Controlling chemical dosing for sulfide mitigation in sewer networks using a hybrid automata control strategy

Yiqi Liu*,, Ramon Ganigué*, Keshab Sharma*, Zhiguo Yuan***

* Advanced Water Management Centre, The University of Queensland, St. Lucia, Brisbane QLD 4072, Australia. (e-mail: r.ganiguepages@awmc.uq.edu.au; k.sharma@awmc.uq.edu.au; z.yuan@awmc.uq.edu.au)
** School of Automation Science & Engineering, South China University of Technology, Guangzhou, ,510640, P.R. China. (e-mail: liuyiqi769@sina.com.cn)

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Abstract: Chemicals such as $Mg(OH)_2$ and iron salts are widely used to control sulfide-induced corrosion in sewer networks, composed of interconnected sewer pipe lines and pumping stations. Chemical dosing control is usually non-automatic and based on experience, thus often resulting in sewage reaching the discharge point receiving inadequate or even no chemical dosing. Moreover, intermittent operation of pumping stations makes traditional control theory inadequate. A hybrid automaton-based control method is proposed in this paper to coordinate sewage pumping station operation by considering their states, thereby ensuring suitable chemical concentrations in the network discharge. The performance of the proposed control method is validated through a simulation study of a real sewer network using real sewage flow data. The physical, chemical and biological processes were simulated using the well-established SeweX model. The results suggest that the HA-based control strategy significantly improves chemical dosing control performance and sulfide mitigation in sewer networks, compared to the current common practice.

INTRODUCTION

Sulfide is a major concern in sewer systems due to pipe corrosion, health hazards and odour nuisance (Hvitved Jacobsen et al. 2002). When anaerobic conditions prevail in sewers, hydrogen sulfide (H_2S) is formed and emitted, primarily as a product of sulfate reduction by sulfate reducing bacteria (SRB) residing in sewer biofilms and sediments. This results in pipe corrosion and odour problems. To control H_2S emissions, chemicals, including oxygen, nitrate, iron salts and alkali, among others (Hvitved Jacobsen et al. 2002; Gutierrez et al. 2008), are often dosed to sewers to prevent sulfide formation, to remove dissolved sulfide after its formation, or to reduce its transfer rate to the sewer atmosphere.

To date, chemical dosing for sulfide control has mainly focused on single pipes (Ganigue et al. 2011). However, a sewer system is rarely composed of a single pipe but rather presents a network structure consisting of interconnected pipes and pumping stations, with different flows converging to main trunks. A more optimal and cost-effective way of managing sulfide is to implement control strategies on a network basis. This could lead to fewer dosage stations, less chemical consumption and/or improved performance. Despite this fact, few studies focussed on sewer network control (Bentzen et al. 1995; Mathioudakis et al. 2006). Mathioudakis and co-workers (Mathioudakis et al. 2006) proposed continuous addition of nitrate at a constant rate at a few points to mitigate sulfide problem in a sewer network, which was successfully tested in the Corfu city sewer network, thus making a major step forward compared with single pipe-based dosage strategies. However, due to the intermittent operation of pumping stations some wastewater slugs could reach the discharge point without receiving adequate or any chemical dosing if chemical dosing is not dynamically controlled, leading to poor sulfide control, whereas other slugs could receive excessive dosing causing wastage of chemicals. Furthermore, sewer network manifests a complex behaviour, which is characterized by interactions between continuous dynamics (continuous sewage flow in the pipes) and discrete events (discontinuous pump station operation). Traditional control theories, developed for either pure continuous systems or pure discrete systems, are unable to properly describe hybrid system behaviour. One potential way to address this problem is to transform hybrid systems to pure continuous or discrete systems (Tiwari and Khanna 2002). However, this requires a simplification of the system, with assumptions potentially leading to biases or loss of information. The hybrid automata theory provides a better alternative, as it is not only suitable for describing network structures, but also allows the accurate characterisation of interactions between continuous dynamics and discrete events. Up to date, this has not been applied to chemical dosing in sewer networks, even though the use of hybrid automata for this purpose in chemical industries is widespread (Fibrianto et al. 2003; Millan and O'Young 2008; Uzam and Gelen 2009).

This work is the first attempt to develop an online control system for chemical dosing in sewer networks for sulfide mitigation. The method is based on the hybrid automata theory, which coordinates autonomous (autonomous pump stations) and controlled hybrid automata (controlled pump stations) to allow more effective control of sulfide on one hand and avoiding chemical over-dosing on the other. The discrete changes are modelled using a form of transition diagram dialect similar to state charts, while the continuous changes are modelled using differential equations.

HYBRID AUTOMATA-BASED CONTROL

HA definition

An automaton is a formal model for a dynamic system with discrete and continuous components (Henzinger 1996). A hybrid automaton is a tuple $H = (X, Q, Inv, Flow, E, Jump, Reset, Event, Init)$ where:

- X is a finite set of n real-valued variables that model the continuous dynamics;
- Q is a finite set of control locations (mode);
- *Inv* is a mapping, which assigns an invariant condition to each location $q \in Q$. *Inv*(q) is a predicate over the variables in *X*. The control of a hybrid automaton remains at a location $q \in Q$, as long as *Inv*(*q*) holds;
- *Flow* is a mapping, which assigns a flow condition to each control location $q \in Q$. The flow condition Flow(*q*) is a predicate over *X* that defines how the variables in X evolve over the time *t* at location *q*;
- $E \subseteq Q \times Q$ is the discrete transition relation over the control locations;
- *Jump* is a mapping, which assigns a jump condition (guard) to each transition $e \in E$. The jump condition *jump*(e) is a predicate over *X* that must hold to fire *e*. Omitting a jump condition on a transition means that the jump condition is always true and it can be taken at any point of time. Conventionally, writing *Jump*(*e*)[*v*] means that the jump condition on a transition *e* holds, if the variations of variables on the transition *v*;
- *Reset*(*e*) is a predicate over *X* that defines how the variables are reset;
- *Event* is a finite set Σ of events, and an edge labelling function *event* : $E \rightarrow \Sigma$ that assigns to each control switch an event;
- *Init* is the initial state of the automaton. It defines the initial location together with the initial values of the variables *X*.

A hybrid automaton can be divided into autonomous and controlled types, which depend on whether their transitions are uncontrollable or controllable.

Application of HA-based control to sewer networks

A sewer network consists of interconnected sewage pump stations (SPSs) and sewer pipes, which convey sewage from households and industries to Wastewater Treatment Plants (WWTP). Sewage is first collected into SPSs, which pump the sewage into the pipes. These are usually operated in a discontinuous way, with pump events occurring when the water level in the wet well reaches the pre-specified level, and pumps stopping when the level gets to the lower limit. Unlike traditional pure continuous or discrete systems, sewer systems are characterized by the interactions between continuous dynamics (wastewater flow, which can be modelled as a plug-flow system and described by traditional continuous state functions) and discrete events (intermittent pump operation, usually controlled based on wet well levels). Hybrid systems theory can be used to model this, capturing both the continuous and discrete behaviour of sewer networks. Chemical dosing in such systems can be controlled using a hybrid automaton, which can prevent wastewater slugs to reach the discharge point receiving too low or too high chemical dosing.

To further illustrate hybrid automata, a pump station model based on autonomous hybrid automata is shown as follows. The hybrid automaton of **Error! Reference source not found.** models a pump station, which turns on and off according to the sensed water level. The variable *x* represents the water level. In control mode OFF, the pump station is off, and the water level rises according to the flow condition (*Flow*) $\dot{x} = \frac{inflow(t)}{S}$, where *S* is pump station wet well area, *t* is the time, and *inflow* is incoming flow into pump station. In control mode ON, the pump station is on, and the water level falls or rises according to the Flow condition $\dot{x} = \frac{inflow(t)-outflow}{S}$, where outflow is constant due to constant pump speed operation. In this example, initially, the pump station is off and the initialized water level is 0.5. According to the jump condition $x > UL$ (water level upper limit), the pump station may go ON as soon as the water level reaches *UL*.

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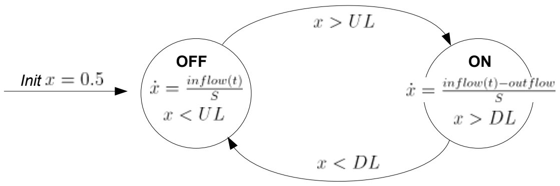

Figure 1. Pump station autonomous hybrid automaton

According to the invariant condition (*Inv*) $x < UL$ in the OFF circle, the pump station will stay OFF when the water level is lower than *UL*. Similar behaviour will occur once water level is lower than *DL* (water level down limit) in the ON circle, if pump station is ON.

In sewer networks, level-based pump stations are modelled as autonomous hybrid automata. On the other hand, controlled hybrid automata are used to model controlled pump stations where chemicals are dosed to mitigate sulfide. These are similar to autonomous hybrid automata, with the only difference being their different *Jump* conditions. Their state transition depend on, not only the water level in the wet well, but also behaviours of other autonomous hybrid automaton. For instance, a change of state of a controlled hybrid automata can be triggered by the change of ON/OFF states of any autonomous hybrid automata (level-based pump stations) within the network. In this particular case this could ensure that the flow delivered by the controlled hybrid automata (controlled pump stations) with chemical dosing will be adjusted to ensure suitable chemical concentration in the entire network, when the chemical-containing sewage is mixed with fresh sewage (not containing chemicals) delivered by downstream SPSs.

CASE STUDY: $Mg(OH)_2$ DOSING IN THE TUGUN-ELANORA SEWER NETWORK

The suitability and performance of the hybrid automata chemical dosing control was tested through a simulation study of the Tugun-Elanora sewer network (Gold Coast, Australia).

Tugun-Elanora sewer network

The Tugun-Elanora sewer network is shown in Figure 1. The network consists of rising mains with diameter ranging from 100 mm to 600 mm and combined total length of about 23 km. There are 14 pumping stations including one with a large Balancing Tank (BT) having a volume of 2394 m^3, located in the middle of the sewer network. The network receives an average daily flow of approximately 13,000 m^3/d. The average daily flow delivered by the BT pump station is 3500 m^3/d with the maximum pump capacity of 14,700 m^3/d. Downstream to the BT pump station, C1 is the largest pump station, which carries average daily flow of 3500 m3/day with the maximum pump capacity of 15400 m3/day. All the SPSs in the sewer system except the BT operate in an intermittent mode with short pumping events followed by relatively long quiescent periods. The BT currently operates 4 times a day with the pump time ranging from 1 hour in the morning to 4 hours in the evening. The average daily flow at B21 and B17 is 1100 and 800 m3/day, respectively. Different from these large pump stations, the remaining pump stations deliver low flows ranging from 100 m^3/d to 2500 m^3/d. All SPSs including BT are currently controlled based on water levels in the respective wet wells.

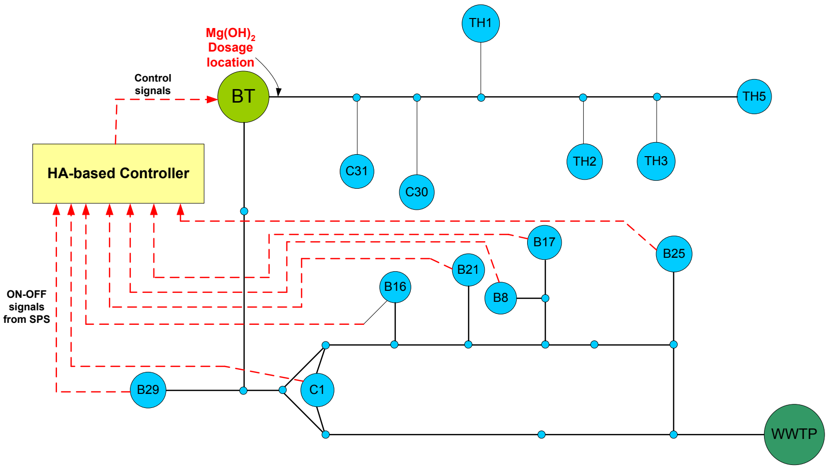

Figure 2. Schematic of the Tugun-Elanora sewer network

Magnesium hydroxide ($Mg(OH)_2$) is dosed in the sewer network to increase pH. Elevated pH reduces hydrogen sulfide transfer from the liquid to the gas phase. At pH 7.0, the percentage of hydrogen sulfide, the volatile fraction of dissolved sulfide, is approximately 50% of the total dissolved sulfide, whereas at pH 9.0 this value is reduced to less than 1% due to the shift of the sulfide equilibrium (Gutierrez et al. 2009). In this case, $Mg(OH)_2$ is added at the location immediately upstream of BT (see Figure 2) with a flow-proportional dosing rate, resulting in a $Mg(OH)_2$ concentration of 300 mg/L in the sewage flowing into BT. Due to the discontinuous operation of the BT and also other SPSs, sewage pumped into the network by SPSs downstream of BT does not receive $Mg(OH)_2$, leading to an non-elevated pH and hence a higher transfer rate of H_2S from the liquid to the gas phase.

HA-based network control for Tugun-Elanora sewer network

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The aim of this case study is to develop an HA-based sewer network control strategy to ensure suitable $Mg(OH)_2$ concentrations at the discharge point of the sewer network, which is recognised as a corrosion and odour hot spot.

Given the large volume of the BT, this work focuses on the manipulation of the BT outflow based on the HA control methodology. The flow rate of the BT (variable speed pump) is controlled based on the operational states (ON or OFF) of the downstream SPS. ON/OFF signals of these SPSs are sent from these SPSs to the controller. The flow rates delivered by these constant speed pumps are known. While the chemical dosing rate to the inflow of the BT may also be controlled, it is not considered in this study for simplicity.

The autonomous transition (level-based pump stations) can be modelled as autonomous hybrid automata with two possible modes, *On* and *Off*. For each mode, we have to specify the domain in which the mode is valid. When water level reaches the boundary of the domain, a new type of behaviour is selected to represent that a transition belonging to *E* is selected. If system is in location *Off* and the condition guard (upper limit and lower limit for water level) becomes true, then the system transits to the new mode at location *On*.

However, to achieve proper sulfide control, the behaviour of the controlled pump station at BT needs to be modelled as a controlled hybrid automaton, dissimilar to autonomous hybrid automata. To manipulate the BT SPS operation, two states are defined for this SPS: BT_ON and BT_OFF. State BT_OFF is the default state, in which the BT pump station is turned off. State BT_ON is triggered when any pump stations in the downstream network is turned on. In this state, the BT pump station is turned on, to ensure that fresh sewage delivered by downstream SPSs is mixed with $Mg(OH)_2$-containing sewage. When turned on, the outflow from BT is manipulated such that the BT flow is 0.65 times that of the maximum flow of the operational SPSs. The factor 0.65 was chosen based on the ratio between the average daily sewage flow from BT and the total average daily sewage flow from the downstream pumping stations. A ratio much higher than 0.65 was found to lead to the quick depletion of sewage in BT, reducing the availability of $Mg(OH)_2$-containing sewage for network-wide control. In contrast, a ratio much lower than this results in the accumulation of $Mg(OH)_2$-containing sewage in BT, not being used for network-wide pH control. It is worth to note that BT is controlled as specified above only when the water level in BT is within its absolute lower and upper limits, being 10% and 80%, respectively. The BT pump station is forced to stop when the water level is less than 10%, and forced at a flow of 12,200 m^3/d to operate when it is higher than 80%.

Mathematically, the transition between the two states is based on their conditions *Inv* as described above. For example, the transition between BT_ON=$\{q_1,v_1,t_1\}$ and BT_OFF=$\{q_2,v_2,t_2\}$ (v is the BT flow) expresses that when the system is in the state of BT_ON, if all pump stations downstream are turn off, then the system transits to the BT_OFF state, which initializes the continuous variable v according to the relations *Jump*.

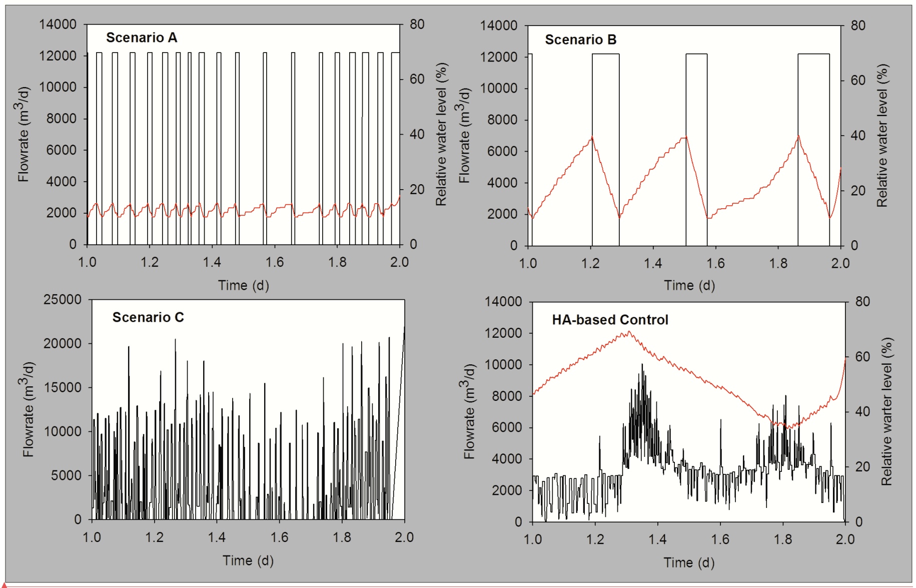
Simulation studies

To test the control methodology through a simulation study, the Tugun-Elanora sewer network was modelled using SeweX model, which is a dynamic mathematical model for the simulation of physical, chemical and biological processes in sewer systems (Sharma et al. 2008). The model predicts both the time and spatial variations of the main wastewater quality parameters including various organic and inorganic carbonaceous, nitrogenous and sulfurous compounds in both the liquid and gas phases. The biological processes modelled include carbon, sulfur and nitrogen conversions under aerobic, anaerobic and anoxic conditions occurring in sewer biofilms and in the bulk liquid. The chemical processes considered include e.g. sulfide oxidation, precipitation reactions, and acid-base systems. pH calculation is achieved based on charge balances. The mass transfer of H_2S, O_2 and other volatile compounds is also modelled. To run the model, the sewer system characteristics (network layout, diameter, lengths and slopes of pipes, and pump station information) were provided by the operators. The wastewater composition and hydraulic data were collected from the network through on-line monitoring and manual sampling and off-line chemical analysis, as previously described in Sharma et al. (2008).

Control performance is accessed by comparing the HA-based network control with two scenarios using the classical level-based control of the BT SPS and one other scenario without any wastewater retention in the BT. The two level-based control strategies are characterised by duty level at 15% (A) and at 40% (B), respectively, of the total wet well volume of BT. In both cases, the lower limit of the water level was 10% of the total wet-well volume. The 'no retention' scenario implies that the outflow is always equal to the inflow, leading to no wastewater storage in BT (C). The $Mg(OH)_2$ dosing rate to the inflow to the BT was the same for all scenarios, and hence the difference in performance would be solely due to the BT operation.

Control performance and results

For a typical pump station, a pump event occurs when the water level in the wet well reaches the pre-specified level (duty level, e.g. 15% in Scenario A, 40% in Scenario B for BT) and stops when the level gets to the lower limit. As can be seen in Figure 3, when level control was applied, sewage was pumped from the BT at very high flow rate (about 12ML/d) in a few pump events per day (17-18 for Scenario A, 3-4 for Scenario B). To further illustrate the efficiency of HA-based control, a scenario with no retention time at BT (Scenario C) was also simulated showing semi-continuous flowrate. On the contrary, flow



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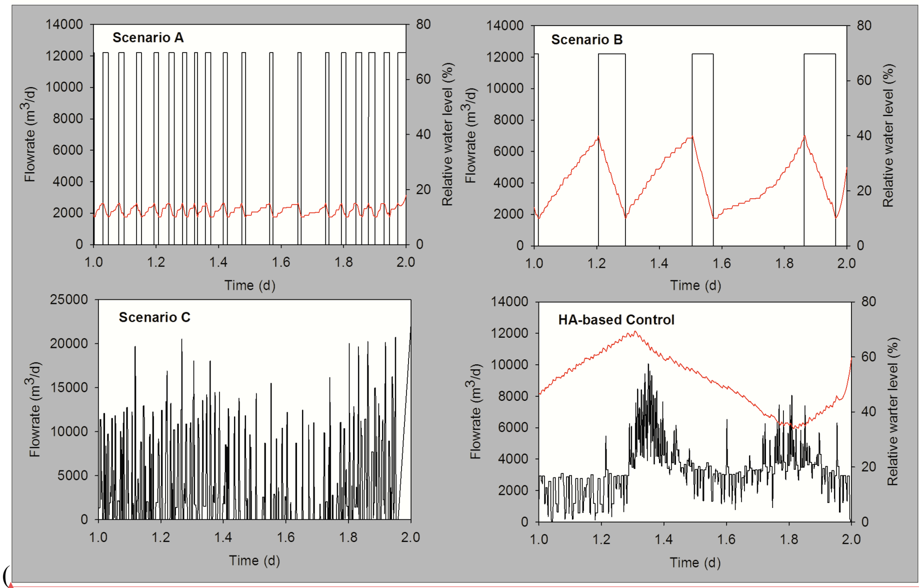
from BT fluctuated largely during the HA-based control



(Figure 3), with the flow adjusted based on the abovementioned rules.

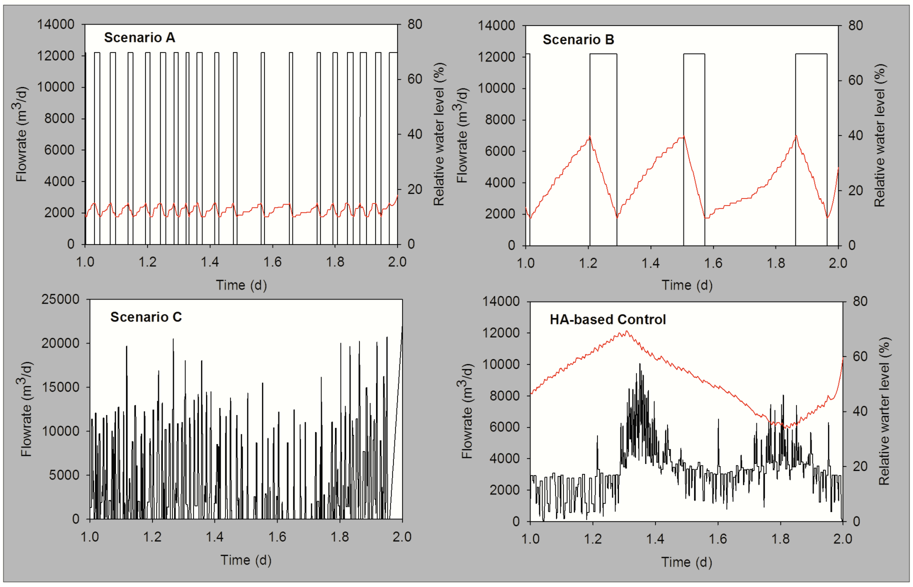


Figure 3. Pump events and water levels in Scenarios A, B, C and with HA-based control

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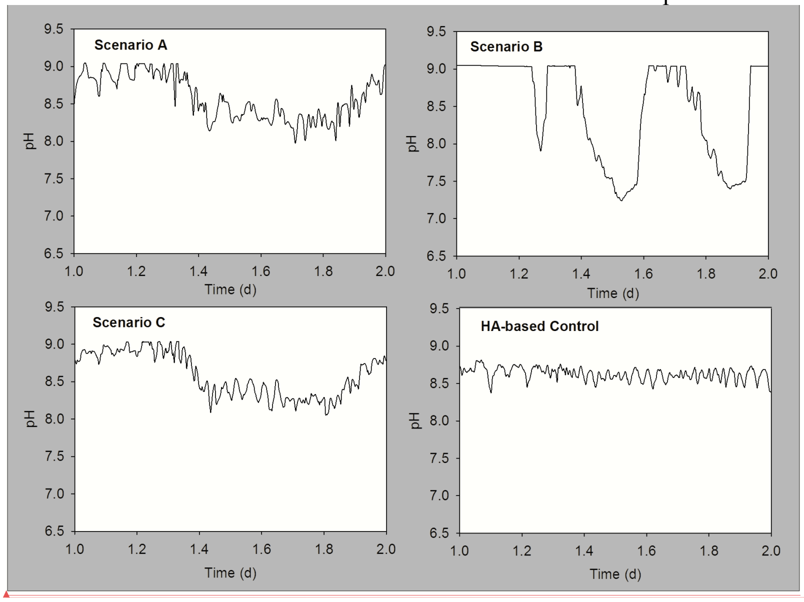

To illustrate the performance of the different control strategies, the pH profiles at the end of the network are presented in Figure 4, which shows that HA-based control achieves the most stable pH when compared with other three scenarios. A similar pH control performance was observed throughout the whole network, with HA control keeping pH above 8.5 at all locations and all time.

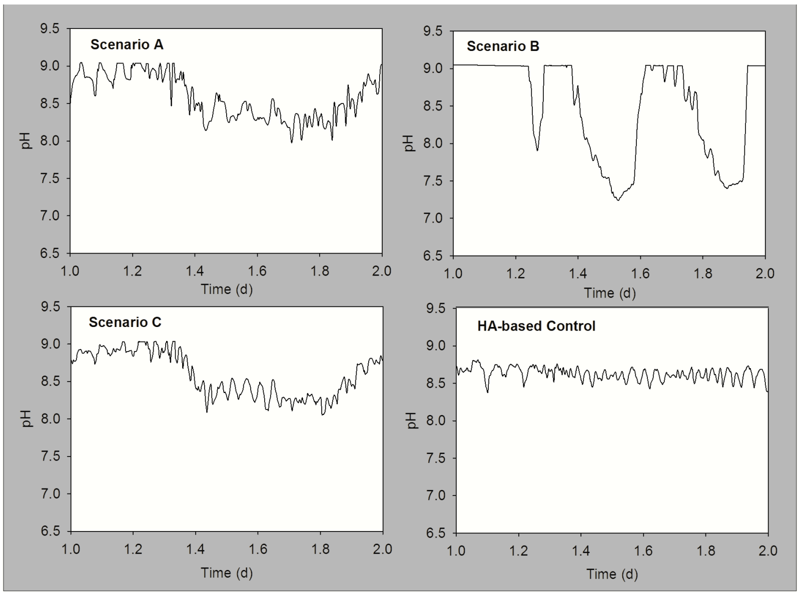

Figure 4. pH at the end of the network in Scenarios A, B, C and with HA-based control

The dissolved hydrogen sulfide (i.e. H_2S, which is a fraction of the total dissolved sulfide) concentration at the end of the network is shown in Figure 5. Results clearly show that the

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HA-based control strategy achieved stable H_2S concentrations at low levels (0.1-0.3 mgS/L) in the entire network. In comparison, significant H_2S peaks (up to 1.5 mgS/L) existed in all other three scenarios. The reduced H_2S concentration is expected to significantly reduce odour and corrosion problems at the inlet of the WWTP.

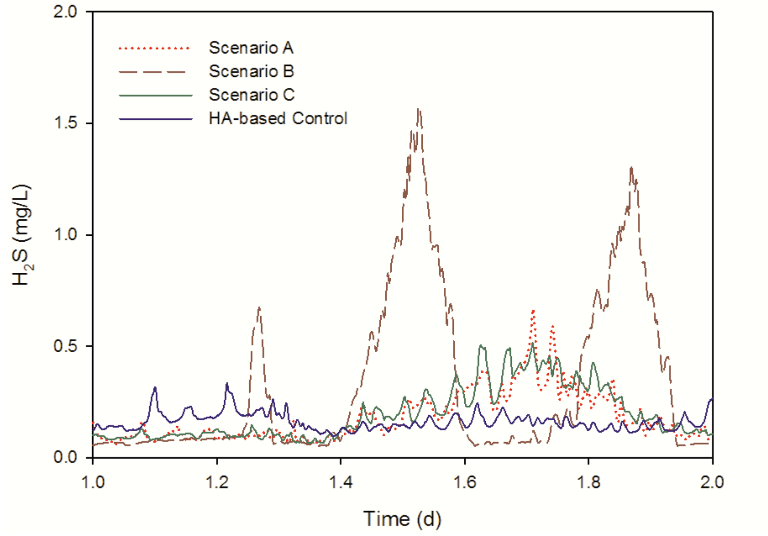
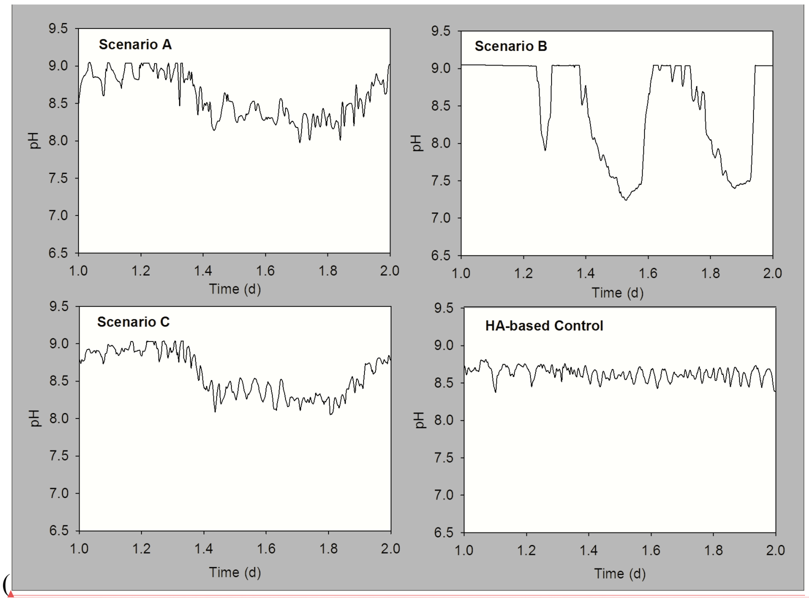


Figure 5. H_2S in sewage at the end of the network in all the four simulated scenarios.

Discussion

HA-based control achieved a very stable pH at the discharge, with an average level of 8.7 and a standard deviation of 0.08



(Figure 4). This is due to the accurate control of the BT operation by the HA, which provides proper flow to inject the $Mg(OH)_2$-containing wastewater into flows delivered by the

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downstream SPSs, while minimising the amount of sewage with $Mg(OH)_2$ pumped, which can then be further used for control in the coming period. On the contrary, the other three strategies showed much poorer performance. pH level was above 8.7 in periods when the BT SPS was operated at a high flow. However, pH decreased sharply in periods when the BT SPS was switched off or delivering a low flow rate, reaching levels below 7.5 in some cases. This results from the fact that the level-based control strategy does not consider the operation of the downstream SPSs. Hence, when the downstream wastewater enter the main pipe and the BT is off, pH in sewer network decreases because the fresh sewage from the side-streams is not mixed with chemical-containing sewage.

The present work is the first attempt to use an online control system for the optimization of chemical dosing for sulfide control in sewer networks. Both autonomous and controlled pump stations were modelled as hybrid automata, allowing the proper description of hybrid behaviours and coordination of pump stations for sewer network control. The methods proposed can be extended to more complex scenarios. This case study focuses only on the control of one pump station, although the features of the HA would allow the application of the proposed methodology to more complex sewer networks, with several SPS being controlled or the chemical dosing rate being dynamically adjusted. Additionally, the current approach is not only valid for alkali dosing for pH elevation, but also for iron salts dosing, which remove sulfide from the sewage by precipitation.

CONCLUSIONS

A methodology to control chemical dosing for sulfide mitigation in sewer networks was successfully developed based on hybrid automata, which coordinates autonomous (autonomous pump stations) and controlled hybrid automata (controlled pump stations) to allow more effective control of sulfide on one hand and avoiding chemical over-dosing on the other. Simulation study results showed that the proposed method can achieve stable pH and H_2S control than the currently used level-based control. This study further demonstrated the potential of network-based chemical dosing control.

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