Climate change and WWTPs: Controlling greenhouse gas (GHG) emissions and impacts of increased wet weather disturbances

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Abstract

An Activated Sludge Model for GHG (ASMG) was implemented in the framework of the Benchmark Simulation Model No. 2 (BSM2) and several strategies were proposed to study their performance in terms of GHG emissions, effluent quality and operational cost and their ability to deal with the hydraulic shocks induced by storm events. A new influent file was generated containing an increasing number of intense rain events to mimic the influent characteristics in the future under climate change. The separate DO control strategy which applies separate DO setpoints for each aerobic tank indicated that the DO spatial distribution influences the N_2O production and the N_2O emissions can be reduced by properly controlling the DO distribution. The cascade plus 1 DO strategy combines the advantages of both NH_4^+-DO cascade strategy and an additional separate DO strategy, giving small ammonia violations and reducing N_2O emissions. Finally, two rain event control strategies, i.e. step feeding and sludge recycling control, were applied in conjunction with the NH_4^+-DO cascade plus 1 DO strategy, yielding good performance on treating the effects from increased hydraulic shocks.

Keywords

Activated sludge; benchmarking; control strategies; greenhouse gas; influent shocks; nitrous oxide

NOTATION

ASMG	Activated Sludge Model for GHG
AOB	Ammonia oxidizing bacteria
BSM2	Benchmark Simulation Model No. 2
EQI	Effluent Quality Index
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
IQI	Influent Quality Index
OCI	Operational Cost Index
WWTP	Wastewater treatment plant

INTRODUCTION

The relationship between wastewater treatment plants (WWTPs) and climate change is a two-way relation. On the one hand, WWTPs directly produce greenhouse gases (GHGs) during wastewater and sludge treatment; on the other hand, climate change causes an increasing number of storms with increasing intensity which bring influent shocks to WWTPs, threatening plant operation. A plant operator might as well decide to protect the plant and divert the shock load to the combined sewer overflows (CSOs). This requires a study on reducing impacts of CSOs in an integrated framework (Guo et al., 2012a).

Although the effect of climate change on future rainfall distribution is still not clear, the Intergovernmental Panel on Climate Change (IPCC) suggests that in the future there may be more intense rainfall events over many areas (Giorgi et al., 2001). This is consistent with recent increases in rainfall intensity observed (Frich et al., 2002; Ekström et al., 2005; Fowler et al., 2005; Van Steenbergen and Willems, 2012). In the case of the UK, it seems that the climate will become warmer leading to increases in annual precipitation by up to 10 % by the end of the century (Hulme et al., 2002; Butler and Davies, 2004).

For a long time, there has been an interest to study the response and suggest strategies for WWTPs under wet weather conditions (Lessard and Beck, 1990; Bauwens et al., 1996; Risholt et al., 2002). However, few studies were carried out on plant GHG emissions under wet weather conditions and few control strategies were implemented in the frame of the benchmark simulation models (BSMs) which are important tools for comparing and analysing control strategies.

Nitrous oxide (N_2O) is a powerful GHG according to the IPCC report (1995). It can be produced during nitrogen removal in WWTPs by both heterotrophs and autotrophs (Colliver and Stephenson, 2000; Kampschreur et al., 2008; Mampaey et al, 2011). The Activated Sludge Model for GHG (ASMG) proposed by Guo et al. (2012a) is capable to simulate those processes. It was implemented in a plant-wide frame (Guo et al., 2012a), the Benchmark Simulation Model No.2 (BSM2). This paper uses this model to study GHG emissions and other plant performance criteria under different control strategies. The simulations were first run with the current BSM2 influent file and then with a new influent file which contained an increased number of intense rain events in order to analyse the plant performance under future climate conditions.

METHODS

Models

Next to the traditional process for carbon and nitrogen removal, ASMG (Guo et al., 2012a) combined N_2O production by heterotrophic denitrification and ammonia oxidation bacteria (AOB) denitrification. The former was modelled by the Activated Sludge Model for Nitrogen (Hiatt and Grady, 2008), i.e. ASMN, which includes the 4-step heterotrophic denitrification which produces N_2O as an intermediate product. The AOB denitrification was simulated by a modified model based on the aerobic scenario of Mampaey et al. (2011). The modification includes a growth correction factor for the AOB denitrification and replacing the dissolved oxygen (DO) inhibition term by a competitive term. Detailed information about the model and the parameter values are described by Guo and Vanrolleghem (2012b).

The ASMG model was subsequently implemented in BSM2. Figure 1 shows the scheme of BSM2 (Nopens et al., 2010). It is a plant-wide layout, consisting of wastewater treatment by an activated sludge process and sludge treatment primarily by anaerobic digestion. The activated sludge reactor is divided into five activated sludge units (ASUs), the first two of which are anoxic and the last three aerobic. This benchmark provides a dynamic influent file for 609 days which is also used in this paper to represent the influent under current climate conditions.

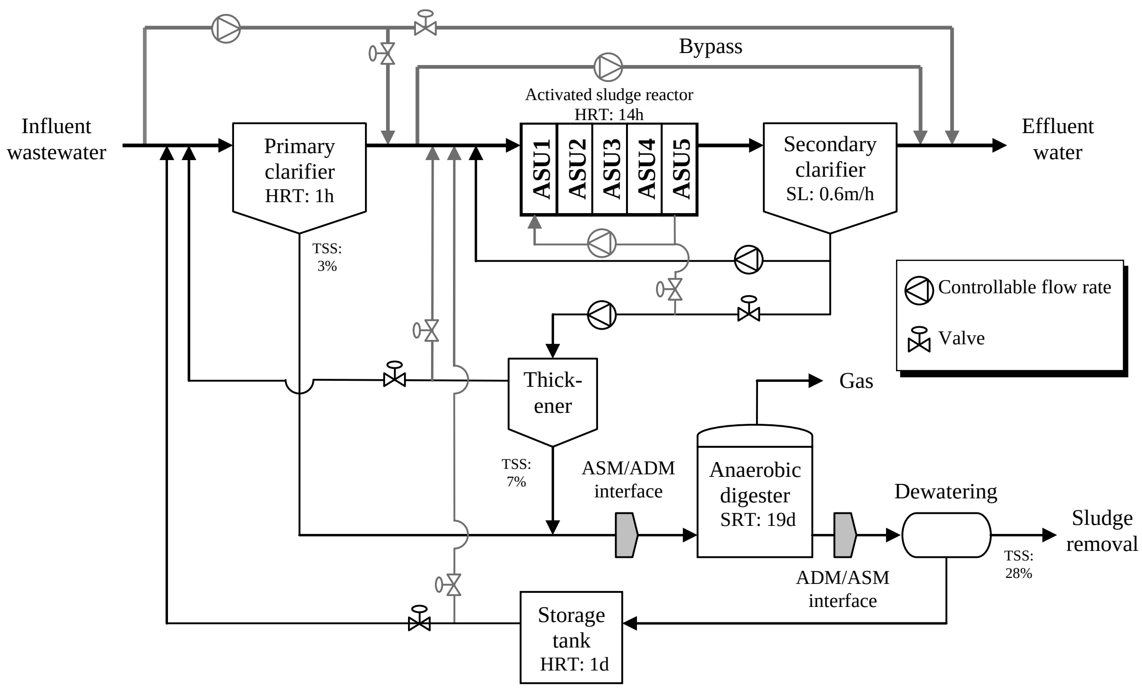

Figure 1 BSM2 plant configuration with possible control handles (Nopens et al., 2010)

Control strategies

Table 1 lists the control scenarios studied in the paper. A former study (Guo et al., 2012a) showed a requirement on designing new strategies when taking into account GHG emissions. Controlling the DO spatial distribution is an appropriate way for reducing the N_2O production. Therefore, a separate DO control strategy was tested. It controls the DO concentration of each aerobic ASU individually. A 3 DO control strategy was also studied by Vanrolleghem and Gillot (2002) inspired by the constant aeration intensity of BSM1 causing insufficient DO in the aerobic tanks at daytime and excessive DO at night. This simple 3 DO strategy proved to give acceptable performance on effluent quality, energy cost and investment cost in the case of BSM1 (Vanrolleghem and Gillot, 2002). In this paper, this strategy is proposed and studied with a particular consideration on N_2O and GHG emissions.

An ammonia-DO cascade control strategy in which the ammonia controller sets the DO setpoint has the advantage of limiting ammonia violations whereas controlling the spatial DO distribution is meaningful for the N_2O production. Consequently, a combination strategy, i.e. Scenario 2, was studied, as presented in Figure 2.

Table 1 Control strategies tested in the paper

Scenario 1	Scenario 2	Scenario 3	Scenario 4
Separate DO	Cascade + 1 DO	Step feeding + Scenario 2	Sludge recycling + Scenario 2
DO_SP3 = 2 DO_SP4 = 2 DO_SP5 = 1	DO_SP3 = 2 NH_4^+_SP5 = 1.5 DO_SP5=NH_4^+_u5 Kla4=2Kla5	DO_SP3 = 2 NH_4^+_SP5 = 1.5 Kla4=2Kla5 f3=f4=f5=1/3 Q_T = 60000	DO_SP3 = 2 NH_4^+_SP5 = 1.5 Kla4=2Kla5 r_{under} = 0.5

Note: DO_SP3, DO_SP4 and DO_SP5 are the DO set points (mg/l) of ASU3-ASU5 respectively; NH_4^+_SP5 is the ammonia (NH_4^+) concentration setpoint (mg/l) of ASU5; NH_4^+_u5 is the controller output (mg/l) of the NH_4^+ controller in ASU5; Kla4 and Kla5 are the oxygen transfer coefficients (d^{-1}) of ASU4 and ASU5 respectively; f3, f4 and f5 are the setpoints for the inflow distribution fractions to ASU3-ASU5; Q_T (m^3/d) is the threshold of the plant inflow at which step feeding begins; r_{under} is the ratio of the settler underflow rate to the inflow rate of the secondary settler.

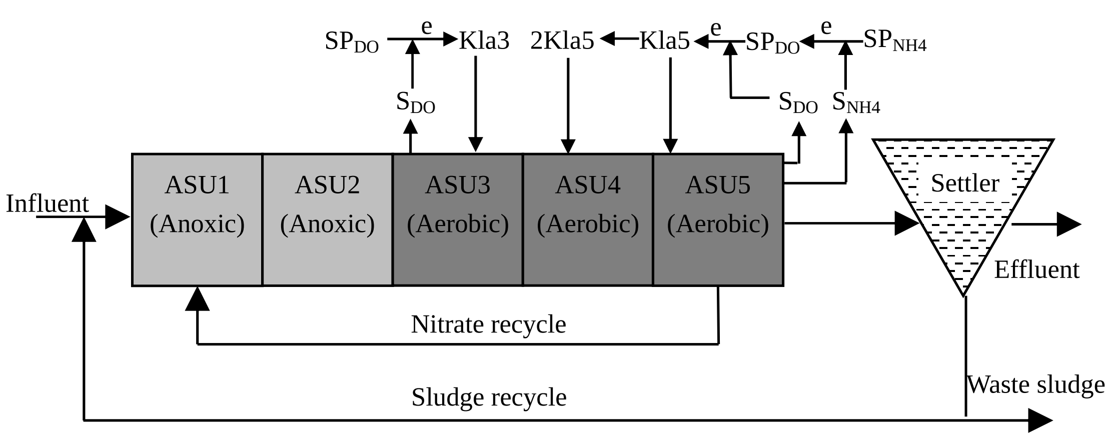

Figure 2 NH_4^+-DO cascade plus 1 DO controller strategy. S_{DO} (mg/l) is the measured DO concentration; S_{NH4} (mg/l) is the measured ammonia concentration; SP_{DO} (mg/l) is the DO setpoint; SP_{NH4} (mg/l) is the ammonia setpoint; e (mg/l) is the error between measured value and setpoint.

To deal with hydraulic shocks two control strategies were tested, a step feeding strategy and a sludge recycling control strategy. The step feeding strategy equally distributes the influent over the three aerobic tanks. The sludge recycling strategy uses a ratio controller, i.e. the underflow rate of the secondary settler is proportional to its inflow rate. Considering the hydraulic propagation under rain events (Olsson and Stephenson, 1985), it is the inflow rate of the secondary settler multiplied with a ratio in the sludge recycling strategy that is used as a basis. The two rain event control strategies were combined with the Scenario 2 controller. All scenarios were evaluated in terms of GHG emissions, effluent quality and operational cost, with criteria as defined in Guo et al. (2012a).

New influent file

In order to further study the effect of rain events on plant performance, a new 609-day input file was generated using the influent disturbance scenario generator of Gernaey et al. (2011). This generator is a phenomenological model that represents the main characteristics of a catchment area (rainfall, household and industry discharges, soil infiltration, sewer network, etc.) to describe the typical dynamic characteristics observed in a full scale WWTP influent such as: diurnal phenomena, weekend effect, seasonal phenomena (e.g. increased infiltration in the wet season compared to the dry season), holiday periods, and rain events. The output is the influent flow rate and temperature profile and the pollutant concentrations in terms of the ASM1, ASM2d or ASM3 state variables.

In view of the effect that climate change might have on the intensity and frequency of rain events (Hulme et al., 2002) a new influent profile was generated by modifying the parameters in the rainfall generator (Gernaey et al., 2011). The generation of the rain intensity in the influent generator depends on 2 parameters: the constant converting the output of the random number generator to a value representing rainfall intensities, *LLrain*, and flow rate per mm rain, *Qpermm*. A sensitivity analysis of the model (Flores-Alsina et al., 2011) showed that *LLrain* is related to the number of rain events and the lower value corresponds to more rain events, and *Qpermm* is related to the intensity of the rains and the larger value gives higher intensity. In order to generate an influent file with more rain events and higher rain intensity, *LLrain* was set at 3.4 mm/d and Qpermm at 1600 m^3/mm. The influent generator also considers the effect of the sewer system and includes a simple model to describe the first flush effect (Gernaey et al., 2011).

The new rain profile exhibits more rain events (324 against 318 of the original file) and of higher intensity (maximum intensity of 85687 m^3/day against 78800 m^3/day). Overall, a total rainfall increment of 16% was considered (from 1.43×10^6 to 1.67×10^6 m^3). However, the effect on the final flow rate entering the WWTP is not so important since the contribution from the household and industries (around 60 % of the flow) was not modified. The influent quality does not change too much either since the same influent composition was used. The influent Quality Index (IQI) for the last 364 days is 74785 pollution units/d for the current influent file compared to 75301 pollutions units/d for the adapted influent file.

RESULTS AND DISCUSSION

Figure 3 and 4 compared the performance of the different control strategies for 8 criteria under the current influent file and the future influent file respectively. The open loop and the traditional NH_4^+-DO control strategy results are the ones of a former paper (Guo et al., 2012a).

Current conditions. When comparing the different controllers under current climate conditions, the separate DO control shows the largest reduction on N_2O emissions and the lowest total net GHG emissions. The cascade strategy does not reduce N_2O as much as the separate DO strategy, but it showed no ammonia violation and a low EQI combined with low aeration energy consumption and low OCI. Compared to the open loop, the EQI and the OCI are reduced by 11.6% and 10.6% respectively under cascade control. Although the separate DO control strategy also reduced ammonia violations a lot compared to the open loop, the value is still larger than the cascade control, and it comes as well with higher OCI and EQI. Compared to the open loop, the OCI is decreased only by 2.7% under separate DO control and the EQI is even increased slightly by 0.6%. Actually the cascade control focuses on limiting the ammonia effluent violation with low aeration energy consumption. Therefore, it tends to set a low DO setpoint which may lead to more N_2O production by AOB denitrification (Guo et al., 2012a). On the other hand, although the 3 DO control strategy proved to have good performance on making balance among different criteria in terms of energy cost, effluent quality and investment cost (Vanrolleghem and Gillot, 2002), the original motivation for designing the separate DO control strategy was not focused only on effluent quality, but e.g. either aiming at N_2O control as in the current paper or optimizing aeration as in Vanrolleghem and Gillot (2002). Therefore, such kind of control strategy is not reliable for effluent quality control, i.e. the effluent quality is unpredictable when only focusing on DO control. Actually the separate DO strategy presented the highest ammonia violations among all control strategies, i.e. 5.7% under current conditions, and this violation was further increased to 9.4% under future conditions. Therefore, in order to optimize for objectives on both N_2O emission reduction and ammonia violation control, the cascade plus 1 DO control strategy was proposed. Figure 3 shows that this strategy has a lower N_2O emission than the cascade control and lower ammonia violation and EQI than the separate DO control. It suggests that this coupled strategy makes a balance between N_2O mitigation and effluent quality control.

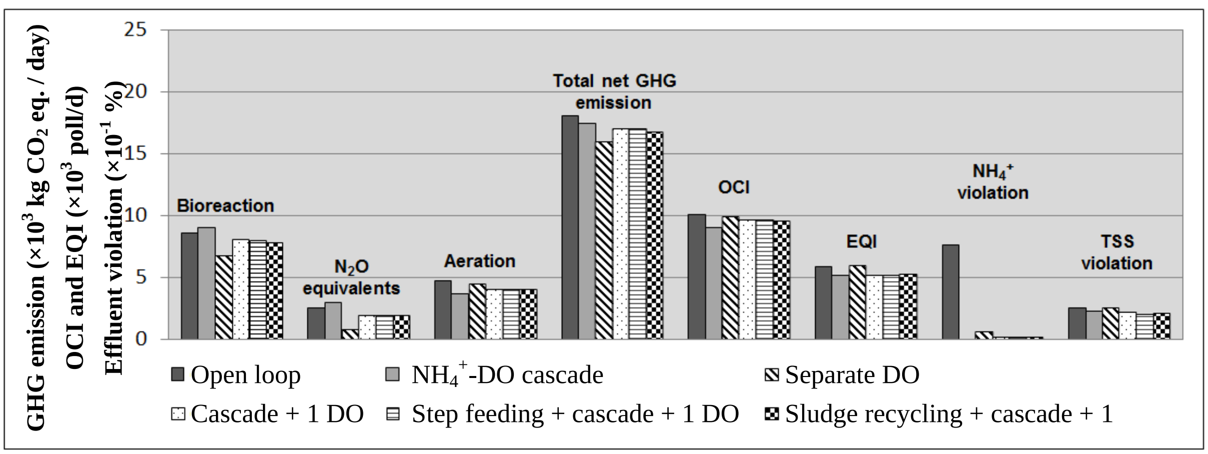

Figure 3 Comparison of different control strategies using current influent file. OCI: Operation Cost Index; EQI: Effluent Quality Index. First 4 criteria relate to GHG; next 4 to traditional BSM criteria.

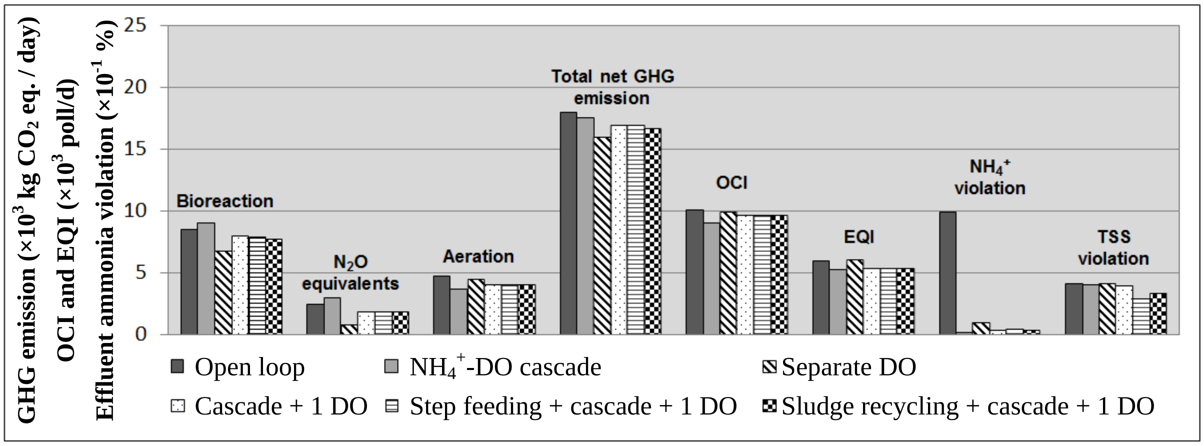

Figure 4 Comparison of different control strategies using future influent file.

With these promising results, the step feeding and the sludge recycling control were added to the cascade plus 1 DO control strategy. The two strategies present very similar performance. The sludge recycling control emitted slightly less GHG (16.7×10^3 kg CO_2 eq./day against 16.9 kg CO_2 eq./day) and violated the ammonia limitation less than the step feed strategy (0.6% against 1.4%), but its TSS violation is a little higher (20.6% against 19.2%). Such differences are negligible under current conditions, but the differences on effluent violations are amplified a little under future conditions, i.e. 2.6% under sludge recycling control against 4.0% under step feeding for ammonia violation, and 32.9% against 28.3% for TSS violations.

Future conditions. Figure 4 clearly shows that although the rain events are predicted to increase by 16%, not too much difference is found in the evaluation results, probably because of their similar IQI values. However, some difference is still present in the ammonia and TSS violations. One thing that must be kept in mind though is that in BSM2 the primary settler is simulated by the Otterpohl-Freund model, the secondary settler is modelled by a Takács 10-layer model and the sludge thickener is described by point settler model. It is generally accepted that such kind of state-of-the-art models are not really applicable to describe settlers under storm conditions and further development is required in terms of better simulating the effluent solid concentration and modelling the continuous sedimentation (Plósz et al., 2007; Plósz et al., 2009; Bürger et al., 2011). However, it is expected that the limitations of current settler models may not affect the comparison on TSS violation among the different plant scenarios, because all scenarios used the same models.

It is shown in Figure 4 that without any control strategy, i.e. in open loop, the effluent ammonia and TSS exceed the effluent limits more under future climate conditions, while the N_2O and GHG emissions remain essentially the same. All strategies still have good performance on limiting the ammonia violation but the effluent TSS is better controlled by the step feeding strategy and the sludge recycling control strategy. The step feeding shows the smallest TSS violation. The results tell that these extended strategies handle the hydraulic shocks well and maintain a good balance between the N_2O emissions and the effluent quality.

CONCLUSIONS

The GHG emissions from WWTPs and the effect of increasing rain events on WWTPs were studied. The effect of the DO spatial distribution on reducing the N_2O emission observed by Guo et al. (2012a) was further validated by the separate DO strategy. Strategies were proposed with a combined consideration of GHG emissions, effluent quality and hydraulic shocks. A cascade plus 1 DO strategy was proposed and proved to appropriately limit the ammonia violation and the N_2O emissions. This strategy was coupled with two wet weather control strategies, i.e. step feeding and sludge recycling control. The two extended strategies inherited the advantage of the cascade plus 1 DO strategy and also showed a good control on the TSS violation. A new 609-day influent file with 16% more rain events was generated to account for future conditions under climate change. With this influent file, the performance of the plant without control deteriorates in terms of ammonia violation and TSS violation while the two extended strategies were able to handle this challenge.

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