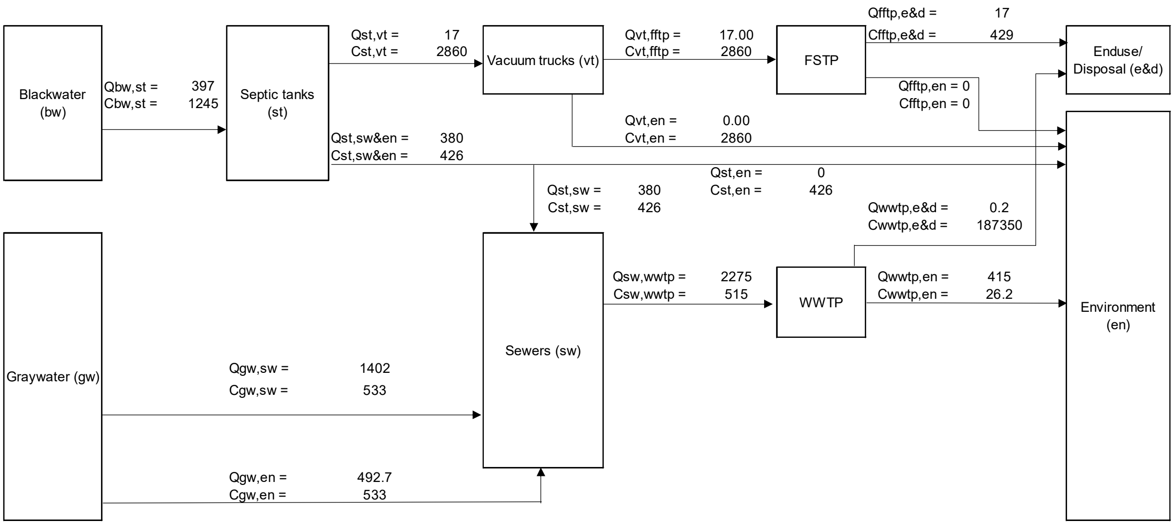

Figure S1–5 Mass balance diagram for scenario A*

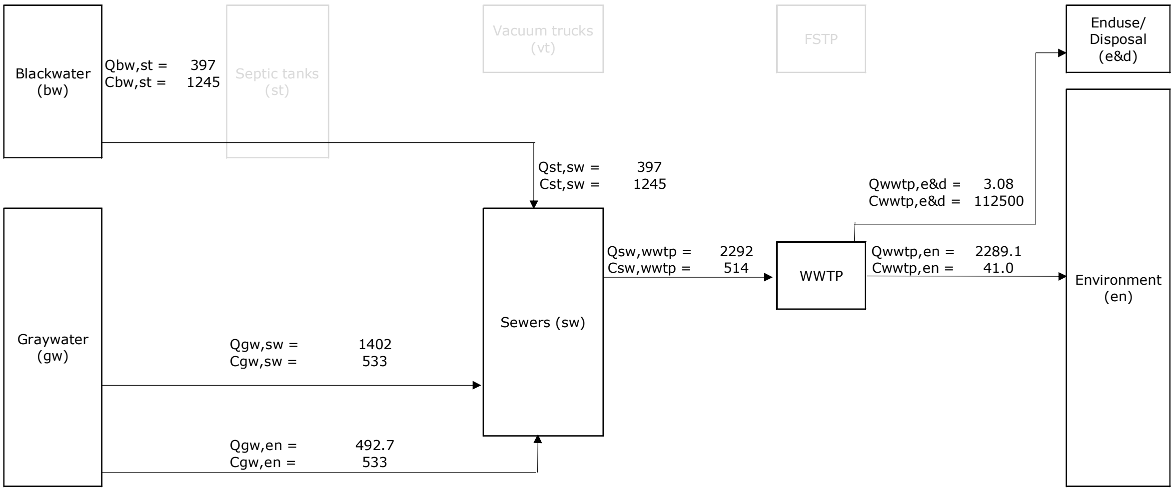

Figure S 1–6 Mass balance diagram for scenario B*

S2 Estimation of GHG emissions from sewers

Derivation of concentration of unknown wastewater

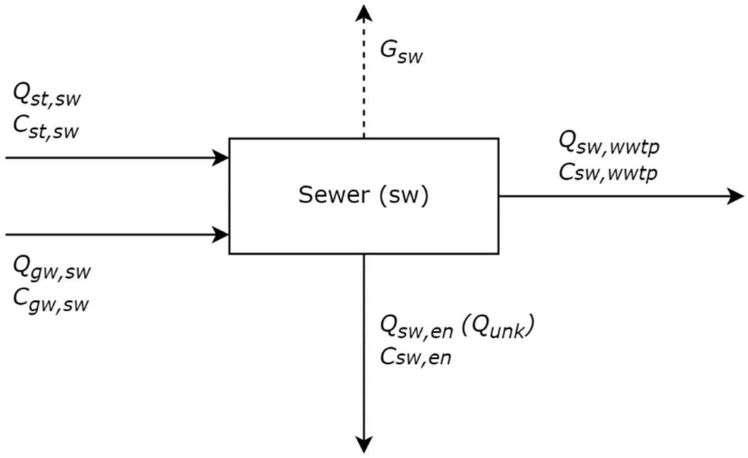

Figure S2–1 Mass balance around sewers

$$\sum Q_{sw-in} - \sum Q_{sw-out} = 0 \tag{2.1}$$

$$Q_{st,sw} + Q_{gw,sw} - Q_{sw,wwtp} - Q_{unk} = 0 \tag{2.2}$$

$$Q_{unk} = Q_{st,sw} + Q_{gw,sw} - Q_{sw,wwtp} \tag{2.3}$$

Where Q_{unk} is flow rate of unknown wastewater not transferred to WWTP (m^3/d); $Q_{st,sw}$ is flow rate of effluent from septic tanks to sewers (m^3/d); $Q_{gw,sw}$ is flow rate of graywater discharged to sewers (m^3/d); and $Q_{sw,wwtp}$ is flow rate of wastewater from sewers transferred to WWTP (m^3/d).

Gas production (G_{sw}) was calculated from COD that is removed in sewers (Δ_{sw}). Δ_{sw} was calculated by using COD loading entering sewers (L_{sw-in}) and a removal fraction or *MCF* suggested from IPCC for the CH_4 conversion as shown in eq. (2.4).

$$\Delta_{sw} = \sum L_{sw-in} \times MCF_{sw} \tag{2.4}$$

$$\sum L_{sw-in} - \sum L_{sw-out} - \Delta_{sw} = 0 \tag{2.5}$$

$$L_{unk} = Q_{st,sw} \times C_{st,sw} + Q_{gw,sw} \times C_{gw,sw} - Q_{sw,wwtp} \times C_{sw,wwtp} - \Delta_{sw} \tag{2.6}$$

$$C_{unk} = \frac{L_{unk}}{Q_{unk}} \tag{2.7}$$

Where Δ_{sw} is COD loading that is removed in sewers (g COD/d); L_{sw-in} is COD loading entering sewers (g COD/d); *MCF* is methane collection factor (fraction) of sewers; L_{unk} is unknown COD loading discharged from sewers to environments (g COD/d); $L_{sw\text{-}out}$ is COD loading leaving sewers (g COD/d); and C_{unk} is COD concentration of unknown wastewater not transferred to WWTP (g COD/d).

S3 Estimation of CH4 emission from septic tanks

$$EF_{CH4-st1} = 3.83 + 0.622T_{st} \tag{8}$$

$$EF_{CH4-st2\&3} = EF_{CH4-st1} \times \frac{S_{st2\&3}}{S_{st1}} \tag{9}$$

$$EF_{CH4-st} = EF_{CH4-st1} + EF_{CH4-st2\&3} \tag{10}$$

$$E_{st} = EF_{CH4-st} \times N_{pop} \times GWP_{CH4} \times 365 \times 10^{-6} \tag{11}$$

Where $EF_{\mathrm{CH4\text{-}st1}}$ is CH_4 emission factor of the 1st compartment of septic tanks (g CH_4/(cap·d)); T_{st} is emptying intervals of septic tanks (year); $EF_{\mathrm{CH4\text{-}st2\&3}}$ is CH_4 emission factor of the 2nd and 3rd compartment of septic tanks (g CH_4/(cap·d)); $S_{st2\&3}$ is a fractional surface area of the 2nd and 3rd compartments to the total surface area (0.47); S_{st1} is a fractional surface area of the 1st compartments to the total surface area (0.53); $EF_{CH4\text{-}st}$ is CH_4 emission factor of septic tanks (g CH_4/(cap·d)); E_{st} is GHG emissions from septic tanks (tonCO_2e/year); N_{pop} is population (persons); GWP_{CH4} is global warming potential of CH_4 (28); 365 is the number of days in a year; and 10^{-6} is a conversion factor from gram to ton.

S4 Estimation of GHG emissions from vacuum trucks

$$N_{trip/d} = \frac{N_{st-area}}{N_{st/trip} \times T_{st}} \tag{4.1}$$

where $N_{trip/d}$ is number of emptied trips per day (trip/d); $N_{st\text{-area}}$ is number of septic tanks in a study area (tank); $N_{st/trip}$ is number of septic tanks to be emptied per trip (septic tank/trip); and T_{st} is average emptying interval of septic tanks (year).

$$E_{CO2-vt} = \frac{D}{FC_{vt}} \times EF_{CO2,vt} \times N_{trip/d} \times 365 \times 10^{-3} \tag{4.2}$$

where $E_{CO2\text{-}vt}$ is CO_2 emission from vacuum trucks (tonCO_2e/year); D is a round-trip distance from the drainage area to a FSTP (km); FC_{vt} is fuel consumption of a diesel vacuum truck (km/L); and $N_{trip/d}$ is number of emptied trips per day (trip/d).

$$E_{CH4-vt} = D \times EF_{CH4,vt} \times N_{trip/d} \times GWP_{CH4} \times 365 \times 10^{-3} \tag{4.3}$$

where $E_{CH4\text{-}vt}$ is CH_4 emission from vacuum trucks (tonCO_2e/year); $EF_{CH4,vt}$ is emission factor of CH_4 from a diesel vacuum truck (kg CH_4/km); and $N_{trip/d}$ is number of emptied trips per day (trip/d); GWP_{CH4} is global warming potential of CH_4; 365 is the number of days in a year; and 10^{-3} is a conversion factor from kilogram to ton.

$$E_{N2O-vt} = D \times EF_{N2O,vt} \times N_{trip/d} \times GWP_{N2O} \times 365 \times 10^{-3} \tag{4.4}$$

where $E_{N2O\text{-}vt}$ is N_2O emission from vacuum trucks (tonCO_2e/year); $EF_{N2O,vt}$ is emission factor of N_2O from a diesel vacuum truck (kg N_2O/km); and $N_{trip/d}$ is number of emptied trips per day (trip/d); GWP_{N2O} is global warming potential of N_2O; 365 is the number of days in a year; and 10^{-3} is a conversion factor from kilogram to ton.

S5 Estimation of GHG emissions from WWTP

S5.1 Truc Bach WWTP process diagram

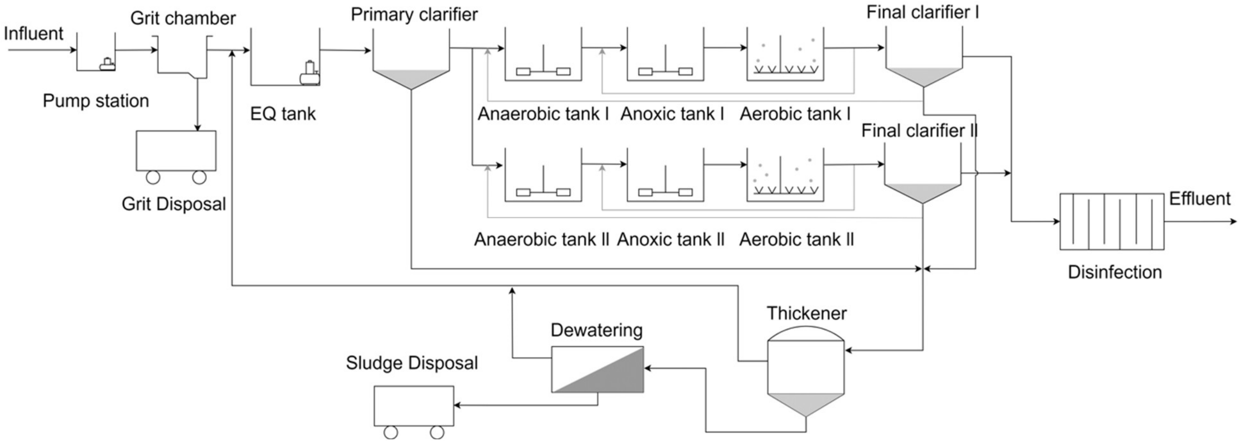

Figure S5–1 Truc Bach WWTP process diagram

S5.2 Input data for GPS-X's WWTP simulation

Table S5-1 Truc Bach WWTP configuration

Unit operation	Size	Unit	Qty.	Operated	Stand by	total kW	Remark
Influent pump pit							
Volume	52.1	m^3	1				assume HRT is 30 mins
Transfer pump	5.5	kw	3	2	1	11	
Grit chamber							
Grip pump	3.7	kw	2	1	1	3.7	1 operated 1 stand by
Fine Screen	0.2	kw	2	2	0	0.4	2 operated
Grit separation	2.2	kw	1	1	0	2.2	1 operated
Equalization tank							
Volume	156.25	m^3	1				assume HRT is 1.5 hrs
Agitator	2	kw	2	2	0	4	2 operated
Transfer pump	3.7	kw	3	2	1	7.4	2 operated 1 stand by
Primary sedimentation							
Volume	171.5	m^3	1				wepa n.d.
Sludge scraper	0.4	kw	1	1	0	0.4	
sludge pump	2.2	kw	2	1	1	2.2	
Anaerobic tank							
Volume	105	m^3	2				
Anaerobic mixer	1.5	kw	2	2	0	3	
Anoxic tank		tank	2				
Volume	274	m^3	2				
Anoxic mixer	2.8	kw	2	2	0	5.6	
Aerobic tank		tank					
Volume	180.4	m^3	2				
Recirculation pump	5.5	kw	2	1	1	5.5	
Coagulant dosing pump	0.2	kw	2	2	0	0.4	
Air blower	15	kw	3	2	0	30	
Secondary sedimentation							
Volume	224	m^3	2				
Sludge scraper	0.4	kw	2	2	0	0.8	
Return sludge pump	2.2	kw	1	1	1	2.2	
Disinfection							
Volume	52.1	m^3	1				assume contact time is 30 mins
Treated water discharge pump	3.7	kw	2	1	1	3.7	
Recycle water pump	3.7	kw	2	1	1	3.7	
Thickener							
Surface area	9.6	m^2					diameter 3.5 m
Sludge scraper	0.4	kw	1	1	0	0.4	
Sludge pump	0.75	kw	1	1	0	0.75	
Dewatering	1	tank	1	1	0	1	
Sludge cake hopper	1.5	kw	2	2	0	3	
Dehydrator	0.75	kw	1	1	0	0.75	
Sludge feed pump	1.5	kw	1	1	0	1.5	
Polymer dosing pump	0.75	kw	1	1	0	0.75	
Booster pump	1.5	kw	1	1	0	1.5	
Filtrate return pump	0.75	kw	2	1	1	0.75	
Drainage pump	0.4	kw	1	1	0	0.4	

Table S5-2 Influent characteristics of Truc Bach WWTP

Influent	Value (median)
SS (g/m^3)	49
BOD (g/m^3)	58
COD (g/m^3)	244.5
TN (g N/m^3)	44.5
NH_4-N (g N/m^3)	N.A.
NO_3-N (g N/m^3)	N.A.
TP (g P/m^3)	2.18
PO_4-P (g/m^3)	N.A.
Temperature (°C)	28

Source: Watanabe (2018)[5]

S5.3 Scope 2 and Scope 3 emissions estimation in GPS-X

$$E_{scope2} = E_{wwtp} \times EF_{elec} \tag{5}$$

Where E_{scope2} is GHG emissions from scope 2 (tonCO$_2$e/year); E_{wwtp} is electricity consumption in the WWTP (MWh/year); EF_{elec} is grid emission factor of Vietnam (0.7221 tonCO2e/MWh).[16]

$$E_{scope3} = M_i \times F_i \times 10^{-3} \tag{6}$$

Where E_{scope3} is GHG emissions from scope 2 (tonCO$_2$e/year); M_{i} is chemical consumption in WWTP (kg/year); and F_{i} is emission factors of chemicals (kg CO$_2$e/kg).

Other operational parameters for simulation in all scenario were maintained as shown in Table S5-3

Table S5-3 Operational parameters in GPS-X model

Parameter	Value
DO in aeration tanks (g/m^3)	2
Internal recycle ratio (%)	200
Temperature (°C)	28
C:N ratio	5.5

For emissions from transportation of sludge, the approaches are in the same basis as in GHG emissions for vacuum trucks.

S6 Estimation of GHG emissions from FSTP

S6.1 Current Cau Dzien FSTP process diagram

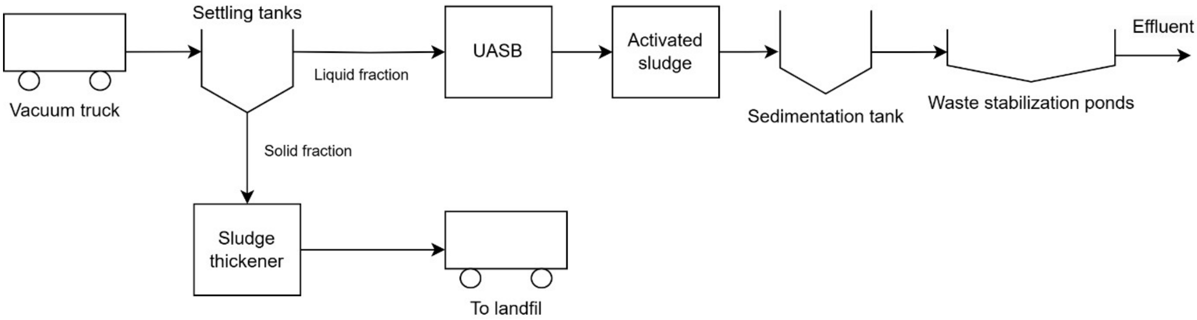

Figure S6–1 Current Cau Dzien FSTP process diagram (Brandes et al., 2016)

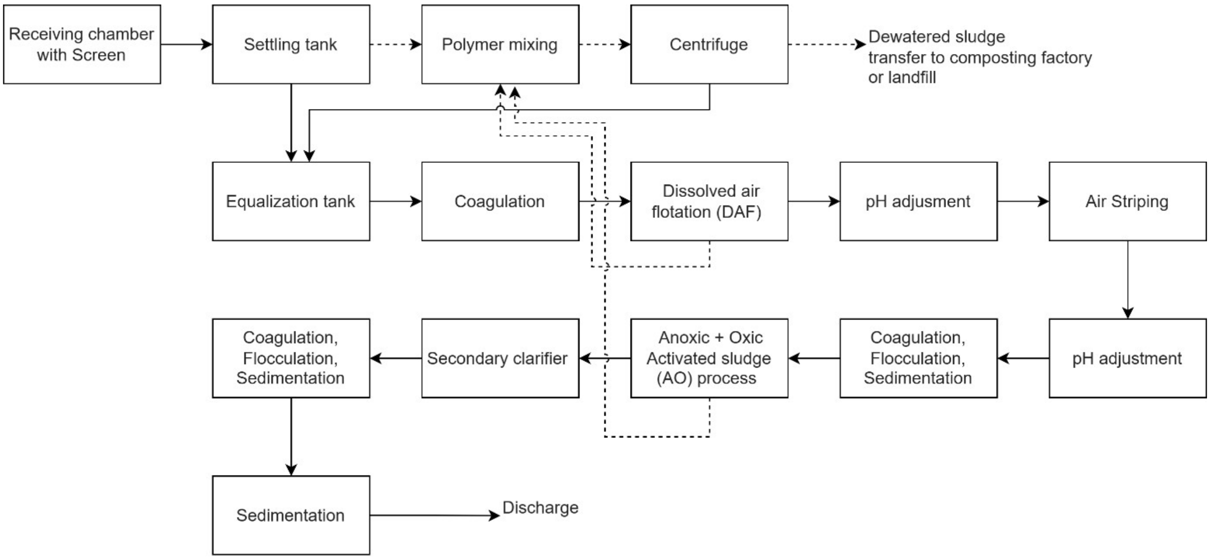

Figure S6–2 Upgraded (future) Cau Dzien FSTP process diagram (URENCO Hanoi and CENIC Co 2023)

S6.2 GHG emissions estimation from FSTP for Scenario A*

$$E_{CH4,fstp} \ = \ COD_{vt,fstp} \times EF_{CH4} \times GWP_{CH4} \times 365 \times 10^{-3} \tag{7}$$

Where E_{fstp} is emissions from FSTP (tonCO$_2$e/year); CH$_4$ emission factor for aerobic treatment (0.0075 kg CH$_4$/kg COD); GWP_{CH4} is global warming potential of CH$_4$.

$$E_{N2O,fstp} \ = \ COD_{vt,fstp} \times EF_{N2O} \times GWP_{N2O} \times 365 \times 10^{-3} \tag{8}$$

Where E_{fstp} is emissions from FSTP (tonCO$_2$e/year); N$_2$O emission factor for aerobic treatment (0.016 kg N$_2$O/kg N); GWP_{N2O} is global warming potential of N$_2$O.

For emissions from transportation of sludge, the approaches are in the same basis as in GHG emissions for vacuum trucks.

S7 Mass balance at each component (baseline)

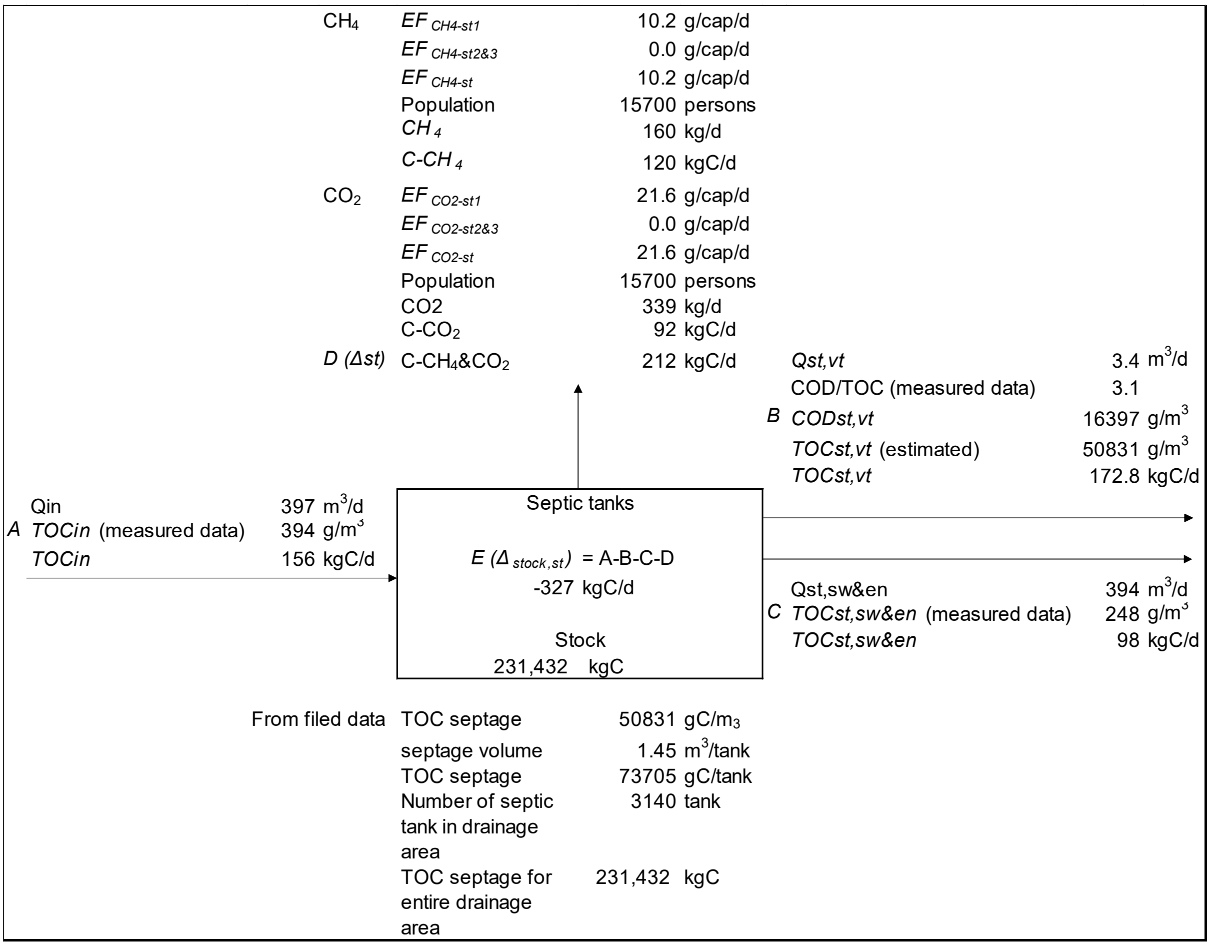

Figure S7–1 Mass balance around septic tanks at minimum emissions

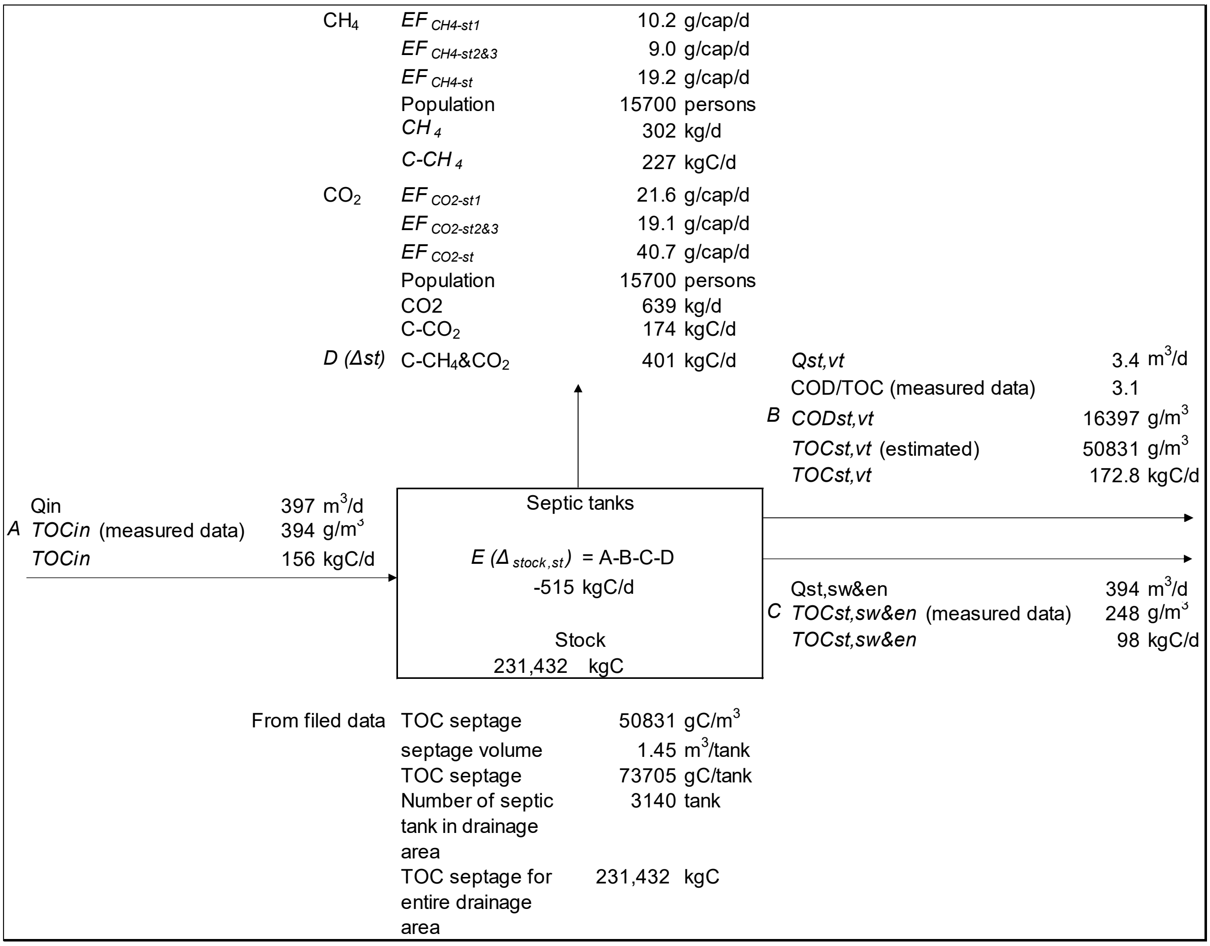

Figure S7–2 Mass balance around septic tanks at maximum emissions

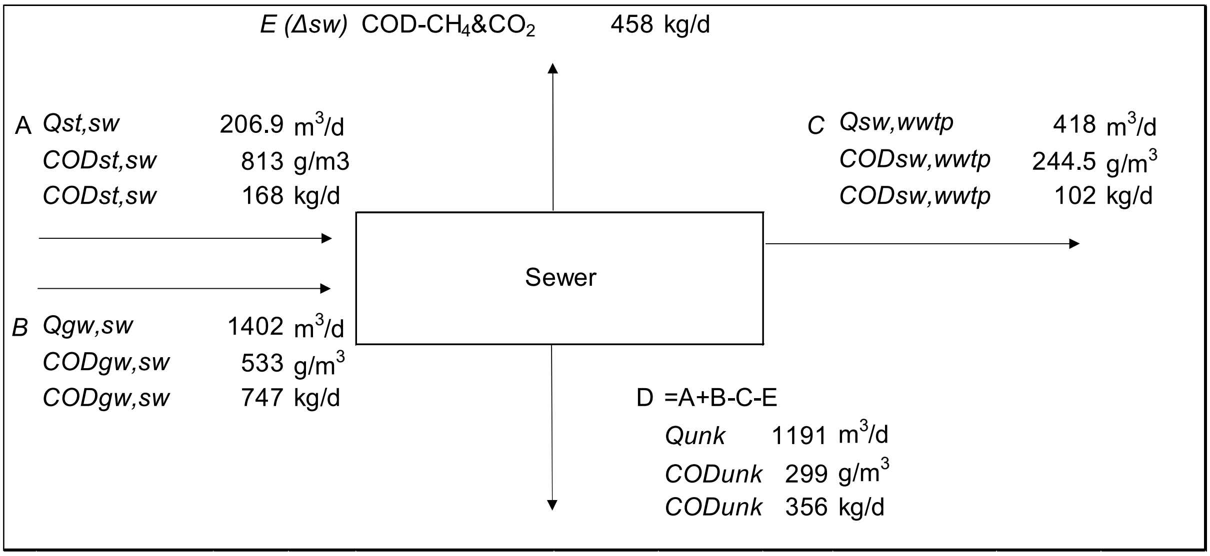

Figure S7–3 Mass balance around sewers

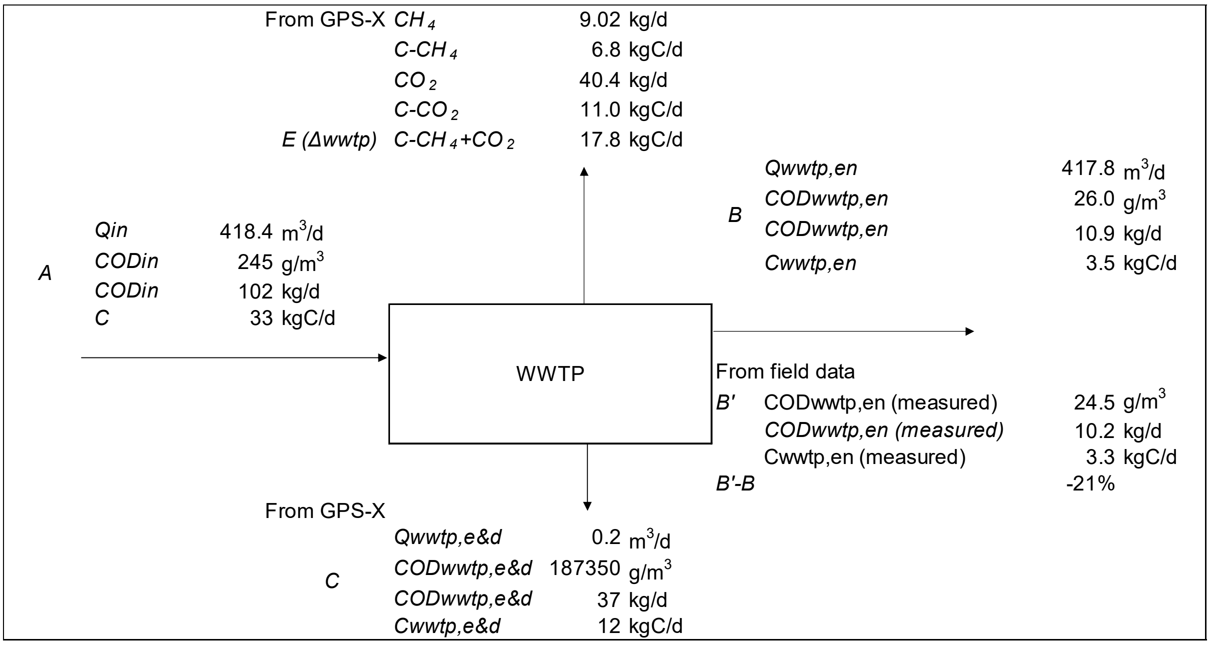

Figure S7–4 Mass balance around WWTP

S8 Scenario development

S8.1 Variable application in each scenario

Table S8-1 Variable application in each mitigation scenario

Symbol	**Description**	**Baseline:** Current state	**Scenario A:** Increased frequency of septic tank emptying	**Scenario B:** No septic tanks without improved sewer conditions	**Scenario C:** No septic tanks with improved sewer conditions
T_{st}	Average emptying interval of septic tanks	10.2	1.00	-	-
$P_{bw,sw}$	Proportion of blackwater discharged into sewers	0.00	0.00	1.00	1.00
$P_{t,st}$	Proportion of toilets connected to septic tanks	1.00	1.00	0.00	0.00
$P_{st,sw}$	Proportion of septic tanks connected to sewers	0.53	0.53	0.00	0.00
$P_{gw,sw}$	Proportion of graywater discharged into sewers	0.74	0.74	0.74	1.00
$P_{sw,wwtp}$	Proportion of wastewater collected by sewers and transferred to WWTP	0.26	0.26	0.26	1.00
$P_{vt,fstp}$	Proportion of fecal sludge emptied by vacuum trucks and transported to FSTP	0.04	0.04	0.00	0.00

S8.2 Scenario A

$$EF_{CH4-st1} = 3.83 + 0.622T_{st} \tag{8.1}$$

$$COD_{st-fs} = 1600 + 1260T_{st} \tag{8.2}$$

$$COD_{st,eff} = 394 + 32T_{st} \tag{8.3}$$

S9 Detailed GHG emissions along the SSC in all scenarios

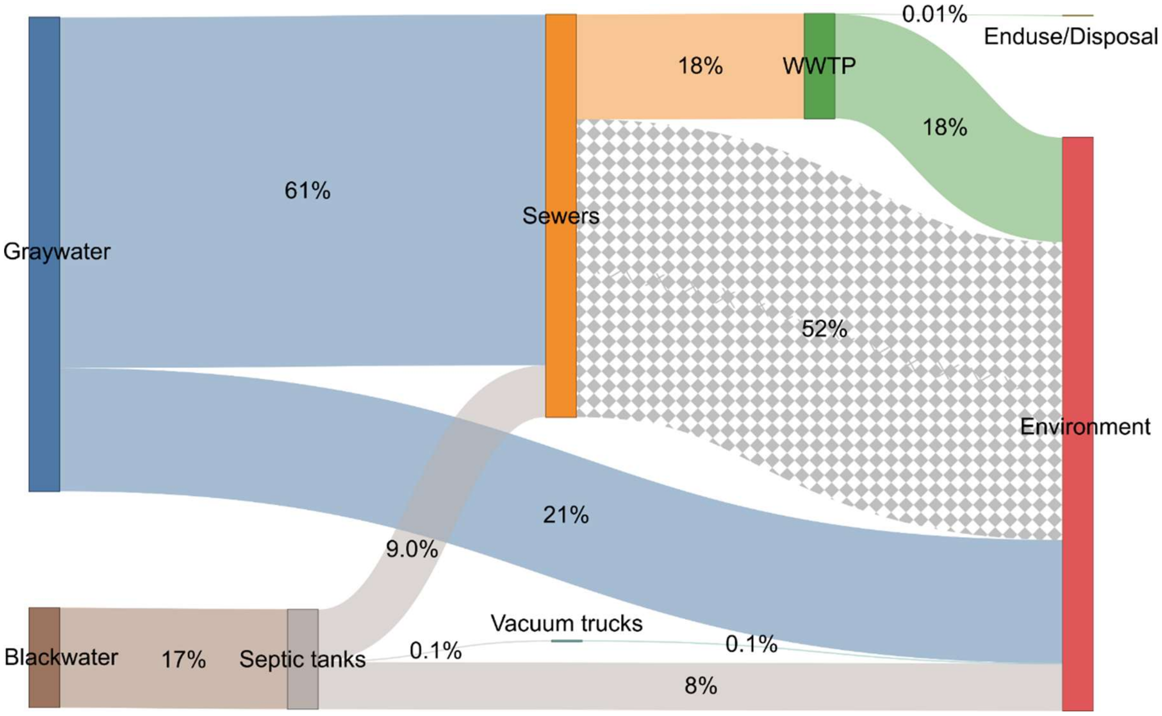

Figure S9–1 Wastewater flow diagram of Hanoi, Vietnam. All percentages are in relation to the total quantity of wastewater generated in the study area.

Table S9-1 GHG emissions along the SSC in Baseline

Sanitation service	**tonCO_2e/year**						
	Baseline	**CO_2**	**CH_4**	**N_2O**	**Scope1**	**Scope2**	**Scope3**
Septic tanks (min, 1st compartment)	1,633	0	1,633	0	1,633	0.00	0.00
Septic tanks (additional from 2nd and 3rd compartments)	1,448	0	1,448	0	1,448	0.00	0.00
Vacuum trucks	3	3	0	0	0	0.00	3.33
Sewers	1,177	0	1,170	7	1,177	0.00	0.00
WWTP	886	599	100	187	272	613.01	0.76
FSTP	0	0	0	0	0	0	0
Total GHG emissions (max.)	5,146	603	4,350	194	4,529	613	4
Total GHG emissions (min.)	3,698	603	2,902	194	3,081	613	4

Table S9-2 GHG emissions along the SSC in Scenario A

Sanitation service	**tonCO$_2$e/year**						
	Baseline	**CO$_2$**	**CH$_4$**	**N$_2$O**	**Scope1**	**Scope2**	**Scope3**
Septic tanks (min, 1st compartment)	714	0	714	0	714	0	0
Septic tanks (additional from 2nd and 3rd compartments)	633	0	633	0	633	0	0
Vacuum trucks	34	34	0.01	0.06	0	0	34
Sewers	1,067	0	1,060	7	1,067	0	0
WWTP	755	599	52	104	142	613	0.74
FSTP	0	0	0	0	0	0	0
Total GHG emissions (max.)	3,204	633	2,459	111	2,556	613	35
Total GHG emissions (min.)	2,570	633	1,826	111	1,923	613	35

Table S9-3 GHG emissions along the SSC in Scenario B

Sanitation service	**tonCO$_2$e/year**						
	Baseline	**CO$_2$**	**CH$_4$**	**N$_2$O**	**Scope1**	**Scope2**	**Scope3**
Septic tanks (min, 1st compartment)	0	0	0	0	0	0.00	0.00
Septic tanks (additional from 2nd and 3rd compartments)	0	0	0	0	0	0.00	0.00
Vacuum trucks	0	0	0	0	0	0.00	0.00
Sewers	1,594	0	1,587	7	1,594	0.00	0.00
WWTP	725	600	81	44	110	614	1.14
FSTP	0	0	0	0	0	0	0
Total GHG emissions	2,319	600	1,667	51	1,704	614	1.1

Table S9-4 GHG emissions along the SSC in Scenario A*

Sanitation service	**tonCO$_2$e/year**						
	Baseline	**CO$_2$**	**CH$_4$**	**N$_2$O**	**Scope1**	**Scope2**	**Scope3**
Septic tanks (min, 1st compartment)	714	0	714	0	714	0.00	0.00
Septic tanks (additional from 2nd and 3rd compartments)	633	0	633	0	633	0.00	0.00
Vacuum trucks	34	34	0	0	0	0.00	33.94
Sewers	0	0	0	0	0	0.00	0.00
WWTP	4,160	972	0	3,187	3,164	982	91
FSTP	99.9	78	4	18.6	4	19	0
Total GHG emissions (max.)	5,642	1,084	1,352	3,206	4,516	1,001	125
Total GHG emissions (min.)	5,008	1,084	718	3,206	3,882	1,001	125

Table S9-5 GHG emissions along the SSC in Scenario B*

Sanitation service	**tonCO$_2$e/year**						
	Baseline	**CO$_2$**	**CH$_4$**	**N$_2$O**	**Scope 1**	**Scope 2**	**Scope 3**
Septic tanks (min, 1st compartment)	0	0	0	0	0	0	0
Septic tanks (additional from 2nd and 3rd compartments)	0	0	0	0	0	0	0
Vacuum trucks	0	0	0	0	0	0	0
Sewers	0	0	0	0	0	0	0
WWTP	4,278	980	0	3,299	3,275	989	14
FSTP	0	0	0	0	0	0	0
Total GHG emissions	4,278	980	0	3,299	3,275	989	14