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A benchmark simulation model to describe plant-wide phosphorus transformations in WWTPs

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Summary of key findings

The key findings of this study can be summarized in the following points:

- Simultaneous C, N and P descriptions require substantial Activated Sludge (ASM), Anaerobic Digestion (ADM) and Physico-chemical (PCM) model modifications/upgrades.
- Special attention must be placed on model interfacing, particularly regarding ASM-ADM-ASM and ASM-ADM with PCM.
- The numerous interactions of P with other elements (cations/anions) force an increase in the number of considered compounds that must be explicitly described (Ca, Mg, K…).
- The proposed WWTP design will not ensure an optimal performance for P removal. Nevertheless, it represents the P adaptation/retrofit of many C and N removal facilities.
- The addition of metals and the possibility to recover products, lead to significant modifications of the evaluation indices used until now and open the door to new ways of how to operate plants.
- Preliminary results satisfactorily describe all the relevant processes taking place in wastewater treatment system (with regard to C, N and P).

Background and relevance

It is more than 10 years since the publication of the BSM1 technical report (**Copp, 2002**). The main objective of BSM1 was to create a platform for benchmarking C and N removal strategies in activated sludge systems. The initial platform evolved into BSM1_LT and BSM2, which allowed for the evaluation of monitoring and plant-wide control strategies, respectively. In addition, researchers working within the IWA Task Group on Benchmarking of Control Strategies for Wastewater Treatment Plants developed other BSM related spin-off products, such as the dynamic influent generator, sensor/actuators/fault models and the different implementations of the ADM1, which have been widely used as stand-alone applications in both industry and academia. The fact that the BSM platforms (or related material) have resulted in 500+ publications demonstrates (**Gernaey et al., 2014**) the interest for the tools within the scientific community. In this paper, a highly necessary extension of the BSM2 is proposed. This extension aims at facilitating simultaneous C, N and P removal process development and performance evaluation at a plant-wide level. The main motivation of the work is that numerous wastewater treatment plants (WWTPs) pursue biological/chemical phosphorus removal. However, realistic descriptions of combined C, N and P removal, adds a major, but unavoidable degree of complexity in wastewater treatment process models. This paper identifies and discusses important issues that need to be addressed to upgrade the BSM2 to BSM2-P, for example: 1) new/upgraded mathematical models; 2) model integration; 3) new influent characterization; 4) new plant layout; and, 5) new/extended evaluation criteria. The paper covers and analyses all these aspects at a reasonable level of detail, identifies the main bottlenecks that need to be addressed and presents the simulation results of the first software prototype.

New process models

A modified version of ASM2d (Henze et al., 2000) is selected to describe C, N and P removal in the biological reactor. The original implementation of the ADM1 (Batstone et al., 2012) is upgraded with the Bio-P module proposed by Ikumi et al. (2014). Finally, there is a need of a plant-wide physico-chemical framework (Batstone et al., 2012) in order to correctly describe anionic/cationic behaviour in both Activated Sludge (AS) and Anaerobic Digestion (AD) units. This framework is comprised of: 1) a weak acid-base chemistry model (Solon et al., 2015); and, b) a multiple mineral precipitation model (Kazadi Mbama et al., 2014).

Model integration

Additional modifications in ASM2d/ADM were necessary to implement the weak acid-base chemistry model and the precipitation model (PCM). Additional details can be found elsewhere (Solon et al., 2015; Kazadi-Mbama et al., 2014). Finally, the interfaces between the ASM–ADM–ASM are based on the principles stated in the continuous-based interfacing model (Volcke et al., 2006).

Additional modifications

4.4.1. New influent characteristics

The principles stated in Gernaey et al. (2014) are used to generate the WWTP influent dynamics. Cations and anions profiles had to be added.

4.2. New plant layout

The main modification with respect to the original design (Gernaey et al., 2014) is related to the activated sludge (AS) configuration. An anaerobic section (ANER1 & 2) without oxygen (O_2) and nitrate (NO_3^-) is needed to promote anaerobic P release and to provide the PAOs with a competitive advantage over other bacteria. It is important to highlight that this configuration does not represent an optimal design to remove P. Nevertheless, it well exemplifies the retrofit of many (C, N removal) plants adapting their plant layout to satisfy new and stricter effluent requirements.

4.3. New evaluation criteria / control handles

The effluent quality index (EQI) originally used to evaluate the quantity of pollution leaving the plant is extended in order to include P related compounds. The operational cost index (OCI) is upgraded in order to account for the use of chemicals (carbon source, iron, aluminum, magnesium…) and their impact on sludge production/disposal (P_{sludge}). Indeed, the addition of certain chemicals can substantially influence this cost. Finally, the potential benefit for recovering struvite ($X_{MgNH4PO4}$) (fertilizer) must be added.

Results

Figure 1 shows the predicted nitrogen (TKN, TN and S_{NO3}) and phosphorus (TP and S_{IP}) concentration using the predefined operational conditions (Gernaey et al., 2014). Simulation results show that the set of models presented herein produces a good mathematical description of some of the most relevant processes taking place in wastewater treatment systems (involving C, N and P). For instance, N limits are well below the limits fixed in the BSM (TN < 18 g.m^{-3} at all times based on grab samples), which demonstrates the good nitrification/denitrification potential of the studied plant. Nevertheless, there is room for improvement regarding P removal (limit for TP = 2 g.m^{-3} based on grab samples). This is mainly due to that all the soluble P, which result from X_{PP} decay in the sludge line, is just partially sequestered in the particulates (X). Therefore, it is returned again to the activated sludge unit via the anaerobic digester supernatants. The small fraction, which is removed from the water stream, is either part of organic particulates (biomass, X_S and X_I) or removed via mineral precipitation in form of struvite/calcium phosphate ($X_{MgNH4PO4}$ and $X_{Ca3(PO4)2}$). This particulate fraction is retained in the dewatering system and goes directly to disposal.

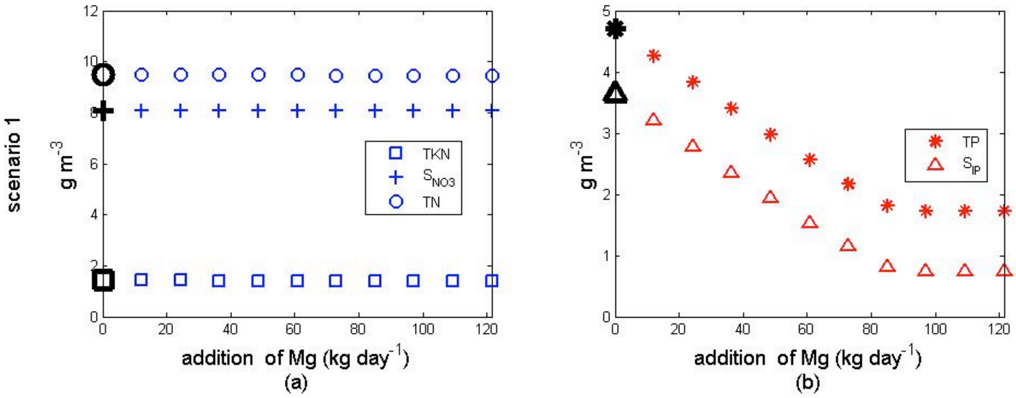

Figure 1. Preliminary simulation results using the BSM2-P prototype. Default operational conditions are presented in black.

Discussion

Additional simulations show that ($X_{MgNH4PO4}$) precipitation could be promoted by adding magnesium hydroxide (either as MgO or $Mg(OH)_2$) (**Figure 1**). The latter modifies the Mg/P ratio (Mg is the limiting element) and increases struvite precipitation. It is important to highlight that the presented control strategy is far from being optimal. Other strategies, such as 1) separate side stream treatment and 2) higher air flow promoting CO_2 stripping, would substantially reduce the quantity of magnesium. Indeed, an increased pH would make phosphate ions (S_{PO4-3}) more available and would also increase the magnesium (S_{Mg+2}) concentration. Nevertheless, the results depicted in **Figure 1** serve well as an example to visualize the potential benefits of the presented tool.

The reader should be aware that the results presented herein are somewhat preliminary. In the way results are presented in this study, P precipitation is just used as a control mechanism. This is mainly due to that there is no recovery process and N and P compounds are part of the overall total suspended solids stream. Additional plant layout modifications, for example the addition of a stripping unit for pH control and the construction of a crystallizer, will be added. Finally, dynamic simulations together with suitable performance index evaluation (EQI/OCI) will provide better insights into the real benefits of implementing automatic control strategies.

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