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Identifying sensitive sources and key control handles for the reduction of greenhouse gas emissions from wastewater treatment

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ABSTRACT

This research investigates the effects of adjusting control handle values on greenhouse gas emissions from wastewater treatment, and reveals critical control handles and sensitive emission sources for control through the combined use of local and global sensitivity analysis methods. The direction of change in emissions, effluent quality and operational cost resulting from variation of control handles individually is determined using one-factor-at-a-time sensitivity analysis, and corresponding trade-offs are identified. The contribution of each control handle to variance in model outputs, taking into account the effects of interactions, is then explored using a variance-based sensitivity analysis method, i.e., Sobol's method, and significant second order interactions are discovered. This knowledge will assist future control strategy development and aid an efficient design and optimisation process, as it provides a better understanding of the effects of control handles on key performance indicators and identifies those for which dynamic control has the greatest potential benefits. Sources with the greatest variance in emissions, and therefore the greatest need to monitor, are also identified. It is found that variance in total emissions is predominantly due to changes in direct N_2O emissions and selection of suitable values for wastage flow rate and aeration intensity in the final activated sludge reactor is of key importance. To improve effluent quality, costs and/or emissions, it is necessary to consider the effects of adjusting multiple control handles simultaneously and determine the optimum trade-off.

1. Introduction

Developing strategies for the reduction of greenhouse gas (GHG) emissions is a topic of great interest and current relevance, as countries have committed to emission reduction targets under the Kyoto Protocol to mitigate the effects of global warming. Energy use in the water industry is an important source of GHG emissions; whilst in Europe it only typically contributes 1% of national consumption, this is predicted to increase (Olsson, 2012), and in the U.S.A. 4% of electricity demand is attributable to the movement and treatment of water and wastewater (Mo et al., 2010). Wastewater treatment also results in the formation and direct

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emission of the GHGs carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The wastewater sector was responsible for over 5% of global non-CO_2 GHG emissions in 2005, and these emissions are predicted to increase by 27% by 2030 (U.S. Environmental Protection Agency, 2012). Wastewater utilities must contribute to emission reduction targets, but are faced with the challenge of simultaneously improving effluent quality and managing costs.

Appropriate operation of wastewater treatment processes can play a significant role in reducing GHG emissions (Gori et al., 2011) and wastewater treatment plant (WWTP) control strategies which both improve effluent quality and reduce GHG emissions have been developed (Flores-Alsina et al., 2011; Guo et al., 2012). However, control handles with the greatest impact on GHG emissions need to be identified if significant further improvements are to be made. The effects of adjusting the dissolved oxygen (DO) setpoint, sludge retention time (by alteration of the wastage flow rate), carbon source addition rate, primary clarifier TSS removal efficiency, anaerobic digester temperature and control of the digester supernatant return flow on GHG emissions from different sources, as well as effluent quality and operational cost, have been assessed previously (Flores-Alsina et al., 2011, 2014). Since the effects of interactions due to simultaneous adjustments or strategy implementations were not considered and variation within the full range of feasible values not explored, however, key findings regarding the effects of these adjustments are of limited use in further control strategy development. The importance of analysing a wide range of values for each control handle is evidenced by the identification of non-linear relationships between parameter values and effluent quality, and control handle values beyond which further increase produces no additional gain (Nopens et al., 2007). Previous analysis (Benedetti et al., 2012) has identified control handles to which effluent quality and operational cost are most sensitive in the Benchmark Simulation Model No. 2 (BSM2) (Jeppsson et al., 2007), taking into account simultaneous variation across a range of values, but the impacts on GHG emissions have not been considered. Furthermore, whilst the effects of interactions are automatically considered when multiple control changes are implemented, the relative significance of specific interactions between control handles cannot be revealed explicitly to inform control strategy development by focusing on interactions.

It would also be beneficial to investigate variance in GHG emissions from different sources, in order that control strategy development can focus on those with greatest potential for improvement. For example, manufacture of material for on-site usage is a key source of GHG emissions (Shahabadi et al., 2010) but, given that previous studies show little variation in emissions resulting from chemical consumption under different control strategies (Guo et al., 2012), attempts to reduce GHG emissions by reduction of carbon source addition may be ineffective without introduction of alternative treatment processes such as Anammox. Conversely, it has been found that implementation of different control strategies can result in significant variation in the magnitude of N_2O emissions from activated sludge (Guo et al., 2012), suggesting that there is great potential for reduction of total GHG emissions from wastewater treatment by reducing N_2O emissions. It is known that DO concentration and COD/N ratios, which are controlled by adjustment of aeration and carbon source addition rates, play a key role in controlling production of N_2O (Kampschreur et al., 2009; Guo et al., 2012), yet there is a need to investigate the effects on net emissions of varying these control handles simultaneously, as well as the effluent quality and operational cost. At present, there are conflicting observations regarding the effects of WWTP control on N_2O emissions: Clippeleir et al. (2014), for example, measured increased N_2O emissions when operating with a high DO setpoint, whilst Guo et al. (2012) found a reduction in DO setpoint to correspond with an increase in N_2O emissions.

This research aims to detect control handles to which key performance indicators (including GHG emissions, effluent quality and operational cost) are sensitive and to identify the most significant sources of variance in total GHG emissions, taking into account interaction effects. It is important to identify control handles to which GHG emissions are significantly more sensitive than effluent quality or operational costs, since selection of their values might be attributed little importance in conventional design practices. This knowledge will guide the selection of control handles for efficient and effective control strategy development, based on those with potential to yield the greatest improvements. Knowledge of control handles to which no key model outputs are sensitive will also reduce the number of decision variables required, therefore reducing computational demand and improving the feasibility of multi-objective optimisation for control strategy development.

Sensitivity analysis is employed to identify important parameters controlling model outputs (Tang et al., 2007a); this approach can be utilised to assist system optimisation by detecting the most influential control handle(s) (Naessens et al., 2012), and has previously been shown to be effective (Fu et al., 2012). Analysis is carried out through the combined use of a local sensitivity method - one-factor-at-a-time (OAT) – and a variance-based global method – Sobol's method; this allows trade-offs to be investigated, and reveals control handles with significant individual effects on GHG emissions, effluent quality and operational cost, as well as those with interaction effects which contribute significantly to variance in the model outputs. Model evaluations carried out with global sensitivity analysis (GSA) also reveal the most significant sources of variance in GHG emissions and, therefore, the sources from which it is most important to control and monitor GHG emissions.

2. Materials and methods

2.1. *Wastewater treatment plant description and modelling*

Wastewater treatment processes are simulated in this work using BSM2-e (Sweetapple et al., 2013), a WWTP model based on the BSM2 (Jeppsson et al., 2007) but with modifications made to enable dynamic modelling of GHG emissions (Sweetapple et al., 2013). The plant consists of a primary