Model-based Methodology for Plant-wide Analysis of Wastewater Treatment Plants: Industrial Case Study

C. Puchongkawarin*[,a], C. Menichini*[,a], C. Laso-Rubido*, S. Fitzgerald** and B. Chachuat*[,b]

* Centre for Process Systems Engineering (CPSE), Imperial College London, South Kensington Campus, London SW7 2AZ, UK

** Corporate Strategy, Sydney Water, 1 Smith St, Parramatta NSW 2150, Australia

[a] Equal contributors
[b] Corresponding author. Email : *b.chachuat@imperial.ac.uk*

Abstract

This paper presents the application of a model-based methodology for improved understanding of the tight interplay between effluent quality, energy use, and fugitive emissions in wastewater treatment plants. Dynamic models are developed and calibrated in an objective to predict the performance of a conventional activated sludge plant owned and operated by Sydney Water, Australia. A scenario-based approach is applied to quantify the effect of key operating variables on the effluent quality, energy use, and fugitive emissions. Operational strategies that enable a reduction in aeration energy by 10-20% or a reduction of total nitrogen discharge down to 3 mg L^{-1} are identified. These results are also compared to an upgraded plant with reverse osmosis in terms of energy consumption and GHG emissions. This improved understanding of the relationship between nutrient removal, energy use and emissions will feed into discussions with environmental regulators regarding nutrient discharge licensing.

Keywords

Modeling; plant-wide simulation; effluent quality; energy consumption; fugitive emissions; operational strategies; process optimization

INTRODUCTION

Among the alternatives for the sewage industry to reduce their energy consumption without compromising effluent quality, improving operational and process control strategies holds much promise. These strategies may be particularly useful for energy intensive processes such as activated sludge aeration, which can account for 45-75% of a plant’s energy expenditure (Owen, 1982). Overall, it is estimated that energy consumption of most wastewater treatment plants (WWTPs) could be reduced by 10-40% (Water Environment Federation, 1997). Nonetheless, WWTPs are comprised of a large number of treatment and separation units, which involve a great variety of processes acting on different time scales and interacting with each other via recycling loops. Failure to account for these interactions, for instance by optimizing in a unit-wise manner, may not lead to the largest possible improvements and can even be detrimental overall (Descoins et al., 2012). In this context, developing effective operational strategies can defy engineering intuition, and plantwide simulation models, such as BSM2 (Jeppsson et al., 2007), have started playing an increasingly important role (Descoins et al., 2012; Flores-Alsina et al., 2014).

The main objective of this work is the application of a model-based methodology to provide a better understanding of how changing the effluent quality targets impacts plant-wide energy use and fugitive emissions. Dynamic models based on the commercial simulator BioWin are developed and calibrated in an objective to predict the performance of an activated sludge plant with sludge treatment owned and operated by Sydney Water. A scenario-based approach is applied to quantify the effect of key process variables and to identify operational strategies that reduce the energy consumption and fugitive emissions at different nutrient discharge levels. These operational improvements are also compared to an alternative plant upgrade scenario based on reverse osmosis to achieve a better effluent quality. This improved understanding of the relationship between energy use and nutrient removal will feed into discussions with environmental regulators regarding nutrient discharge licensing.

METHODOLOGY

The WWTP under investigation is a tertiary plant owned and operated by Sydney Water. Over the years, the pollution load on this WWTP has increased significantly and its effluent discharge constitutes a potential point source of pollution for the receiving surface water. The general layout is shown on Fig. 1. It operates two parallel primary/secondary treatment lines, called Stage 1/2 and Stage 3 hereafter: Stage 1/2 operates a primary clarifier followed by a Bardenpho process to remove total nitrogen (TN); Stage 3 operates an A^2O process to remove both TN and total phosphorus (TP) using primary sludge from Stage 1/2 in the initial anaerobic zone. These parallel stages are followed by a common tertiary treatment for effluent polishing, while the secondary sludge is digested aerobically before disposal. The nutrient discharge limits currently in application are 5 mg L^{-1}, 45 mg L^{-1} and 5 mg L^{-1} for ammonia, TN and TP, respectively, although a much higher effluent quality is produced. This WWTP is flexible enough to explore a wide range of scenarios and presents excellent potential for optimization due to large interactions between its two treatment lines.

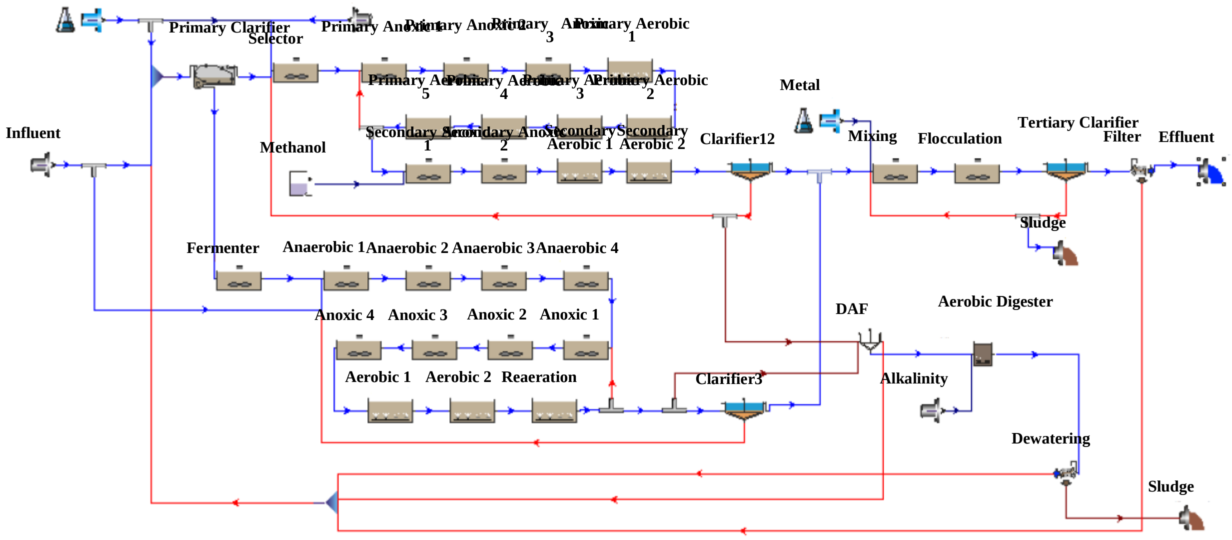

Figure 1: Activated sludge plant layout

The main modelling platform used to conduct the analysis is BioWin (http://envirosim.com/), and we have cross-validated the results with an implementation of BSM2 in the equation-oriented process simulator gPROMS (http://www.psenterprise.com/ - results not discussed for brevity). BioWin is routinely used in the wastewater industry as a process analysis tool and to design or upgrade WWTPs. It implements state-of-the-art models of biological and physical treatment units, and it can also predict fugitive nitrous oxide (N_2O) emissions on account of the following three mechanisms: (i) nitrification by-product, whereby part of the ammonia is converted to N_2O by ammonia oxidizing bacteria (AOB) via hydroxylamine oxidation, normally when ammonia is present in excess and without oxygen limitation; (ii) nitrifier denitrification, also mediated by AOBs but under oxygen-limited conditions, whereby free nitrous oxide (FNA) is used as a terminal electron acceptor to remove nitrite; and (iii) heterotrophic denitrification, whereby N_2O is produced as an intermediate in denitrification by heterotrophs. In addition to modelling the effluent quality and N_2O emissions, BioWin is also used to predict the aeration energy consumed by the activated sludge and aerobic digestion units here. Other energy consumptions corresponding to mixing and pumping, as well as the energy consumption and effluent quality relative to reverse osmosis, are computed using regression analysis based on historical data from Sydney Water's data management system.

RESULTS AND DISCUSSIONS

A calibration and first validation is carried out in the BioWin model using a combination of routine and non-routine monitoring data. The calibrated models are then used in a scenario-based analysis in order to quantify the links between energy use, effluent quality and fugitive emissions and to determine improved operational strategies.

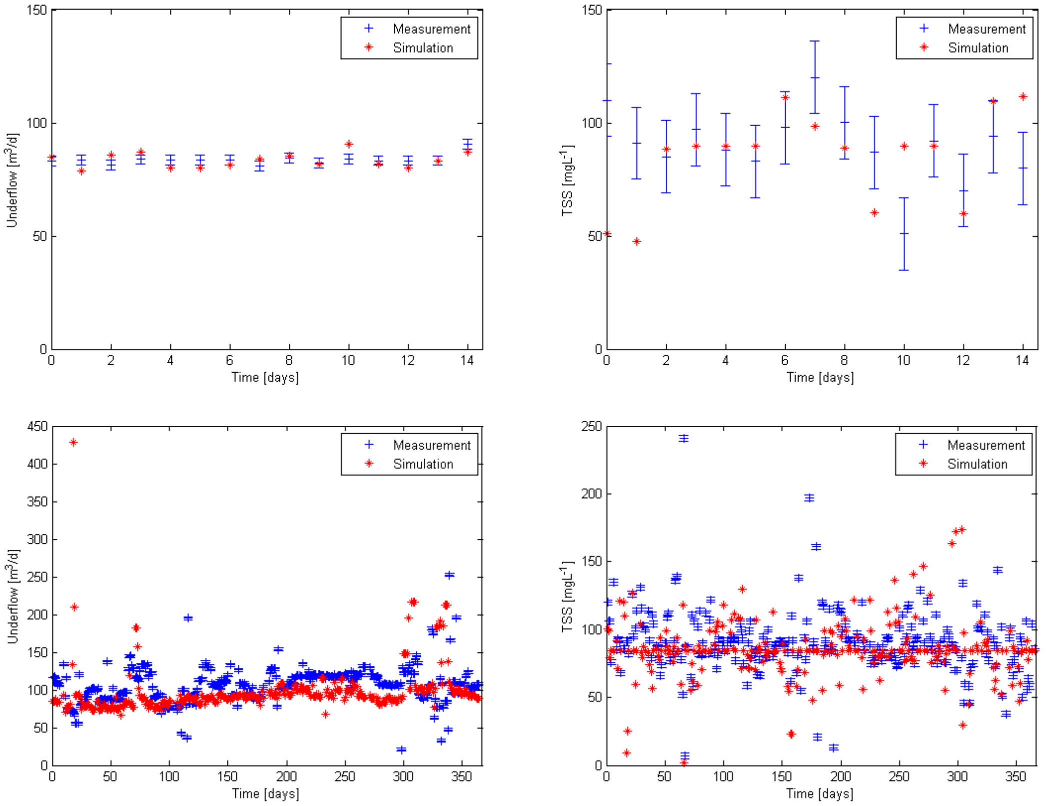

Figure 2: Calibration (top plots) and validation (bottom plots) of liquid and solid flows in primary sedimentation tank: underflow, $m^3\ d^{-1}$ (left plots) and TSS , mg L^{-1} (right plots).

Plantwide Model Development

The main objective of the calibration is to capture the major trends in the plant, focusing primarily on mass conservation and flow splitting (Dold et al., 2003; Vanrolleghem et al., 2003). In a first step, the primary sedimentation tanks, the DAF units, the sludge dewatering units, the tertiary clarifiers and the dual media filters are calibrated based on data from a two-week non-routine monitoring campaign, and validated with 12 months of data (from April 2012-April 2013) from Sydney Water's data management system. These physical separation units are calibrated by adjusting either the efficiency of solids removal or sludge settling parameters as appropriate, in order for the predicted liquid and solid outflows to match the available data. The results of the calibration and validation are shown in Fig. 2 for a primary sedimentation tank.

In a second step, the bioreactors are calibrated by adjusting a minimal number of kinetic parameters from their default values. These parameters are selected based on a sensitivity analysis in order for the predictions to be in good agreement with the primary, secondary and tertiary effluent data collected during the two-week non-routine monitoring campaign. The adjusted parameters in the BioWin model correspond to the nitrite oxidizing biomass (maximum specific growth rate, half-saturation constant for NO_2) and the ordinary heterotrophic organisms (fermentation rate). Comparison results are reported in Table 1 for the tertiary effluent, showing good agreement between the measured and calibrated values – average values are considered here as the variations during the two-week period were small (dry weather). We note however that a more precise (dynamic) calibration could not be conducted for this plant based on the available data as the average influent composition was not monitored on a daily basis.

Table 1: Comparison of the BIOWIN predictions (after calibration) against measurements during the 2-week non-routine monitoring campaign for the tertiary effluent (averaged values).

	Measurements	BioWin
NH_4-N, mg L^{-1}	0.02	0.08
NO_3-N, mg L^{-1}	4.3	4.4
PO_4-P, mg L^{-1}	0.02	0.04
COD, mg L^{-1}	34	31
MLSS, mg L^{-1}	7.7	7.4

Strategies for Energy Reduction

We start by investigating possible strategies for reducing the energy consumption of the plant, without significantly deteriorating the effluent quality or increasing the fugitive emissions (e.g., in the form of N_2O). The overall energy consumption in the current plant operation is dominated by compression energy for aeration of the activated sludge tanks in both treatment lines. This high level of aeration results in a very low ammonia effluent concentration, less than 0.1 mg L^{-1}. This presents a question of whether there could be a better balance between these two parameters. Here, a sensitivity analysis reveals that the dissolved oxygen (DO) set-points in either treatment line and, to a lesser extent, the sludge retention time (SRT) in either treatment line, are most sensitive with respect to the aeration energy among the key operational variables.

The effect of various DO set-points (simulated as identical in both treatment lines) on the energy consumption, ammonia discharge, TN discharge and N_2O emissions is presented on the top plots of Fig. 3, showing a tight interplay between these key process performance indicators. A decrease of the DO set-point from 2 mg L^{-1} to 1 mg L^{-1} is predicted to decrease the aeration energy by about 15%, with minimal impact on the ammonia discharge and a reduction in total nitrogen (TN) discharge by 1 mg L^{-1} (top-left plot). A further reduction of the DO set-point down to 0.5 mg L^{-1} could provide an extra 10% reduction in aeration energy, while still keeping the ammonia effluent concentration below 0.2 mg L^{-1} and achieving a further 0.5 mg L^{-1} reduction of the TN effluent concentration. In contrast, decreasing the DO set-point tends to increase the N_2O emissions due to incomplete nitrification; here, by a factor of 3 between 0.5 mg L^{-1} and 2 mg L^{-1} (top-right plot). This, in turn, may lead to an increase in the overall GHG emissions at lower DO set-points, as shown in Table 2. Besides, we note that operating at low DO levels may also have adverse effects on the treatment quality, such as poor sludge settleability, which is not accounted for in the model.

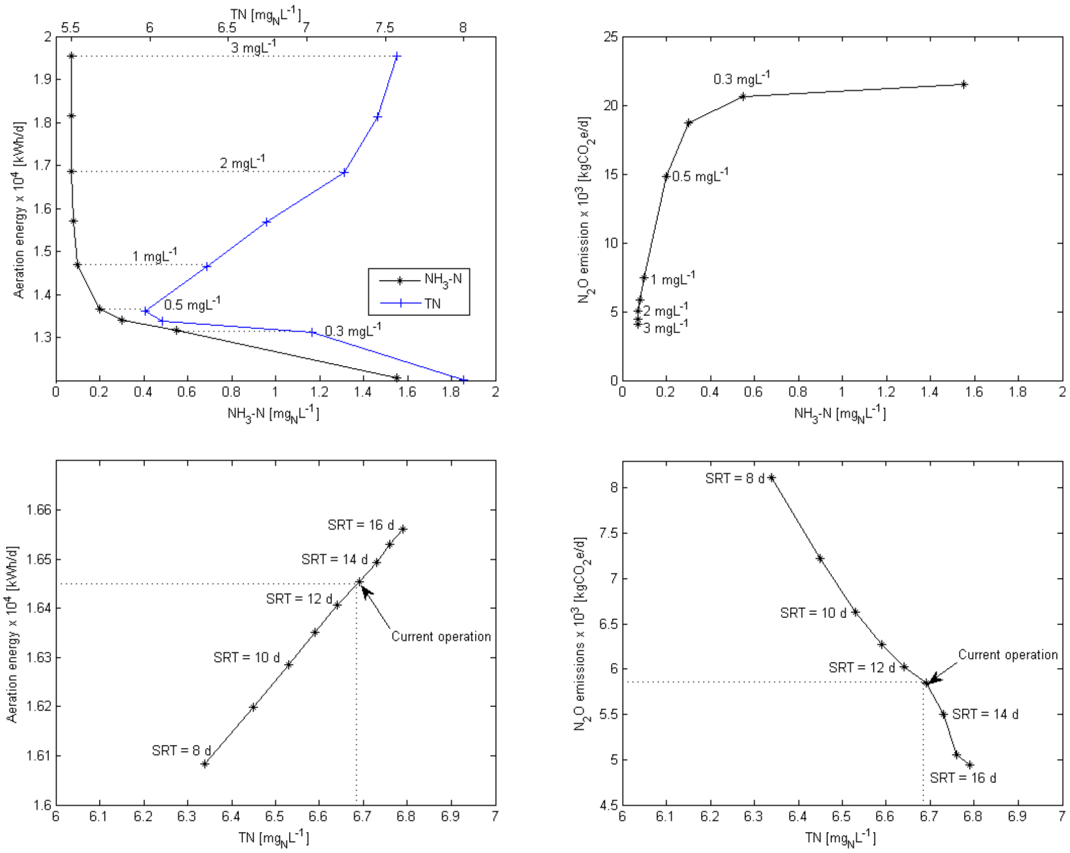

Figure 3: Effect of DO set-points in Stage 1/2 and Stage 3 (top plots) and SRT in Stage 1/2 (bottom plots) on the aeration energy, effluent quality, and N_2O emissions.

Other studies have also investigated the general trends in N_2O and overall GHG emissions when varying the DO set-point. A comparison between our results and those reported by Flores-Alsina et al. (2014) is presented in Table~2. We note that the overall GHG emission values at various DO set-points are consistent and show a similar trend for lower DO set-points: although off-site CO_2 emissions may decrease, this effect is counterbalanced by increased N_2O emissions, especially since N_2O has a 300-fold stronger greenhouse effect than CO_2. In addition, our modelled N_2O emissions are between 0.009-0.027 kgN_2O per kgN in the influent. This is in the medium range compared to other full-scale wastewater treatment plants, typically between 0.001-0.25 kgN_2O/kgN, which vary widely depending on a plant's configuration or operation (Law et al., 2012; Filali et al., 2013).

Table 2: Comparison of the overall GHG emissions at various DO set-points with those from the work by Flores-Alsina et at (2014) – The reported values are per m^3 of treated wastewater.

	GHG emissions	
DO set-point	This work	Flores-Alsina et al (2014)
0.5 mg L^{-1}	1.19 kgCO_2e m^{-3}	N/A
1 mg L^{-1}	1.02 kgCO_2e m^{-3}	ca. 1.6 kgCO_2e m^{-3}
2 mg L^{-1}	1.00 kgCO_2e m^{-3}	ca. 1.25 kgCO_2e m^{-3}
3 mg L^{-1}	1.04 kgCO_2e m^{-3}	ca. 1.3 kgCO_2e m^{-3}

The bottom plots of Fig. 3 show the effect of varying the SRT in Stage 1/2 (keeping the SRT in Stage 3 at its current nominal value) on the energy consumption, TN discharge and N_2O emissions – although not depicted, the effect of varying the SRT in Stage 3 has similar results. Reducing the aeration energy by a small percentage appears possible by decreasing the SRT (bottom-left plot), and therefore the extent of endogenous decay, but this then leads to increasing the energy/cost of sludge treatment at the same time. A reduction in the SRT is also accompanied by an increase in N_2O emissions (bottom-right plot), although, again, this is small compared to GHG emission from the related energy use. Regarding the effluent quality, Fig. 3 shows that the effect of reducing the SRT would be beneficial in terms of the TN concentration, with possible reductions over 1 mg L^{-1}. This is mainly due to a reduction in nitrate concentration, whereas the ammonia concentration remains below 0.2 mg L^{-1} despite a decrease of the nitrifier biomass for lower SRT values.

On the whole, decreasing the DO set-points and the SRT could lead to a significant reduction in energy consumption and a lower TN effluent concentration, while maintaining a very high treatment quality regarding ammonia and keeping N_2O emissions at an acceptable level compared to other GHG emissions.

Strategies for Enhanced Nutrient Removal

We now investigate strategies for improving the effluent quality, without causing a large increase in energy consumption or fugitive emissions. Given the plant already achieves low ammonia and phosphates discharge, the analysis has been focused on enhancing nitrate removal. The major bottleneck in the current operation appears to be low carbon availability for denitrification in the anoxic tanks of both treatment lines. Especially sensitive in this context are the operational variables corresponding to the influent flow split between Stage 1/2 and Stage 3 and the mixed-liquor recirculation (MLR) rate.

The effect of varying the influent fraction between Stage 1/2 and Stage 3 is presented in Fig. 4. Increasing this fraction (range 35-65%; current operation 46 %) results in a possible reduction of the NO_3 effluent concentration by about 1 mg L^{-1} (top-left plot). The breakdown indicates that the NO_3 concentration in the Stage 1/2 effluent is at a minimum for a split around 55% (compromise between the need for a high enough C:N ratio and a sufficient residence time in the anoxic tanks). On the other hand, the NO_3 concentration in the Stage 3 effluent is predicted to decrease with increasing flow to Stage 1/2. We also note the limited effect of the influent flow splitting on the aeration energy or on the ammonia final effluent concentration, which remains below 0.2 mg L^{-1} for influent fractions in the range 35-65%. The N_2O emissions are predicted to increase as a larger fraction of wastewater is treated in Stage 1/2 (top-right plot), mainly due to nitrite accumulation in the anoxic tanks of Stage 1/2 and despite a decrease of these emissions in Stage 3; we also observe a small increase in the methane emissions from the anaerobic reactor of Stage 3. However, as previously noted, all these fugitive emissions remain small in comparison to energy-related GHG emissions.

Increasing the MLR in either treatment lines results in sending a larger amount of NO_3 back to the anoxic zone where denitrification occurs and, consequently, a reduction in the NO_3 effluent concentration is observed. In the case of Stage 1/2, this effect is illustrated in the bottom-left plot of Fig. 4, showing a potential reduction in NO_3 concentration of several mg L^{-1}; a similar behavior is observed with Stage 3. Naturally, this reduction would come at the price of higher pumping energy/costs. Regarding N_2O emissions, the trend shows larger emissions when increasing the MLR in Stage 1/2 (bottom-right plot). This is likely to be caused by an excessively low C:N ratio, which leads to nitrite accumulation. On the other hand, increasing the MLR in Stage 3 results in a reduction of the N_2O emissions since the C:N ratio is not limiting for this treatment line.

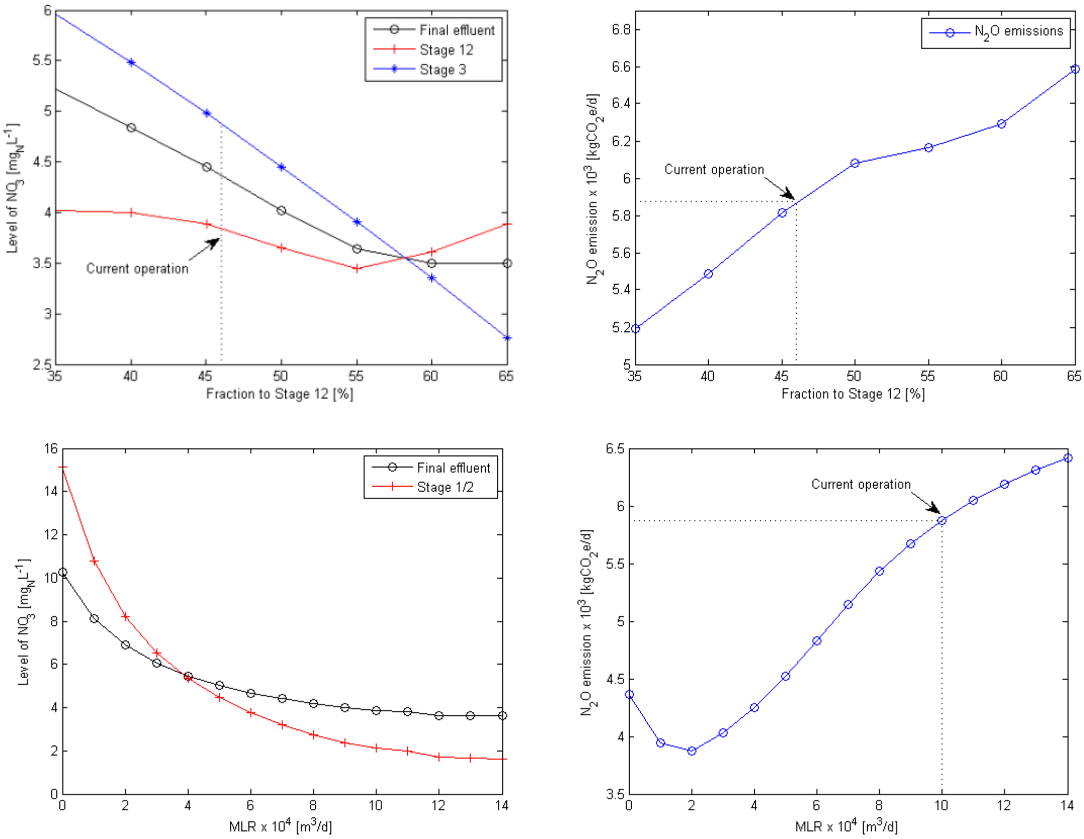

Figure 4: Effect of influent split between Stage 1/2 and Stage 3 (top plots) and mixed-liquor recycling in Stage 1/2 (bottom plots) on the nitrate discharge and N_2O emissions.

By and large, this analysis suggests that increasing the influent split to Stage 1/2 as well as increasing the MLR in both stages could lead to lowering the TN discharge concentration to about 3 mg L^{-1}, while not causing a large increase in aeration energy and keeping fugitive emissions at a low level compared to other GHG emissions.

An alternative option for enhanced nutrient removal is the use of reverse osmosis. With stricter effluent regulations, or in a context of some wastewater reclamation uses, membrane processes such as reverse osmosis might become necessary in order to achieve the required level of effluent quality (Wilf & Alt, 2000; Wintgens et al., 2005). With a reverse osmosis unit connected to the existing plant, the TN concentration in the effluent as low as 0.3 mg L^{-1} could be achieved. The energy use and GHG emissions for this scenario were compared with three scenarios from the modelled treatment plant with TN discharge concentrations of 3 mg L^{-1}, 5 mg L^{-1} and 8 mg L^{-1}. All these scenarios are represented in Fig. 5 with their respective CO_2-equivalent emissions[1]. It can be seen that the energy consumption and GHG emissions from reverse osmosis would be significantly larger (by about 50%) compared to those of the actual plant, which have an overall detrimental effect on the environment. This scenario-based modelling therefore gives a means of incorporating a broader picture of the environmental benefits and drawbacks of upgrading to reverse osmosis.

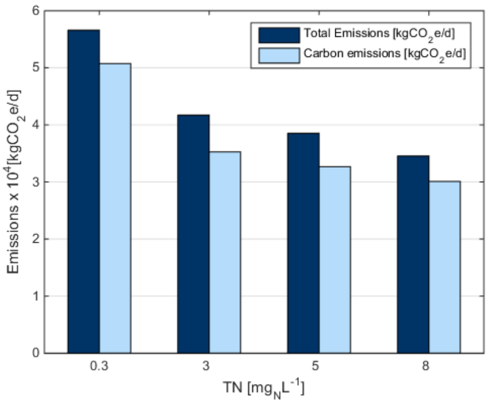

Figure 5: Comparison of plant upgrade scenarios, including reverse osmosis and operational changes, in terms of TN discharge and GHG emissions (both fugitive and energy-related).

CONCLUSIONS

This article has presented the application of a model-based methodology to analyze and quantify the impacts of operational strategies on effluent quality, energy use and fugitive emissions for an existing WWTP operating two parallel treatment stages. In quantifying these parameters, our models have successfully identified potential improvements to decrease nutrient discharge. This includes the potential reduction of the nitrate concentration in the tertiary effluent down to about 3 mg L^{-1} through operational changes to the influent split between both treatment stages and to the MLR rate in both stages. The models also increased our understanding of how to balance the need for enhanced nutrient removal with increased energy requirements, for example, the use of reverse osmosis could entail an energy penalty and a corresponding increase in GHG emissions as high as 50%.

---

[1] A conversion factor of 0.86 kgCO_2-eq/kWh is used to quantify the CO_2 emissions associated with energy consumption, considering electricity purchased from the grid in the local area (Australian Government, 2014).

In addition to identifying potential process improvements to reduce nutrient discharge, the scenario-based analysis reported in this paper suggests that the energy consumption could also be reduced by up to 10-20% by reducing the DO set-points and SRT in both treatment stages. Such operational changes typically lead to an increase in N_2O emissions due to incomplete nitrification or denitrification, yet these fugitive emissions are small compared to other, energy-related GHG emissions in the plant. As part of future work, it will be interesting to apply a systematic optimization approach in order to assess more precisely the potential energy savings and overall environmental impacts.

This model-based methodology gives us access to information to think more broadly about the impact of wastewater treatment on the environment and will therefore provide an important contribution to discussions about appropriate environmental licensing.

Acknowledgments

CP is grateful to the Royal Thai Government Scholarship programme for financial support. BC gratefully acknowledges financial support by ERC career integration grant PCIG09-GA-2011-293953 (DOP-ECOS).

REFERENCES

Australian Government, 2014, *National greenhouse accounts factor*, Department of Environment, Available at: http://www.environment.gov.au/system/files/resources/b24f8db4-e55a-4deb-a0b3-32cf763a5dab/files/national-greenhouse-accounts-factors-2014.pdf (Accessed: 17 February 2015).

Descoins, N., Deleris, S., Lestienne, R., Trouvé, E. & Maréchal, F., 2012, "Energy efficiency in waste water treatments plants: Optimization of activated sludge process coupled with anaerobic digestion", *Energy*, vol. 41, no. 1, pp. 153-164.

Dold, P.L., Jones, R.M., Takacs, I. & Melcer, H., 2003, "Practical guidance for WWTP model calibration and associated data gathering requirements", *Proceedings of the Water Environment Federation, WEFTEC 2003*, Los Angeles, CA, USA.

Filali, A., Fayolle, Y., Peu, P., Philippe, L., Nauleau, F., & Gillot, S., 2013, "Aeration control in a full-scale activated sludge wastewater treatment plant: impact on performances, energy consumption and N_2O emission", *11th IWA conference on instrumentation control and automation. ICA2013*, Narbonne, France.

Flores-Alsina, X., Arnell, M., Amerlinck, Y., Corominas, L., Gernaey, K.V., Guo, L., Lindblom, E., Nopens, I., Porro, J., Shaw, A., Snip, L., Vanrolleghem, P.A. & Jeppsson, U., 2014, "Balancing effluent quality, economic cost and greenhouse gas emissions during the evaluation of (plant-wide) control/operational strategies in WWTPs", *Science of the Total Environment*, vol. 466-467, pp. 616-624.

Jeppsson, U., Pons, M.N., Nopens, I., Alex, J., Copp, J.B., Gernaey, K.V., Rosen, C., Steyer, J.P. & Vanrolleghem, P.A., 2007, "Benchmark simulation model no 2: general protocol and exploratory case studies", *Water Science & Technology*, vol. 56, no. 8, pp. 67-78.

Law, Y., Ye, L., Pan, Y., & Yuan, Z. 2012. "Nitrous oxide emissions from wastewater treatment processes", *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *367*(1593), pp. 1265–1277.

Vanrolleghem, P.A., Insel, G., Petersen, B., Sin, G., De Pauw, D., Nopens, I., Dovermann, H., Weijers, S. & Gernaey, K., 2003, "A comprehensive model calibration procedure for activated sludge models", *Proceedings of the Water Environment Federation, WEFTEC 2003*, Los Angeles, CA, USA.

Owen, W. F., 1982, *Energy in wastewater Treatment,* Prentice-Hall.

Water Environment Federation, 1997, *Energy Conservation in Wastewater Treatment Facilities,* Water Environment Federation.

Wilf, M. & Alt, S., 2000, "Application of low fouling RO membrane elements for reclamation of municipal wastewater", *Desalination*, vol 132, no. 1, pp. 11-19

Wintgens, T., Melin, T., Schäfer, A., Khan, S., Muston, M., Bixio, D. & Thoeye, C., 2005, "The role of membrane processes in municipal wastewater reclamation and reuse", *Desalination*, vol 178, no. 1-3, pp. 1-11