A sewer process model as planning and management tool – hydrogen sulfide simulation at catchment scale


ABSTRACT

The collection system of a major city at the Persian Gulf was simulated for bulk water hydrogen sulfide and the release of sewer gas to the urban atmosphere. Geometry data on 870 km of sanitary sewer and data on dry weather flow entering all nodes in the catchment was exported from a Mike Urban database and imported to the sewer process model WATS. The process model then routed sewage and sewer gas through the system and simulated relevant physical, chemical and biological processes. In its non-calibrated state, the model was used as a planning tool to identify problem areas and to identify locations to install monitoring equipment and make preliminary choices for control strategies in terms of dosing of nitrate and iron salts. The monitoring equipment consisted of flow meters, level gauges, UV-Vis spectroscopes, and H2S gas sensors. Data from the first set of installed monitoring equipment were applied to calibrate and validate the model. It was illustrated how the calibrated model can be applied to assess compliance with quantitative formulated service levels and to design control strategies in terms of dosing of iron and nitrate salts.

Key words | hydrogen sulfide, modeling, sewer processes

INTRODUCTION

Waterborne human waste can cause diseases, malodors and unaesthetic conditions if not managed appropriately. Sewers are the most common technology here for, conveying sewage to treatment and discharge. Even though this technology significantly reduces odor and health problems by confining human waste to underground structures, it does not prevent microbial and chemical transformations. It only constricts the processes to where they cause less harm. The in-sewer transformation processes cause formation of compounds with adverse effects, namely health risks, malodors, and corrosion. The long sewage residence times typically seen in collection systems of large cities increases these problems.

It is an engineering objective to quantify the adverse effects of in-sewer processes and to design strategies for their reduction. In this context a conceptual based numerical model of the biological, chemical and physical processes in the conveyance system is needed. The WATS model concept was developed for this purpose with its first concepts and simulation examples presented in the late nineties by Hvitved-Jacobsen et al. (1998). Since then much work and research has gone into sophisticating the knowledge on in-sewer processes and the model concept has continuously been extended, calibrated and validated (e.g. Nielsen et al. 2008a, b; Jensen et al. 2009).

Today the WATS concept comprises aerobic, anoxic and anaerobic processes in the bulk water, biofilms and sediments, as well as oxidation of sulfur compounds on moist sewer surfaces and consequent corrosion. A numerical instance of the WATS model concept has been created, which simulates processes in complete sewer networks by routing the wastewater from source to discharge. It simulates transport and processes in force mains, in the two-phase flow of gravity sewers and drop structures (water phase and gas phase), and it simulates corrosion of concrete structures. It routes sewer gas through gravity sewers and keeps track of gas released from the sewer and atmospheric gas entering the system. It furthermore simulates management strategies like addition of oxygen, nitrates and iron salts (Vollertsen et al. 2008).

The objective of this work is to demonstrate the application of the sewer process model WATS on a complex...
sewer network to manage hydrogen sulfide related problems. The latest numerical instance of the model is used in a non-calibrated state for planning on catchment scale. In a calibrated state it is used to assess quantitative formulated service levels and to choose and dimension control strategies.

**METHODS**

The sewer network on which the WATS model was applied is located in a major city in the United Arab Emirates. It comprises some 870 km of sanitary sewer of which the 66 km are force mains (Figure 1). Diameters range from 0.1 to 2.2 m and the total load of water conveyed is about 270,000 m$^3$ day$^{-1}$. All pipes in the catchment are corrosion resistant plastic pipes.

The catchment is characterized by capacity problems of both conveyance system and treatment plant. There are problems with sanitary sewer overflows, hydrogen sulfide (H$_2$S) and malodors. To mitigate the experienced problems, the asset owner has requested that the catchment be analyzed with respect to capacity issues and H$_2$S problems, as well as management strategies developed. To reduce sanitary sewer overflows and to equalize the load on the treatment plant, control of upstream pumping stations is planned to retain sewage when downstream capacities are insufficient. The hydraulic part of this control is managed by real-time simulations with the hydrodynamic model Mike Urban while WATS is used to predict H$_2$S levels and to design management strategies.

**Management master plan**

To monitor the operation of the system and to qualify model simulations, a large number of control stations and warning stations are planned and installed in the catchment. Each warning station is equipped with a H$_2$S gas sensor and a level meter. The control stations consist of dosing equipment for iron and nitrate salts as well as a flow meter, an UV–Vis spectrometer for TSS, total COD, dissolved COD, NO$_3$-N, HS$^-$, temperature and pH, and a H$_2$S gas sensor.

Control stations are generally envisioned to be placed at pumping stations while warning stations will be strategically placed in the network. Data from the stations are continuously transmitted to a control center and processed. Flow measurements are used on-line in the hydrodynamic real-time simulations, while bulk water and sewer gas quality data are used off-line to routinely calibrate and validate the WATS simulations. When needed, the WATS model is to be applied to evaluate and optimize operational strategies, for example H$_2$S control during upstream detainment of sewage.

**Field measurements**

At the present stage of the project, measurements from 3 locations in sub-catchment A were applied to calibrate and validate the model, namely data from PS 2/2, PS 3/2 and PS 3/18 (Figure 1). The catchment is mainly residential with some commerce and public institutions. Flow was measured by Doppler flow meters from Teledyne Isco (ISCO 2150). The flow at all pumping stations in the...
catchment was furthermore assessed by analyzing SCADA data for December 2009 on duty-flow and pump operation time. The UV-Vis spectrometers used for TSS, total COD, dissolved COD, NO3-N, HS-, were spectrolyser from S:CAN Messtechnik GMBH and the pH meters were pH:lyser from S:CAN. Software from S:CAN calculated the bulk water H2S concentration from the measurement of HS-, pH and temperature. The probes were equipped with automatic cleaning by compressed air. The spectrolyser probe has previously been shown to give good determination of hydrogen sulfide in sewage when calibrated to the concrete application (Sutherland-Stacey et al. 2008; Gutierrez et al. 2010). In the present application, sensors were manufactured pre-calibrated with no further calibration on site. The H2S gas sensors were iTrans from Industrial Scientific with a range from 0 to 500 ppm H2S gas.

Routing of water and gas by WATS

The numerical WATS model is programmed in Delphi Pascal and capable of holding an unlimited number of pipes and nodes. It accepts individual input at all nodes. Network data and flow input to network nodes were exported from a Mike Urban database as ASCII files and subsequently imported by WATS. In the context of the project, WATS was tailor made to accept input on this form. The input flow to all network nodes were then routed through the network by the WATS model applying stationary hydraulics. In-sewer transformations were simulated following plugs of sewage and sewer gas through the network and observing mixing, continuity equations and mass balances. In a sewer system with closed manholes, the space for sewer gas changed for example where pipes met, slope or diameter changed, or the water entered a pumping station. This then resulted in the model emitting or taking in gas at those nodes.

The sewer process model

Processes are simulated by the latest instant of the sewer process concept WATS. Details can be found in e.g. Hvitved-Jacobsen (2002), Nielsen et al. (2008a), Vollertsen et al. (2005, 2008), and Jensen et al. (2009). When predicting H2S, its rate of formation in the sewer biofilm is a most crucial parameter. In the WATS model, it is described as a half-order process in the easily degradable COD fractions – an approach often applied for simulating H2S formation in sewer biofilms and assumed valid for typical wastewater compositions (Nielsen et al. 1998; Tanaka & Hvitved-Jacobsen 2001; Hvitved-Jacobsen 2002). The average wastewater BOD and COD at the treatment plant was 235 mg BOD/L and 375 mg COD/L, i.e. levels rather typical for domestic wastewater. Sulfate limitation was in the current case not taken into account as the wastewater when entering the treatment plant still contained sulfate in excess of 60 mg SO4/L. In the present model instant the rate was determined as \( r_{112S} = k_{112S} \alpha (S_A + S_F + X_{St})^{0.5} a^{T-20} \) (Tanaka & Hvitved-Jacobsen 2001), where \( k_{112S} \) is a rate constant (\( gS/m^3h \)), \( S_A \) is fermentation product (\( gCOD/m^3 \)), \( S_F \) is fermentable substrate (\( gCOD/m^3 \)), \( X_{St} \) is readily hydrolysable substrate (\( gCOD/m^3 \)), \( T \) is temperature (\( ^\circ C \)) and \( \alpha \) is a constant (\( - \)). The temperature constant, \( \alpha \), was chosen to 1.05 as the average of values reported by Kitagawa et al. (1998) and Nielsen et al. (1998). Bulk water concentrations were calculated taking the actual biofilm to bulk water areas into account. Other and more detailed models have been suggested for description of the formation of H2S, e.g. by Guisasola et al. (2009). However, in the present case the boundary conditions are only poorly determined and the more simple approach is therefore deemed the most appropriate choice.

RESULTS AND DISCUSSION

As a first step the catchment was analyzed for locations with potential for high H2S bulk water concentrations and for locations where much H2S gas could escape to the urban atmosphere. For this step, the model had been crudely calibrated to typical downstream levels of H2S and run with average boundary conditions (Figure 2). The absolute values obtained were deemed less crucial as focus was on identifying hot-spots of bulk water H2S and odor release. Based on these initial simulations and on data needs of the hydrodynamic model, the location of monitoring stations and control stations was decided and installation of the equipment was set in progress.

For sub-catchment A, 4 control stations were chosen based on the simulations with the non-calibrated WATS model, namely at the pumping stations PS 2/2, PS 3/1,
PS 3/2 and PS 3/18 (Figure 2). The stations were first equipped only with sensors and not with dosing facilities in order to calibrate the model and produce more accurate simulation results prior to committing the comparatively large investment of dosing equipment.

In the next step, data from the control stations PS 2/2, PS 3/2 and PS 3/18 were analyzed and applied to calibrate the model on the catchment upstream of these stations. In total 302 days of UV–Vis and pH measurements were collected from these stations. However, most of the data were rejected due to sensor drift caused by insufficient maintenance of the probes. Originally it was envisioned that manual cleaning every 2–3 weeks would suffice, however, the sensors only gave valid data for a day or two after manual maintenance. Furthermore, the measurement of nitrate was generally deemed unrealistic high and also tended to correlate with the TSS and COD of the sample. As a rule, only HS−, soluble COD, pH and temperature were deemed trustworthy and intensive manual maintenance as well as sensor calibration prior to use was concluded a necessity. For 1 of the 3 stations, the ISCO flow meter gave unrealistic results, most likely due to inappropriate placement of the flow sensor. The placement of the flow probe was subsequently corrected, and good quality flow data is now acquired. After quality control of the data-sets, the typical values of Table 1 were obtained.

### Table 1

Typical flow results from SCADA and flow meters as well as typical water quality results. Values are average/typical range. ‘∼’ indicates comparatively high uncertainty on the value stated.

<table>
<thead>
<tr>
<th>Flow (L s⁻¹)</th>
<th>COD sol (g m⁻³)</th>
<th>pH (–)</th>
<th>Temp. (°C)</th>
<th>HS (g m⁻³)</th>
<th>H₂S (g m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SCADA</td>
<td>ISCO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS 2/2</td>
<td>626 (150/950)</td>
<td>537 (310/870)</td>
<td>~180 (120−240)</td>
<td>7.9 (7.6−8.2)</td>
<td>31.5 (29−32)</td>
</tr>
<tr>
<td>PS 3/2</td>
<td>132 (50/220)</td>
<td>109 (0/260)</td>
<td>~125 (105−170)</td>
<td>8.3 (7.8−9.2)</td>
<td>31 (28.5−31.5)</td>
</tr>
<tr>
<td>PS 3/18</td>
<td>92 (20/160)</td>
<td>–</td>
<td>~190 (150−230)</td>
<td>~7.4 (6.7−8.2)</td>
<td>27.5 (25.5−28.5)</td>
</tr>
</tbody>
</table>
Model calibration

The first step in calibrating the model was to adjust node input flows to rates obtained by SCADA data (Table 1). The model was then calibrated to average quality data observed at PS 2/2. The pH was set to 7.9, temperature to 31°C and the sum of $S_A$, $S_F$ and $X_{S_f}$ to the measured soluble COD ($S_A$: 40, $S_F$: 40 and $X_{S_f}$: 100 g COD m$^{-3}$). The model was calibrated to average bulk water H$_2$S levels by adjusting the H$_2$S formation rate constant $k_{H2S}$ to 0.032 gS g COD$^{-0.5}$ m$^{-0.5}$ h$^{-1}$, which is a comparatively high value. For a similar half order process and for Danish force mains, Nielsen et al. (1998) found rate constants in the range from 0.001 to 0.010 gS g COD$^{-0.5}$ m$^{-0.5}$ h$^{-1}$, Nielsen et al. (2008a) found around 0.006 gS g COD$^{-0.5}$ m$^{-0.5}$ h$^{-1}$ for another Danish force main. On the other hand, the rate constant applied corresponds to a biofilm sulfide generation rate of 0.43 gS m$^{-2}$ h$^{-1}$ when normalized to 20°C. Sulfide generation rates in this range have been reported for warm countries, e.g. by Mohanakrishnan et al. (2009) who report from 0.37–1.12 gS m$^{-2}$ h$^{-1}$ at 20–25°C in a setup operated parallel to a force main. The calibration to H$_2$S data from PS 2/2 was validated by data from the upstream located PS 3/2 and PS 3/18 (Figure 3). This comparatively simple calibration procedure yielded a reasonable validation of the model and the stated parameters were therefore applied in the further simulations.

The variability in measured data (data not shown) was significantly higher than what could be explained by diurnal variations. The main cause of this discrepancy is believed to be a natural variability in boundary conditions, for example in terms of organic matter composition and flow. For further analysis of the system, a stochastic simulation approach was therefore applied. A simple Monte Carlo technique was used where the most crucial model parameters and boundary conditions were varied according to predefined statistical distributions. The diurnal flow variation was simulated 500 times with model parameters drawn from known distributions according to Vollertsen et al. (2005). The outcome of the stochastic simulation is a series of bands indicating values exceeded at a certain probability. Figure 4 shows examples of diurnal variations of such bands throughout sub-catchment A. The bands can be interpreted as a statement of service level, for example in terms of exceeding a certain H$_2$S sewer gas concentration for a certain percentage of time.

The calibrated model can be applied to dimension control strategies, for example in terms of iron or nitrate salts addition to achieve a quantitative defined service level. As an example, stochastic simulation show that addition of 350 kg/d of Fe(II) at pumping station PS 3/2 ensure that H$_2$S gas phase concentrations at pumping station PS 2/2 stay below 10 ppm in 95% of the time, whereas nitrate addition does not ensure this service level to be met. The reason why nitrate in this case is inadequate is that lateral inflows containing H$_2$S enter the main sewer a short way upstream of PS 2/2. While the iron rapidly precipitates the H$_2$S present, the nitrate causes the much slower process of biological oxidation. A process for which there, in this case, was insufficient time.

In the present project, the asset owner has the objective to formulate quantitative service levels and to ensure the sewer system operates within these limits. Control strategies such as iron or nitrate salt dosing will be chosen, designed and implemented and on-line monitoring together with WATS model simulations will be applied to ensure
compliance with the service levels. When real-time control and control strategies are fully in operation, the optimal setting of control strategies will routinely be evaluated using monitoring data in combination with simulations to ensure that the service levels are met at lowest possible operational costs.

CONCLUSION

Modeling in-sewer processes and related problems on catchment scale can be applied as a planning tool to identify problem areas in terms of odor and corrosion. Already in a crudely calibrated state, in-sewer process models can on catchment scale help to identify hotspots and preliminary selection and sizing of strategies, hereby assisting in planning and optimizing of management efforts. The data requirements of such models with respect to network geometry and dry weather flow are similar to that of hydrodynamic models and such data can therefore readily be imported here from.

Although quantitative correct predictions require substantial efforts for model calibration and validation, such approach allows compliance with quantitative defined service levels, for example in terms of the frequency of a certain H₂S gas concentrations in the network. Where in-sewer processes cause unacceptable nuisances, a combination of monitoring and reliable simulation is likely the most cost-effective approach to ensure compliance to quantitative defined service levels.

REFERENCES


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