Model-based Management and Control of the Bioreactions in a Collection System

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ABSTRACT

A fast, convenient and user-friendly modelling tool was used to model biochemical and physico-chemical processes in the collection system. With this new tool two case studies were investigated with different scopes and purposes: one with a focus on the integrated modelling of sewer and wastewater treatment plants (WWTP) and the other aiming at a large-scale sewer network. Scenario analysis was carried out under different chemical dosing strategies. The work proves that processes in sewers can cause a significant impact on a downstream WWTP, and the wastewater treatment process can be better managed and optimized with the help of sewer-WWTP integrated modelling. The tool can also identify hotspots of key indicators like total dissolved sulfide in a large-scale collection system. It is suggested that investigating the network from a wider perspective can help target key issues and regions.

KEYWORDS in-sewer process, sewer-WWTP integrated modelling, corrosion, nutrient removal, optimization

INTRODUCTION

The sewage collection system, the largest man-made underground infrastructure, plays an important role for the sanitation of modern cities. Though previous concerns have focused on hydraulic efficiency, recent studies are trying to evaluate collection system as both a sewage transporter and a bioreactor. New modelling approaches and empirical field studies are now being pursued by industry and academia to further understand and attempt to engineer the biochemical processes in the sewer.

There are several motivations for a better understanding of the sewer as a bioreactor; these include finding means to optimize the production of readily biodegradable carbon for biological nutrient removal plants and to manage odors and corrosion problems caused by hydrogen sulfide produced in sewers. The latest goals for energy efficiency, nutrient removal, and nutrient recovery suggest that an integrated approach of sewer and WWTP will be more successful.

Downstream of the sewer, the modelling of individual and combined wastewater treatment processes has a long history and has been successfully used for the smart design and operation of wastewater processes. However, the modelling of collection systems can be more challenging than WWTPs. By looking at the map of a sewage collection and treatment system, the WWTP is usually represented as a point, for which it is crucial to follow and model the dynamic variations that significantly influence plant operation and control. However, the spatial scale of a collection system, covering tens to hundreds of kilometers or even more, imposes that the modelling of collection system should consider the variation in time and space.

In this contribution, by using a fast, convenient and user-friendly modelling tool, two case studies with different sizes were carried out to model the biochemical and physio-chemical processes occurring in the collection system. The first case study focused on a simple local system to study the influence of the sewer on a downstream WWTP, while the second case study dealt with a catchment-scale system with a focus on the spatial distribution for large networks. Key indicators, like VFA and hydrogen sulfide concentrations, were investigated in terms of dynamic and spatial variations.

METHOD AND RESULTS

The developed collection system modelling tool of collection system has the capability to handle collection systems of different sizes, and it has the flexibility to incorporate different biochemical models for in-sewer process modelling. Currently, users can select between the SeweX model (Sharma et al., 2008) and a simple biofilm model (Rauch et al., 1999). In this contribution, the SeweX model was chosen, which describes process kinetics of sulfate reduction, denitrification and other transformations that commonly occur between organics, sulfur species, nitrogen species, etc. in the sewer environment.

On the other hand, a WWTP modelling package was developed to handle sewer-WWTP integrated systems. The integrated system can be run either simultaneously in one MATLAB-Simulink layout or separately. The WWTP modelling package was derived from a WWTP model that expanded ASM2d and ADM1 with a simple physico-chemical model for iron, phosphate and sulfur transformation (Guo et al., 2016). Besides commonly used process units like settlers and activated sludge tanks, the package also includes modelling blocks for trickling biofilter and chemical enhanced primary clarifier (CEPT). The trickling biofilter is modelled by adapting the biofilm model of Rauch et al. (1999), and a simple CEPT model was built by implementing the simple physico-chemical model (Guo et al., 2016) into the traditional primary clarifier model (Otterpohl and Freund, 1992). A more advanced CEPT model is under development. An interface model was developed to connect the sewer and WWTP models.

Case study 1

The first case study was carried out on a force main system in California, US. The force main system receives wastewater from three catchments and transports the wastewater to a WWTP (Figure 1). The aim of the study was to optimize nitrate dosing strategies to control VFA and sulfide in the collection system and to evaluate the performance of sewer-WWTP performance under different chemical dosing strategies.

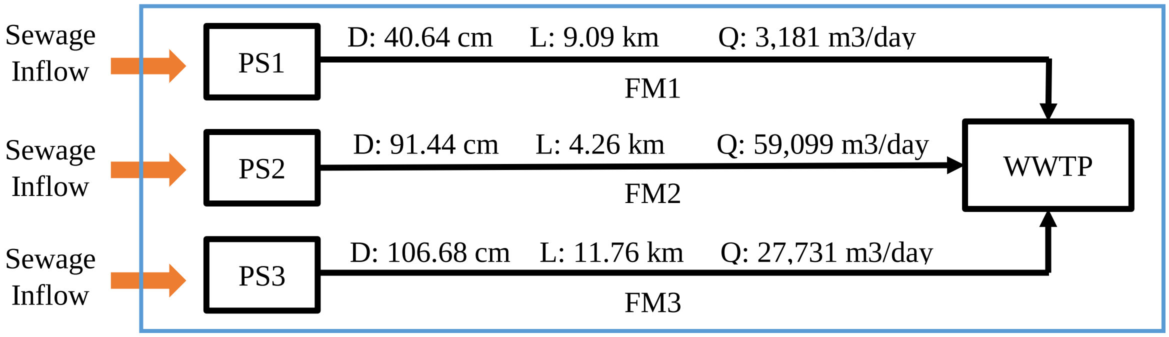


Figure 1: Schematic map of the force main and WWTP integrated system studied in California, USA (Note: "PS" means pumping station; "FM" means force main)

The collection system model was calibrated using the results from a 24 hours on-site sampling and measurement campaign (Figure 2).

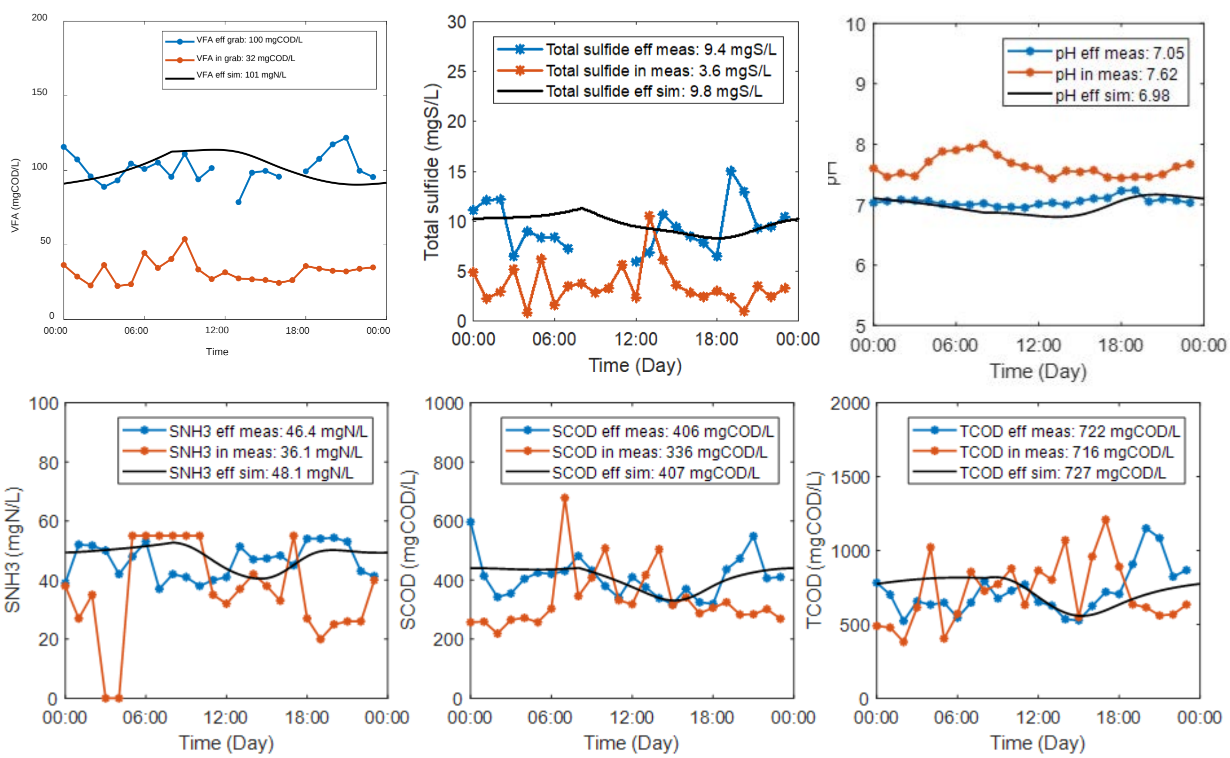


Figure 2: Comparison of measurement and simulation results for different water quality variables in Force Main 1 (Note: "eff" means effluent, "in" means influent, "meas" means measurement, "sim" means simulation)

Based on the calibrated model, a nitrate dosing scenario analysis was carried out. The dosing amount of nitrate should be estimated carefully on the one hand to efficiently reduce VFA production and on the hand to avoid overdosing of nitrate fed to the downstream WWTP. Therefore, 10 nitrate dosing scenarios were tested and compared in order to find the optimal dosing plan for each force main (Table 1). The nitrate dosing solution contains 122 g Nitrate-N/L (i.e. 3.5 lb Nitrate-O/gal in US unit). The dosing rate is adjusted dynamically in a relationship with force main flow rate in order to get nitrate concentrations at a certain level at pumping stations fed into downstream force mains. With an increment of 10 mgN/L, Scenario S*i* (*i*=1,2…10) refers to nitrate concentration at pump stations are 10×i mgN/L.

Table 1: Comparison of scenario analysis results

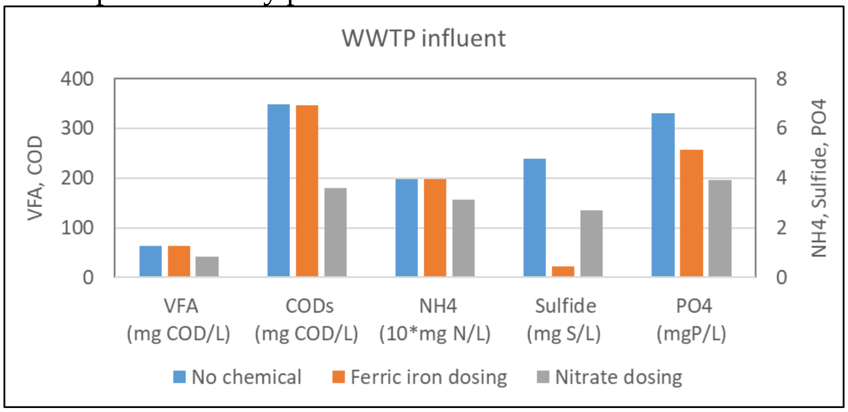
Scenario	Aimed Nitrate at PS (mg N/L)	VFA (mg COD/L)			Sulfide (mg S/L)			Nitrate (mg N/L)		
		FM1 eff.	FM2 eff.	FM3 eff.	FM1 eff.	FM2 eff.	FM3 eff.	FM1 eff.	FM2 eff.	FM3 eff.
Baseline	0	100	63	61	9.4	4.7	4.5	0.0	0.0	0.0
S1	10	109	57	55	8.4	3.9	3.8	0.0	0.0	0.0
S2	20	117	51	49	7.5	3.2	3.3	0.0	0.0	0.0
S3	30	124	43	42	6.7	2.6	2.8	0.0	0.0	0.0
S4	40	125	33	32	6.1	2.2	2.4	0.0	0.0	0.0
S5	50	116	18	19	5.6	1.7	1.9	0.0	0.0	0.0
S6	60	97	7	5	5.0	1.0	1.2	0.0	0.8	0.2
S7	70	70	3	2	4.3	0.7	0.9	0.0	5.2	4.1
S8	80	46	1	1	3.2	0.6	0.8	0.0	12.7	12.4
S9	90	29	1	1	2.1	0.5	0.8	0.0	22.0	21.9
S10	100	16	1	1	1.2	0.5	0.8	0.6	31.8	31.7

Note: green cells are the results of selected scenarios

The selection of the dosing rate is based on the consideration of VFA and sulfide removal and nitrate overdosing. For the force main FM1, Scenario S8, which gets 80 mgN/L of nitrate concentration at PS1, shows a better performance from an overall consideration, because it cuts about half of the VFA production compared to the baseline, and leaves no nitrate flowing into the WWTP. Sulfide production is also cut by two thirds of the baseline. The dosing amount is about 1.41 m^3/day. For FM2 and FM3, Scenario S3 was selected as the nitrate dosing strategy. The nitrate dosing amount at FM2 is about 9.33 m^3/day and 5.78 m^3/day at FM3.

Following that, a sewer-WWTP integrated model was run under three scenarios. In this case, the baseline scenario means that no chemical was dosed in the collection system or WWTP. The ferric dosing scenario uses 40% (by mass) $FeCl_3$ solution. The dosing amount was chosen based on baseline simulation results and the real situation at the WWTP. The dosing rate is 1.95 m^3/day at PS2, 1.21 m^3/day at PS3 and 0.70 m^3/day at primary clarifier inlet. The nitrate dosing scenario uses the optimal selection obtained from the collection system scenario analysis described above. The comparison of the three scenarios are shown in Figure 4.

a. Comparison of key parameters at WWTP inlet



b. Comparison of key parameters at trickling biofilter effluent

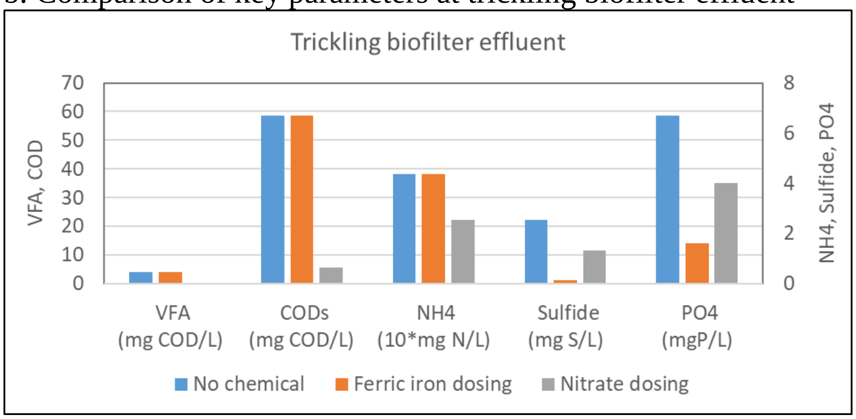


Figure 4: Comparison of integrated system modelling results under different scenarios

The findings from integrated modelling can be summarized as below:

- Ferric dosing shows the most significant removal of sulfide in the collection system. It also removes phosphate in both collection system and WWTP. The mechanism related to ferric dosing is mainly related to physico-chemical reactions.

- Nitrate dosing decreases sulfide production in the collection system. It makes that less VFA and CODs is fed into the WWTP by promoting denitrification in the sewer. Interestingly, more ammonia is removed at the WWTP, because less organics flow into the WWTP, leaving more oxygen for nitrification. The mechanism related to nitrate dosing is mainly biological reactions.

- Ammonia and phosphate can be assimilated significantly by bacteria in collection system and WWTP as nutrient sources.

Case study 2

The second case study was carried out at a catchment-scale collection system in Quebec City, Canada, found in the literature (Wipliez, 2011). The network consists of 211 pipes, covering 10 catchments. The aim was to find out the network sections that could suffer from high sulfide levels and propose a mitigation strategy, because hydrogen sulfide can cause odor and corrosion problems.

A SWMM model was used to get the information about sewage flow and network dimensions and connections (Wipliez, 2011). Based on that, the simulation for in-sewer processes was first run under the baseline scenario for 5 days. By using the new tool, a dynamic distribution map can be obtained for key parameters according to the user's preference, for example, every 1 hour. In this case, Figure 5 presents the spatial distribution map of total dissolved sulfide at 12:00 am, 6:00 am, 12:00 pm and 6:00 pm.

With the help of result visualization, hot spots and regions where high sulfide levels could be observed were easily identified (yellow lines in the graph). Moreover, the dynamic distribution map shows when the high sulfide level mostly occurs during a day. Clearly, the worst situation occurs at night. At 6:00 am, a high level of sulfide covers a large proportion of the network, and is even stretched to the WWTP inlet. This is because at night the sewage flow rate is at its lowest, especially at the branches (Figure 6), and the increase of the hydraulic retention time results in a build-up of sulfide.

Based on the result analysis under baseline simulation, the study can focus on those problematic areas for further scenario analysis using sulfide mitigation and control strategies. In this case, a $FeCl_2$ solution is added at location A and B as shown on the map. The $FeCl_2$ dosing rate at A and B is around 0.2 m^3/day each. Figure 7 shows that under iron dosing the sulfide level can be reduced significantly at the hot-spot regions throughout the day. Consequently, the sulfide in the downstream trunk pipes is also decreased. Still, some pipes still show high levels of sulfide at 6:00 AM. Therefore, the chemical dosing rate should be further optimized regarding the dynamic variation of sulfide.

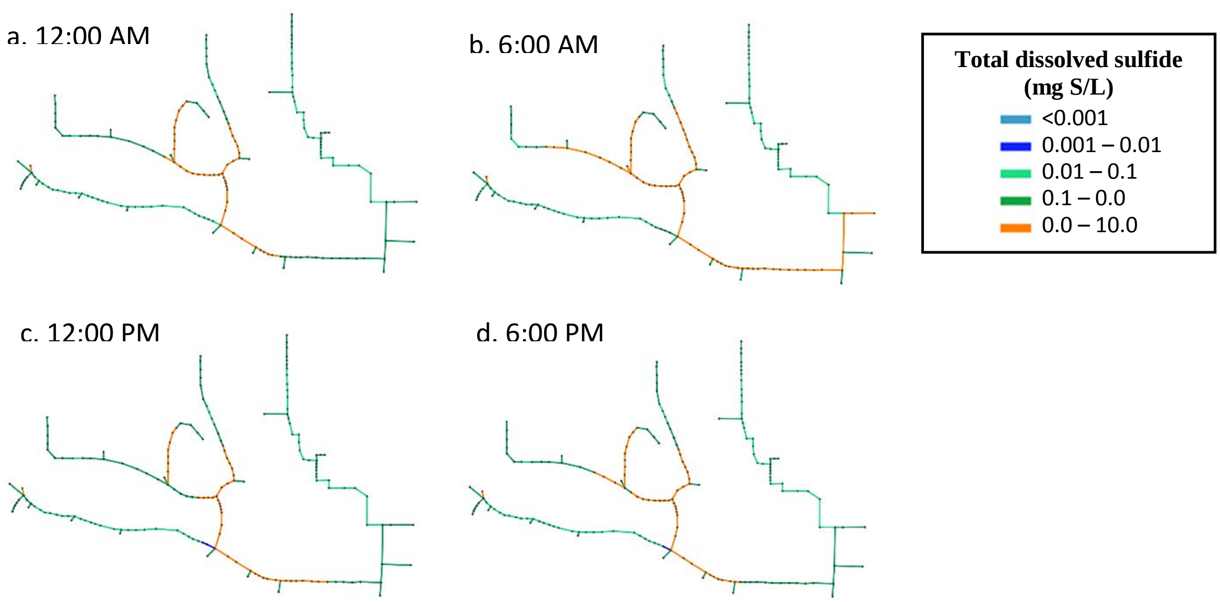


Figure 5: Spatiotemporal variation map of total dissolved sulfide under the baseline

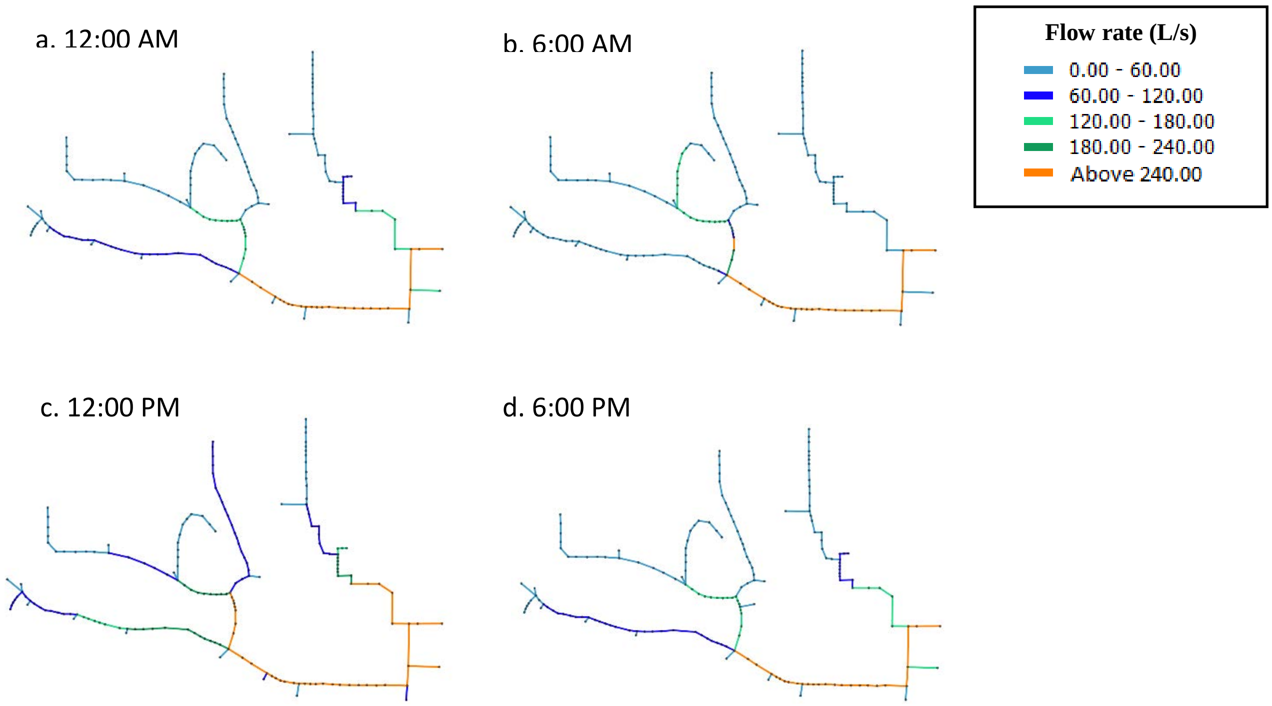


Figure 6: Spatiotemporal map of flow rate under the baseline

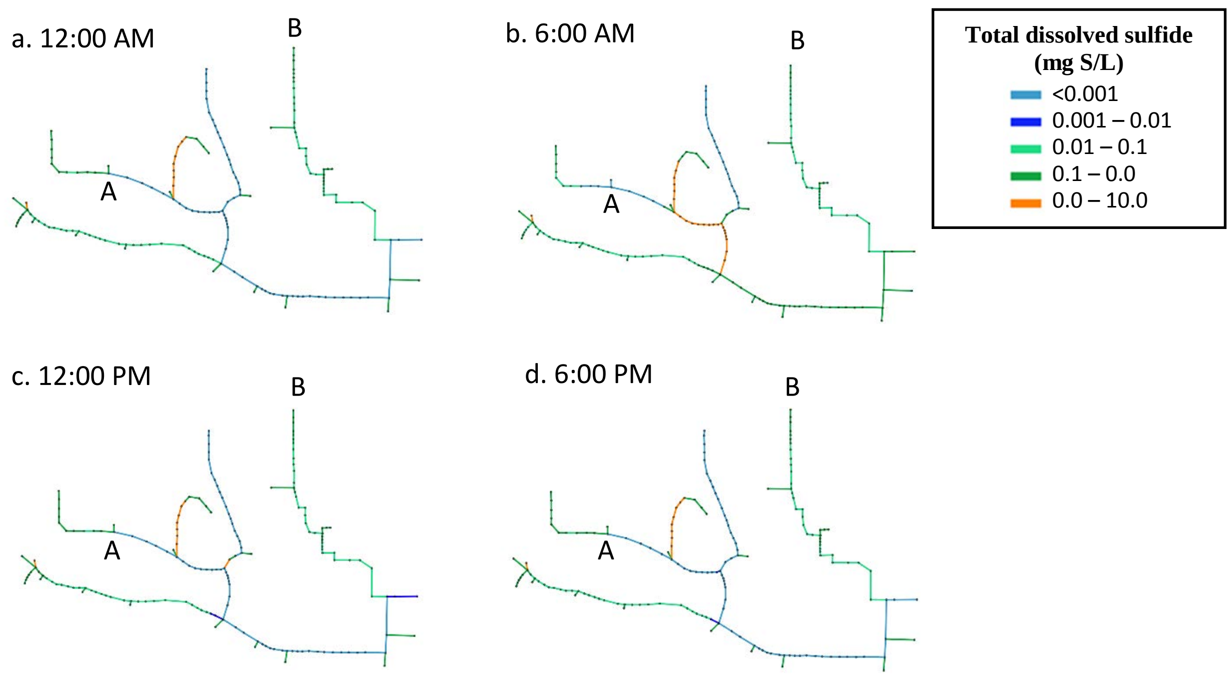


Figure 7: Spatiotemporal variation map of total dissolved sulfide under iron dosing (A and B are dosing locations)

CONCLUSIONS

The presented case studies show that the proposed modelling tool can be used in the management and optimization of collection systems with different sizes and purposes based on in-sewer process modelling. Important findings from the modelling efforts include:

- Sewers can cause a significant impact on a downstream WWTP. By adjusting dosing strategies, a modified wastewater quality can be achieved at the WWTP inlet.
- Collection system and WWTP should be managed and optimized as an integrated system.
- The result of chemical dosing does not only depend on the chemical type, the concentration and the amount of the dosing solution, but also on the characteristics of the collection system. For instance, excessive dosing may not improve the performance due to a too short hydraulic retention time.
- The selection of dosing strategies should be based on an overall assessment, including the required WWTP influent quality, the dosing cost and side effects, especially the impact of the chemical dosing on other indicators and unit processes at WWTPs.
- The investigation can start from a large-scale system analysis to identify local critical regions that need further study.

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REFERENCE

Guo L., Sharma K.R. and Yuan Z. (2016) Modeling of iron, sulfur and phosphorus interactions in sewer system and wastewater treatment plant under different sewer iron dosing strategies. In: the 5th IWA/WEF Wastewater Treatment Modelling Seminar 2016 (WWTmod2016). Annecy, France, 2-4 April 2016.

Otterpohl R. and Freund M. (1992) Dynamic Models for Clarifiers of Activated Sludge Plants with Dry and Wet Weather Flows. Water Science and Technology, 26 (5-6), 1391-1400.

Rauch W., Vanhooren H. and Vanrolleghem P. A. (1999) A simplified mixed-culture biofilm model. Water Research, 33 (9), 2148-2162.

Sharma K. R., Yuan Z., de Haas D., Hamilton G., Corrie S. and Keller J. (2008) Dynamics and dynamic modelling of H2S production in sewer systems. Water Research 42, 2527-2538.

Wipliez, B. (2011) Caractérisation et gestion de la vidange de réservoirs de rétention d'eaux unitaires. *Master thesis*, Université Laval, Québec, Canada (in French)