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

Yiqi Liu, Ramon Ganigué, Keshab Sharma and Zhiguo Yuan

ABSTRACT

Chemicals such as magnesium hydroxide ($Mg(OH)_2$) 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 automata-based (HA-based) control method is proposed in this paper to coordinate sewage pumping station operations by considering their states, thereby ensuring suitable chemical concentrations in the network discharge. The performance of the proposed control method was 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 suggested that the HA-based control strategy significantly improved chemical dosing control performance and sulfide mitigation in sewer networks, compared to the current common practice.

Key words | chemical dosing control, hybrid automata, sewer corrosion, sewer network, sulfide control

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INTRODUCTION

Sulfide is a major concern in sewer systems due to pipe corrosion, health hazards and odor 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 residing in sewer biofilms and sediments. This results in pipe corrosion and odor 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, lower chemical consumption and/or improved performance. Despite this fact, few studies have focussed on sewer network control (Bentzen *et al.* 1995; Mathioudakis *et al.* 2006). Mathioudakis and co-workers (Mathioudakis *et al.* 2006) proposed the continuous addition of nitrate at a constant rate at a few points to mitigate the 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 networks manifest complex behavior, 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

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system behavior. One potential way to address this problem is to transform hybrid systems to pure continuous or discrete systems (Tiwari & 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 characterization of interactions between continuous dynamics and discrete events. 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 & O'Young 2008; Uzam & 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 was 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 were modeled using a form of transition diagram dialect similar to state charts, while the continuous changes were modeled using differential equations.

HYBRID AUTOMATA-BASED (HA-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 variation of variables on 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 labeling 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 (WWTPs). 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 modeled 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 behavior of sewer networks. Chemical dosing in such systems can be controlled using a hybrid automaton, which can prevent wastewater slugs from reaching 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 Figure 1 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*) $\dot{x} = inflow(t)/S$, where S is pump station wet well

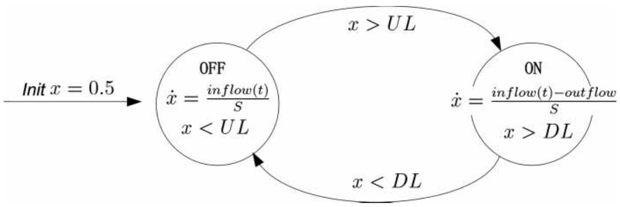

Figure 1 | Pump station autonomous hybrid automaton.

area, t is the time, and *inflow* is incoming flow into the pump station. In control mode ON, the pump station is on, and the water level falls or rises according to the Flow condition $\dot{x} = (inflow(t) - outflow)/S$, where outflow is constant due to constant pump speed operation. In this example, initially, the pump station is off and the initial 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.

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 behavior will occur once the 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 modeled 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 depends on, not only the water level in the wet well, but also the behaviors of other autonomous hybrid automata. For instance, a change of state in a controlled hybrid automaton 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 2. 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 2,394 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

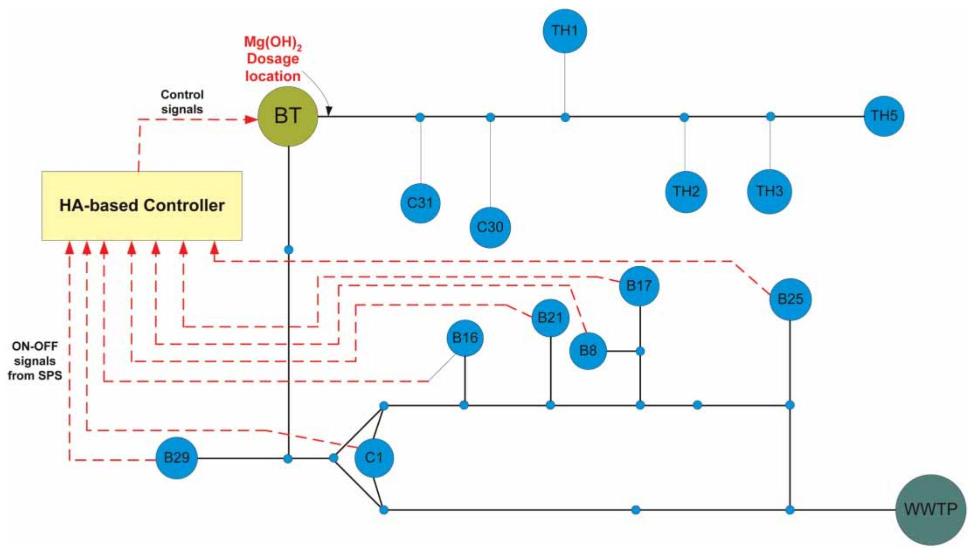

Figure 2 | Schematic of the Tugun-Elanora sewer network.

pump station is 3,500 m^3/d with a maximum pump capacity of 14,700 m^3/d. Downstream to the BT pump station, C1 is the largest pump station, which carries an average daily flow of 3,500 m^3/day with a maximum pump capacity of 15,400 m^3/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 four times a day with the pump time ranging from 1 hour in the morning to 4 hours in the evening. The average daily flow of B21, B29 and B17 ranges from 800 to 1,100 m^3/day. In contrast to these large pump stations, the remaining pump stations deliver low flows (ranging from 20 m^3/d to 750 m^3/d). All SPSs, including BT, are currently controlled based on water levels in the respective wet wells.

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). To raise sewage pH, $Mg(OH)_2$ 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 a 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

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 odor hot spot.

Given the large volume of the BT, this work focused on the manipulation of the BT outflow based on the HA control methodology. The flow rate of the BT (variable speed pump) was controlled based on the operational states (ON or OFF) of the downstream SPS. ON/OFF signals of these SPSs were 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 was not considered in this study for reasons of simplicity.

The autonomous transition (level-based pump stations) can be modeled as autonomous hybrid automata with two possible modes, *On* and *Off*. For each mode, the domain in which the mode is valid needs to be specified. When water level reaches the boundary of the domain, a new type of behavior is selected to represent that a transition belonging to E is selected. If the 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 behavior of the controlled pump station at BT needs to be modeled as a controlled hybrid automaton, dissimilar to autonomous hybrid automata. To manipulate the BT SPS operation, two states were defined for this SPS: BT_ON and BT_OFF. State BT_OFF was the default state, in which the BT pump station was turned off. State BT_ON was triggered when any pump station in the downstream network was turned on. In this state, the BT pump station was turned on, to ensure that fresh sewage delivered by downstream SPSs was mixed with $Mg(OH)_2$-containing sewage. When turned on, the outflow from BT was manipulated such that the BT flow was 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 resulted in the accumulation of $Mg(OH)_2$-containing sewage in BT, not being used for network-wide pH control. It is worth noting that BT was controlled as specified above only when the water level in BT was within its absolute lower and upper limits, being 10% and 80%, respectively. The BT pump station was forced to stop when the water level was less than 10%, and forced to operate at a flow of 12,200 m^3/d when levels were higher than 80%.

Mathematically, the transition between the two states was based on their conditions *Inv* as described above. For example, the transition between BT_ON $= \{q_1, v_1, t_1\}$ and BT_OFF $= \{q_2, v_2, t_2\}$ (where q indicates whether the pump station is running or not, in what state and what flow the pump station should hold, v is the BT current flow and t is the time) expresses that when the system is in the state of BT_ON, if all pump stations downstream are turned off, then the system transits to the BT_OFF state, which initialises 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 modeled using the 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 modeled 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 and pH calculation in the model is achieved based on charge balances. The mass transfer of H_2S, O_2 and other volatile compounds was also modeled. To run the model, the sewer system characteristics (network layout, diameter, length and slope 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 was assessed by comparing the HA-based network control with two scenarios using the classical level-based control of the BT, and one other scenario without any wastewater retention in the BT. The two level-based control strategies were characterized by duty level at 15% (A) and at 40% (B), respectively, of the total wet well volume of the BT. In both cases, the lower limit of the water level was 10% of the total wet-well volume. The "no retention" scenario implied that the outflow was always equal to the inflow, leading to no wastewater storage in the BT (C). The $Mg(OH)_2$ dosing rate at the inlet of the BT was the same for all scenarios, and hence the difference in performance was 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 the 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 about 12 ML/d (the maximum pump capacity) in a few pump

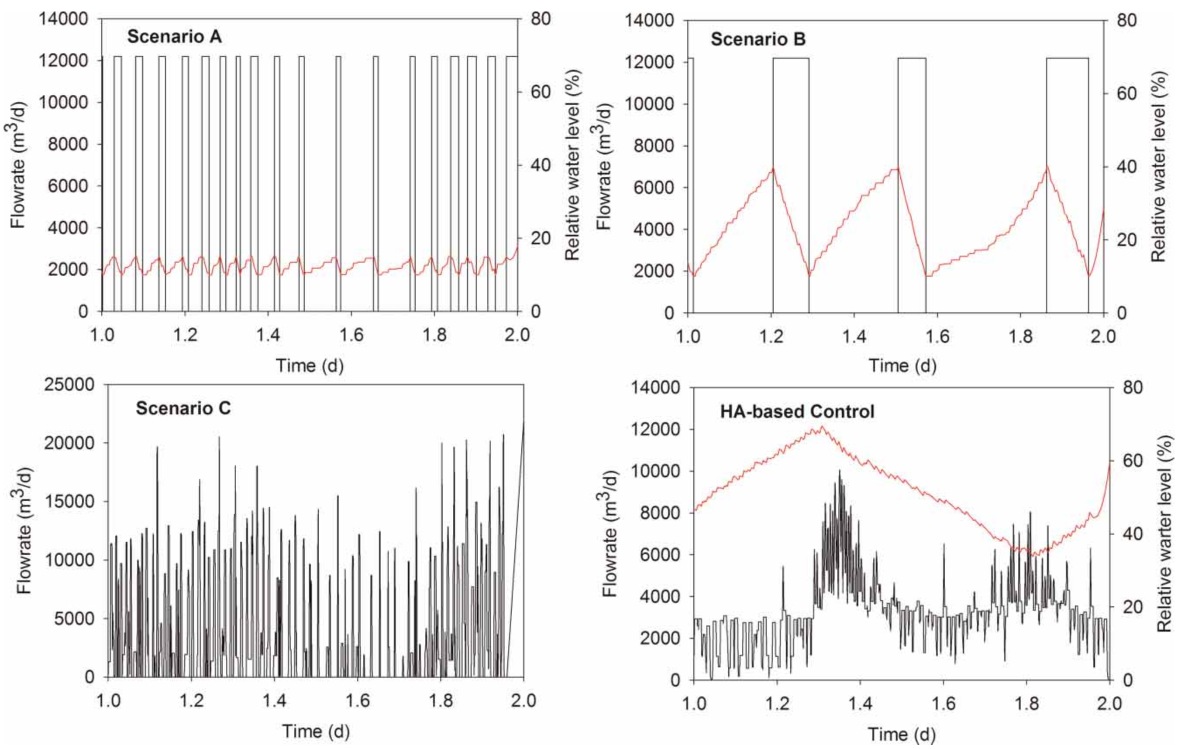

Figure 3 | Pump events and water levels in Scenarios A, B, C and with HA-based control.

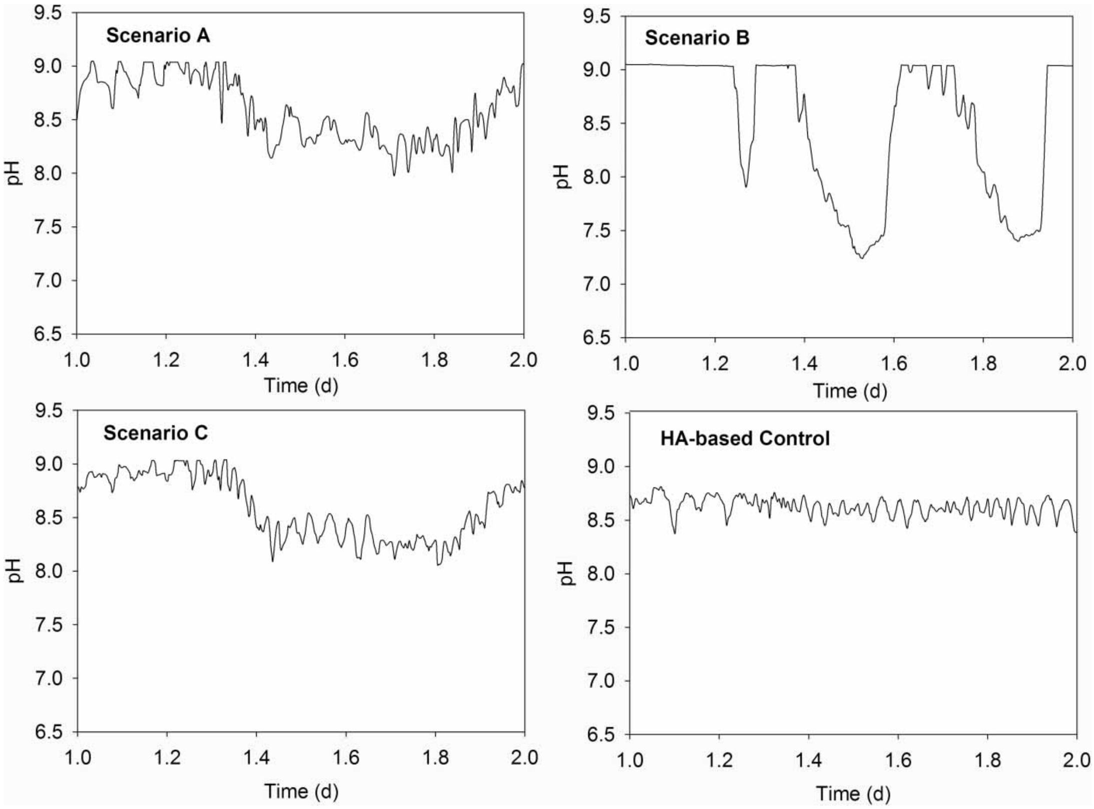

Figure 4 | pH at the end of the network in Scenarios A, B, C and with HA-based control.

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 the BT (Scenario C) was also simulated showing a semi-continuous flow rate. On the contrary, flow from the BT fluctuated greatly during the HA-based control (Figure 3), with the flow adjusted based on the above-mentioned rules.

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 achieved the most stable pH when compared with the 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 at all times.

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 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

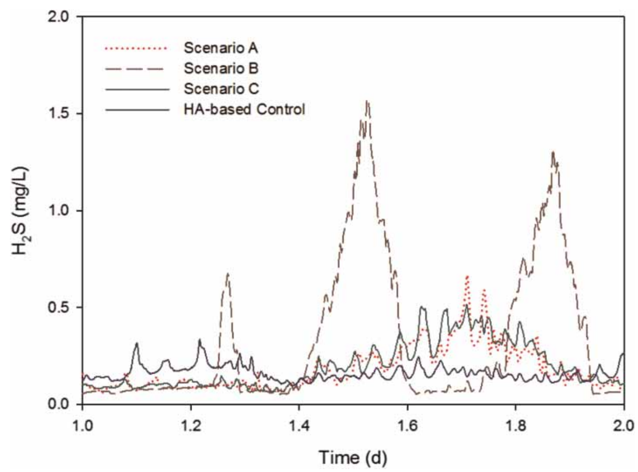

Figure 5 | H_2S in sewage at the end of the network in all four simulated scenarios.

H_2S concentration is expected to significantly reduce odor and corrosion problems at the inlet of the WWTP.

Discussion

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

0.08 (Figure 4). This was due to the accurate control of the BT operation by the HA, which provided appropriate flow to inject the $Mg(OH)_2$-containing wastewater into flows delivered by the downstream SPSs, while minimizing the amount of sewage with $Mg(OH)_2$ pumped, which could then be further used for control in the coming period. On the contrary, the other three strategies showed much poorer performance, with a pH level 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 resulted from the fact that the level-based control strategies did not consider the operation of the downstream SPSs. Hence, when the downstream wastewater entered the main pipe and the BT was off, the pH in the sewer network decreased because fresh sewage from the side-streams was not mixed with chemical-containing sewage.

The present work is the first attempt to use an online control system for the optimisation of chemical dosing for sulfide control in sewer networks. Both autonomous and controlled pump stations were modeled as hybrid automata, allowing the proper description of hybrid behaviors and coordination of pump stations for sewer network control. The methods proposed can be extended to more complex scenarios. This case study focused 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 SPSs 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 coordinated autonomous hybrid automata (autonomous pump stations) and controlled hybrid automata (controlled pump stations) to allow more effective control of sulfide on the one hand and to avoid chemical over-dosing on the other. Simulation study results showed that the proposed method can achieve more stable pH and H_2S control than the currently used level-based control. This study further demonstrated the potential for network-based chemical dosing control.

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