Towards a benchmarking tool for minimizing wastewater utility greenhouse gas footprints

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Abstract

Growing voluntary and regulatory pressures require the performance evaluation of urban wastewater treatment systems to extend beyond the traditional scope of effluent quality and operational cost, to include greenhouse gas emissions (carbon footprint). To address this, the IWA Task Group on “the use of water quality and process models for minimizing wastewater utility greenhouse gas footprints” (Task Group GHG) includes a subgroup that is developing a benchmark simulation model that includes a plant-wide model and rising main sewer model for testing mitigation strategies to reduce the system’s GHG footprint. The sewer model was run to predict methane emissions and its output used for the plant-wide model input. The latest nitrous oxide (N_2O) models from literature were implemented within the plant-wide model to predict nitrification and denitrification pathway N_2O emissions, in addition to electric consumption and production (from anaerobic digestion methane). Different scenarios were tested to assess the relative impacts of various process parameters and simple control strategies. Methane predicted in the sewers generally accounted for 8% of the total sewer and plant-wide GHG emissions, while N_2O emissions from denitrification and nitrification accounted for approximately 25% of the total GHG emissions. Aeration control played a clear role in N_2O emissions, which in some cases increased the net GHG emissions when significantly reducing aeration electricity use to reduce CO_2 emissions. The best among the few controllers studied reduced the GHG footprint by 7%, the operating costs by 10% and improved effluent quality by 2%. Finally, noteworthy, steady state simulation results were found to be 11% below the average of the equivalent dynamic simulation, stressing the importance of dynamic interactions in the system. As the GHG models used are not mature and some have yet to be validated, these results may not be accurate; however, they served to fulfill the objective of this study - demonstrate the potential of a dynamic system-wide modelling and benchmarking approach for balancing water quality, operational costs, and GHG emissions.

Keywords: Greenhouse gas, dynamic modelling, optimization, water quality, benchmarking

INTRODUCTION

In light of increasing voluntary and regulatory pressure on wastewater utilities to reduce their greenhouse gas (GHG) footprints, the IWA Task Group GHG is tracking and communicating ongoing efforts and proposing research directions on GHG emissions of wastewater systems. These efforts comprise both research into the source of wastewater nitrous oxide (N_2O) and methane (CH_4) emissions and model development for use in model-based optimization and control. The wastewater systems considered by the Task Group include both collection systems and wastewater treatment plants. A balance between energy, operational costs, greenhouse gas emissions, and water quality is essential for a sustainable water sector, and so the aim of the Task Group is to develop modelling tools that can help find this balance. This paper summarizes the results of the Task Group's first steps in developing a benchmark for testing mitigation strategies of urban water systems, by extending the current plant-wide benchmark (BSM2) (Jeppsson et al., 2007; Nopens et al., 2010; Flores-Alsina et al., in press), and coupling it to a detailed model for CH_4 emissions from sewers (Guisasola et al., 2009).

BACKGROUND

Methane in Collection Systems

As CH_4 emissions from sewers have been found to make up 20 percent or greater of overall wastewater utility GHG emissions (Foley et al., 2009), it is important to understand the GHG emissions from sewers for reporting accurate emissions inventories of wastewater utilities. In addition, methanogenesis within sewers has been seen to reduce wastewater chemical oxygen demand (COD) significantly (Guisasola et. al, 2008), which can have a significant impact on both nutrient removal performance, and N_2O production at the treatment plant. Given the complexity of sewer networks and the dynamic nature of sewer flows, modelling will be an effective tool/methodology to quantify CH_4 emissions from sewers.
Researchers have made some strides in modelling CH_4 emissions from pressure sewers systems (Guisasola et al., 2009; Foley et al., 2009); however, there is still work to be done to link this knowledge back to the utility level, integrate into a system-wide framework, and apply it in practice. In addition, the research to date has mainly addressed pressure sewer systems; research is required to develop a model for predicting CH_4 emissions from gravity systems.

Nitrous Oxide

Recent research has shed new light into some of the mechanisms/conditions leading to N_2O emissions from wastewater treatment plants (WWTPs) (Kampschreur et al., 2008; Ahn et al., 2010; Yu et al., 2010; Schneider et al., 2011). Some of this knowledge has been or is currently being translated into mathematical models that can extend existing process models to include GHG-related state variables. Full-scale data collected from N_2O monitoring campaigns such as in The Netherlands (STOWA), U.S. (WERF), France (CIRSEE - Suez Environment) and Australia (WSSA), will be critical for calibrating and validating N_2O model equations developed to describe N_2O production from nitrification (Yu et al., 2010; Houweling et al., 2011; Mampaey et al., 2011) and denitrification (Hiatt and Grady, 2008; Houweling et al., 2011) pathways. Once calibrated, validated, and implemented within a plant-wide model, these models will be a significant improvement over the current use of generic emissions factors used by USEPA (2009) and the Intergovernmental Panel on Climate Change (IPCC) (2006) to estimate N_2O emissions for WWTPs, as they will be capable of simulating the dynamic conditions that have been seen to trigger higher N_2O emissions (Kampschreur et al., 2008; Yu et al., 2010). Implemented within a plant-wide model and a system-wide model (including both collection system and WWTP), these models will also be critical for assessing and mitigating overall GHG emissions, not just N_2O emissions.

CO_2 and Overall GHG Footprint

It is critical to consider how control strategies to minimize N_2O emissions impact the overall GHG footprint and vice versa as they can have opposing effects. For example, an energy and CO_2 emissions reduction measure, such as reducing a dissolved oxygen (DO) process aeration set point can potentially increase N_2O under certain conditions (Kampschreur et al., 2008). Methane production in sewers and through anaerobic digestion will also have a significant impact on indirect CO_2 emissions through either COD loss in raw wastewater, or the amount of electric CO_2 emissions offset by methane production for on-site power generation. Therefore, it will be critical to understand all the interactions and transformations from a system-wide standpoint in order to properly balance GHG emissions, energy consumption/production, operating costs, and effluent water quality. There currently are no methodologies, tools, nor approaches available to the industry for accomplishing this, and especially not for accurately capturing and representing all of the dynamic wastewater system interactions and transformations impacting the overall GHG footprint. Research is needed on model integration for system-wide modelling that can account for: (1) CH_4 production in sewers and the interaction with remaining COD entering the WWTP; (2) N_2O and electric CO_2 emissions related to the secondary treatment process; (3) CH_4 production through anaerobic digestion; (4) critical sidestreams impacting activated sludge GHG emissions; and (5) wastewater influenced N_2O emissions from rivers.

Figure 1 is a schematic of the major system-wide (i.e. collection system, treatment plant, and river) and plant-wide interactions described above and the model integration (dark arrows) required. The green arrows indicate main GHG pathways and required modelling for predicting GHG emissions.

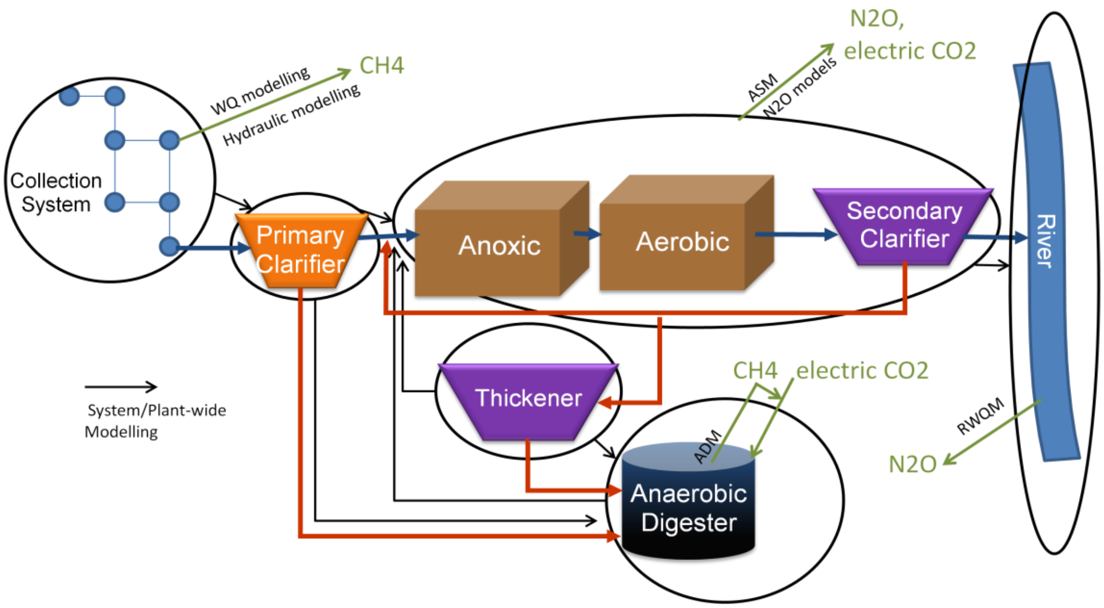

Figure 1 - System/Plant-wide GHG Modelling Schematic

METHODS

General

To demonstrate the first steps in building the system-wide modelling framework and how it can be applied for identifying/benchmarking control strategies for minimising GHG emissions, models for the sewers and the treatment plant that have been accepted and/or published were used and coupled in terms of flow and load (i.e. sewer flows and predicted COD at the outlet were used for plant influent). To date, there is no knowledge of the extension of process models for predicting GHG emissions in the receiving water body and, hence, for the time being, it is not included in this analysis. The steps and models used for predicting system-wide (minus receiving water) GHG emissions are described below.

Modelling of CH_4 Formation in Collection System

For the sewer system, the model of Guisasola et al. (2009) was used to predict methane production in rising mains. This model adds methanogenic activity (hydrogenotrophic and acetoclastic methanogenesis) to the sewer model presented in Sharma et al. (2008), which describes hydrogen sulfide formation in sewers. The model has been verified with laboratory results as well as the field data collected from a number of pressure mains. However, the possible oxidation and consumption of methane in gravity sewers, where oxygen is present, are not included in the model. Although the model in its current form can still be used for sewer networks consisting of both gravity and pressure mains, the accuracy in such a case cannot be ascertained. A realistic default network was used for the analysis and consists of pressure mains with diameters varying from 150 mm to 600 mm, 150 mm mains collecting sewage from gravity sewers, 300 mm mains collecting sewage from 150 mm pressure mains, and 600 mm mains collecting sewage from 300 mm mains. There are also three identical catchments feeding to the WWTP. The network is shown in Figure 2. The sewer model was run dynamically for 609 days and CH_4 production calculated. It was assumed that all of the dissolved CH_4 produced in the model is transferred to the gas phase at the sewer outlet/plant influent, where there is typically a significant amount of turbulence and mixing in real systems, lending to ideal stripping conditions. Actual liquid-to-gas mass transfer coefficients in the open environments should be investigated further as indicated by Foley et al. (2009).

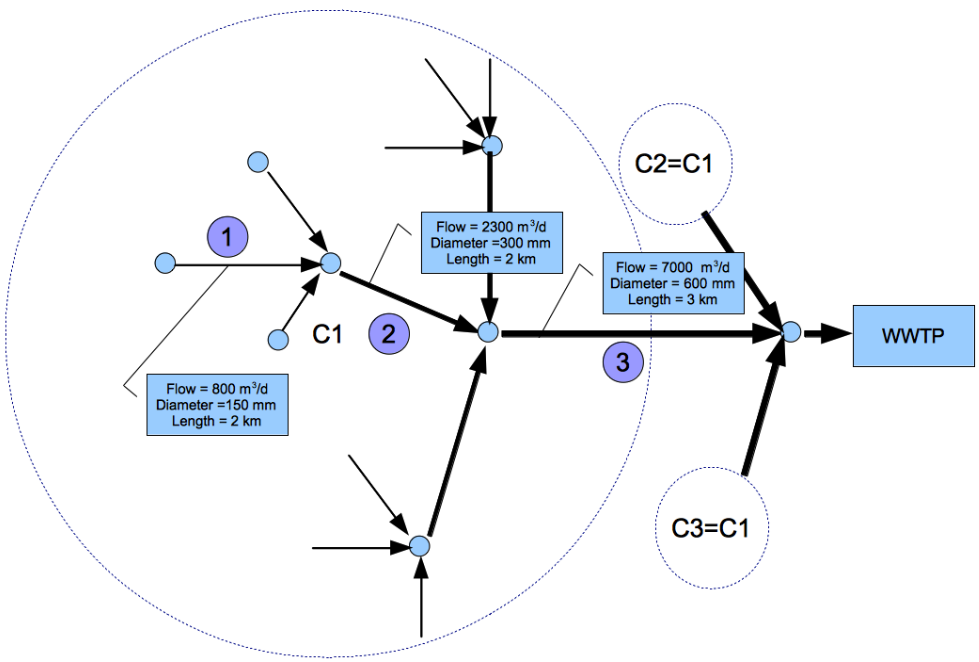

Figure 2 - Modelled Sewer Network

Modelling of Sewer and Plant Interaction

Since the models are currently not available in the same software platform, they were not directly coupled. For demonstration purposes, the sewer model/network was adjusted to produce an influent with approximately the same flow and load as the default BSM2 influent (subject to temperature variations and a typical rain series, Gernaey et al., 2006), and thereby estimating the CH_4 formation based upon the optimized network. Both models were run for 609 days and reflected the same dynamic patterns with respect to both flow and the wastewater composition.

Modelling of CO_2 and N_2O emissions from WWTP

As the basis of the WWTP model, the BSM2 modelling platform (Jeppsson et al., 2007; Nopens et al., 2010) was used to predict plant-wide GHG emissions. However, rather than using the typical ASM1 (Henze et al., 2000) implementation, Corominas et al. (2010) replaced it with the ASMN model of Hiatt and Grady (2008), This model incorporates ASM1 for several processes without change, but also provides two-step nitrification as opposed to single step, and four-step denitrification for modeling sequential reduction of nitrate to nitrogen gas via nitrite, nitric oxide, and nitrous oxide using individual, reaction-specific parameters. The ASMN incorporates two nitrifying populations - ammonia oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) - using free ammonia and free nitrous acid, respectively, as their true substrates. ASMN also predicts N_2O emissions from the denitrification pathway. Some parameter adjustments were required because ASMN was developed for high strength wastewater treatment (Flores-Alsina et al., in press). ASMN's extended set of state variables also required modifications to the interfaces with ADM1. Moreover, in this work, the BSM2 model was extended with the submodel proposed by Mampaey et al. (2011) for predicting N_2O emissions from the nitrification pathway. The latter model considers two scenarios for NO and N_2O formation mechanisms: Scenario A in which ammonia is the electron donor; and Scenario B in which biomass is the electron donor. For this study the Scenario A was implemented. A comparison with Scenario B is ongoing.

The BSM2 model configuration is shown in Figure 3 (Nopens et al., 2010). The activated sludge unit is a Modified Ludzack-Ettinger (MLE) configuration consisting of 5 tanks in series. Tanks 1 (ASU1) and 2 (ASU2) are anoxic, while Tanks 3 (ASU3), 4 (ASU4) and 5 (ASU5) are aerobic. ASU5 and ASU1 are linked by means of an internal recycle. The yearly average influent flow of the plant is 20648 $m^3 \cdot d^{-1}$ and the organic and nitrogen loads are 12240 kg $COD \cdot d^{-1}$ and 1140 kg $N \cdot d^{-1}$ respectively.

The plant-wide evaluation criteria (EQI – Effluent Quality Index and OCI – Operational Cost Index; Nopens et al., 2010) were extended and the overall CO_2 emissions from the treatment plant were quantified according to Flores-Alsina et al. (in press). These included the emissions of N_2O, digester CH_4 and the indirect emissions from power consumption and recovery of biogas.

The simulations were performed in WEST$^{(R)}$ (Vanhooren et al., 2003), running a steady state simulation (200 days) followed by a dynamic simulation of 609 days. Only the data generated during the last 364 days of the dynamic simulation are used for plant performance evaluation.

Scenario Analysis

To examine the overall behaviour of the N_2O models and the relative impact of different control strategies, the following scenarios were investigated, each with two cases for comparison:

- Open loop: C/N effect. The flow rate of external carbon source is 2 m^3/d (Case 1) and 4 m^3/d (Case 2); K_La = 210, 140, 70 for ASU3, ASU4, and ASU5, respectively for both cases.
- Scenario1: The K_La in ASU4 is set by a PI controller with a DO set point in ASU4 of 2mg/l (Case 1) and 1.3mg/l (Case 2); For both cases the K_La(ASU3) is set as 1.5K_La(ASU4), and K_La(ASU5) is set as 0.5K_La(ASU4).
- Scenario2: The DO set point is 1.3 mg/l for ASU4's PI controller and 1.7mg/l for ASU3's PI controller (Case 1); The DO set point is 1.5 mg/l for both ASU3 and ASU4 (Case 2); The K_La in ASU5 is set as half the K_La in ASU4, for both cases.

These simple control strategies were selected as they could reflect the response by operators to increasing pressure to reduce energy and CO_2 emissions.

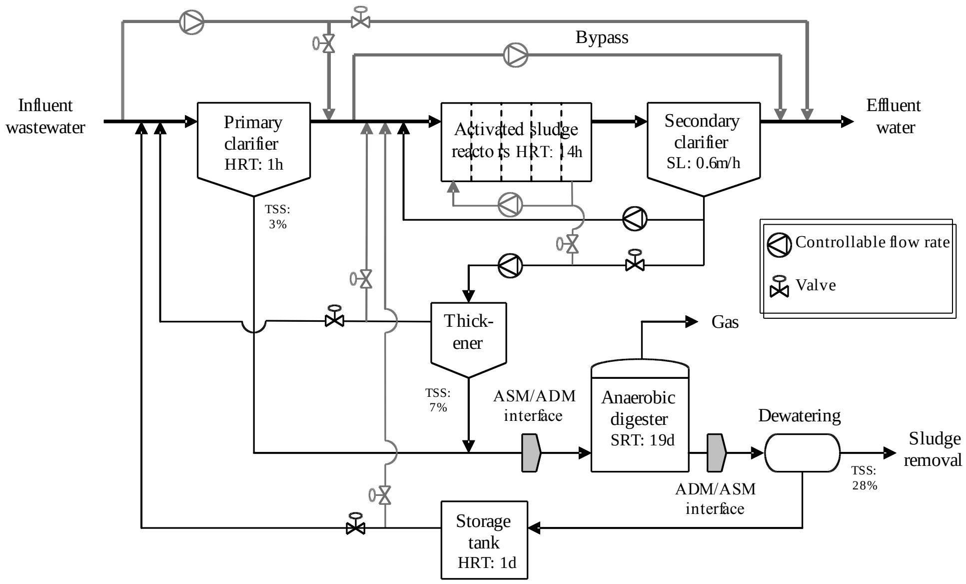

Figure 3 – BSM2 Plant Configuration (Nopens et al., 2010)

Effluent quality (EQI) and operational cost (OCI) indices

Results were post-processed to calculate the EQI and OCI for each scenario using the BSM2 methodology (Nopens et al., 2010). This allows each control strategy to be benchmarked based on not only effluent quality and operational costs, but also GHG emissions as performed by Corominas et al. (2010) and Flores-Alsina et al. (in press).

RESULTS AND DISCUSSION

CH_4 Emissions from the Collection System

The methane concentration at the WWTP feed reached a maximum of 35 mg COD/L in summer with a mean of 12 mg COD/L. Total methane production was 235.3 kg COD/day (58.8 kg CH_4/day), which gives an annual methane production of 21.5 tons. Figure 4 shows the variation of the methane produced in the sewers, and released at the outlet, indicating the methane concentration can vary significantly under the imposed dynamic conditions, including rain events. This highlights the importance of modelling the system dynamically to understand the potential GHG emission from sewers. It also points to the need for better understanding CH_4 formation in sewers in relation to treatment plant performance, and the N_2O emissions potential based upon COD/nitrogen ratios. To assess the potential impact sewer design can have on CH_4 emissions, the diameter of segment 3 (see Figure 2) was enlarged slightly and the model rerun. Methane production increased by five percent, which indicates sewer design could potentially play a big role in methane emissions, considering the detention time only increased slightly.

It should be noted that the production of methane in sewers depends upon the characteristics of sewer networks such as the type of sewer (gravity or pressure main), length of sewer pipe, pipe diameter, hydraulic retention time, and temperature. Any changes to these characteristics/conditions will result in a different methane production rate.

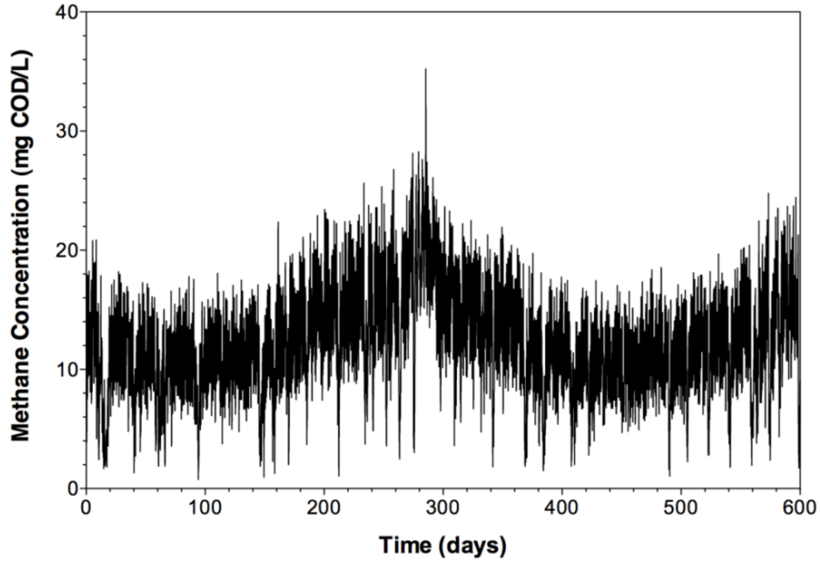

Figure 4 - Methane Concentration at Sewer Outlet

CO_2 and N_2O Emissions from WWTP

Figure 5 summarizes the averaged results for the dynamic simulations using the plant-wide extended BSM2 model and includes the total system emissions including those from the sewer.

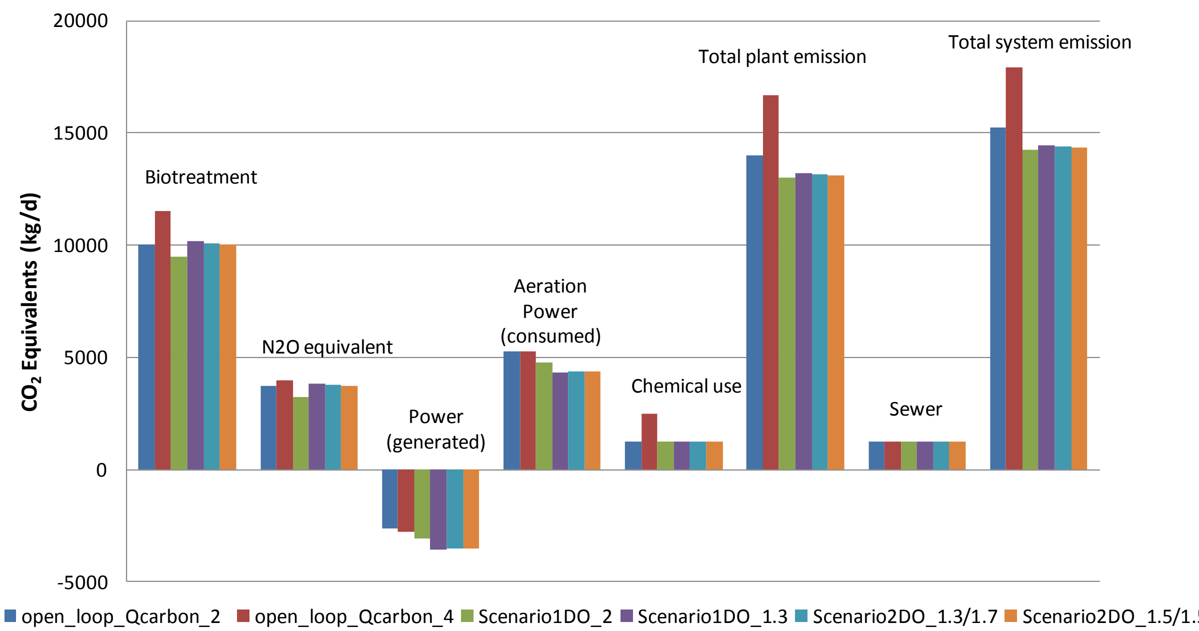

Figure 5 - Daily averaged GHG Emissions Summary for Evaluated Scenarios

As seen in Figure 5, Biotreatment, which includes the CO_2 generated from biomass respiration and BOD oxidation, the N_2O generated from nitrogen removal, and the CO_2 credit from nitrification, makes up the largest component of the system-wide emissions. N_2O, which makes up approximately 25 percent of the total system emissions, is also broken out of Biotreatment and shown separately for comparative purposes. The sewer CH_4 emissions made up approximately eight percent of the total emissions.

Open Loop Scenario – Effect of COD/N ratio

As can be seen from Figure 5, increasing the carbon addition increases the overall GHG emissions. Although denitrification would be expected to improve, and hence reduce N_2O emissions, N_2O emissions were seen to increase slightly. After examining the flux from each reactor, it was seen that ASUs 1 – 3 saw reduction in N_2O emissions; however, ASUs 4 and 5 had increased N_2O emissions, amounting to a slight net increase in N_2O emissions with increasing COD/N ratio. This will need to be investigated further. Regardless, there is also a significant increase in the overall GHG emission by increasing carbon addition, mainly due to the indirect/embedded GHG emissions related to the chemical use.

As mentioned previously, each scenario was simulated under steady state and dynamic conditions. This was done to assess the implications of using steady state models or emission factors to describe N_2O emissions, which have been seen to vary substantially under dynamic conditions (Yu et al, 2010; Kampschreur et al., 2008). The open loop, 2 m^3/d carbon addition case was looked at in particular. Figure 6 shows both steady state and dynamic results for ASU3 (first aerobic zone). It is clear from this figure that the steady state results do not accurately capture the variability and magnitude of the potential N_2O emissions, and in fact results in 11 percent lower total emissions, which is consistent with the dynamic and steady state experiments of Kampschreur et al. (2008). This clearly highlights the need for dynamic models to accurately predict N_2O emissions and, hence, to develop mitigation strategies.

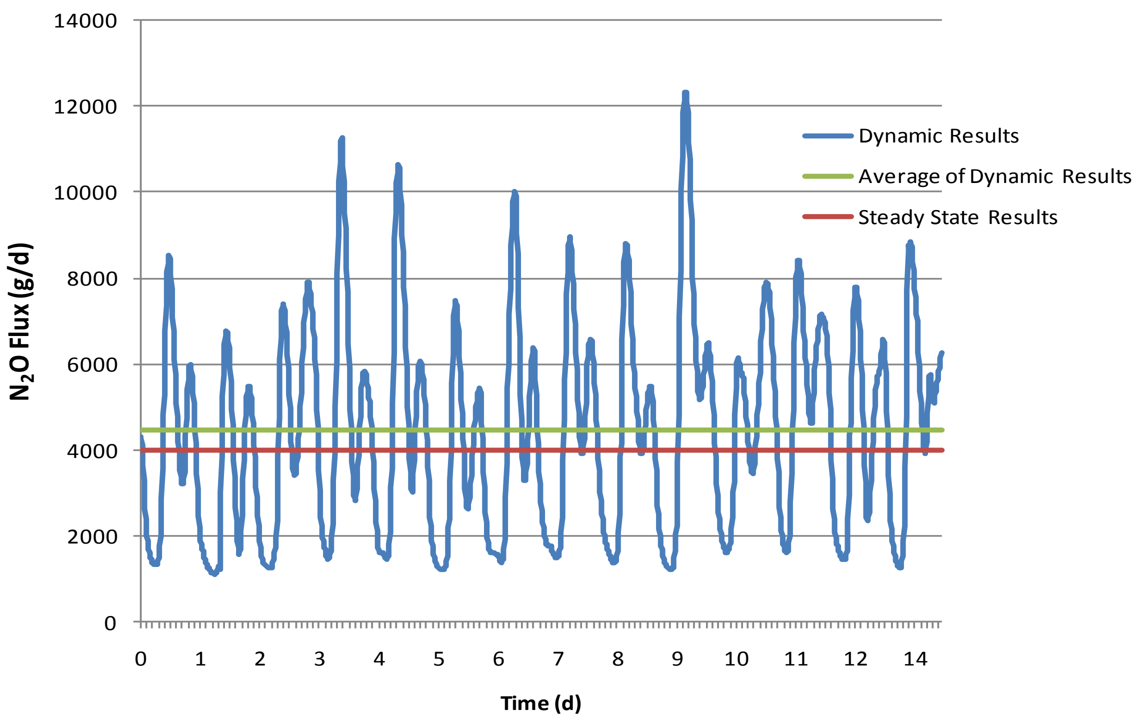

Figure 6 - Steady State versus Dynamic Results for N2O flux in ASU3 (first aerobic reactor)

Scenario 1 – Effect of single DO set point

The results of this scenario are interesting because although aeration energy was reduced significantly by lowering the DO set point to 1.3 mg/L from 2.0 mg/L, the overall GHG emissions increased due to increased N_2O emissions. Increased N_2O concentrations with low DO concentrations is consistent with Kampschreur et al. (2009).

Scenario 2 – Effect of multiple DO set points

The case with a DO set point of 1.7 mg/L for ASU3 and 1.3 mg/L for ASU4 exhibited slightly higher N_2O emissions and slightly higher overall GHG emissions than maintaining 1.5 mg/L DO in both reactors. These slightly higher emissions may be due to the higher mass transfer rate with the higher air flow rate in the first aerobic zone.

Effluent quality (EQI) and operational cost (OCI) indices

Table 1 summarizes the resulting total GHG emissions, EQI, and OCI for each scenario/case. Highlighted are the most favourable results for each category.

Table 1 - Summary of Total GHG Emissions, EQI, and OCI Results

	open_loop_ Qcarbon_2	open_loop_ Qcarbon_4	Scenario1 DO_2	Scenario1 DO_1.3	Scenario2 DO_1.3/1.7	Scenario2 DO_1.5/1.5
Total System GHG emissions (kg $CO_2e \cdot d^{-1}$)	15244	17903	14243	14434	14399	14345
EQI (kg poll$\cdot d^{-1}$)	5787	5782	5694	5612	5701	5669
OCI (-)	11026	13507	10023	10537	10066	10068

It would appear that Scenario 1, with a DO set point of 2 mg/L, provides the best balance between GHG emissions, effluent water quality, and operating costs as it represents the smallest GHG footprint, the second best effluent water quality, and lowest operating costs. This represents a reduction in the GHG footprint by seven percent, the operating costs by 10 percent, and improved effluent quality by two percent from the base open loop case. The use of the BSM2 tool to evaluate scenarios in this manner clearly demonstrates the potential to evaluate various control strategies and find the right balance for a specific system, which will depend on the individual utilities' priorities. For the purpose of demonstrating the capability, only simple control strategies were evaluated; however, control strategies incorporating more sophisticated control loops can certainly be included and evaluated to identify sustainable control strategies and minimize GHG footprints. It should be noted that the results obtained are preliminary in the sense that the N_2O model extensions of ASM1 have not been rigorously calibrated and validated. Nevertheless, the results look promising as they are consistent to those observed from measurements (Kampschreur et al., 2009; Ahn et al., 2010). Moreover, the framework is now in place and can easily be rerun in case model structure changes or parameter updates would be necessary.

CONCLUSIONS AND PERSPECTIVES

Initial steps in developing a system-wide modelling framework for minimizing GHG footprints of urban wastewater systems based on BSM2 were presented. A sewer and plant-wide model were used and coupled indirectly to assess the potential system-wide emissions and to evaluate various simple control strategies. Sewer methane emissions accounted for approximately eight percent of the total system GHG emissions, while WWTP N_2O emissions accounted for approximately 25 percent.

COD/N ratio and DO concentration were seen to impact total GHG emissions. In one case, lowering the DO and aeration electric CO_2 emissions actually increased the overall GHG emissions due to an increase in N_2O emissions. This demonstrates the need for a tool to evaluate control strategies to not only reduce N_2O or CO_2 emissions, but to evaluate strategies to minimize the overall GHG footprint.

Steady state and dynamic simulations were also compared and were found to differ significantly. In one case, steady state N_2O emissions were 11 percent lower than the average calculated from dynamic simulations. This indicates that steady state models and/or emission factors may not adequately capture the full N_2O emission potential as it is largely dependent on system dynamics.

Using the BSM2 platform with EQI, OCI and (new) GHG indices, one of the tested control strategies (constant DO set point of 2.0 mg/L) could be identified as having the most sustainable balance between GHG emissions, effluent water quality, and operating costs. This demonstrates the capability for using the tool to evaluate more sophisticated control strategies, similar to those implemented by Ayesa et al. (2006), and finding solutions with even more aggressive reductions in GHG emissions, operating costs, and effluent loads. This tool can be instrumental in key decision making by water professionals wanting to practice sustainable water management.

It is important to keep in mind that the GHG models used are not fully mature and some have yet to be validated, therefore, these results may not be accurate. The use of these models for this particular study was to demonstrate the potential and construction of a system-wide modelling and benchmarking approach for balancing water quality, operational costs, and GHG emissions, and to test its sensitivity to logical changes in system design and control. The development of this tool is also purposely working in parallel to the development of GHG models, which will actually help the progression of GHG models by allowing them to be tested.

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