

Sewer Corrosion and Odour Research Linkage Project



Sub-Project 5: Online control of chemical addition for the control of H₂S, methane and odorous compounds in sewage and sewer air

FINAL REPORT

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Executive Summary

This research report was prepared by the Sub-project 5 (SP5) of the Sewer Corrosion and Odour Research (SCORe) project, Advanced Water Management Centre at The University of Queensland (AWMC-UQ). The research study on “Online control of chemical addition for the control of H₂S, methane and odorous compounds in sewage and sewer air” was undertaken by the SCORe SP5 team of AWMC-UQ in conjunction with Sydney Water Corporation, Melbourne Water, Gold Coast City Council, SA Water, Barwon Water, South East Water, United Water International and WA Water Corp during June 2008 and December 2014.

The cash budget was \$1,240,669 including \$400,000 cash contribution from the ARC. Additionally, all partners involved including the University also made substantial in-kind contributions to the sub-project.

The sub-project aimed to develop reliable and robust on-line control methodologies and algorithms to dynamically manipulate the dosage of chemicals including oxygen, nitrate, magnesium hydroxide, ferrous and/or ferric ions and other chemicals identified by SP6 to achieve satisfactory control of the production/emission of H₂S and other compounds of concern with minimized consumption of chemicals.

The sub-project delivered strong outcomes with all milestones achieved, in addition to generating some related knowledge about the sewer modelling and prediction as an extra. Novel findings, in terms of control methodology and field validation, have been published in top international journals. The practical outcomes generated are being applied by the Australian industry partners for the management of their sewer systems to prevent and mitigate harmful gaseous compounds.

The main outcomes of the project are summarized below.

- ***Industry survey of chemical dosing in sewers***

Controlling sulfide (H₂S) production and emission in sewer systems is critical due to the corrosion and malodour problems that sulfide causes. Chemical dosing is one of the most commonly used measures to mitigate these problems. Many chemicals have been reported to be effective for sulfide control, but the extent of success varies between chemicals and is also dependent on how they are applied. This industry survey summarised the current practice in Australia with the view to assist the water industry to further improve their practices and to identify new research questions. Results showed that dosing is mainly undertaken in pressure mains. Magnesium hydroxide, sodium hydroxide and nitrate are the most commonly used chemicals for sewers with low flows. In comparison, iron salts are preferentially used for sulfide control in large systems. The use of oxygen injection has declined dramatically in the past few years. Chemical dosing is mainly conducted at wet wells and pumping stations, except for oxygen, which is injected into the pipe. The dosing rates are normally linked to the control mechanisms of the chemicals and the dosing locations, with constant or profiled dosing rates usually applied. Finally, key opportunities for improvement are the use of mathematical models for the selection of chemicals and dosing locations, on-line dynamic control of the dosing rates and the development of more cost-effective chemicals for sulfide control.

- ***Design of control methodologies for single pipes***

The traditional way of chemical dosing based upon flow or predefined profiles usually lead to over or under dosing. Due to the dynamic plug flow and biological activities in sewers, online control can potentially achieve better performance and reduce the chemical consumptions. This task designed control methodologies for four commonly used chemicals: O₂, NO₃⁻, Fe²⁺/Fe³⁺, Mg(OH)₂. Factors including dynamic flow, hydraulic retention time, different reactions (oxidation, precipitation, biological inhibition) were considered with the objective to reach a minimal level of sulfide in sewage at the discharge point of a rising main pipe. In most cases, feed forward control was the primary approach although feedback control can be added to fine tune dosing rates, further improving the control performance. To assist the feed forward control, a specified algorithm (ARMA) was developed to predict the future flow in sewers. The dosage was thus determined by the flow, biological sulfide production (primarily related to the hydraulic retention time), and the chemical working mechanisms.

- ***Control design for sewer networks***

The development of control methodologies for network-wide sulfide control has been explored through desktop studies, using the SeweX model as a simulation platform. The findings of the desktop studies are summarized to establish general guidelines for network-wide control system design. It is proposed to establish potential hot-spots using modelling tools in a sewer network, which can be further confirmed with field sampling. If the number of corrosion and odour hot-spots is limited, and/or these are geographically isolated, it is recommended to undertake the control on a local basis. This can be achieved using the control methodologies developed for single pipes. On the other hand, if many hot-spots scattering around the network were identified, a holistic network approach must be adopted. Network control can only be done using conservative chemicals (i.e. iron salts and magnesium hydroxide). The dosing location should be arranged at the sewer pipes with large flow to minimize the dilution. Overall, dynamic control is critical for the ensured performance.

- ***Field-site validation of the control algorithms***

To validate the control methodologies developed for the commonly used chemicals by water industry, three case study were carried out at real sewers. The dosing was implemented using the developed algorithms by writing it up in either a PLC program (magnesium hydroxide and iron salts) or in forms of optimized daily dosing profiles (nitrate). The achieved sulfide concentration was then compared with the baseline, obtained using the existed dosing controls. Overall, the developed methodologies using dynamic control achieved better performance while reducing the chemical consumption. Thus, the control algorithms were successfully validated.

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1. INTRODUCTION

Sewer networks for the transport of wastewater (sewage) are among the most important infrastructure elements of modern cities, and their establishment has been achieved through the continuous public investment for more than a century. The total asset value of these networks is estimated to be about one trillion dollars in the USA and \$100 billion in Australia (Brongers et al., 2002). The production of H₂S is a critical problem in sewer systems due to the corrosion of sewer pipes and the generation of malodors. The main strategy adopted to date to mitigate this problem has been the dosage of chemical products to wastewater to control H₂S generation or its transfer to sewer air. Among the most used products one can find air/oxygen, nitrate, magnesium hydroxide or iron salts. Besides, the effectiveness of other chemicals such as nitrite and other biocides has been reported recently.

The dosing rates of chemicals are important as they have not only major influence on the effectiveness of the strategies, but also significant cost implications. They also potentially affect the performance of the downstream wastewater treatment plants particularly their biological nutrient removal performance. However, finding the optimal dosing strategy is far from being straightforward especially for large sewer networks. There is at present clearly a lack of knowledge and expertise in this area. Indeed, no information could be found in literature on this topic.

This project (SP5) addressed this shortfall through an in-depth and detailed study of online control methodology for the widely-used chemicals, which was also validated in real sewers. These include industry survey of chemicals across Australia, the design of control strategies for mostly typical chemicals. The designed strategies were then implemented and verified in real sewer systems.

1.1 Background

Sewer systems are a truly dynamic entity. They are subject to dynamic conditions in terms of both hydraulics and wastewater compositions. The flows typically display diurnal variations (lower flow over night), resulting in a wide range of hydraulic retention time (HRT) of wastewater in sewer systems. Wastewater composition also varies considerably with time due to the in-sewer biotransformation, seawater or ground water infiltration, and/or the dynamic discharge of industrial wastewaters. The intermittent operation of pumping stations adds further complexity to the sewer dynamics. These variations cause both spatial and temporal variations of sulfide production (Figure 1). A rising main could produce sulfide to a level of as high as 10 – 20 mgS/L (overnight and in the early morning) or as low as below 2-3 mgS/L when wastewater flow peaks leading to a short HRT. Similar variations in the production of methane and other compounds of concern have also been observed.

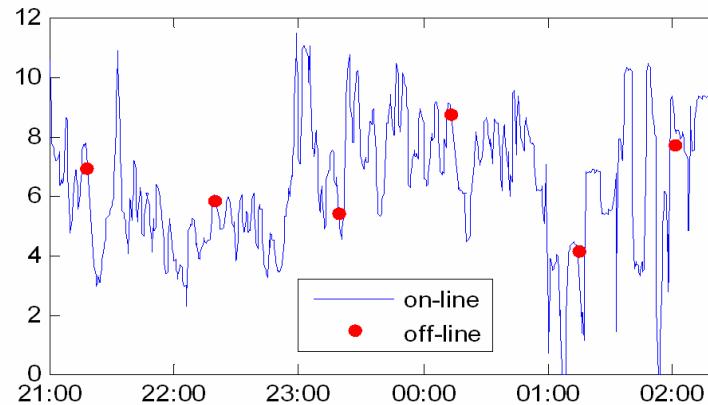


Figure 1-1. Variation of dissolved sulfide concentration at the inlet of the Tugun-Elanora wastewater treatment plant of GCW, measured using the s::can UV/VIS spectrolyser as an on-line sulfide sensor and also using off-line laboratory analysis.

The dynamics in sulfide production has to date not been taken into consideration in determining the rate of chemical dosage for H₂S control. Constant or flow-paced dosage rates are widely applied leading to over dosage during periods with low levels of sulfide production, and under dosage during some other periods. Figure 2 compares the effectiveness of three nitrate dosing strategies on sulfide control in a single rising main system. The experiments were carried out by the University of Queensland under the previous ARC project with Gold Coast Water and Sydney Water Corporation (known as the ARC 1 project). The rising main had a hydraulic retention time ranging between 2 – 10 hours. Nitrate was added at the beginning of the pipe. Very similar amounts of nitrate were added in all three cases. The sulfide data presented was measured with an on-line s::can UV/VIS spectro-analyser, which produced data with excellent quality for process control.

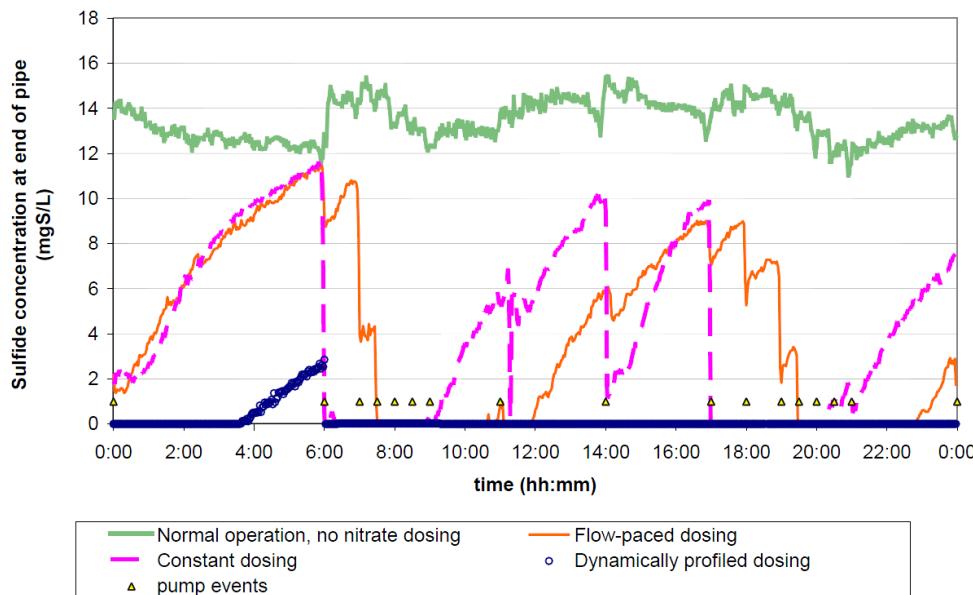


Figure 1-2. Comparison of several strategies for nitrate dosing to a rising main: effluent sulfide concentration profiles with various nitrate dosage strategies. Similar amounts of nitrate were added in all cases, but different levels of sulfide control were achieved.

While both constant and flow-paced dosing significantly reduced the average sulfide concentration at the end of the pipe, sulfide level varied considerably over a day, peaking in both cases at 9 – 12 mgS/L in the early morning and mid-afternoon, indicating under dosage in these periods (confirmed by online nitrate measurement, data not shown). In the periods when sulfide was successfully controlled to below detectable levels, significant amounts of nitrate was discharged (data not shown), leading to wastage of chemicals. In contrast, the effluent sulfide level was consistently controlled to below 2-3 mgS/L (not detectable during most of the time) with a ‘dynamically profiled dosing strategy’. Further tests showed that, with this strategy, much better sulfide control than the cases of constant or flow-paced dosage could be achieved even when the amount of nitrate was reduced considerably, despite of the fact that the strategy could still be optimized. The study clearly shows the potential benefits of on-line controlled chemical dosages in terms of both performance and cost savings.

1.2 Objectives

The key objectives of this sub-project are as the following.

1. To develop on-line control methodologies and algorithms to dynamically manipulate the dosage of chemicals to achieve satisfactory control of H₂S and other compounds of concern with minimised consumption of chemicals.
2. To establish guidelines for the design and development of on-line control in sewer networks.
3. To validate and demonstrate the effectiveness and reliability of online control algorithms in real sewers.

1.3 Outline of report

The report is organized as follows.

First, the overall project is described briefly. This is followed by a summary of findings of the various research activities undertaken at Advanced Water Management Centre, the University of Queensland. These include first an industry survey of the chemicals used by water industry to control sulfide in their sewerage systems. According to the survey results, control strategies were designed for the four most frequently used chemicals, i.e. oxygen, nitrate, ferrous/ferric salts and magnesium hydroxide. Furthermore, a network wide control guideline was developed for sulfide control at bigger scales. These strategies were validated in four field trials by implementing the control algorithms in real sewers.

During the course of the present work, about 20 Quarterly Project Reports, 8 Detailed Technical Sub-project Research Reports were delivered. These contain all the technical details of the project evolution during the 4 years. A summary of the main findings of this project are also available through the SCoRe project knowledge management system.

2. PROJECT OVERVIEW

SP5 research activities mainly encompassed an industry survey, the design of control algorithms, their evaluation in desktop simulation studies and case studies at the various field sites around Australia. A summary of all the research activities leading to these substantial research outcomes are summarized below.

Activity 1: Industrial survey

The industrial survey was carried out to determine what chemicals are nowadays being applied to mitigate hydrogen sulfide production in Australia, how this dosing is being controlled, and where these actions are taking place. Therefore, the first activity of this sub-project was focused on cataloguing the different field sites where chemical dosage is being carried out, together with their main characteristics. The survey aimed to identify the different chemicals used to prevent/reduce H₂S formation/transfer and its dosing control methodology. The survey also intended to find out what dosing equipment is available on each site, as well as the existing instrumentation for on-line process monitoring and control. In addition, the main characteristics of the sewer and wastewater were also collected and analyzed for some sites. The control methodologies were analysed and served as a starting point for further optimisation of the chemical dosing (Activity 2). This information was also used to identify the most representative sites for the validation of the control strategies in Activity 4.

Activity 2: Design of control methodologies for single pipes

The highly dynamic nature of sewer flow and sulfide concentration within a time scale of minutes to hours make on-line control essential for chemical dosing. However, the implementation of common feedback controls is difficult because sewers are very different to the biological reactors used for wastewater treatment due to the plug flow feature. There is typically a considerable physical distance/time delay between the location/time of ‘action’ and the location/time that the ‘impact’ of control would be seen.

Thus, feed-forward control based on the on-line measurement of wastewater flow rates and the key wastewater parameters (such as dissolved sulfide concentration), would be more appropriate. Besides, from field measurements, and using a full model of a sewer network, one can also predict the daily or weekly chemical dosage profiles without further requirement for on-line instrumentation. Activity 2 was therefore focused on the design of control methodologies for the dosage of the commonly used chemicals (O₂, NO₃⁻, Mg(OH)₂ and Fe²⁺/Fe³⁺) and other effective chemicals identified by SP6 (e.g. FNA and caustic shock) in single pipes (whether rising mains or gravity sections).

The control system provided by the chemical supplier, together with the information obtained on the surveys was used as a starting point when designing dosing strategies. Besides, the specificity of each of these chemicals was taken into consideration. Trade-offs between degree of performance improvement and level of sophistication of control systems were examined. Preference was given to simple technologies, which, while may not be optimal, will deliver good savings. In many cases, the UQ SeweX model was used to assist with the design and preliminary assessment of these strategies.

In some cases, the dosage could be controlled through implementing pre-determined dynamic dosage profiles. In this case, there will be no need for continuous use of on-line sensors. This

could be particularly useful for smaller systems, where the use and maintenance of on-line sensors is not justifiable based on cost and time requirements.

Activity 3: Control design for sewer networks

Sewer systems are composed of pipes in a network structure, with different flows converging in a main trunk, along with the possible injection of industrial wastewaters and possible groundwater infiltration. Therefore, the design of control strategies for chemical dosing in sewer networks is a more complex and challenging task.

Activity 3 aimed to develop control methodologies for network-wide sulfide control. These methodologies include the selection of the most effective dosing location(s) in a given network by taking into consideration the specificities of the chemical(s) to be used, the identification of optimal location(s) for on-line sensors to support dynamic control of dosing rates, and the integrated use of network-wide information for control algorithm design.

This activity was undertaken based on the control design knowledge acquired in Activity 2. Given the diversity of the sewer networks, this task was carried out primarily through desktop studies on a typical sewer networks, utilising the SeweX model. The findings were then synthesized with the aim of establishing general guidelines for network-wide control system design.

Activity 4: Field-site validation of the control algorithms

Any control algorithm needs to be tested and validated prior to its applications. Activity 4 thus focused on the field trials to validate the control algorithms designed in Activity 2. The performance of the control strategy was assessed and adjusted based upon the benefits arising from its application, i.e. increased control efficiency and/or chemical savings.

The validation step was carried out at several field sites identified from the survey stage (Activity 1). In each case study, the control methodology was implemented and the success of the strategy was assessed by means of regular monitoring through sampling campaigns and on-line data collection. This activity was carried out in close collaboration with the industrial partners.

3. SUMMARY OF OUTCOMES

3.1 Industry survey of chemical dosing in sewers

The main goal of this sub-project is the design of control strategies for the optimised dosing of chemicals. However, prior to optimisation it is essential to determine what chemicals are nowadays being applied in Australia, how this dosing is being carried out and controlled or where these actions are being conducted. A survey was conducted among the industrial partners to know the state of the art of the chemical dosing in Australia.

3.1.1 Introduction

The production of sulfide is a critical problem in sewer systems due to the corrosion of sewer infrastructure and the generation of malodours (Boon, 1995; Pomeroy, 1959). Sulfide also has a detrimental effect on human health (USEPA, 1974). One of the main approaches adopted to date to mitigate such issues has been the dosage of chemicals to the wastewater (Melbourne, 1989).

Among them, the addition of air or oxygen to prevent anaerobic conditions and to oxidise sulfide to sulfate (SO_4^{2-}) has been widely used (Hvitved-Jacobsen, 2002; USEPA, 1992). Nitrate, another thermodynamically favourable electron acceptor, has also been employed over the last 70 years to prevent anaerobic conditions and thus to control odours and sulfide concentration in many environments (Bentzen et al., 1995; Bertrán de Lis et al., 2007). However, Mohanakrishnan et al. (2009) and Jiang et al. (2009) recently demonstrated that the actual mechanism leading to sulfide mitigation is the oxidation of H₂S to SO₄²⁻ via elemental sulfur by nitrate reducing-sulfide oxidising bacteria (NR-SOB).

Strong oxidants such as H₂O₂, NaOCl or KMnO₄ have also been applied for chemical sulfide oxidation (Tomar and Abdullah, , 1994; USEPA, , 1992). Another widely used strategy for H₂S mitigation is the addition of iron salts including ferrous chloride, ferric chloride and in some cases ferrous sulfate (Jameel, , 1989; Padival et al., , 1995). Ferrous ions (Fe²⁺) precipitate sulfide by forming highly insoluble metallic sulfide precipitates (WERF, , 2007). On the other hand, Ferric ions (Fe³⁺) oxidize sulfide to elemental sulfur while being reduced into Fe²⁺, which precipitates with sulfide to form ferrous sulfide precipitants (Dohnalek and Fitzpatrick, , 1983).

pH elevation is another strategy to control H₂S. A pH increase to 8.5-9, typically achieved through the continuous addition of magnesium hydroxide, prevents sulfide release to the gas phase (WERF, , 2007). A recent study showed that pH elevation to 8.5-9 diminishes sulfate reducing bacteria (SRB) activity by 30-50% (Gutierrez et al., , 2009), further enhancing the controlling effect. On the other hand, pulse addition of sodium hydroxide to increase pH to 12.5-13 for a short time (20-30 min) has been shown to inactivate SRB in the slime layer for a period of a few days to 2 weeks, effectively suppressing sulfide production (USEPA, , 1992; WERF, , 2007). The wastewater pulse or slug with high pH has to be isolated at the wastewater treatment plant (WWTP) and fed slowly into the system if it is not diluted in the collection system (USEPA, , 1992). Finally, the use of microbial inhibitors such as formaldehyde (Zhang et al., , 2008) or nitrite (Jiang et al., , 2010; Mohanakrishnan et al., , 2008) have also been proposed, successfully demonstrated at laboratory and field-scale systems and in the near future may represent a more cost-effective methods for sulfide mitigation.

While many different chemicals are being used in practice for sulfide control and widely reported in literature, the extent of their use and the way how they are applied are not well known. The present work aims to establish the state of the art of chemical dosing for sulfide control in Australia, to summarise the key experiences of industry partners, and to identify ways to improve the dosing practices. Due to its warm climate in general, sewer corrosion and odour problems are wide spread in Australia and are of major importance, and consequently sulfide control is receiving strong attention, with tens of millions spent each year. Nevertheless, it is important to note that sewer corrosion and odours are widespread problems, and chemical dosing for sulfide control has been conducted in many other countries as well, including Austria (Bertrán de Lis et al., 2007; Matsch et al., 2005), EUA (USEPA, 1992), Germany (Barjenbruch, 2003), Spain (Delgado et al., 1999) and United Arab Emirates (Vollertsen et al., 2011), among others.

The industry survey aimed to answer four main questions:

- i) what chemicals are being used or have been used in the recent past to mitigate hydrogen sulfide production in sewer systems
- ii) to what extent each chemical is being used in terms of number of sites and wastewater flows treated
- iii) where each chemical is added and
- iv) how the dosing is carried out and controlled. These dosing practices are discussed in the context of the current understanding of the mechanisms by which each chemical works and improvement opportunities are identified. Questions for future research are also raised.

3.1.2 Methodology

3.1.2.1 Industrial survey

Design of the survey.

The survey sought to identify the different chemicals dosed by the industry for sulfide control and the extent of their uses in terms of the number of locations, and the flow treated. The main characteristics of the pipes (dimensions, flow, hydraulic retention time, dosing location) where various chemicals are/were dosed were also collected. Other aspects covered by the survey included the selection or control of the chemical dosing rate, which is critical for successful sulfide control performance and costs. The survey was composed of 4 parts. Parts 1 and 2 covered general information of the systems, and specially aimed to identify the different chemical products used or in use. Part 3 targeted specific details of past and on-going sites, such as complete information of the installation and the dosing system, available instrumentation and off-line monitoring, as well as operation performance. Finally, Part 4 of the survey sought to identify dosing sites under design or construction, and collect detailed information of the site characteristics and dosing system. For further details see Appendix A.1, where the survey form is provided.

Conduct of the survey.

The survey was conducted with seven water utilities across Australia, which provide sewage services to 13 million people (60% of the total population of the country). Table 3-1 lists all

these utilities, together with their location and main climate features (obtained from the Australian Bureau of Meteorology, www.bom.gov.au).

Table 3-1. Water utilities surveyed, location and main climate characteristics of the areas

Water Utility	State	Mean minimum temperature in winter (°C)	Mean maximum temperature in summer (°C)	Annual rainfall (mm)
Allconnex Water	Queensland	9.3	29.3	1443.6
Barwon Water				
Melbourne Water	Victoria	6.5	25.3	648.9
South East Water Limited				
Sydney Water	New South Wales	8.7	25.6	1211.9
United Water International				
South Australian Water	South Australia	7.9	28.5	546.7
Water Corporation	Western Australia	8.0	30.4	734.0

After the collection and preliminary analysis of the data, supplementary information was obtained with direct enquiries to the representatives of the water utilities to clarify specific issues.

3.1.3 Results and discussion

3.1.3.1 Dosing sites

The first step of the survey was cataloguing the different field sites where chemical dosage has been or will be carried out. Results are shown in Figure 3-1.

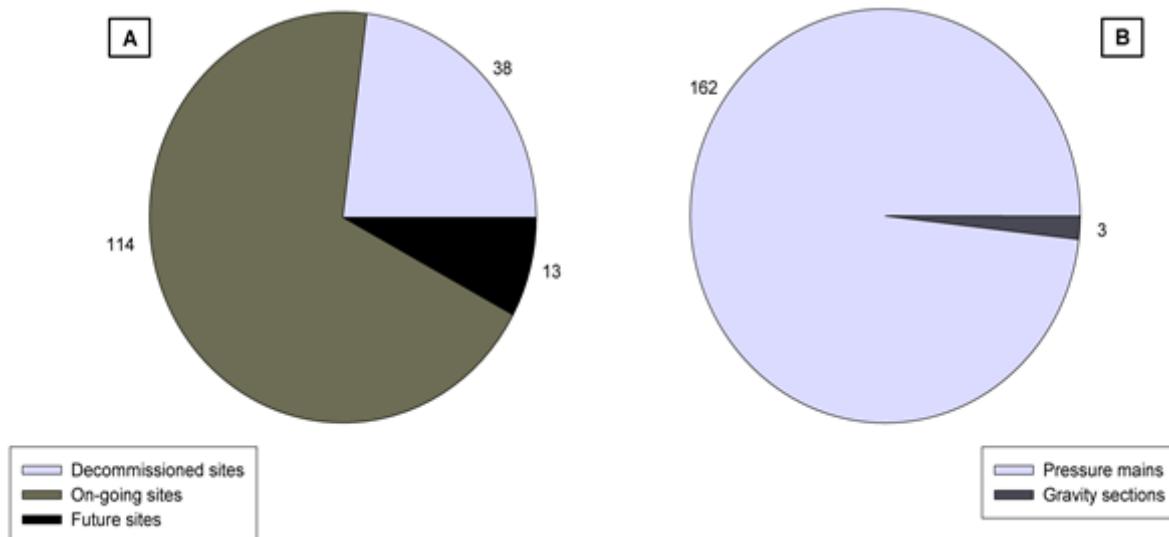


Figure 3-1. A) Status of identified sites; B) Type of pipes.

In June 2010, a total of 165 dosing sites were identified through the survey. From these, 38 sites were reported to be no longer operative (in some of these, dosing was not required anymore, while others had been decommissioned because the dosing system had been proven not to be suitable to control sulfide production/release). At the time of the survey, chemical dosing was on-going at 114 sites and a further 13 dosing sites were due to be started in the near future.

The vast majority of dosing systems were located in pressure mains (162 sites), with only three gravity sites having been dosed with chemicals. These results clearly show a preference for control in rising mains where sulfide is normally generated in relatively large quantities, thus preventing possible adverse effects of H₂S at the discharge point or in the gravity section.

Sulfide production in a sewer pipe highly depends on factors like pipe dimensions (length and diameter), sewage flow and detention time. The characteristics of the surveyed pipes are presented in Figure 3-2.

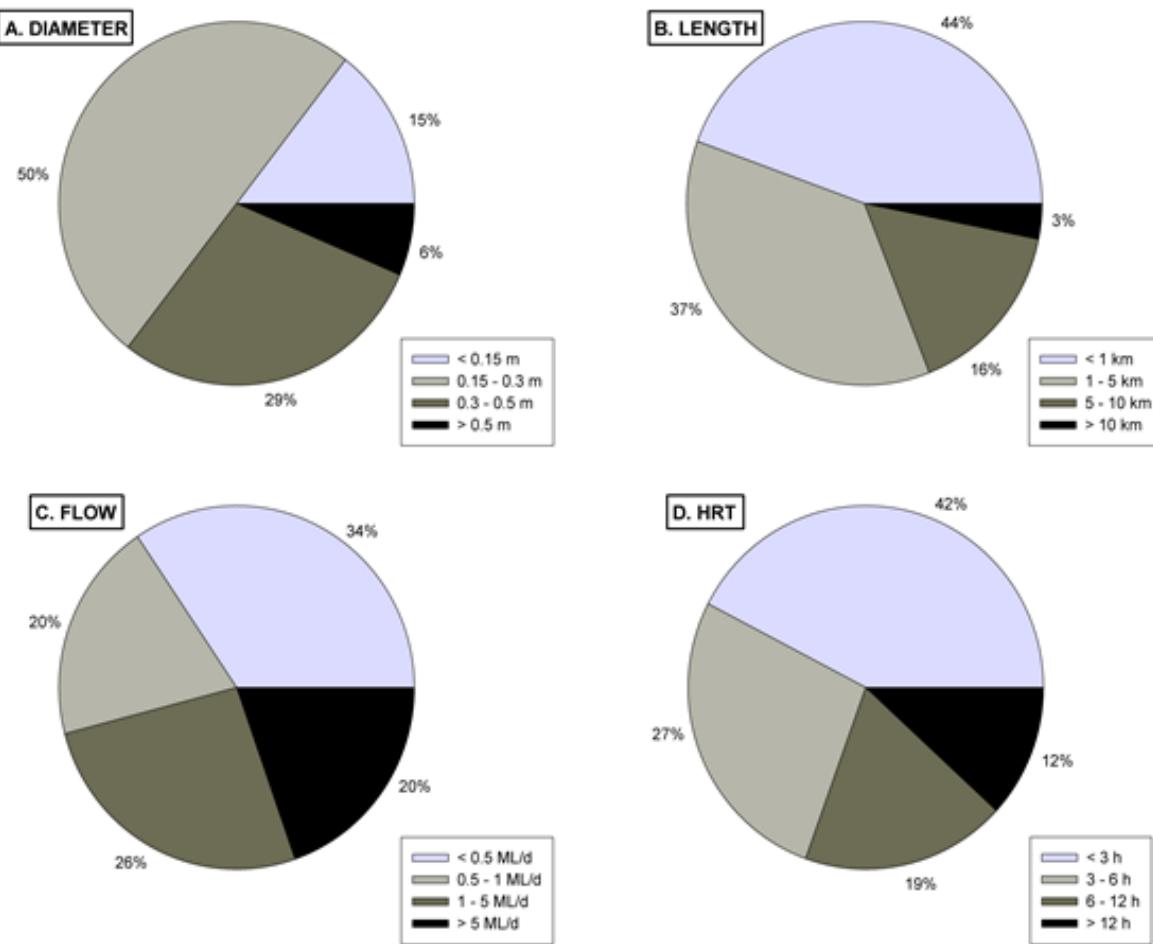


Figure 3-2. Main characteristics of the systems surveyed. A) Pipe diameter; B) Pipe length; C) Average dry weather flow (ADWF); D) Hydraulic retention time (HRT).

As can be observed in Figure 3-2.A, around 80% of the surveyed sites had pipe diameters between 0.15 and 0.5 meters, while only 6% of the sites had a large pipe diameter (> 0.5 m). 15% of the sites corresponded to very small pipes, with diameters below 0.15 m. The area to volume ratio (A/V) of a pipe is inversely proportional to the diameter of the pipe ($A/V = 4/D$, where D is the pipe diameter). Higher A/V values (i.e. smaller diameter pipes) generally present a more significant biofilm contribution because sulfide production occurs mainly in biofilms attached to sewer walls (WERF, , 2007). In addition, pipe diameter also has an impact on sewage hydraulic retention time (HRT).

With regards to the pipe length (Figure 3-2.B), almost half of the sites (44%) had a length below 1 km. Pipes between 1 and 5 km were 37% of the total, whereas longer pipes represented only around 20% (5-10 km, 16%; >10 km, 3%). Similarly to pipe diameter, pipe length also impacts on HRT. The larger the diameter and the longer the pipe, the larger the HRT will be for a given flow.

According to the average dry weather flow (ADWF) results presented in Figure 3-2.C, the majority of the dosing sites were located in pipes with very low flows (< 0.5 ML/d, 34%). About 20% and 26% of the pipes had an ADWF between 0.5-1 ML/d and 1-5 ML/d, respectively, whereas only 20% of the pipes had a large flow (> 5 ML/d).

With regards to the HRT (Figure 3-2.D), about 70% of the pipes with chemical dosing had an average HRT lower than 6 hours. From the remaining systems, 19% have retention times in the range of 6-12 h, and only 12% of the pipes had HRT longer than 12 hours. Theoretically, the longer the HRT of the sewage, the higher the sulfide production at the end of the pipe (Boon, , 1995; Delgado et al., , 1999; Sharma et al., , 2008). However, other parameters such as the A/V ratio (linked to the pipe diameter) and the wastewater characteristics also have an impact on sulfide production.

3.1.3.2 Chemicals applied

Seven chemicals are in use or were used in the recent past. Figure 3-3 presents the number of sites that each of the chemicals are/were applied.

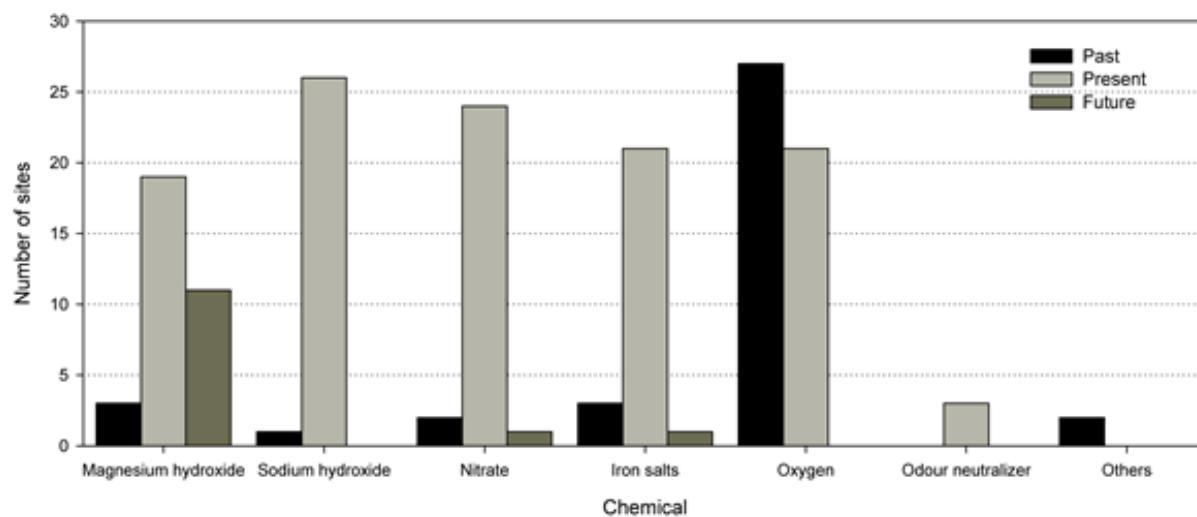


Figure 3-3. Chemical products used for sulfide control

The most used chemical to mitigate the effects of sulfide, by number of sites, is presently magnesium hydroxide, which is applied at 30 locations. The second chemical in the ranking is sodium hydroxide, used for caustic shock to suppress activity of sulfate reducing bacteria (SRB) due to high pH. It is important to point out that sodium hydroxide is dosed all year round at only 16 of these 27 sites, while at the rest of the sites, sodium hydroxide is dosed during spring and summer seasons only. Nitrate and iron salts are used to a similar extent (25 and 22 sites, respectively). These two chemicals are also commonly used in Europe (Barjenbruch, 2003; Bertrán de Lis et al., 2007; Matsché et al., 2005). Oxygen was widely applied in the past to prevent anaerobic conditions, but its utilisation has significantly decreased due to its poor performance in some systems (27 decommissioned sites) and is now used in only 21 locations. Odour neutralizers are currently dosed at 3 sites, while biomaterials had been used in the past but were reported to be no longer applied at any site. As a final remark, a large number of biomaterials and bio-products are currently available in the market. However, the survey has shown that they are not gaining wide application in Australia. The effectiveness of several such products were tested recently in the laboratory of the Advanced Water Management Centre at The University of Queensland. All the chemicals tested so far did not show any positive results (Gutierrez et al., , 2010).

The number of application sites may not represent a full picture of the extent of usage of each product, and sewage flows receiving chemical dosing should be included in the analysis. Therefore the use of each chemical was also quantified based on the total flow treated for H₂S

mitigation (calculated from the individual average flows). Only on-going and future sites have been considered in this analysis. Results are presented in Figure 3-4.

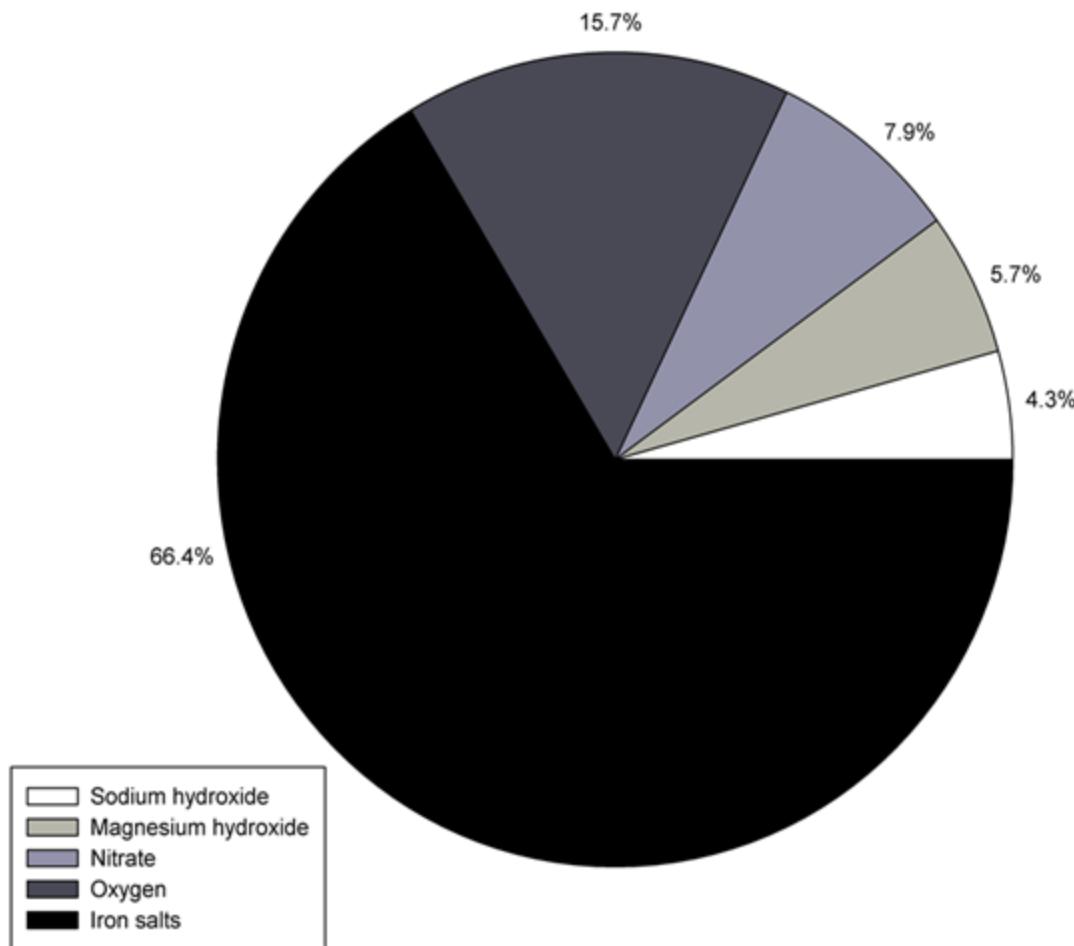


Figure 3-4. Contribution of each chemical to the overall sulfide control.

Figure 3-4 clearly illustrates the lower contribution of some of the most commonly used chemicals (in terms of number of sites). Only about 10% of the sewage was treated by sites with sodium hydroxide or magnesium hydroxide dosing (4.3 and 5.7%, respectively), while low percentages were also observed for nitrate (7.9%). Although iron salts and oxygen are dosed at only a few sites, these two chemicals have a much higher contribution than the others in terms of sewage flow treated. Around 16% of the total sewage is treated with oxygen, while the sewage receiving iron salts dosing accounts for about 66% of the total sewage with chemical dosing.

Figure 3-5 below presents the analysis of the results based on the average ADWF (A) and pipe diameters (B) for the five most used chemicals: NaOH, Mg(OH)₂, NO₃⁻, Fe²⁺/Fe³⁺ and O₂.

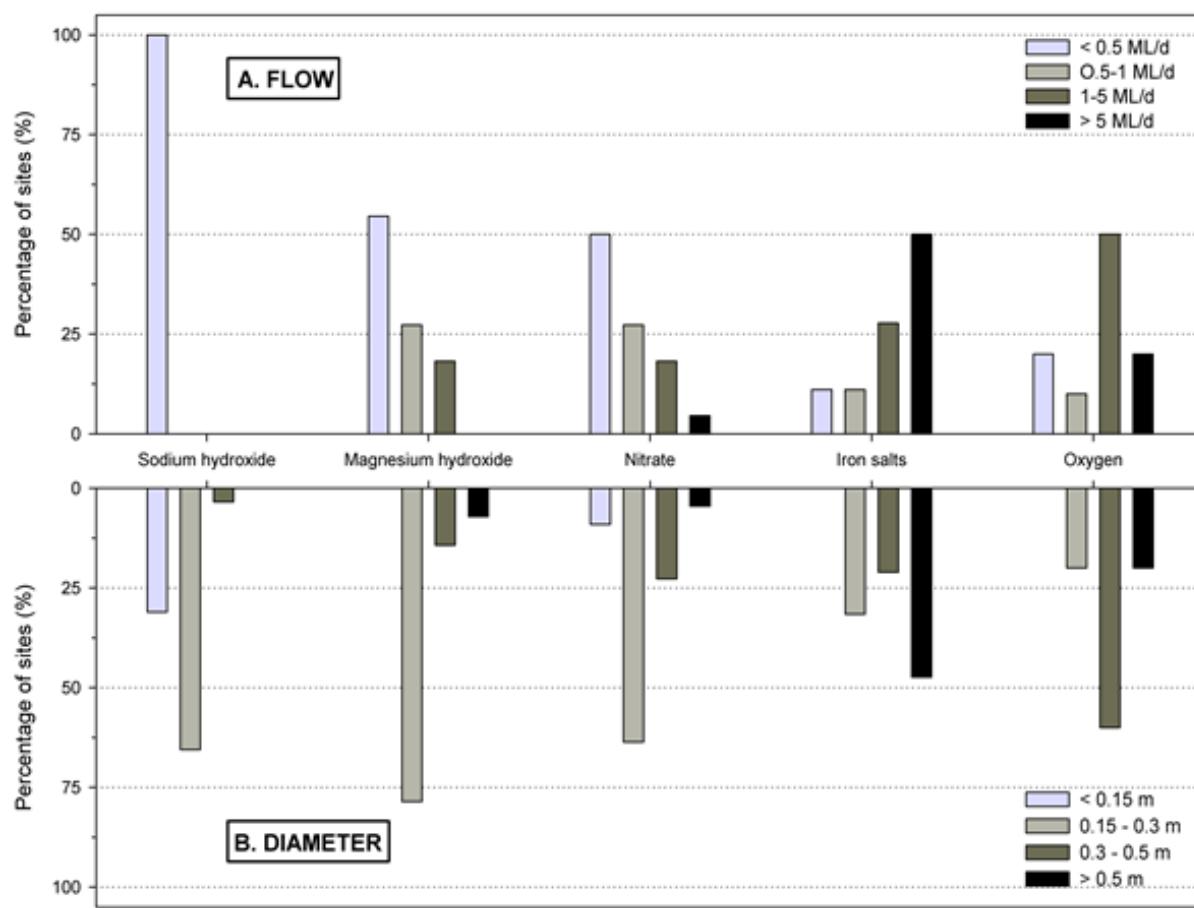


Figure 3-5. Site classification based on: A) Average daily flow rate of the sewer; B) Pipe diameter.

It can be seen that sodium hydroxide is only used in systems with low flows (ADWF lower than 0.5 ML d^{-1}) and small pipe diameters (more than 95% of the dosing is conducted in pipes with diameters smaller than 0.3 m). The mechanism for the caustic shock relies on the suppression of SRB from the biofilm attached to the sewer walls. In this respect, pipes with high surface area to volume ratios (A/V) are more favourable for this treatment since less amount of NaOH is required per volume of sewage. Therefore sodium hydroxide represents a cost-effective solution for sulfide control in small systems with low flow rates and high A/V ratios.

Similarly to sodium hydroxide, magnesium hydroxide is mainly applied in sewers with low flows and small diameters. About 80% of the magnesium hydroxide dosed sites are applied in sewers with average dry weather flows below 1 ML d^{-1} and pipe diameters between 0.15 and 0.3 meters (Figure 3-5.B). Magnesium hydroxide effectiveness does not depend on the pipe size, but relies only on the pH and volume of sewage to treat (Parsons et al., , 2003) and therefore could be suitable for sulfide control in systems of all sizes.

Figure 3-5.A, shows that iron salts are preferentially used in medium and large systems (around 80% of the sites with flows larger than 1 ML d^{-1}). Accordingly, these systems have big pipe diameters (Figure 3-5.B). Iron salts dosing is a simple and cost-effective method for H₂S control. Precipitation reactions occur in the bulk liquid phase and iron salts dosing in the past has been considered not to have any interaction with the biofilm. Thus, iron dosing is appropriate for both small and large systems. It has gained a wider application in large systems

because probably other chemicals are less suitable for sulfide control in such pipes. It should be noted that recent laboratory studies have shown that iron salts do interfere with biofilm activities. Zhang et al. (2009) showed that the activity of sulfide reducing bacteria in biofilms receiving FeCl₃ dosage was lowered by approximately 50% in comparison to that not receiving FeCl₃ dosage. Zhang et al. (2010) further revealed that the interactions between iron salts and biofilm activity lowered the demand for FeCl₂ for sulfide control. Both of the above effects are positive, and may further enhance the prospect of the use of FeCl₃ or FeCl₂ for sulfide control in sewers.

Based on the results depicted in Figure 3-5, oxygen is injected in systems of all sizes, but is mainly used in medium and high flow systems (pipes with ADWF between 1 and 5 ML d⁻¹) with large pipes (most of the pipes have diameters larger than 0.3 m). Oxygen relies on sulfide oxidation as the mechanism for H₂S control, although this can be chemical or biological (Gutierrez et al., , 2008) i.e. this oxidation happens in both the biofilm and in the bulk liquid. Oxygen also promotes biological organic matter oxidation, with the subsequent consumption of oxygen and volatile fatty acids. Because this process primarily occurs in the biofilm (Sharma et al., , 2011), oxygen is used more efficiently in pipes with large diameters (i.e. low A/V ratios) which usually deal with larger flows. Figure 3-6 presents the theoretical O₂ utilization efficiency for sulfide oxidation for different pipe diameters, assuming an oxygen consumption rate for biological sulfide oxidation of 5.6 gO₂/m² d (Gutierrez et al., , 2008), an oxygen consumption rate for chemicals sulfide oxidation of 107 gO₂/m³ d (Sharma and Yuan, , 2010) and an oxygen consumption rate due to other heterotrophic microorganisms of 16 gO₂/m² d (Gutierrez et al., , 2008). Oxygen consumption due to biological sulfide oxidation, chemical sulfide oxidation and heterotrophic consumption was calculated for different pipe diameters and expressed as a percentage of the total oxygen consumption.

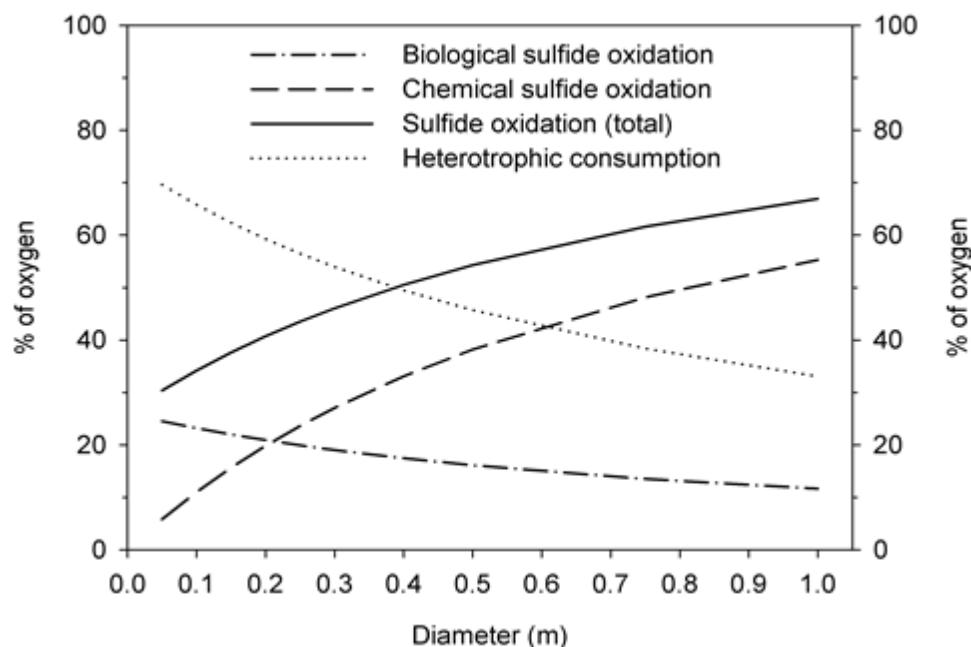


Figure 3-6. Oxygen utilisation efficiency as a function of the pipe diameter for: biological sulfide oxidation, chemical sulfide oxidation, sulfide oxidation (total) and heterotrophic consumption.

Figure 3-6 clearly shows that the larger the diameter, the higher the efficiency of oxygen utilisation for sulfide oxidation purposes. By analysing the contribution of each process, it can

be seen that this is mostly due to the major role of chemical sulfide oxidation in the total sulfide oxidation, whereas the reduction of the A/V ratio for larger pipe diameters also implies the decline in the contribution of the biofilm processes (biological sulfide oxidation and also the heterotrophic consumption of O₂ for purposes other than sulfide oxidation).

With regards to nitrate, it is also preferentially used in small systems, with only around 25% of the sites located in pipes with ADWF higher than 1 ML d⁻¹ (Figure 3-5.A). Concerning the pipe dimensions, more than 60% of the sites where nitrate is dosed have a diameter between 0.15 and 0.3 m. Nitrate is an expensive chemical (de Haas et al., , 2008), usually dosed as NaNO₃ or Ca(NO₃)₂ (Zhang et al., , 2008). It does not inhibit SRB activity in the short- or long-term, and does not decrease the abundance of SRB in the sewer biofilm. Instead, nitrate addition to the start of rising mains increase SRB activity in downstream biofilms (Mohanakrishnan et al., , 2009). Sulfide can be oxidised biologically by nitrate reducing-sulfide oxidising bacteria (NR-SOB), but chemical sulfide oxidation is almost negligible (unpublished results from the authors' group). Similar to oxygen, nitrate is also used as an electron acceptor by other heterotrophic bacteria, with subsequent nitrate consumption. Both the biological processes described above occur mainly in the biofilm (Mohanakrishnan et al., , 2009). Hence, the effectiveness of nitrate does not rely on the A/V ratio. Therefore, nitrate addition is suitable for both small and large pipes, unlike oxygen, which is more suitable for large systems. However, the use of nitrate in large systems may be cost prohibitive due to its high price (Sharma et al., , 2011).

As stated before, sewage HRT has a significant impact on sulfide production (Sharma et al., , 2008b). HRT in systems with chemical dosing was also assessed to complete the analysis and identify if any of the 5 main chemicals is preferentially used to deal with certain conditions. Results are shown in Figure 3-7.

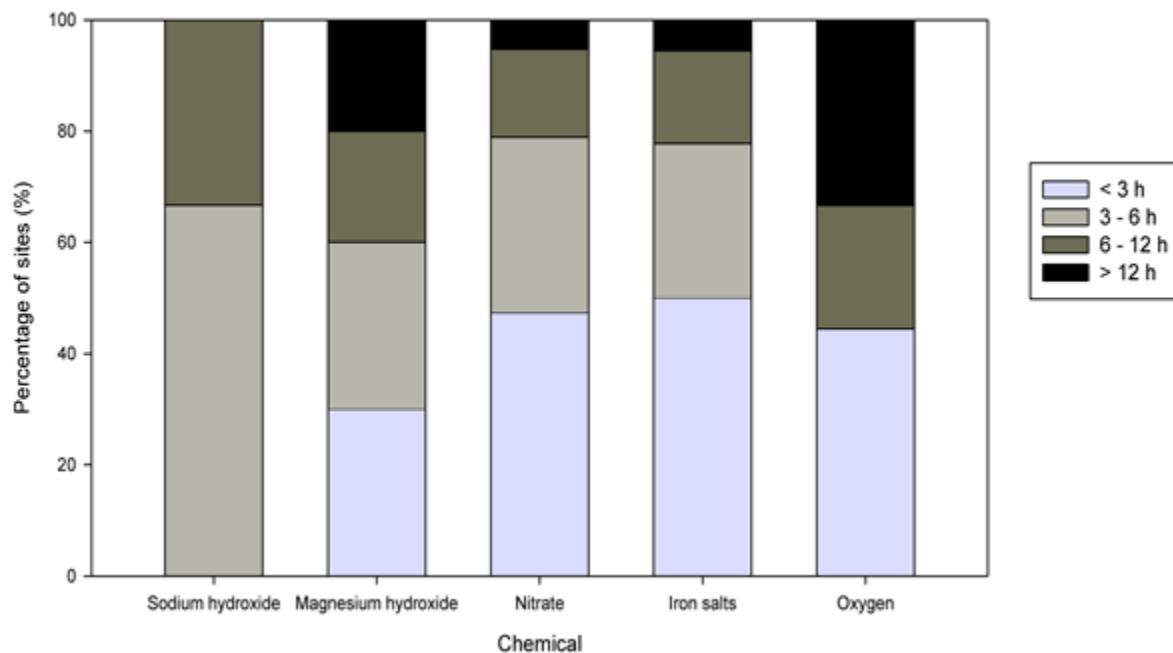


Figure 3-7. Site classification based on HRT for the different chemicals.

It can be observed from Figure 3-7 that the distribution of the HRT for four of the five chemicals, namely magnesium hydroxide, nitrate, iron salts and oxygen, was similar, indicating

that these were not preferentially used for certain retention times or sulfide levels. Only sodium hydroxide is the exception to this. Sodium hydroxide is dosed to pipes with average HRT between 3 and 12 hours. This may be due to the specific characteristics of these systems; small size pipes with low flows, as depicted in Figure 3-5.

3.1.3.3 Dosing location

The location where a chemical is dosed may determine the effectiveness of treatment and the operational cost. The survey showed that chemicals are dosed at the wet wells, pumping stations, an intermediate location along the rising main or at the discharge point of a rising main. These results are depicted in Figure 3-8, where only current and future sites are considered.

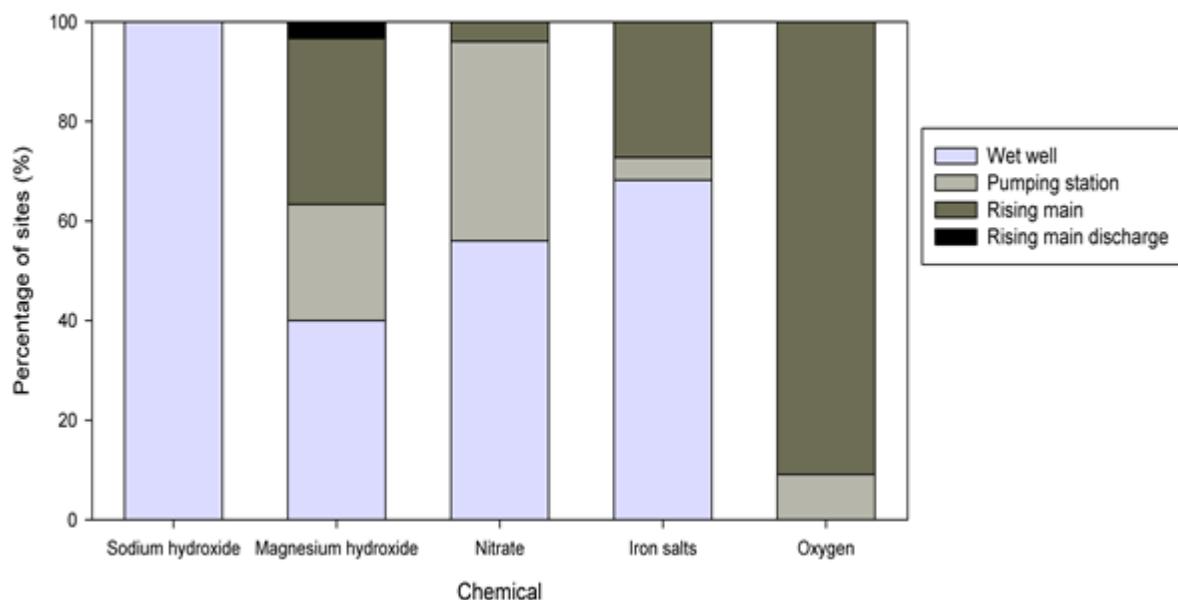


Figure 3-8. Dosing location of the chemicals

In general terms, the preferred dosing location for the majority of the chemicals is before the wastewater enters the rising main (either at the wet well or the pumping station).

Sodium hydroxide was in all cases added at the wet well. This is in agreement with the theory that it should be dosed upstream of the rising main to effectively inhibit/kill all the SRB attached to the walls of the pipe.

Dosing of magnesium hydroxide is conducted primarily (60%) at either wet wells or the pumping stations. However, this chemical is also dosed, albeit to a less extent, directly into the main. It was even applied in one site at the discharge point of the rising main. Magnesium hydroxide is used to increase the pH to prevent sulfide transfer to the gas phase at rising main discharging points and in gravity sections. Therefore, the dosing location should not have a critical impact on the control of H₂S transfer. However, a recent study showed that high pH (pH > 8.5) can partially inhibit SRB activity, diminishing sulfide production (Gutierrez et al., , 2009). As such, adding this chemical upstream would reduce its consumption to achieve the same level of control of sulfide transfer (Gutierrez et al., , 2009). In this respect, the dosing of magnesium hydroxide upstream should be beneficial.

Around 70% of iron dosing was conducted at upstream locations (mainly at the wet well). The dosing location of iron salts is not important in terms of effectiveness of the chemical, as long as the hydraulic retention time (HRT) in the pipe after dosing allows sufficient time for sulfide precipitation (in the order of seconds according to Wei and Osseo-Asare, (1995)). However, a recent lab-scale study demonstrated that the addition of Fe³⁺ significantly inhibits the SRB activity of anaerobic sewer biofilms (Zhang et al., , 2009), although the same phenomenon is yet to be observed in real sewers. If this inhibitory effect is verified in real sewers, iron salts should preferably be added at upstream locations. A further benefit of upstream dosage of iron salts is that sulfide would be controlled along the entire pipe. While iron salts may initially react with some other anions (e.g. phosphate and hydroxide) in the absence of sulfide, iron ions will be made available for sulfide precipitation when the latter is produced due to the lower solubility of FeS in comparison to iron phosphate and iron hydroxide precipitates (Zhang et al., , 2009).

The survey also showed that nitrate is normally added upstream (95% of the dosing was conducted at the wet well or the pumping station), whereas oxygen was dosed at 90% of the sites along the rising main. Neither oxygen nor nitrate inhibit SRB activity in the short- or long-term, but their actual mechanism for H₂S control relies on sulfide oxidation (either chemical or biological) (Gutierrez et al., , 2008; Mohanakrishnan et al., , 2009). If oxygen was supplied at the beginning of the pipe, complete control of sulfide at the discharging points would require the entirety of the pipe to be oxic, which is not possible with the existing method of dosing (i.e. into wastewater when the pump is running) (Gutierrez et al., , 2008). On the other hand, dosing nitrate upstream at a very high rate may ensure anoxic conditions along the whole pipe, although at a very high cost (Mohanakrishnan et al., , 2009). In this respect, locating dosing points for oxygen or nitrate downstream (close to the end of the sewer or target point for sulfide control, but allowing adequate wastewater retention time downstream of dosing for complete oxidation of sulfide) is a more optimal solution in terms of performance and costs (Gutierrez et al., , 2008; Mohanakrishnan et al., , 2009).

3.1.3.4 Dosing rate control

Chemicals are dosed continuously or just during pumping events or periodically for several days/weeks. This mainly depends on the characteristics of the chemical and the dosing location. The dosing rate also has a critical impact on the effectiveness of sulfide mitigation and chemical consumption. According to the survey, four different dosing strategies are used by the industry: i) intermittent dosing, where the same amount of product is dosed periodically; ii) constant dosing, where the chemical is dosed at the same rate independent of the flow and wastewater characteristics; iii) flow-paced dosing, where the amount of chemical delivered is proportional to the wastewater flow, and iv) profiled dosing, where the dosing rate is variable according to a pre-defined profile. The reported dosing strategies used by industry are shown in Figure 3-9.

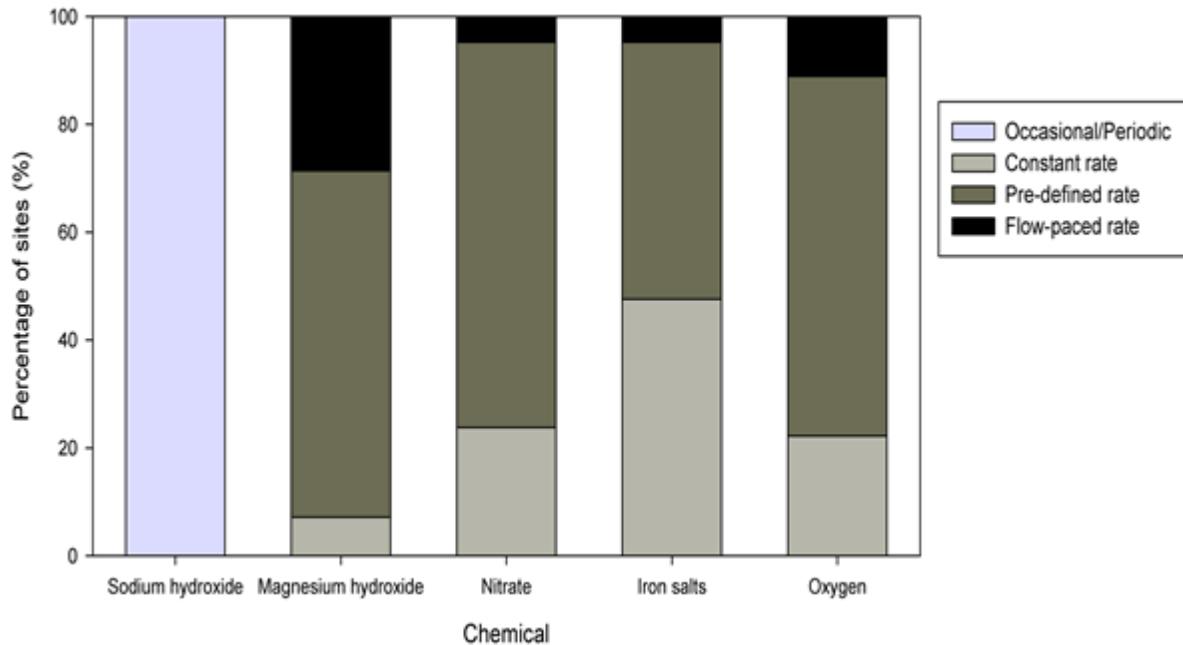


Figure 3-9. Dosing rate control of chemicals

As can be observed in Figure 3-9, sodium hydroxide is only added intermittently and for a short period (one to five pumping cycles) to reach pH 10-11 (O'Gorman et al., , 2011). This is because of its unique mechanism - SRB activity suppression by caustic shock. Magnesium hydroxide, nitrate and oxygen sites are mostly operated at pre-defined dosing rates. Around 50% of the iron dosing sites used pre-defined profile dosing rates, while the other half used constant rates. Constant rates were also used at about 30% of the nitrate and oxygen dosing stations. Finally, flow-paced dosing was seldom applied and was only of relative importance for sites with magnesium hydroxide dosing (25-30%). This is reasonable, given the fact that magnesium hydroxide dosing relies mainly on the volume of sewage and not on the sulfide concentration.

Finally, Table 3-2 summarise the current industry practice in terms of dosing rates and costs for the different chemicals. The effectiveness related to these dosing rates is however not known.

Table 3-2. Chemical dosing current industry practice.

Chemical	Dosing levels	Chemical cost **
Sodium hydroxide*	11.4–28.6 L NaOH/ML*	39.6–99.1 \$/ML*
Magnesium hydroxide	47.9-156.6 kg Mg(OH) ₂ /ML	48.7-159.3 \$/ML
Nitrate	1.33-15.5 kg N-NO ₃ ⁻ /ML	41.3-483.6 \$/ML
Iron Salts	3-47 kg Fe/ML***	10.9-170.6 \$/ML
Oxygen	15.8-91.5 kg O ₂ /ML	12.8-74.0 \$/ML

*To reach pH 10-11 using NaOH 50% w/w.

** Based on the following chemical prices in Australian dollars: \$69.3/20L NaOH (50% w/w); \$590/tonne Mg(OH)₂ 58% w/w; \$1010/m³ Ca(NO₃)₂ 50% w/w; \$526/tonne FeCl₃ 42% w/w; \$1.15/m³ O₂ 99.5% w/w.

*** Dosing levels of up to 705 kg Fe/ML were reported, but were excluded from this comparison as non-representative (abnormally high).

As can be clearly observed, dosing levels differ from one chemical to another and present a wide range. This is due to the different characteristics of the systems where chemical dosing is conducted. Taking into account the dosing frequency and flow, sodium hydroxide dosing rates from 11 to 28.6 L of NaOH (50% w/w) per ML of sewage were reported in the survey. This chemical relies on the suppression of SRB from the pipe biofilm due to the caustic shock. Hence, the pipe diameter plays a critical role and dosing requirements dramatically increase with pipe diameter. Magnesium hydroxide dosing levels ranged from 48 to 157 kg Mg(OH)₂/ML of sewage. The effectiveness of this chemical is independent of the sulfide levels or the pipe diameter, depending mainly on the buffer capacity of the sewage. In addition, biological acidifying reactions could take place along the pipe so longer pipes may require additional Mg(OH)₂ dosing. Nitrate, oxygen and iron salts present also a wide dosing rate range. Nitrate and oxygen oxidise sulfide, while the principle behind iron salts is the sulfide precipitation. In this respect, the dosing of all three chemicals is critically governed by sulfide levels in the pipe. Other aspects such as the dosing location or the pipe length and diameter may also partly explain the disparity among the results.

When the costs are analysed, nitrate dosing is found to be the most expensive option, with a maximum cost of up to \$483.6/ML. Similar chemical costs were reported for Magnesium hydroxide (48.7-159.3 \$/ML) and iron salts dosing (10.9-170.6 \$/ML). Chemical costs for iron salts dosing were comparable to those reported by Matsché et al. (2005) for sulfide control in Austria (42-77\$/ML). The dosing costs for intermittent NaOH dosing were slightly lower, 39.6–99.1 \$/ML, although the constraints of this technology have to be taken into consideration. Finally, these figures show oxygen to be the least expensive chemical with a maximum dosing cost of 74\$/ML of sewage.

3.1.3.5 Chemical dosing performance

Assessing the performance of chemical dosing was one of the objectives of the survey (see Appendix A.1, sections 3.C and 4.C). However, results showed that systems with chemical dosing were seldom monitored and little data was available. For most of the sites, neither online nor periodical monitoring of dissolved sulfide or gas-phase H₂S was conducted. Lack of odour complaints were, in most of the cases, used as an indication of the effectiveness.

3.1.4 Opportunities for operational improvement and future research

Based on the results of the survey, several opportunities for improvement as well as future research questions have been identified.

3.1.4.1 Model-based support for the selection of chemicals, dosing locations and dosing rates

The current selection of chemicals and the design of its dosing locations and rates are mainly based on experience (i.e. iron salts are more suitable for large systems, or oxygen has to be dosed directly into the pipe). However, there are many factors to be considered. The selection and design should be made based on specific features of each site and characteristics of the sewage. In recent years, powerful mathematical models such as the SeweX model (Sharma et al., , 2008b) and the WATS model (Hvitved-Jacobsen et al., , 1998) have been developed to support the decision making and have indeed been demonstrated in several cases (de Haas et al., , 2008; Sharma et al., , 2008a) . However, these models are yet to be taken up widely.

3.1.4.2 On-line control of the dosing rate

Currently constant, flow-paced and profiled dosing rates are used to control chemical dosing. These are commonly based on empirical guidelines developed, again, through experience. However, sulfide concentration and flows have a dynamic behaviour over a day, and constant or flow-paced dosage could lead to over dosage during periods with low levels of sulfide production, and under dosage during some other periods. In some cases, profiled dosing with variable dosing rates are applied based upon historical data (flow rate, sulfide concentration etc). However, this strategy may not be effective as the dynamics of each sewer system is different, and even for the same sewer system the conditions vary from day to day (Sharma and Yuan, , 2009). Recent development in on-line sensor technology has made the on-line measurement of dissolved sulfide levels possible (Sutherland-Stacey et al., , 2008). In this respect, dynamic dosing of chemicals based upon on-line measurement of parameters such as flow rate and liquid phase sulfide concentration may achieve better sulfide control with lower chemical costs. However, the current high price of the dissolved sulfide sensors makes on-line control economically non-viable for small systems. Future work should address this issue by developing more affordable and reliable sensors for dissolved sulfide measurement. In addition, due to the different mechanisms of the chemicals, specific control algorithms need to be developed for each chemical to ensure optimised dynamic control.

3.1.4.3 More cost-effective chemicals

All the above mentioned chemicals (except for NaOH) require continuous dosing of the product, which results in high chemical supply costs. In this respect, research is needed to develop more chemicals to directly target the activities of sewer biofilms. Some bio-material products are available, but there has been little peer-reviewed evidence showing their effectiveness. However, recent lab studies reported the inhibitory effect of nitrite/free nitrous acid (FNA) on SRB and methanogenic activities in sewer biofilms (Jiang et al., , 2010; Jiang et al., , 2011). FNA as low as 0.18 mg-N/L can suppress sulfide production after 24-hour of exposure. The suppression is followed by a slow recovery (several days to several weeks) after stopping the FNA addition (Jiang et al., , 2011). FNA has appears to be promising chemical, but its dosage requires further optimisation.

3.1.5 Conclusions

An industrial survey was conducted among seven major Australian water utilities, cataloguing the different field sites where chemical dosage was/is/will be carried out. A total of 165 sites were identified, the vast majority of them being located in pressure mains.

Seven different chemicals were or are in use: Magnesium hydroxide, sodium hydroxide (caustic shock), nitrate, iron salts, oxygen, odour neutralizers and other biomaterials. Magnesium hydroxide is the chemical applied at most sulfide control sites (30), followed by sodium hydroxide (27) and nitrate (25). However, when taking into account the flow treated, the dosing of iron salts is used to control sulfide in approximately 66% of the sewage treated. Magnesium hydroxide, sodium hydroxide and nitrate are used mainly for small pipes with low flows and their total contribution is only around 18% of the total flow treated with chemicals for sulfide control.

Chemicals are normally dosed at wet wells or pumping stations, except for oxygen, which is mainly injected directly into rising mains. The dosing of nitrate in these upstream locations is likely to result in either low H₂S control efficiency or high chemical costs, while the dosage of other chemicals at such locations appear appropriate.

Constant dosing and profiled-dosing are the two methods predominantly used for dosing rate control. Flow-paced control is also in use. None of the 165 sites use or used on-line control of the dosing.

Finally, there are several key opportunities to achieve more effective and cost-effective sulfide control. Mathematical models are now available to support the selection of the most suitable chemical, dosing location and dosing control for each case. On-line control of dosing rate may also improve the effectiveness of the dosing and reduce chemical costs. Also, more cost-effective chemicals need to be developed, which does appear to be possible.

3.2 Design of control methodologies for single pipes

3.2.1 Introduction

The control of hydrogen sulfide in sewer systems is nowadays one of the main challenges for the Australian water utilities. Sulfide is produced in the liquid phase of sewer systems (mainly pressure mains) under anaerobic conditions by sulfate reducing bacteria (SRB) (Hvitved-Jacobsen, 2002; Melbourne, 1989). The transfer of hydrogen sulfide from the liquid to the gas phase leads to serious sewer corrosion, which accelerates the depreciation of sewer assets (WERF, 2007). In Australia alone, this has an estimated cost of about \$100M per year. As well as this, hydrogen sulfide causes odour nuisances and has important health concerns due to its high toxicity (Boon, 1995).

There are currently several methods to control this problem, with chemical dosing being widely used. According to a recent survey conducted among the major water utilities in Australia (Ganigué et al., 2011), seven different chemicals were or are in use: Magnesium hydroxide, sodium hydroxide (caustic shock), nitrate, iron salts, oxygen, odour neutralizers and other biomaterials. Magnesium hydroxide is the chemical applied at most sulfide control sites (30), followed by sodium hydroxide (27) and nitrate (25). However, when taking into account the flow treated, the dosing of iron salts is used to control sulfide in approximately 66% of the sewage treated. Magnesium hydroxide, sodium hydroxide and nitrate are used mainly for small pipes with low flows and their total contribution is only around 18% of the total flow treated with chemicals for sulfide control.

The way chemical dosing is conducted has not only a major influence on the effectiveness of sulfide control strategies, but also significant cost implications. Controlling chemical dosing in rising mains is very challenging due to the plug-flow behaviour of the system. According to the same industrial survey (Ganigué et al., 2011), flow-paced or profiled dosing are used at the majority of the dosing sites. These are commonly based on empirical guidelines developed through experience (de Haas et al., 2008). However, sewers have a dynamic behaviour, and these control methodologies could easily lead to over or under dosage. On-line dosing control has great potential benefits, allowing improved control performance and a reduction of chemical costs (Sharma and Yuan, 2009). In this light, this work aims to develop on-line control methodologies for the main chemicals used by the Australian water industry to control sulfide in sewer systems.

3.2.2 Magnesium hydroxide

3.2.2.1 Background

Mg(OH)₂ dosing in sewers prevents sulfide transfer from the liquid to the gas phase by increasing the pH of the sewage (Gutierrez et al., 2009). Generally, H₂S is present in the liquid phase as an equilibrium of two sulfide species, H₂S and HS⁻. The rise of pH shifts the equilibrium, reducing the concentration of H₂S in the liquid phase and hence preventing its release to the sewer atmosphere. The maximum pH achievable by Mg(OH)₂ dosing is approximately 9.0-9.2 due to its limited solubility in water (WERF, 2007). At such pH levels, the percentage of H₂S in the liquid is less than 1%. According to Gutierrez et al. (2009), long-term pH elevation to 8.6–9.0 reduces SRB activity by 30%-50%. Methane is a greenhouse gas with a warming potential 21-23 times higher than carbon dioxide (IPCC (2006)). It is also

produced in sewer systems (Guisasola et al., 2008), but its generation is prevented at pH levels around 8.6-9 (Gutierrez et al., 2009).

3.2.2.2 Control Design

There exist mainly two different types of controllers: feedforward and feedback. On the one hand, feedforward control is an open loop control system, which only responds to its control signal in a pre-defined way without considering how the system reacts (Meckl and Seering, 1986). On the other, feedback control is a close loop control system, which adjusts the output based on how does the action affect the load (Phillips and Parr, 2010). Provided that sewer systems have a plug flow nature, chemical dosing cannot be performed based on feedback control and needs to rely on a feedforward loop. In this light, the fundamental knowledge for magnesium hydroxide dosing control design is analysed in this section, focusing on dosing location and dosing requirements. Additionally the prediction of future flow and the use of a supervisory feedback loop are also discussed.

Dosing Location

The main aim of magnesium hydroxide dosing for sulfide control is to rise the pH to reduce sulfide transfer from the liquid to the gas phase. In this respect, the dosing control system has to guarantee stable sewage pH close to the desired set-point at the discharge point, with minimal chemical consumption.

The optimal dosing location will largely depend on specific conditions of each system. Dosing Mg(OH)₂ at the discharge point would be simpler in terms of control. However, a dosing location at the beginning of the pipe minimizes sulfide transfer during the transport (e.g. through air valves), preventing possible odour complaints. Moreover, as stated before high pH levels (8.6-9) decrease sulfide production and stop methane generation (Gutierrez et al., 2009). This is beneficial from the environmental point of view due to the reduction of sulfide and methane (a potent greenhouse gas) emissions. Finally, it is also important to take into account that, even at high pH, biological activity (i.e. fermentation) may drive pH down due to the proton production. However such high pH may also minimise sewage acidification due to fermentative processes, reducing the amount of magnesium hydroxide to be dosed.

Dosing Requirements

If dosing magnesium hydroxide at an upstream location, Mg(OH)₂ requirements to achieve a desired set-point at the discharge point depend basically on two factors: On one hand, the buffer capacity of the sewage and on the other the proton production along the pipe.

I. Buffer capacity

The amount of magnesium hydroxide required to achieve a certain pH is dependent on the actual wastewater pH and the buffer capacity of the sewage. Sewage pH is very dynamic throughout the day (as shown in Figure 3-10), but can be easily monitored on-line using common and inexpensive sensors.

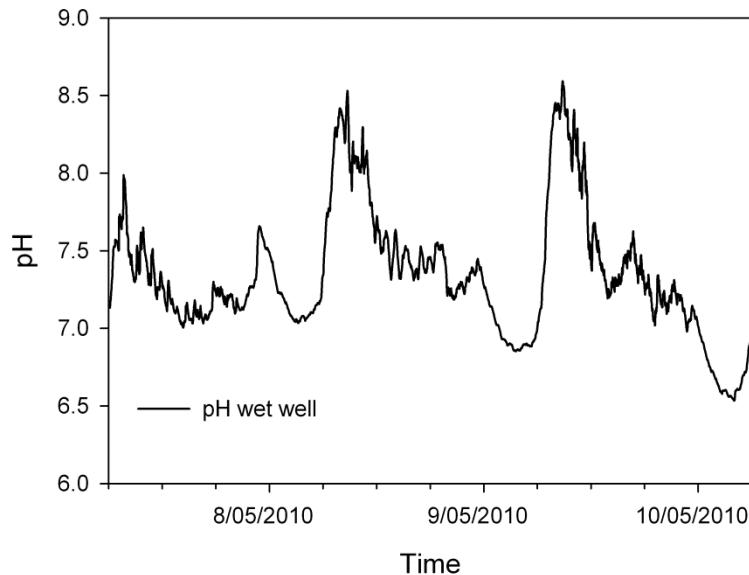


Figure 3-10. Dynamics of sewage pH at a wet well.

On the contrary, buffer capacity of the wastewater cannot be measured on-line, but needs to be determined by titration. This is illustrated in Figure 3-11, which depicts titration curves of sewage at different times of a day. These samples were collected from the wet well of a rising main from Allconnex Water, located at the Gold Coast, and titrated with sodium hydroxide (NaOH) (0.1M) using an automatic titration device. Titration results revealed that buffer capacity of sewage did not vary significantly throughout the day. In this light, a standard titration curve may be used in most of the cases.

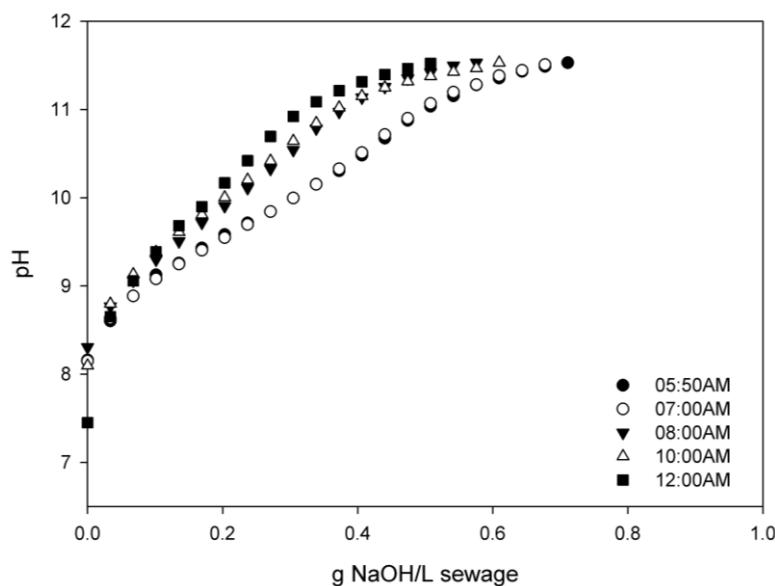


Figure 3-11. Titration curves of sewage from UC09 (Allconnex Water) at different times of the day.

II. Proton production along the pipe

As stated before, although the increase on the pH has a negative impact on biological activities, bio-transformations take place while sewage travels along the pipe. Overall, protons are

produced during the transport, with the subsequent pH decline. If biological activity and/or the retention time are sufficient, this change on pH could impact the effectiveness of sulfide control. To overcome this, an additional amount of magnesium hydroxide should be dosed to achieve the desired pH at the end of the pipe. In order to estimate the amount of protons produced, a simple mathematical model was proposed.

Proton production along the pipe depends on many factors but the most important are hydraulic retention time (HRT), Area to Volume (A/V) ratio, pH and mixing conditions. The longer the HRT, the higher the reaction time and hence the amount of protons produced. Concerning the A/V ratio, the smaller the pipe diameter the higher the relationship between area and volume and the more significant the contribution of the bioprocesses occurring in the biofilm. Furthermore, pH has a direct impact on biological activity, and therefore in the amount of protons produced. Finally, reaction rates are quite different for mixed conditions and quiescent conditions; hence the pump frequency greatly affects the proton production and needs to be taken up. In this respect a series of simulations based on these factors were designed and the results (depicted in Figure 3-12) were used to construct a proton production model.

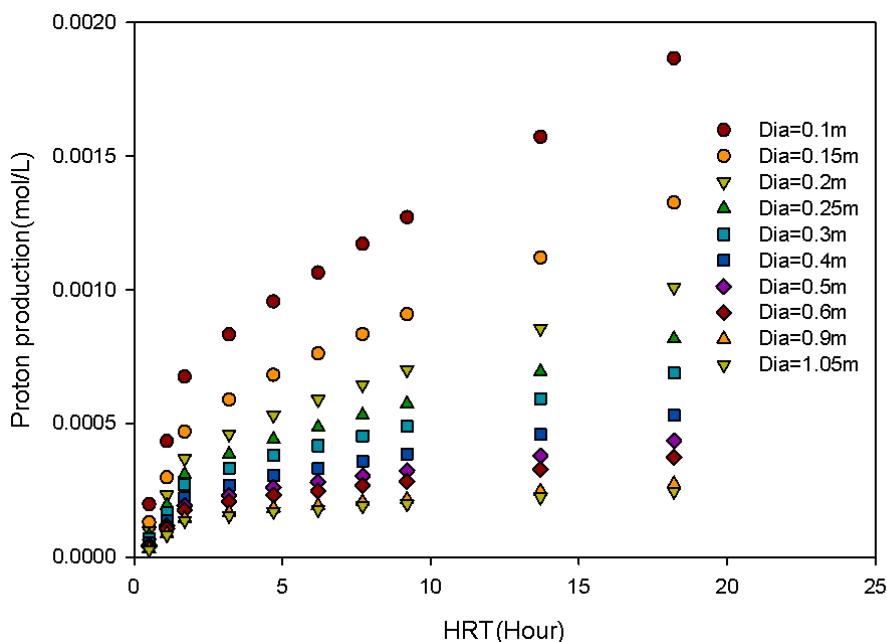


Figure 3-12. Proton production as a function of HRT and A/V ratio.

According to the results in Figure 3-12, a mathematical model (1) for the estimation of the proton production based on HRT and A/V ratio was developed.

$$H^+ \text{production} = r_{max} * \frac{A}{V} * HRT^n ; \quad (1)$$

Where r_{max} is the maximum production rate and n is a parameter of the power function.

The r_{max} , and n results for different A/V ratios are shown in Table 3-3. In addition, the residual error (RES) and the R^2 are also presented.

Table 3-3. r_{max} and n for different diameter.

Diameter (m)	r_{max}	n	RES	R ²
0.1	$1.0872 \cdot 10^{-5}$	0.4963	$3.27013 \cdot 10^{-8}$	0.985695
0.15	$1.1441 \cdot 10^{-5}$	0.503	$1.63962 \cdot 10^{-8}$	0.986204
0.2	$1.2035 \cdot 10^{-5}$	0.4911	$1.11141 \cdot 10^{-8}$	0.983762
0.25	$1.2684 \cdot 10^{-5}$	0.4771	$8.67377 \cdot 10^{-9}$	0.980433
0.3	$1.3318 \cdot 10^{-5}$	0.4661	$7.1918 \cdot 10^{-9}$	0.977194
0.4	$1.4634 \cdot 10^{-5}$	0.4443	$5.59262 \cdot 10^{-9}$	0.969688
0.5	$1.6046 \cdot 10^{-5}$	0.4235	$4.82696 \cdot 10^{-9}$	0.960771
0.6	$1.7452 \cdot 10^{-5}$	0.4068	$4.33417 \cdot 10^{-9}$	0.951855
0.9	$2.1746 \cdot 10^{-5}$	0.3694	$3.5667 \cdot 10^{-9}$	0.925392
1.05	$2.3858 \cdot 10^{-5}$	0.3556	$3.37191 \cdot 10^{-9}$	0.91207

The regression curves for different diameter based on parameters present in Table 3-3 are depicted in Figure 3-13.

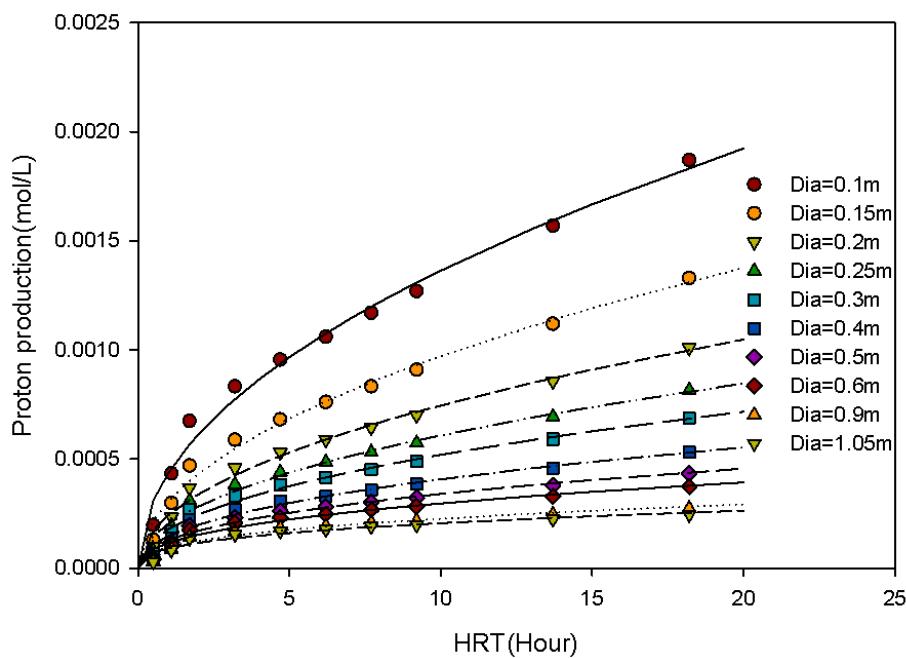


Figure 3-13. The regression of different r_{max} , n.

As can be seen, the model predicts with a reasonably good accuracy the proton production of a pipe with a given diameter and HRT, and can be further used to determine the additional amount of Mg(OH)₂ to be dosed.

Future flow prediction

Sewer systems have a plug-flow nature, which makes sulfide control complex and challenging. The majority of controls designed in SP5 require HRT as input. This cannot be measured, but needs to be predicted. To overcome this problem, typical HRT profiles have been used instead, allowing achieving the desired goal in most of the situations. Nevertheless, this solution is not ideal because does not take into consideration the real state of the system.

To achieve a better HRT estimation, sewer future flow prediction is necessary. There mainly exist two types of methods for sewer influent flow prediction. One approach is based on mass continuity and momentum equations, such as Storm Water Management Model, Hydroworks modelling system, and MOUSE (Singh, 1995). These models require detailed knowledge of drainage area under study and incorporate a large number of parameters, making their calibration complex and time consuming (Lu et al., 2006). The other alternative is the use of black box models, built using historical time series for training, such as transfer function model (TFM) (Zheng, 1989; Zheng and Novotny, 1991), neural network model (NN) (El-Din and Smith, 2002) or integration of TFM and NN (Lu et al., 2006). This second approach is more suitable to sewer systems. In this light, Autoregressive-moving average (ARMA) models have obtained excellent performance in sewer influent flow prediction (Capodaglio, 1994; Zheng and Novotny, 1991). However in these studies, flow was predicted just one step ahead (next day, next month or next year total flow prediction), whereas HRT prediction for on-line control requires multi-step prediction. In this light multi-step ARMA models are required. Another option would be the use of an auto-regressive moving average with exogenous inputs (ARMAX) model, which can also use exogenous inputs, such as for example rainfall, which would improve prediction during rain or storm events.

I. ARMA model development

The ARMA model is composed of both autoregressive (AR) and moving average (MA) models. Equation 2 depicts a general expression to represent an ARMA model:

$$A(z^{-1})y(t) = C(z^{-1})v(t) \quad (2)$$

Where z is the backshift operator, $z^{-1}y(t) = y(t - 1)$, $v(t)$ is zero mean value Gaussian white noise and $y(t)$ is the observed data.

$$A(z) = 1 + a_1z^{-1} + \dots + a_{na}z^{-na} \quad (3)$$

$$C(z) = 1 + c_1z^{-1} + \dots + c_{nc}z^{-nc} \quad (4)$$

Where na , nc are the order of $A(z^{-1})$, $C(z^{-1})$.

The direct influent flow multistep prediction results of ARMA model in the present form would be unsatisfactory due to the large flow variation along the day. However, sewer flow usually shows similar daily profiles. In this light, ARMA model for future flow prediction can be developed based on the typical flows. Model training and parameter estimation was conducted by comparing typical flow profiles with historical data, as shown in Equation 5.

$$y_{dif}(t) = y_{sm}(t) - typicalflow(t) \quad (5)$$

Where y_{dif} data is the difference between historical flows ($y_{sm}(t)$) and $typicalflow(t)$, which is the typical flow at time (t).

Hence, the ARMA model can be expressed as:

$$A(z^{-1})y_{dif}(t) = C(z^{-1})v(t) \quad (6)$$

II. ARMA model training

To determine the coefficients of the ARMA model, this needs to be trained using historical data sets. The orders of model can be determined offline (Box et al., 1970), whereas the error between the typical flow and the historical data can be calculated using Recursive Extended Least Squares (RELS) (Isermann, 1982).

In this case, the ARMA model was trained using historical data from UC09 rising main (Allconnex). This pump station is operated as an on-off process, with the pump being turned on when the wastewater at the wet well reaches a set-point level, and pumping being stopped when the minimum level is reached. Continuous flows are needed in order to use ARMA model. For this reason, average flow for each pumping event was calculated and smoothed (see Figure 3-14).

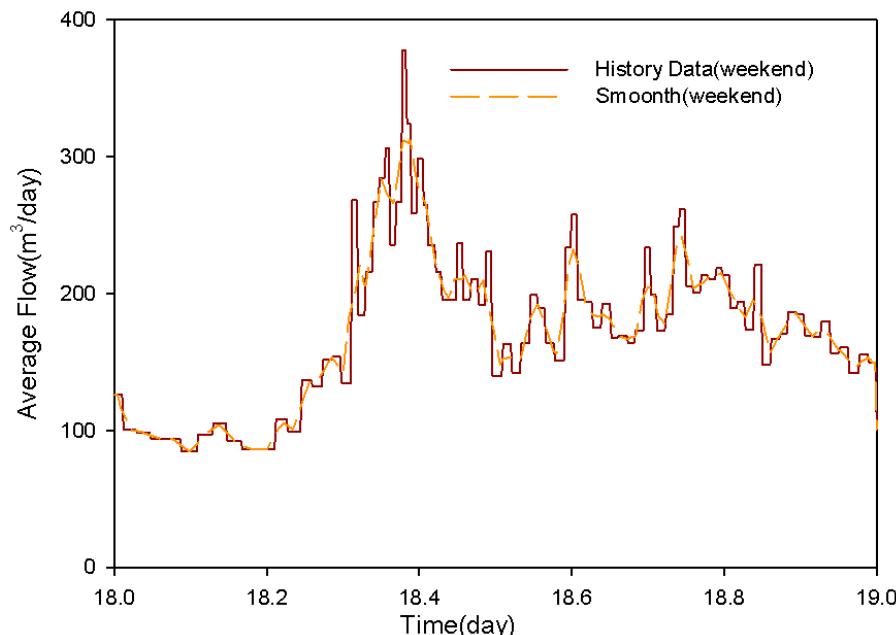


Figure 3-14. One day continuous flow calculation and smoothing.

Next step was establishing typical flow profile for dry weather conditions. Based on the historical data analysis it was concluded that the typical flow profile for working week days (Monday until Friday) was very similar, whereas Saturday and Sunday followed a slightly different trend (Figure 3-15).

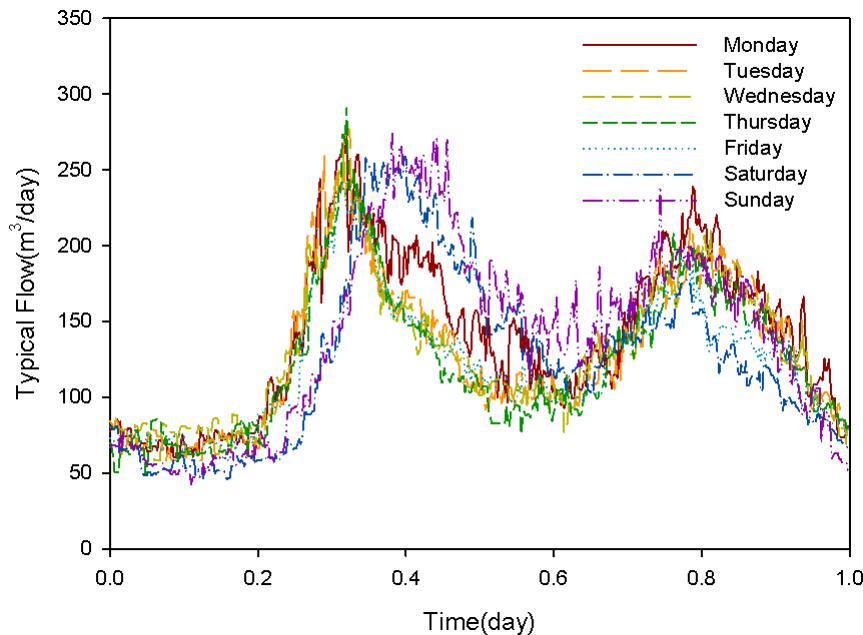


Figure 3-15. Typical flow profile of the different days of a week.

In this light, two different typical flow profiles were defined; one for working days and the other for weekend days. These are depicted in Figure 3-16.

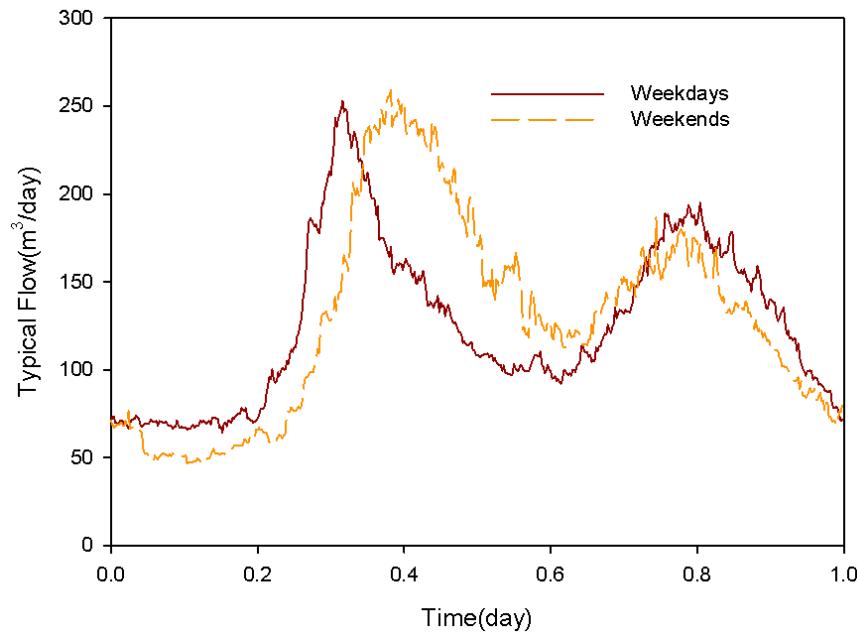


Figure 3-16. Typical flow profile for working days and weekends.

A total of 137 days of historical data were available. From these, 116 days were pre-treated and arranged together for ARMA model training. The order of the model was defined as na=7,nc=7, based on Box et al. (1970).

III. ARMA model validation

Once trained, the ARMA model for multi-step future flow prediction was validated under different weather conditions. First, the model was tested for dry weather conditions. Results are presented in Figure 3-17. As we can observe, ARMA model was able to predict the flow behaviour with extremely good accuracy, even 6 hours ahead in time. However it is also important to consider that the flow profile was very similar to the typical daily flow profile, which did not represent a real challenge for the predictive model.

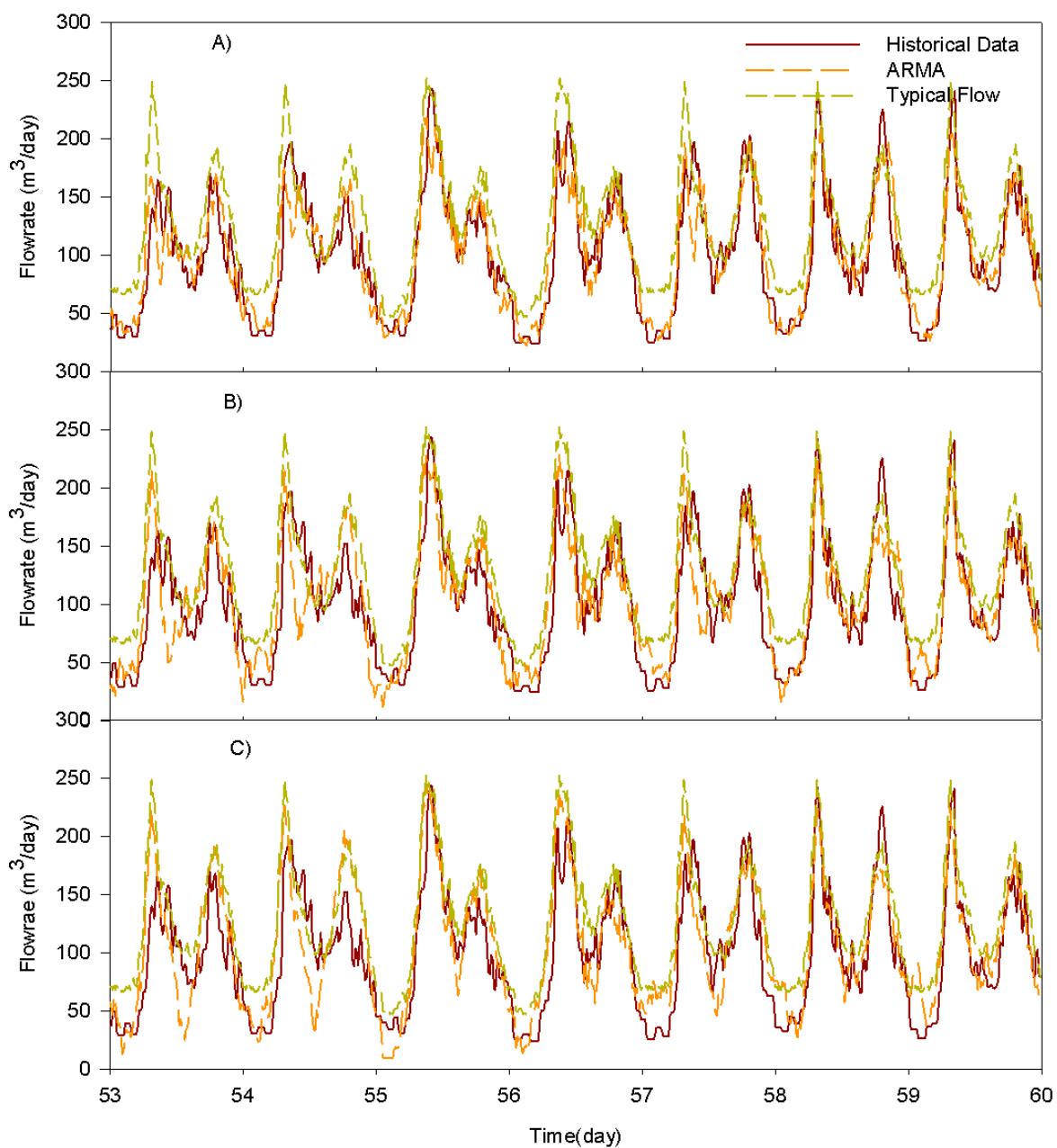


Figure 3-17. Future flow prediction in dry weather. A) One hour ahead; B) Three hours ahead; C) Six hours ahead.

The next step was to assess the performance of the ARMA model during rain weather conditions (intermittent rain). Rainfall is expected to affect flow due to infiltrations, deviating from the typical flow profile. Next, Figure 3-18 shows the model prediction. As can be seen, ARMA model predicted future flow with good accuracy. A slight delay on the prediction was

detected when rain started to affect the system. This delay was more significant for longer prediction times due to the error accumulation during the multi-step prediction.

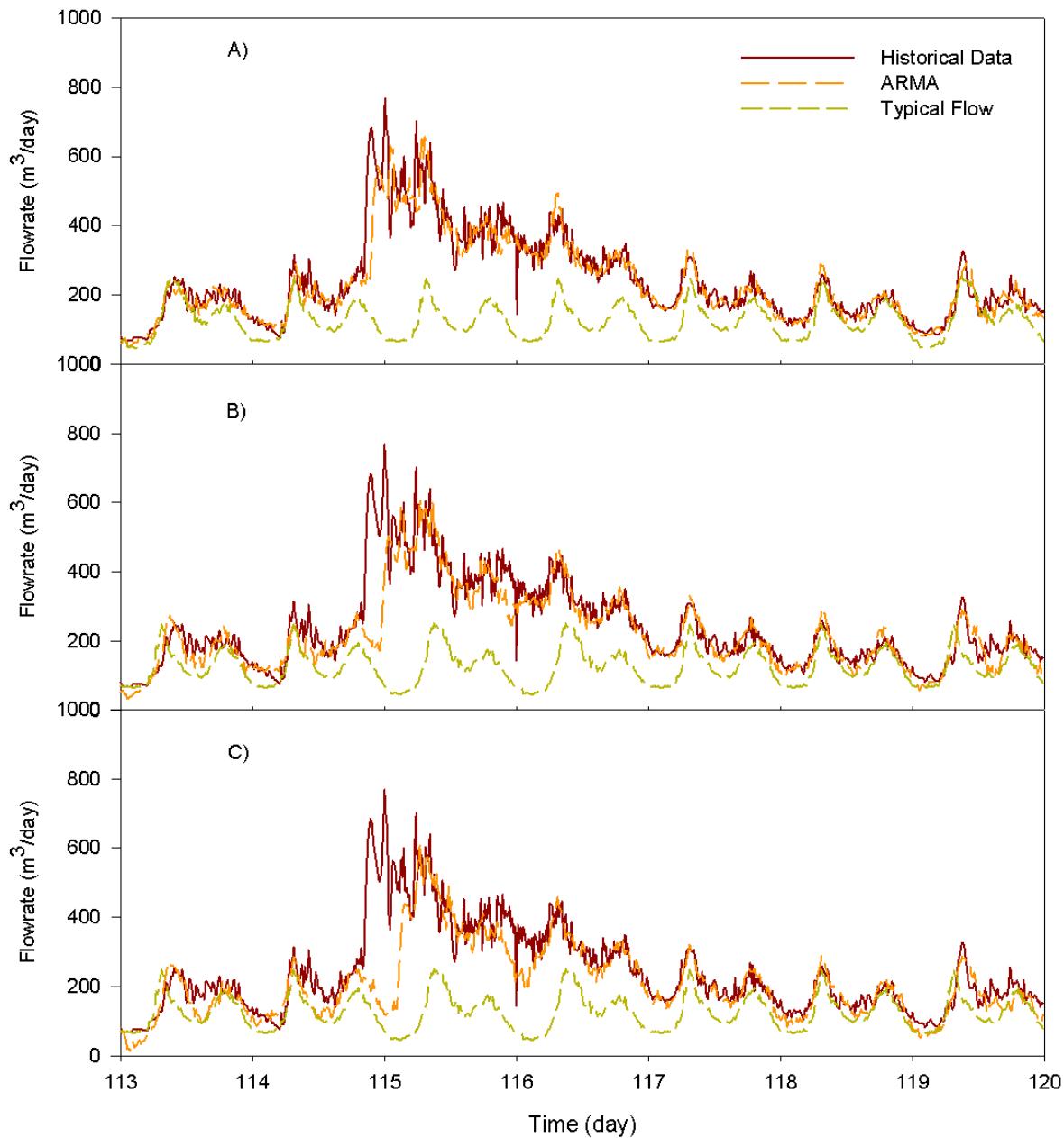


Figure 3-18. Future flow prediction in rain weather. A) One hour ahead; B) Three hours ahead; C) Six hours ahead.

Finally, ARMA model was tested under storm weather conditions to evaluate the model prediction under extreme conditions. Predicted flow is presented in Figure 3-19. As can be seen, predicted results were reasonably close to the historical flow, although the above mentioned delay was also detected.

As an overall conclusion, ARMA model allowed predicting future flow with reasonably good accuracy under different weather conditions. This is a significant improvement to the use of historical typical HRT profiles. Nevertheless, it is also important to highlight the delay on the prediction under changing conditions, which is accented at longer prediction times.

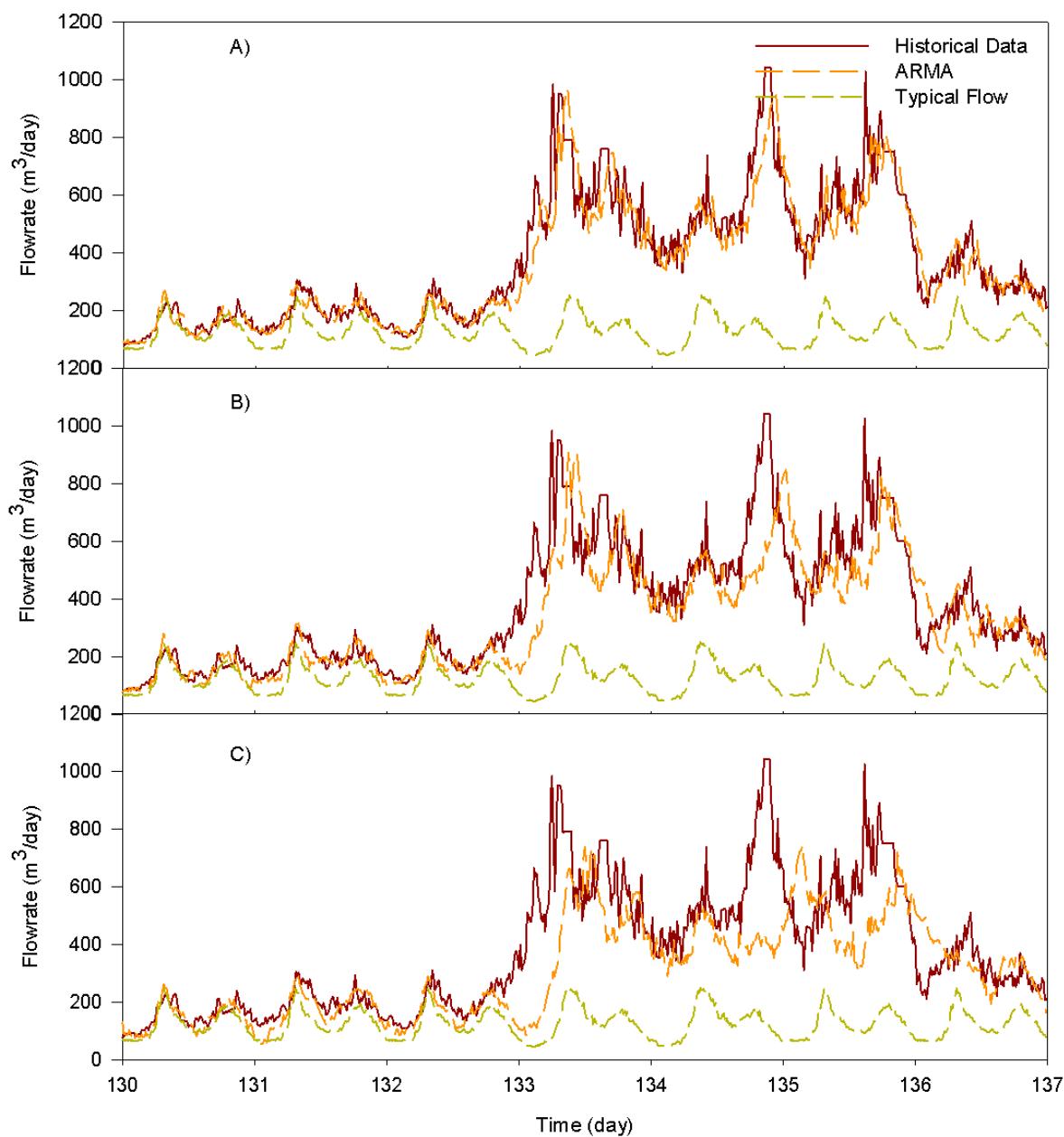


Figure 3-19. Future flow prediction in storm weather. A) One hour ahead; B) Three hours ahead; C) Six hours ahead.

Feedback Loop

As stated before, a feedforward controller determines the control action based on the measurement of perturbations (in this case, pH upstream and predicted HRT in the pipe). Although effective and efficient, feedforward controllers are subject to a certain degree of uncertainty. All disturbances need to be taken into account and predicted accurately, otherwise the controller may perform poorly. Since the great dynamism of sewer systems, a feedback loop could help adjusting the dosing rate based on the long-term evolution of the controllable variable (in this case pH at the discharge point). When designing the control there are several important aspects to take into consideration: i) what is the feedback signal and ii) how to adjust

the dosing rate. Next, the selection of the feedback signal and the development of the control rule are presented.

I. Feedback signal

Due to the plug flow nature of sewer systems, a pH measurement at the discharge point cannot be directly used as an input for the feedback loop. However, the mid/long-term performance of the controller can be assessed by calculating the average discharge pH, and this can be used to adjust the overall dosing. The calculation of the average pH (pH_{ave}) is present in the following equation (7):

$$pH_{ave}(n) = \alpha * pH_n + (1 - \alpha) * pH_{ave}(n - 1) \quad (7)$$

where $pH_{ave}(n)$ is the weighted average pH of present time, $pH_{ave}(n - 1)$ is the weighted average pH of previous time, pH_n is the present pH, and α is a weighting factor ($0 < \alpha < 1$).

Equation 7 can be expressed as:

$$pH_{ave}(n) = (1 - \alpha)^{n-1} * \alpha * pH_1 + (1 - \alpha)^{n-2} * \alpha * pH_2 + \dots + (1 - \alpha) * \alpha * pH_{n-1} + \alpha * pH_n \quad (8)$$

The weighting factor α has a critical role since decides whether the feedback signal relies more on recent pH measurements or takes also into consideration historical pH. This was evaluated in Figure 3-20, which depicts the impact of different α value ($\alpha = 0.0002, 0.0001, 0.0008, 0.00005, 0.000004, 0.000003, 0.000001$) for the coefficients of pH in Equation 8.

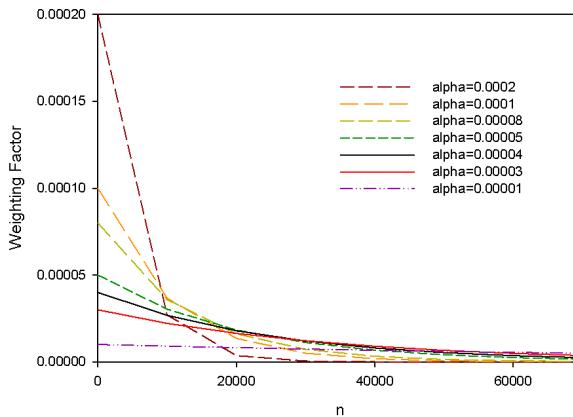


Figure 3-20. Different weight factors based on different α .

Aiming to diminish the variation of pH_{ave} due to the durative variation of pH signal, a much smaller α ($\alpha = 0.00001$) was chosen. Hence, the weighting factor for recent pH measurements will be much smaller and sudden pH changes in the present will have a much smaller impact on pH_{ave} .

II. Control rule

The control rule is the strategy to reduce the error between a set point and the feedback signal. Based on average pH calculation a proportional control rule was designed to adjust Mg(OH)₂ dosing rate. The control rule is presented in Equation 9:

$$R_{fb} = k * (pH_{sp} - pH_{ave}) \quad (9)$$

Where R_{fb} is the control rule, k is a proportion constant that need to be evaluated, pH_{sp} is set point of pH, pH_{ave} is average pH calculated by last part.

The k value governs the control. Very large k values could lead to too high variations of pH, whereas too small k could result in insufficient compensation. Hence, choosing a suitable k value must consider the dosing rate of feedforward control and the error of pH_{sp} and pH_{ave} .

III. Control scheme

The control algorithm for the optimised dosing of Mg(OH)₂ will be composed of a feedforward and a feedback loop. The feedforward loop will predict the amount of Mg(OH)₂ required to increase the pH to 9 and the additional dosing to balance proton production. Moreover, the future HRT will be predicted by the ARMA model using the current flow measurements. On the other hand, the feedback loop will adjust the dosing based on the overall performance. A scheme of the control algorithm is depicted in Figure 3-21.

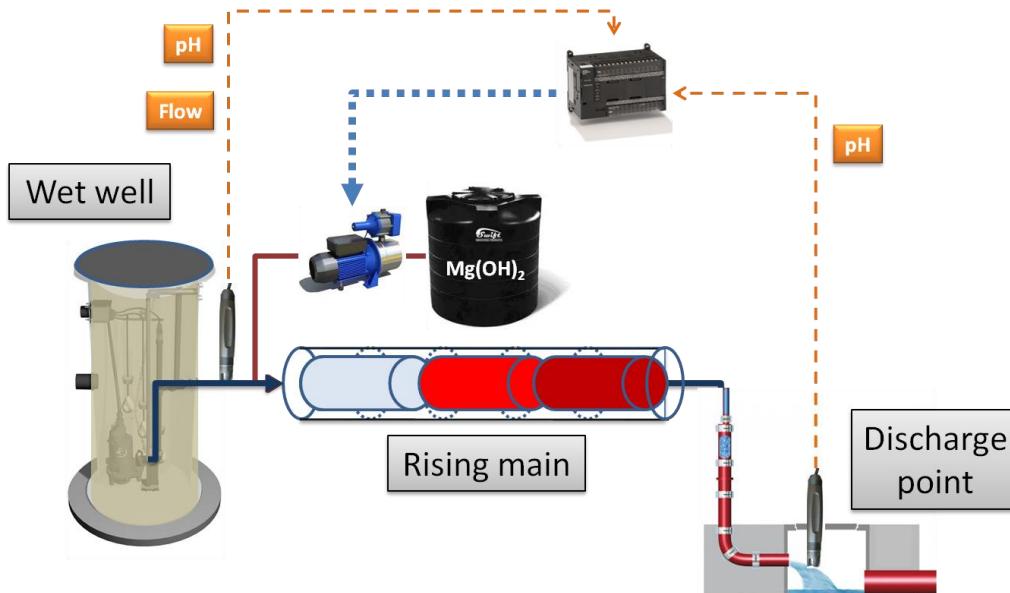


Figure 3-21. Control algorithm scheme for Mg(OH)₂ dosing.

3.2.3 Nitrate

3.2.3.1 Background

Nitrate salts have been used over the last 70 years to control odours and sulfide production in many environments (Bentzen et al., 1995). It was thought that nitrate supply provided with a more favourable electron acceptor for heterotrophic bacteria, preventing sulfide production. However, recent studies demonstrated that the actual mechanism leading to sulfide mitigation is the biological oxidation of H₂S to SO₄²⁻ by means of nitrate reducing-sulfide oxidising bacteria (NR-SOB) (Mohanakrishnan et al., 2009). The same study stated that nitrate does not have any inhibitory effect over SRB. It is also important to highlight that nitrate can be used by heterotrophic bacteria to oxidise organic matter, which would increase nitrate consumption.

3.2.3.2 Control Design

This section discusses the optimal location for nitrate dosing and how to determine suitable location for new nitrate dosing facilities. Moreover, the development of the control methodology and the calculation of nitrate dosing requirements are also described.

Dosing Location

An upstream nitrate dosing at a sufficient rate would ensure anoxic conditions along the whole pipe. However due to the nitrate consumption by heterotrophic bacteria, the amount of nitrate to be dosed would be extremely high, entailing very high chemical costs. In this respect a downstream location would be more cost-effective.

If a dosing location close to the discharge is chosen, nitrate dosing should be sufficient to oxidise sulfide generated upstream and ensure anoxic conditions downstream the dosing location to prevent further sulfide build up. This will largely depend on several factors such as the pipe diameter, downstream Hydraulic Retention Time (HRT), sulfide concentration at the dosing point and the nitrate consumption rate for both sulfide oxidation and heterotrophic organic matter oxidation.

Given this, the selection of the optimal location for a dosing site is a complicated task. A suitable location for nitrate dosing (x) can be theoretically determined from Equation 10.

$$x = \frac{\pi \cdot D \cdot L \cdot (r_{B,ox} - (TDS_0 - TDS_f) \cdot Q_L)}{\pi \cdot D \cdot (r_B + r_{B,ox})} \quad (10)$$

Where D is the pipe diameter (m), L is the pipe length (m), r_B the sulfide production rate of the biofilm (gS/m²·d), $r_{B,ox}$ the biological sulfide oxidation rate of the biofilm (gS/m²·d), TDS_0 the total dissolved sulfide at the beginning of the rising main (g/m³), TDS_f the total dissolved sulfide at the end of the rising main (g/m³) and Q_L is the sewage flow (m³/d).

Dosing requirements

Assuming a nitrate dosing station located in a downstream section, close to the rising main discharge point, nitrate requirements for an optimised dosing depend basically on two factors: i) the amount of sulfide produced upstream that needs to be oxidised and ii) the nitrate that will be consumed for heterotrophic organic matter oxidation during the transport time between the dosing site and the discharge point/control point. Sulfide and nitrate profiles along the pipe are illustrated in Figure 3-22.

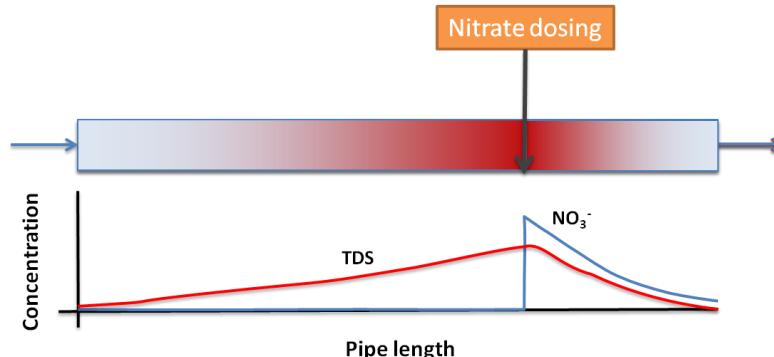
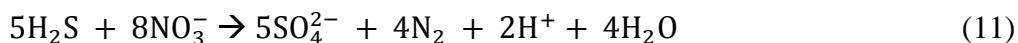


Figure 3-22. Nitrate dosing scheme.

I. Sulfide produced upstream

In the presence of nitrate, and provided sufficient retention time, sulfide produced upstream the dosing point will be completely oxidised by NR-SOB downstream that location. This process mainly occurs on the sewer biofilm and the stoichiometry is presented in Equation 11.



According to this equation, the amount of nitrate required for sulfide oxidation to sulfate is $0.7\text{gN-NO}_3^-/\text{gS-H}_2\text{S}$.

From the control point of view, this can be easily implemented if sulfide concentration before the dosing point is known. This can be easily measured using a s::can UV/VIS spectrometer. However s::can instrumentation for sulfide measurement is expensive and may not be affordable in all systems. When this option is not available, different alternatives could be put in place, such as the use of typical sulfide profiles.

Another alternative for this would be the estimate of sulfide levels based on HRT. Sulfide production depends largely on hydraulic retention time of the sewage in the pipe, as illustrated in Figure 3-23. In this light, for a given pipe, sulfide concentration can be estimated with reasonable accuracy if HRT is known.

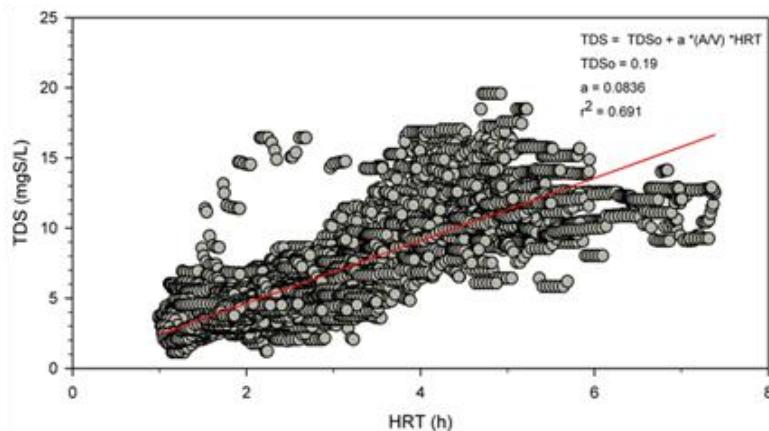


Figure 3-23. Total dissolved sulfide vs. hydraulic retention time. Field data from UC09 (Allconnex Water).

II. Heterotrophic nitrate consumption downstream

As stated before, nitrate is also used as an electron acceptor by heterotrophic bacteria to oxidise organic matter. This implies that apart from the stoichiometric nitrate required to oxidise sulfide, an additional amount of nitrate needs to be also supplied. Heterotrophic nitrate consumption occurs mainly in the biofilm. Hence, the area to volume (A/V) relationship of the pipe determines the volumetric consumption rate. The HRT of the sewage before being discharged is also critical because it is a measure of the reaction time. The longer the retention time in the pipe, the higher the nitrate consumption rate.

Nitrate consumption by heterotrophic bacteria can be modelled using a Monod kinetic according to the following equation:

$$r_{\text{area}} = r_{\text{area,max}} \cdot \frac{S_{\text{NO}_3^-}}{K_{\text{NO}_3^-} + S_{\text{NO}_3^-}} \quad (12)$$

Where r_{area} is heterotrophic nitrate consumption rate of the biofilm (mg N/L); $r_{\text{area,max}}$ is the maximum nitrate consumption rate of the biofilm; $S_{\text{NO}_3^-}$ is the concentration of nitrate in the boundary layer of biofilm (mg N/L) and $K_{\text{NO}_3^-}$ is the half-saturation substrate limitation constant for nitrate in the biofilm.

This expression can be converted to the following derivative equation (Equation 13), which takes into consideration the diameter and time.

$$\frac{d(S_{\text{NO}_3^-})}{dt} = -r_{\text{area,max}} * \frac{A}{V} * \frac{S_{\text{NO}_3^-}}{K_{\text{NO}_3^-} + S_{\text{NO}_3^-}} \quad (13)$$

Hence, for a given pipe diameter and retention time, the amount of nitrate to be dosed to reach the desired concentration at the discharge point can be estimated. However, this is a non-linear function and nitrate dosing needs to be back calculated from the desired set-point (end point). Only numerical solutions can be obtained for this function. In this case, this was solved using a Newton iteration method.

Another important aspect is the mixing. Sewer systems are usually operated in short pumping events followed by stand-by periods of variable duration depending on the wastewater flow. During a pumping event, sewage is mixed and substrate is available for the biofilm, allowing a maximum activity. Shortly after the pump is stopped, the pipe goes under quiescent conditions and, once substrate available at the boundary layer of the biofilm is consumed, reaction rates dramatically decrease. In this light it is important to consider quiescent conditions, since activity could be reduced up to 90% during these periods. This is illustrated in Figure 3-24, for the last pipe section of the UC09 (Allconnex Water, Gold Coast) with a length of 240 m and an average daily flow of 120 m³/d.

As can be seen, in periods with less pumping events and high HRT (up to 4 hours), biofilm activity decreased up to 80% due to quiescent conditions. On the contrary, during the rest of the day activity was close to its maximum due to the frequent pumping which provided mixing conditions in the bulk liquid.

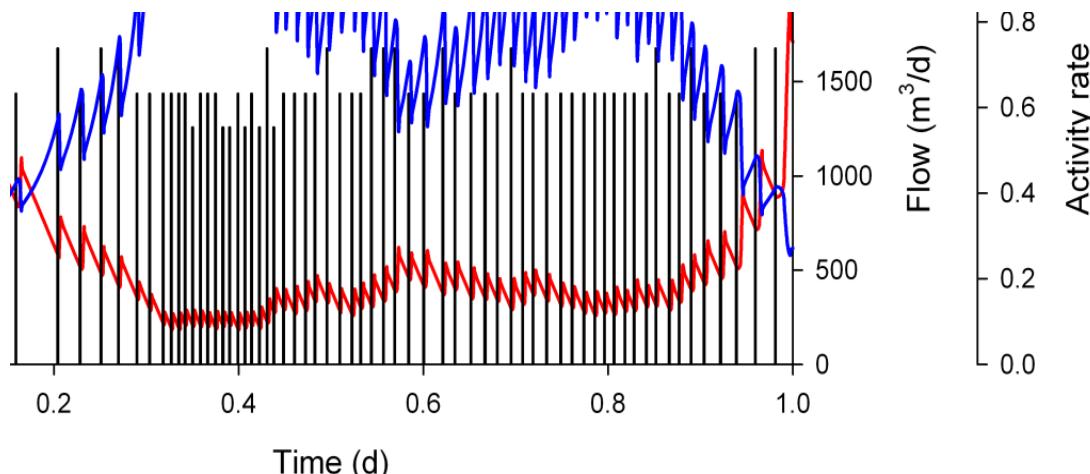


Figure 3-24. Pumping profile, HRT downstream and activity corrected by quiescent conditions.

Future flow prediction

The amount of nitrate to be dosed depends of the time the wastewater will be spend in the last section of the pipe. This cannot be measured, since depends on future flow, and needs to be estimated. Nitrate dosing occurs close to the discharge point. In this respect the use of typical HRT profiles is a simple approach that should yield reasonably good results, although given the high dynamism of sewer systems, future flow prediction based on ARMA models (described in section 2.2.3) should be the preferred option.

Feedback Loop

The present nitrate on-line control algorithm has a feedforward nature, relying on prediction to calculate the suitable dosing rate. In this light, a feedback loop could be put in place to adjust the dosing based on weekly average nitrate concentration at the discharge point (see Section 2.2.4). Nevertheless, this would require additional instrumentation, and two different alternatives would be possible.

1. Nitrate sensor
2. S::can UV/VIS spectrometer

Currently nitrate sensors are more affordable than s::can sensors. However it is also important to bear in mind that the second option would allow also the measurement of sulfide levels at the discharge point which could be used to fine-tune the control too.

Control scheme

The control algorithm for the optimised dosing of nitrate will be composed of a feedforward and a feedback loop. The feedforward loop will predict the amount of nitrate required to oxidise sulfide produced upstream the dosing location and ensure anoxic conditions of sewage until its discharge. Future HRT will be predicted by the ARMA model using the current flow measurements. On the other hand, the feedback loop will adjust the dosing based on the overall performance. A scheme of the control algorithm is depicted in Figure 3-25.

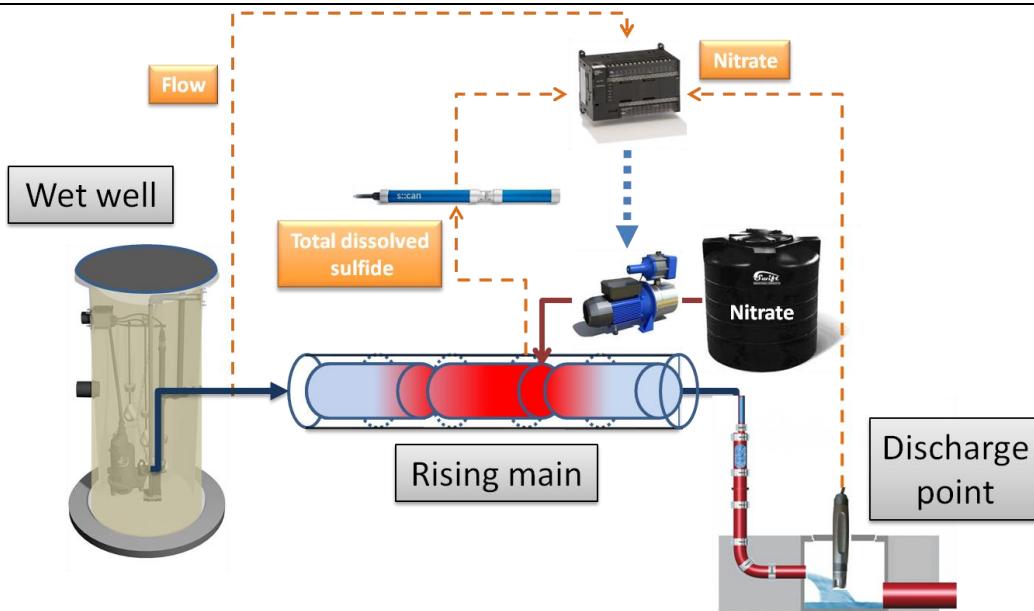


Figure 3-25. Control algorithm scheme for nitrate dosing.

3.2.4 Oxygen

3.2.4.1 Background

Oxygen is one of the most used chemicals for the control of sulfide production (Hvitved-Jacobsen, 2002; USEPA, 1992). Oxygen was thought to prevent anaerobic conditions, avoiding H₂S production. However, Gutierrez et al. (2008a) demonstrated that oxygen relies on sulfide oxidation as the mechanism for H₂S control. This can be chemical, occurring at the bulk liquid, or biological, taking place mainly in the biofilm. Organic matter is oxidized under aerobic conditions, with the subsequent consumption of oxygen. Because this process primarily occurs in the biofilm (Sharma et al., 2011), oxygen is used more efficiently in pipes with large diameters (i.e. low A/V ratios) which usually deal with larger flows. However, to be effective this chemical has to be dosed at suitable location and rates (Gutierrez et al., 2008a).

3.2.4.2 Control Design

This section discusses the optimal location for oxygen dosing and how to determine suitable location for new oxygen dosing facilities. Moreover, the development of the control methodology and the calculation of oxygen dosing requirements are also described.

Dosing Location

If oxygen was supplied at the beginning of the pipe, complete control of sulfide at the discharging point would require the entirety of the pipe to be oxic, which is not possible with the existing method of dosing (i.e. into wastewater when the pump is running) (Gutierrez et al., 2008a). In this respect a dosing location close to the discharge point would be more cost-effective. Oxygen dosing should be sufficient to oxidise H₂S generated upstream and ensure aerobic conditions downstream the dosing location. This will largely depend on the pipe diameter, downstream Hydraulic Retention Time (HRT), sulfide concentration and oxygen consumption rate for both sulfide oxidation and heterotrophic organic matter oxidation.

Given this, the selection of the optimal location for a dosing site is a complicated task. A suitable location for oxygen dosing (x) can be theoretically determined from Equation 14.

$$x = \frac{\pi \cdot D \cdot L \cdot (4 \cdot r_{B,ox} + r_{C,ox} \cdot D) - 4 \cdot (TDS_0 - TDS_f) \cdot Q_L}{\pi \cdot D \cdot (4 \cdot r_B + 4 \cdot r_{B,ox} + r_{C,ox} \cdot D)} \quad (14)$$

Where D is the pipe diameter (m), L is the pipe length (m), r_B the sulfide production rate of the biofilm (gS/m²•d), $r_{B,ox}$ the biological sulfide oxidation rate of the biofilm (gS/m²•d), $r_{C,ox}$ the volumetric chemical sulfide oxidation rate (gS/m²•d), TDS_0 the total dissolved sulfide at the beginning of the rising main (g/m³), TDS_f the total dissolved sulfide at the end of the rising main (g/m³) and Q_L is the sewage flow (m³/d).

Dosing requirements

Assuming an oxygen dosing station located in a downstream section, close to the rising main discharge point, oxygen requirements for an optimised dosing depend basically on two factors: i) the amount of sulfide produced upstream that needs to be oxidised and ii) the oxygen that will be consumed for heterotrophic organic matter oxidation during the transport time between the dosing site and the discharge point/control point. Sulfide and oxygen profiles along the pipe are illustrated in Figure 3-22.

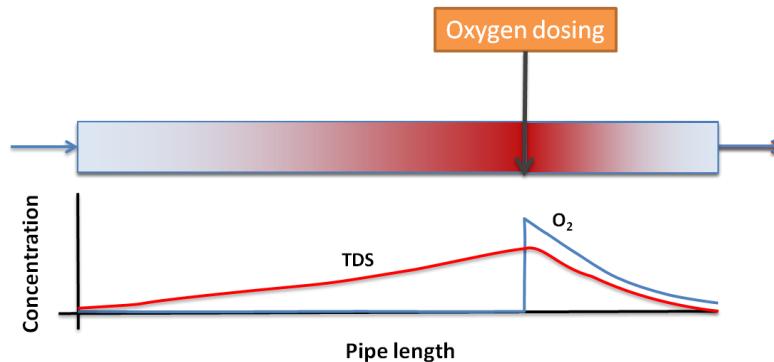


Figure 3-26. Oxygen dosing scheme.

I. Sulfide produced upstream

In the presence of oxygen, and provided sufficient retention time, sulfide produced upstream the dosing point will be completely oxidised, either biologically or chemically, first to sulfite and finally to sulfate (O'Brien and Birkner, 1977). The stoichiometry of these reactions is presented in Equations 15 and 16.



According to these, oxygen requirement for sulfide oxidation to sulfite is 1.5 gO₂/gS-S²⁻, whereas 2 gO₂/gS-S²⁻ are required to convert sulfide to sulfate.

From the control point of view, this can be easily implemented if sulfide concentration before the dosing point is known. This can be available through a s::can UV/VIS spectrometer. However s::can instrumentation for sulfide measurement is still quite expensive. When this option is not available, several alternatives could be put in place, such as sulfide level estimation using HRT upstream/pumping information, or the use of typical sulfide profiles.

Another alternative for this would be the estimate of sulfide levels based on HRT. Sulfide production depends largely on hydraulic retention time of the sewage in the pipe, as previously shown in Figure 3-23.

II. Heterotrophic oxygen consumption downstream

As stated before, oxygen is also used as an electron acceptor by heterotrophic bacteria to oxidise organic matter. This implies that apart from the stoichiometric oxygen required to oxidise sulfide, an additional amount of oxygen needs to be also supplied. Heterotrophic oxygen consumption occurs mainly in the biofilm. Hence, the area to volume (A/V) relationship of the pipe determines the volumetric consumption rate. HRT of the sewage before being discharge is also critical because it is a measure of the reaction time. The longer the retention time in the pipe, the higher oxygen consumption rate. Another important aspect is the mixing. Sewer systems are usually operated in short pumping events followed by stand-by periods of variable duration depending on the wastewater flow. During a pumping event, sewage is mixed and substrate is available for the biofilm, allowing a maximum activity. Shortly after the pump is stopped, the pipe goes under quiescent conditions and, once substrate available at the boundary layer of the biofilm is consumed, reaction rates dramatically decrease.

Oxygen consumption by heterotrophic bacteria can be modelled using a Monod kinetic according to the following expression:

$$r_{\text{area}} = r_{\text{area,max}} \cdot \frac{S_{O_2}}{K_{O_2} + S_{O_2}} \quad (17)$$

Where r_{area} is heterotrophic oxygen consumption rate of the biofilm (mg O₂/L); $r_{\text{area,max}}$ is the maximum oxygen consumption rate of the biofilm; S_{O_2} is the concentration of oxygen in the boundary layer of biofilm (mg O₂/L) and K_{O_2} is the half-saturation substrate limitation constant for oxygen in the biofilm.

This expression can be converted to the following derivative equation (Eq. 18), which takes into consideration the pipe diameter and retention time.

$$\frac{d(S_{O_2})}{dt} = -r_{\text{area,max}} * \frac{A}{V} * \frac{S_{O_2}}{K_{O_2} + S_{O_2}} \quad (18)$$

Hence, for a given pipe diameter and retention time, the amount of oxygen to be dosed to reach the desired concentration at the discharge point can be estimated. However, this is a non-linear function and the oxygen dosing needs to be back calculated from the desired set-point (end point). Only numerical solutions can be obtained for this function. In this case, this was solved using a Newton iteration method.

Another important aspect is the mixing. Sewer systems are usually operated in short pumping events followed by stand-by periods of variable duration depending on the wastewater flow. During a pumping event, sewage is mixed and substrate is available for the biofilm, allowing

a maximum activity. Shortly after the pump is stopped, the pipe goes under quiescent conditions and, once substrate available at the boundary layer of the biofilm is consumed, reaction rates dramatically decrease. In this light it is important to consider quiescent conditions, since activity could be reduced up to 90% during these periods. This is illustrated in Figure 3-27, for the last pipe section of the UC09 (Allconnex Water, Gold Coast) with a length of 240m and an average daily flow of 120 m³/d.

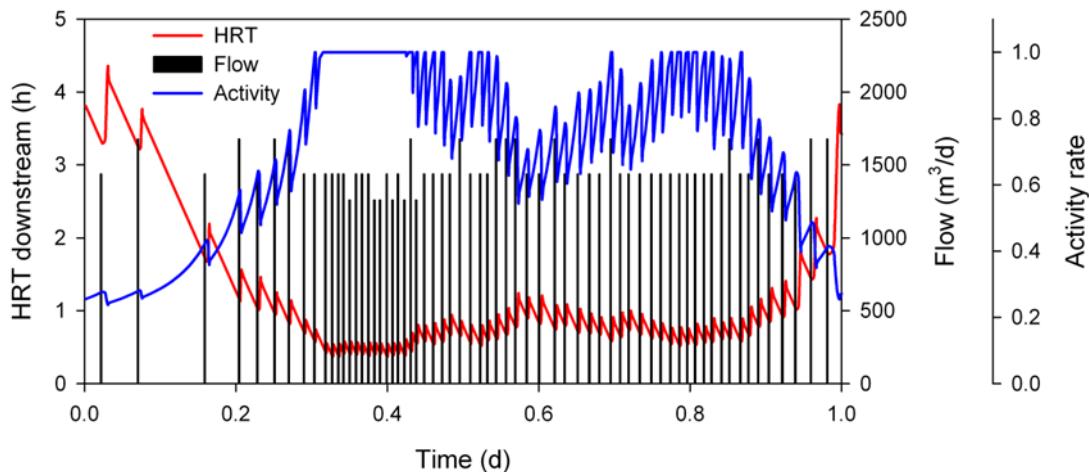


Figure 3-27. Pumping profile, HRT downstream and activity corrected by quiescent conditions.

As can be seen, in periods with less pumping events and high HRT (up to 4 hours), biofilm activity decreased up to 80% due to quiescent conditions. On the contrary, during the rest of the day activity was close to its maximum due to the frequent pumping which provided mixing conditions in the bulk liquid.

Future flow prediction

The amount of nitrate to be dosed depends of the time the wastewater will be spend in the last section of the pipe. This cannot be measured, since depends on future flow, and needs to be estimated. Nitrate dosing occurs close to the discharge point. In this respect the use of typical HRT profiles is a simple approach that should yield reasonably good results, although given the high dynamism of sewer systems, future flow prediction based on ARMA models (described in section 2.2.3) should be the preferred option.

Feedback Loop

The present oxygen on-line control algorithm has a feedforward nature, relying on prediction to calculate the suitable dosing rate. In this light, a feedback loop could be put in place to adjust the dosing based on weekly average oxygen concentration at the discharge point (see Section 2.2.4). Nevertheless, this would require additional instrumentation such as an oxygen sensor.

Control scheme

The control algorithm for the optimised dosing of oxygen will be composed of a feedforward and a feedback loop. The feedforward loop will predict the amount of oxygen required to oxidise sulfide produced upstream the dosing location and ensure aerobic conditions of sewage until its discharge. Future HRT will be predicted by the ARMA model using the current flow

measurements. On the other hand, the feedback loop will adjust the dosing based on the overall performance. A scheme of the control algorithm is depicted in Figure 3-28.

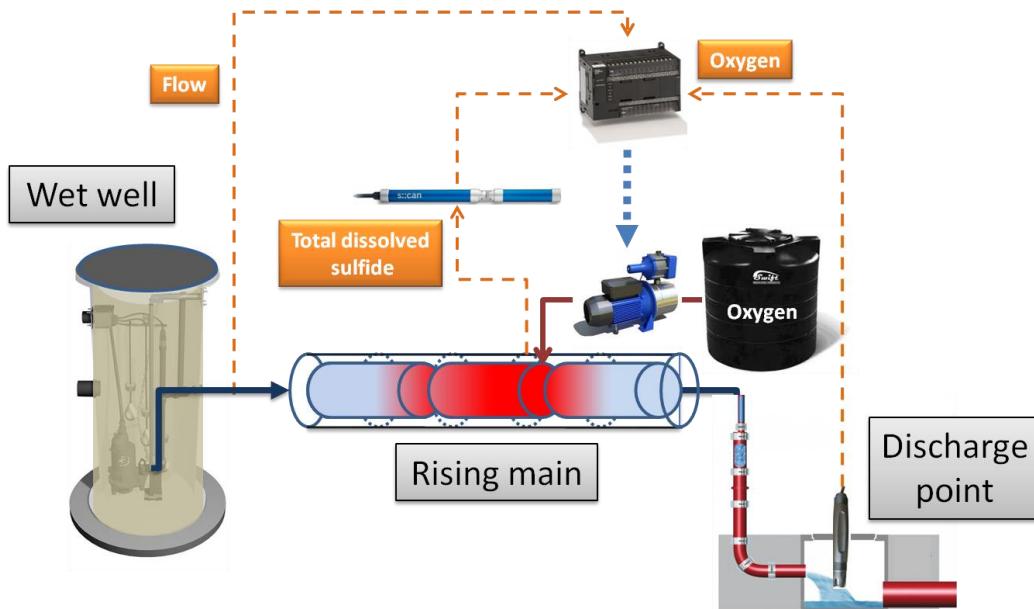


Figure 3-28. Control algorithm scheme for oxygen dosing.

3.2.5 Iron salts

3.2.5.1 Background

One of the most widely used method for H₂S mitigation is the addition of iron salts including ferrous chloride, ferric chloride and in some cases ferrous sulfate (Jameel, 1989; Padival et al., 1995). Ferrous ions (Fe²⁺) precipitate sulfide by forming highly insoluble metallic sulfide precipitates (WERF, , 2007). On the other hand, Ferric ions (Fe³⁺) oxidize sulfide to elemental sulfur while being reduced into Fe²⁺, which precipitates with sulfide to form ferrous sulfide precipitants (Dohnalek and Fitzpatrick, , 1983). The stoichiometry of these reactions can be found in Equations 19 and 20.



However, there is a large inconsistency between this theoretical stoichiometry and Fe:S ratios applied in real systems. For instance, (Jameel, 1989) found at laboratory experiments and field conditions typical doses between 3-7 mg FeCl₃ per mg of sulfide removed. Iron dose can be very dependent on sulfide concentration that wants to be reached. When aiming at lower Total Dissolve Sulfide (TDS) levels, higher ratios need to be applied (WERF, 2007). For example, in the Los Angeles sanitation district where FeCl₂ was added in the early 1990's to large diameter gravity sewers, a ratio of 7:1 was found necessary for 90% sulfide removal for dissolved sulfide concentrations higher than 4 mg S/l, and 15:1 and 100:1 for dissolved sulfide of between 1 and 4 mgS/L, and less than 1 mgS/L respectively (all ratios based on anhydrous FeCl₂ to dissolved sulfide on a weight basis) (Padival et al., 1995). This was theoretically

illustrated by Firer *et al.* (2008), who demonstrated the Fe:S molar ratio to be strongly dependent on wastewater pH, as illustrated in Figure 3-29.

The reason for this is the lower the pH, the less S²⁻ in equilibrium in the liquid phase, requiring higher Fe²⁺ concentrations to reach the point where FeS precipitates.

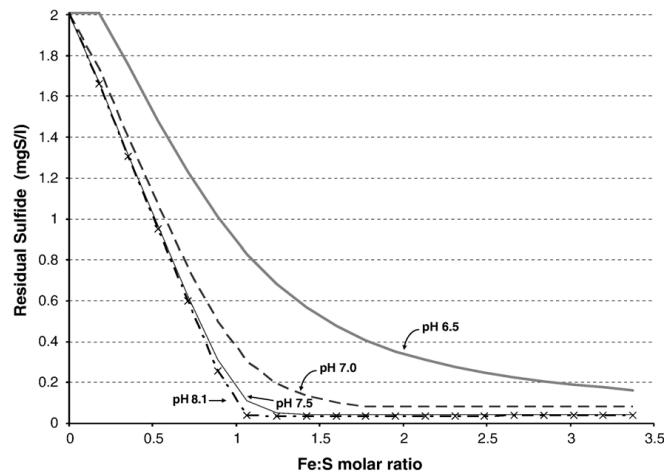


Figure 3-29. Theoretical sulfide concentration at equilibrium as a function of Fe(II) to S(-II) molar ratio applied at various pH values (Firer *et al.*, 2008).

Given the large pH dynamics in sewer systems (see Figure 3-30), this should be taken into consideration in the design of the control algorithm.

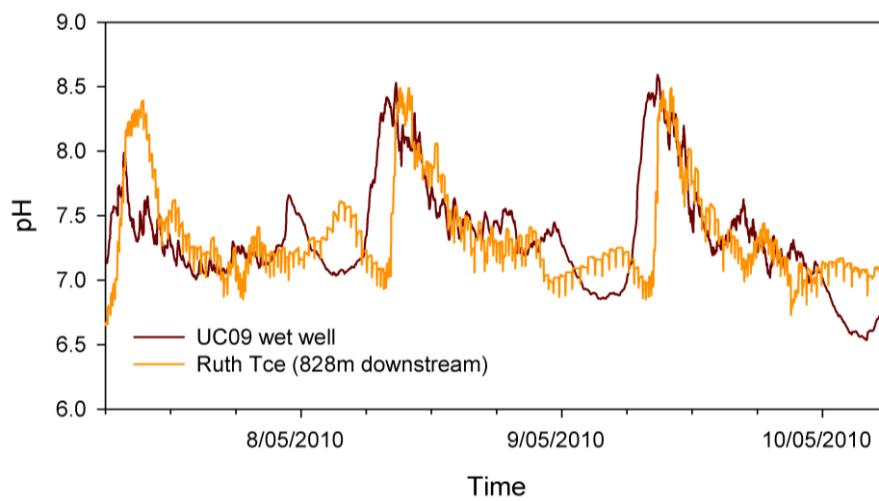


Figure 3-30. pH dynamics at the wet well and downstream location (828m) of the UC09 rising main.

3.2.5.2 Control Design

Dosing Location

The dosing location of iron salts is not important in terms of effectiveness of the chemical, as long as the hydraulic retention time (HRT) in the pipe after dosing allows sufficient time for sulfide precipitation (in the order of seconds according to Wei and Osseo-Asare (1995)). However, a recent lab-scale study demonstrated that the addition of Fe³⁺ significantly inhibits

SRB activity of anaerobic sewer biofilms (Zhang et al., 2009), although the same phenomenon is yet to be observed in real sewers. If this inhibitory effect is verified in real systems, iron salts should preferably be added at upstream locations. A further benefit of upstream dosage of iron salts is that sulfide would be controlled along the entire pipe. While iron salts may initially react with some other anions (e.g. phosphate and hydroxide) in the absence of sulfide, iron ions will be made available for sulfide precipitation when the latter is produced due to the lower solubility of FeS in comparison to iron phosphate and iron hydroxide precipitates (Zhang et al., 2009). However, the disadvantage of upstream dosing is that dosing control becomes more complex and challenging, potentially requiring pH and TDS prediction downstream.

Dosing requirements

Given the theoretical pH dependence of FeS precipitation, dosing requirements for sulfide control need to be calculated based on TDS and pH levels at discharge point. When conducting the dosing at the beginning of the pressure main, both parameters need to be estimated. Sulfide production will largely depend on hydraulic retention time of the sewage in the pipe, as illustrated in Figure 3-23. On the other hand pH downstream will be governed by sewage pH at the dosing point, but also by the bio-transformations taking place during its transportation along the pipe, which also depend on HRT.

HRT prediction

Hydraulic retention time of a certain wastewater slug can be predicted using an Autoregressive-Moving Average (ARMA) model, a black-box model in which both autoregression analysis and moving average methods are applied to a time series to predict future values. The model needs to be calibrated for every different site. This method has been successfully applied to future flow prediction of time series from UC09 rising main. A detailed summary of the model development and its predictive capacity under different weather conditions (dry weather, intermittent rain and storm) is presented in Section 3.2.2.2.

pH prediction at the discharge point

As stated before, pH at the discharge depends on several factors, among them some of the most important ones are pH at the influent, retention time and buffer capacity of the wastewater. Previous field studies demonstrated that buffer capacity is almost constant along the day. Hence, when aiming at pH prediction at discharge the two factors to take up are pH influent and HRT. The impact of both factors is assessed in Figure 3-31.

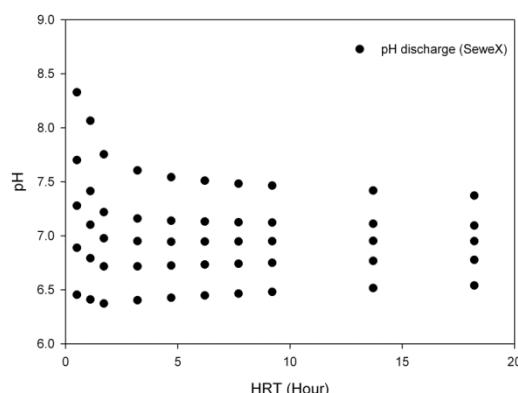


Figure 3-31. pH at discharge as a function of influent pH and HRT.

A model to predict pH downstream based on these two parameters has been developed using simulated data. Predicted pH results are compared to SeweX model pH at discharge (Figure 3-32).

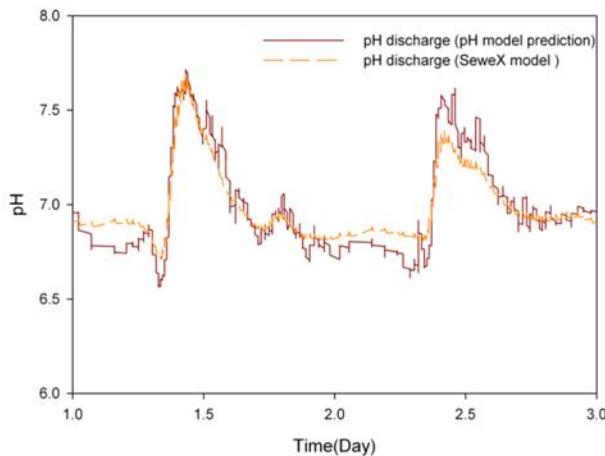


Figure 3-32. Simulated and predicted pH at discharge point.

As can be observed, pH model predicted with good accuracy the pH dynamics, using as inputs pH at the influent and historical HRT. Finally it is important to state that slight biases on HRT prediction should not have a critical impact on pH prediction.

pH prediction at the discharge point

Given the plug-flow nature of sewer systems, upstream dosing locations rely on feedforward controllers to determine the control action based on the measurement of perturbations (in this case, pH upstream and estimated HRT in the pipe). Since the great dynamism of sewer systems, a feedback loop could help adjusting the dosing rate based on the long-term evolution of the controllable variable (in this case TDS at the discharge point). Similarly to the previously developed Mg(OH)₂ control algorithm, a weighted weekly average of the total dissolved sulfide concentration at the discharge point will be used to adjust the dosing. This can be calculated following the guidelines of Section 2.2.4. Apart from a s::can sensor, a pH probe is also required to determine TDS concentration downstream. In this light, this pH signal could be additionally used to assess the pH prediction at the discharge point and, if necessary, re-adjust the model.

Control scheme

The control algorithm for the optimised dosing of iron salts will be composed of a feedforward and a feedback loop. The feedforward loop will predict pH and TDS downstream based on flow measurements and pH at the wet well, and based on that calculate the theoretical iron dosing requirements. On the other hand, the feedback loop will adjust the dosing based on the overall performance. The feedback loop will also assess the pH prediction and re-adjust the pH prediction model if necessary. A scheme of the control algorithm is depicted in Figure 3-33.

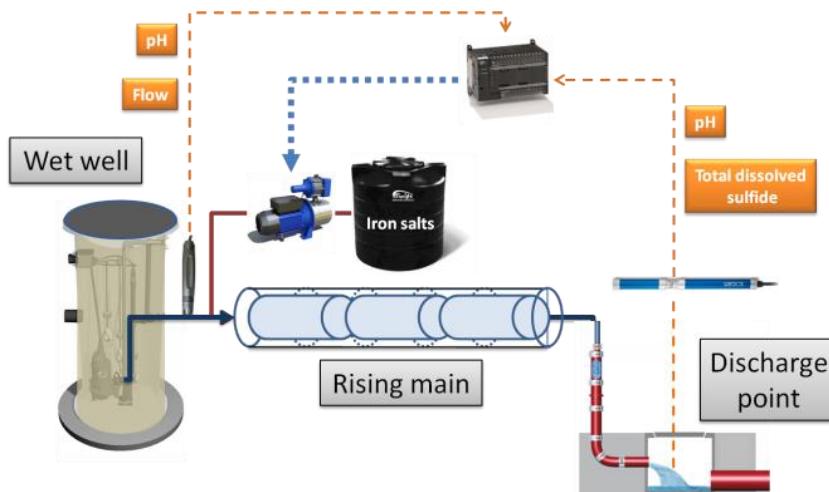


Figure 3-33. Control algorithm scheme for iron dosing.

3.2.6 Caustic shock

3.2.6.1 Background

An alternative strategy to continuous chemical dosing for sulfide control is the caustic shock, based on a drastic increase of the sewage pH level (10-12) for a short time period (Melbourne, 1989). Such a pH rise allows the suppression of SRB and MA, responsible for sulfide and methane production, respectively (O'Gorman et al., 2011). In contrast to the previously described chemicals, caustic is dosed intermittently, and sulfide production is usually completely recovered within 1–2 weeks. In this respect, to maintain low production of sulfide, pH shock has to be applied regularly (e.g. weekly) (Gutierrez et al., 2009).

3.2.6.2 Control Design

Dosing Location

Caustic shock is intermittently dosed in sewer pipes to kill/inhibit SRB growing attached to the walls of pressure mains. To be completely effective, this chemical should be always dosed at the beginning of the pipe to ensure SRB suppression in the whole pipe.

Dosing requirements

Caustic shock aims to increase the pH of the sewage to high levels (pH 10-12) during a short time period. Dosing requirements depend basically on sewage pH, buffer capacity of the wastewater and the desired pH set-point to be reached.

Field studies conducted by SP6 showed that even during a caustic shock at very high pH (pH 10.5-11.5), biological transformations may proceed, decreasing sewage pH. The amount of NaOH dosed has to be sufficient to ensure all sections of the pipe are exposed at least to the desired set-point during the whole pre-defined exposure time. In this light the initial pH at the wet well needs to be accurately estimated to minimise chemical costs and prevent any deterioration of the assets (pumps, pipes and valves) and negative effects over the WWTP due to overdosing. The pH decrease will largely depend on sewage buffer capacity and its retention

time in the pipe. The suitable initial pH to reach the desired set-point can be estimated following a similar methodology as Section 5.2.4. This needs to be assessed for different HRT and wastewater buffer capacities.

Once determined the initial pH to be reached at the wet well, NaOH dosing can be controlled using a combined feedforward-feedback loop. pH at the wet well will be continuously monitored. Dosing will take place before pumping events, based on sump level. Half of the theoretically required NaOH will be dosed based on a titration curve, whereas the rest will be added by the feed-back loop until reaching the desired set-point.

Exposure time

The exposure time is one of the critical aspects of the methodology. Too short exposure times may not be sufficient to suppress SRB, whereas the extension of this increases chemical costs. Dosing duration to reach certain exposure time needs to be properly timed and will depend on future flows, requiring HRT prediction.

Frequency

Although caustic shock can completely stop sulfide production from rising mains, SRB community develops again and sulfide production is resumed in days/weeks. It is difficult to define a dosing frequency, since this will depend on the characteristics of the system, flow dynamics, temperature and degree of acclimation of the biofilm to high pH. In this respect, the use of on-line sensors such as s::can or Odalog will allow to monitor recovery of SRB activity and automatically adjust the dosing frequency.

Dosing scheme

The control algorithm for the optimised dosing of NaOH for caustic shock will be composed of a feedforward and a feedback loop. This will allow achieving the required pH in the wet well. Flow measurements will be used to predict future flow and determine dosing duration to ensure a suitable exposure time. Finally, dosing frequency will be controlled using an Odalog/s::can sensor at discharge. A scheme of the control algorithm is depicted Figure 3-34.

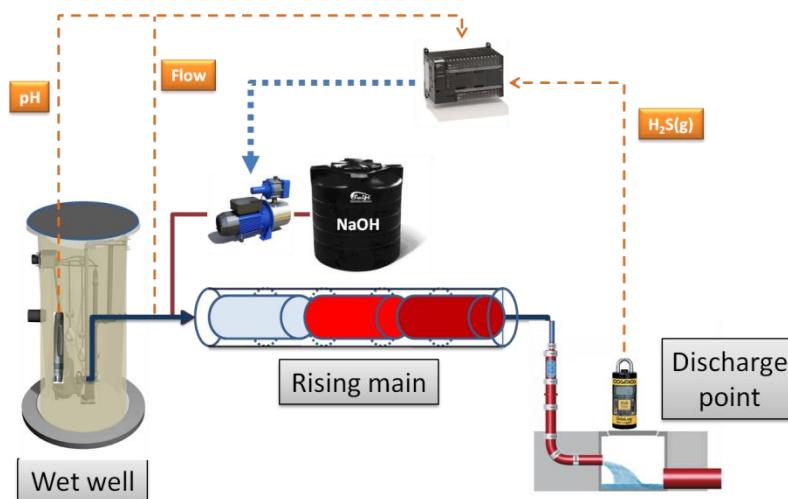


Figure 3-34. Control algorithm scheme for caustic shock.

3.2.7 Free nitrous acid

3.2.7.1 Background

Free nitrous acid (FNA), either dosed alone or together with hydrogen peroxide, was revealed to be biocidal to the sewer biofilms, including sulfate reducing bacteria and methanogens (Jiang et al., 2011b; Jiang and Yuan, 2013). This was further developed as a sulfide control strategy in sewer systems by optimizing the dosing parameters like dosing concentration, exposure time and dosing interval (frequency) (Jiang et al., 2011a). In contrast to the previously described chemicals including nitrate, oxygen, magnesium hydroxide and iron salts, FNA is dosed intermittently, and sulfide production is usually recovered within 1–2 weeks. To maintain low production of sulfide all the time, FNA needs to be dosed regularly at a carefully designed interval.

3.2.7.2 Control Design

Dosing Location

FNA is intermittently dosed in sewer pipes to kill/inhibit SRB attached to the walls of pressure mains. To be completely effective, this chemical should be always dosed at the beginning of the pipe to ensure SRB suppression in the whole pipe.

Dosing requirements

As FNA is used as a biocidal agent, it is thus important to inactivate the target microbes with adequate concentration in the sewage. Due to the fact that FNA concentration is dependent on both nitrite concentration and the sewage pH. Two chemicals are generally required, i.e. nitrite salt and acid. To minimize the potential negative effects of low pH to the sewer structures, a pH level around 6 is recommended. Based upon this pH level, the nitrite concentration can be thus determined from the pre-determined biocidal level of FNA using the following equation.

$$\text{NO}_2^-\text{-N} = \frac{14}{46} \times \text{FNA} \times K_a \times 10^{pH}$$

where K_a is the ionization constant of the nitrous acid equilibrium equation. The value of K_a is determined by $K_a = e^{-2300/(273+^{\circ}\text{C})}$.

Previously the biocidal level of FNA was determined to be around 0.26 mgN/L, which corresponds to 100 mgN/L of nitrite salt in a sewage at pH level of 6. It should be noted that the minimal biocidal level of FNA for a real sewer needs to be trailed *in situ* due to many other environmental factors like dilution and imperfect plug flow in sewer pipes.

Exposure time

The exposure time is one of the critical aspects of the methodology. Too short exposure times may not be sufficient to suppress SRB, whereas the extension of this increases chemical costs. The exposure time for FNA exposure was reported to be as short as a few hours in lab sewers and real sewers (Jiang et al., 2011a; Jiang et al., 2013). In real sewers, the actual dosing duration to reach certain exposure time needs to be properly timed and will depend on future flows, requiring HRT prediction or using typical HRT profiles.

Dosing interval/Frequency

Although FNA can completely stop sulfide production from rising mains, SRB community develops again and sulfide production is resumed in days/weeks. Generally speaking, the dosing interval is determined by the control efficiency of H₂S in sewers {Jiang, 2013 #1507}. However, the actual interval is affected by the flow dynamics, temperature, rainfall and possible acclimation of SRB to FNA. The use of on-line sensors such as s::can or Odalog will allow to monitor recovery of SRB activity and automatically adjust the dosing frequency.

Dosing scheme

The control algorithm for the optimised dosing of FNA will be composed of a feedforward and a feedback loop. This will allow achieving the required FNA level in the wet well for a specified time and with a specified interval. Flow measurements will be used to predict future flow and determine dosing duration to ensure a suitable exposure time. Finally, dosing frequency will be controlled using an Odalog/s::can sensor at discharge. A scheme of the control algorithm is depicted Figure 3-34.

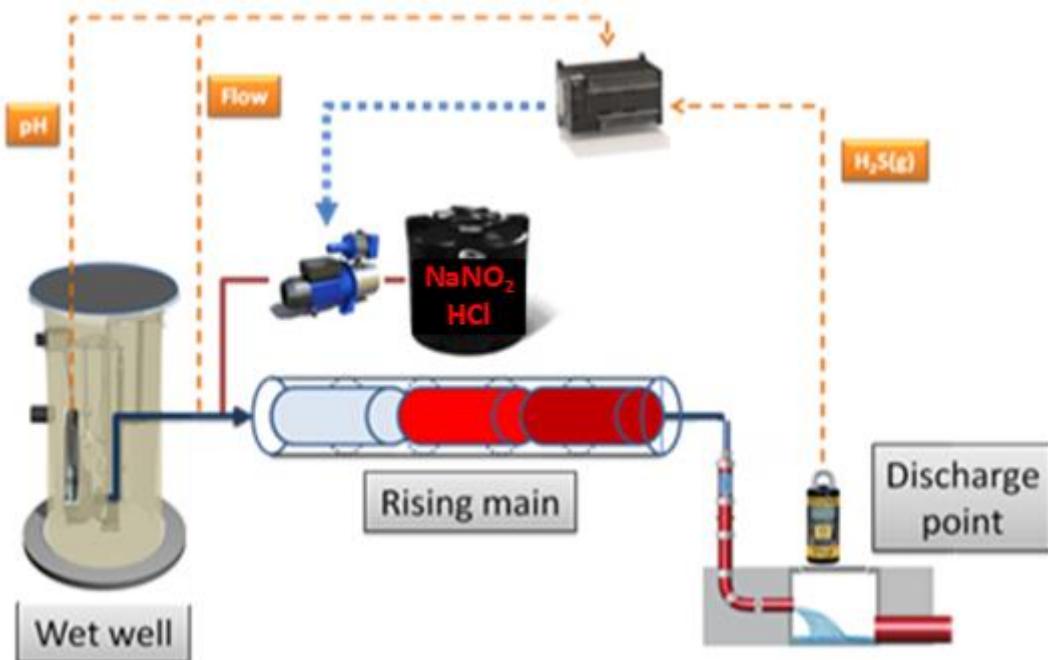


Figure 3-35. Control algorithm scheme for free nitrous acid.

3.3 Control design for sewer networks

3.3.1 Introduction

Activity 3 focuses on the development of control methodologies for network-wide sulfide control. This has been explored through desktop studies, using the SeweX model as a simulation platform. The findings of the desktop studies are summarized in the present document, with the objective of establishing general guidelines for network-wide control system design.

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

3.3.2.1 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 (H₂S) 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 H₂S emissions, chemicals, including oxygen, nitrate, iron salts and alkali, among others (Gutierrez et al., 2008b; Hvitved Jacobsen et al., 2002), 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.

3.3.2.2 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 **Figure 3-36** 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*) $\dot{x} = \frac{\text{inflow}(t)}{S}$, 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 $\dot{x} = \frac{\text{inflow}(t)-\text{outflow}}{S}$, 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 .

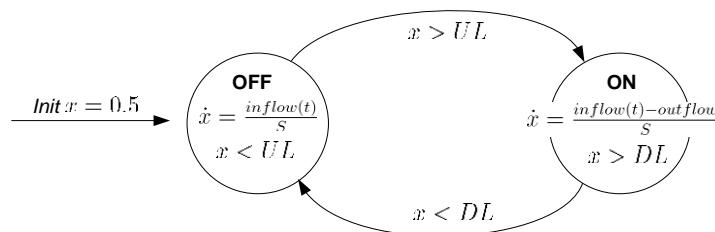


Figure 3-36. Pump station autonomous hybrid automaton

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.

3.3.2.3 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 3-37**. 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 m³, located in the middle of the sewer network. The network receives an average daily flow of approximately 13,000 m³/d. The average daily flow delivered by the BT pump station is 3500 m³/d with the maximum pump capacity of 14,700 m³/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 m³/d to 2500 m³/d. All SPSs including BT are currently controlled based on water levels in the respective wet wells.

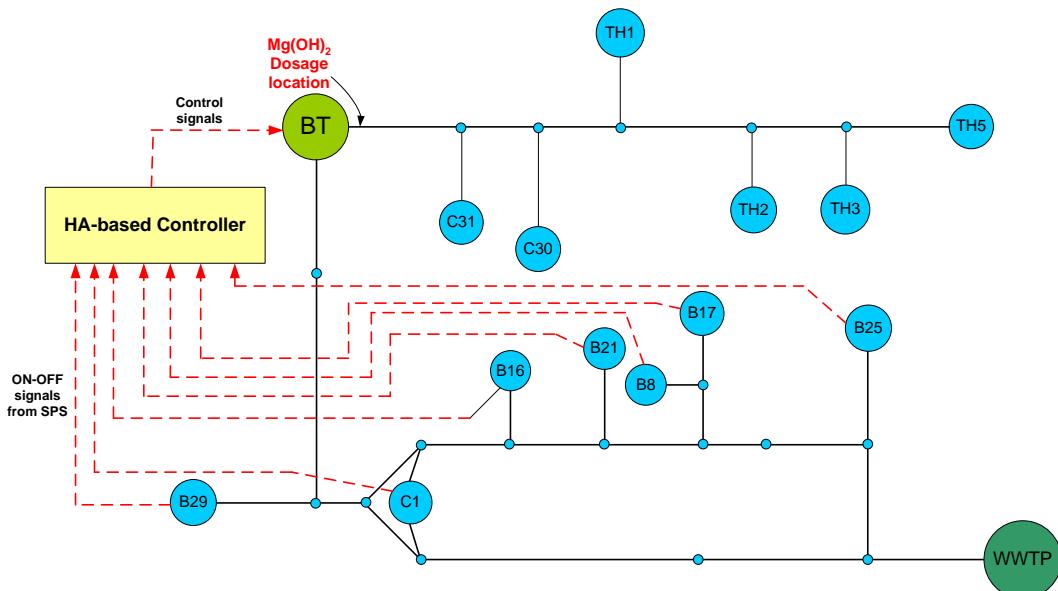


Figure 3-37. Schematic of the Tugun-Elanora sewer network

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 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 H₂S 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 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 m³/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., 2008b). 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 H₂S, O₂ 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 3-38, 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 from BT fluctuated largely during the HA-based control, with the flow adjusted based on the abovementioned rules.

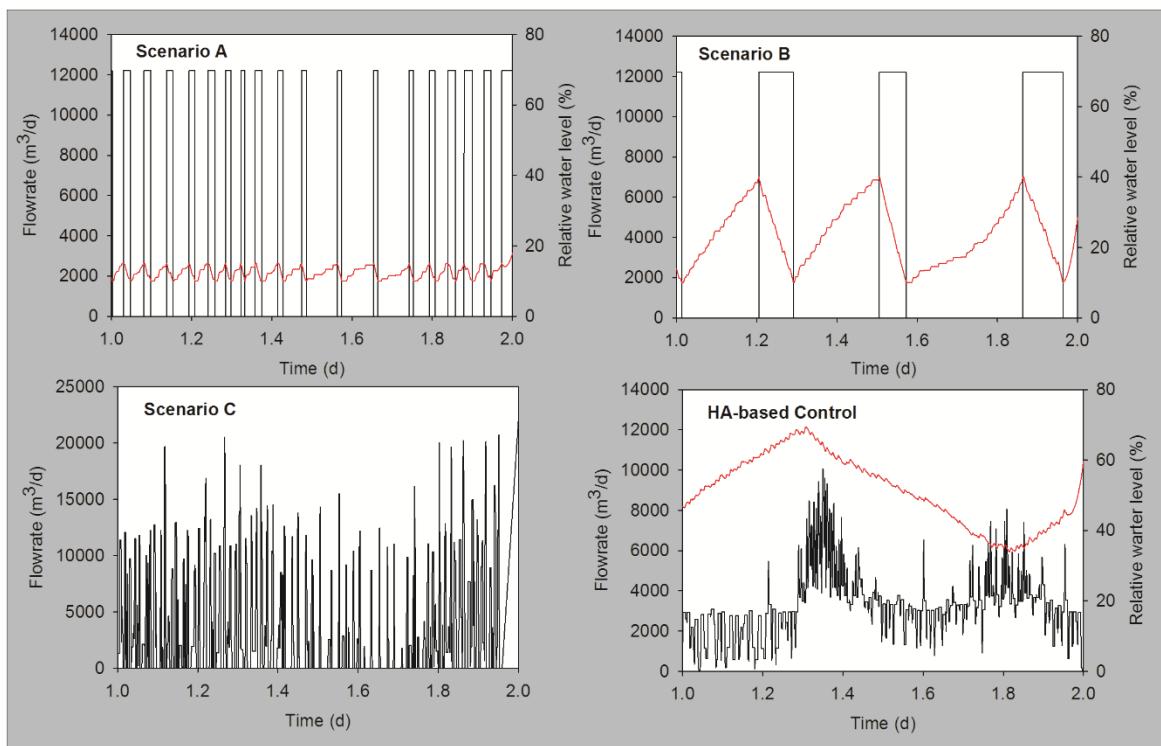


Figure 3-38. Pump events and water levels in Scenarios A, B, C and with HA-based control

To illustrate the performance of the different control strategies, the pH profiles at the end of the network are presented in **Figure 3-39**, 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.

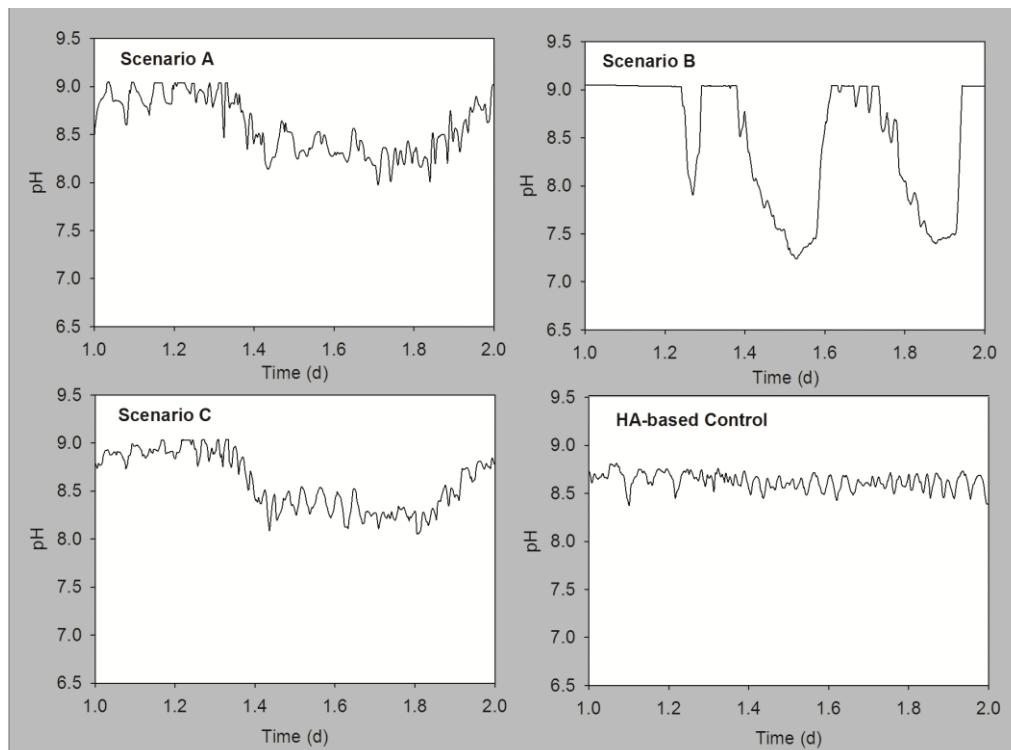


Figure 3-39. pH at the end of the network in Scenarios A, B, C and with HA-based control

The dissolved hydrogen sulfide (i.e. H₂S, which is a fraction of the total dissolved sulfide) concentration at the end of the network is shown in Figure 3-40.. Results clearly show that the HA-based control strategy achieved stable H₂S concentrations at low levels (0.1-0.3 mgS/L) in the entire network. In comparison, significant H₂S peaks (up to 1.5 mgS/L) existed in all other three scenarios. The reduced H₂S concentration is expected to significantly reduce odour and corrosion problems at the inlet of the WWTP.

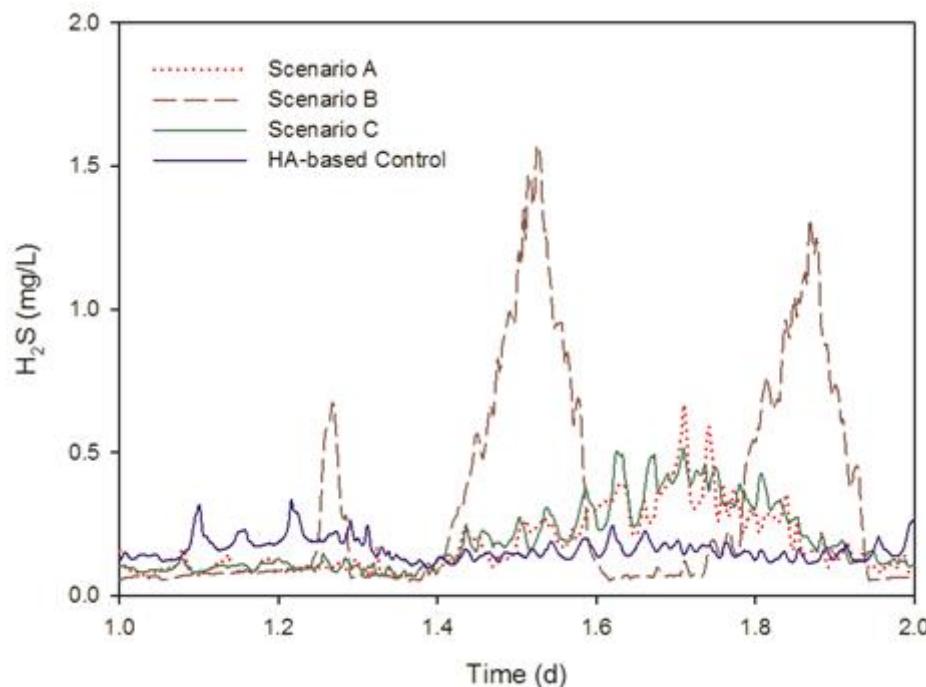


Figure 3-40. H₂S in sewage at the end of the network in all the four simulated scenarios.

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. 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 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.

3.3.2.4 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 H₂S control than the currently used level-based control. This study further demonstrated the potential of network-based chemical dosing control.

3.3.3 Guidelines for network-wide control design

When aiming to design suitable odour and control strategies for a given sewer network, the first step is to analyse the sewer network to identify odour and corrosion hot-spots. This can be done through monitoring campaigns of the network. However, although effective, this approach is costly and highly time consuming. A more cost-effective option is to establish potential hot-spots using modelling tools. Simulation results will identify potential critical points where sulfide needs to be controlled, which can then be validated in the field with minimal monitoring effort.

If the network analysis reveals that the number of corrosion and odour hot-spots is limited, and/or these are geographically isolated, it is recommended to undertake the control on a local basis. For that, any of the commonly used chemicals (i.e. oxygen, nitrate, iron salts, magnesium hydroxide) will achieve effective sulfide control if dosing location and dosing control are adequate. Control methodologies for the optimised dosing of chemicals in single pipes were developed during Activity 3, and are available through the factsheets of SP9.

On the contrary, if multiple hot-spots are localized in a close area, corrosion and odours control should be addressed on a network basis. If that is the case, not all the chemicals are suitable for network control. When dosed in sewer pipes, oxygen and nitrate oxidise dissolved sulfide to sulfate. However they are also used as electron donors by other heterotrophic bacteria and in consequence they are quickly depleted. Once the pipe is under anaerobic conditions again, sulfate reduction resumes and sulfide is built up. In this light, oxygen and nitrate cannot be used in a network control approach, and should only be used for local control. On the other hand, magnesium hydroxide ($Mg(OH)_2$) and iron salts are “conserved” chemicals suitable for network control. $Mg(OH)_2$ increases sewage pH and prevents the transfer of sulfide into the gas phase. If dosed in excess, the surplus will remain undiluted, and when sewage receiving dosing will eventually mix with fresh sewage this will dissolve keeping the pH at a suitable level and preventing sulfide transfer. In a similar way, iron salts will precipitate with sulfide when this is available in the liquid phase. The choice between iron salts or magnesium hydroxide is dependent on specificities of the network and sewage characteristics, such as buffering capacity of the sewage or sulfide concentration, which will determine the cost-effectiveness of the control.

The selection of the dosing location is one of the key steps of the development of a network-based strategy for corrosion and odour control, as it will govern the effectiveness of the control and the complexity of the control strategy. When possible, dosing should be conducted in a pipe/wet well with large daily flows, as this will help to convey larger amounts of chemicals and minimise the chances of over-dilution due to the mix with side-streams located downstream the dosing point. Additionally, and with view of the potential control of the sewage pumping station (SPS) receiving chemical dosing, a large sewage flow provides flexibility on the SPS operation control.

Last but not least, the control of chemical dosing and the operation of the SPS where this chemical dosing is conducted is critical for the success of the network control. Suitable dosing rates can be established off-line based on experience or through simulation studies. Nevertheless, although these approaches could yield satisfactory results, they are far from optimal, as the control of the system is complex. Due to the intermittent operation of pumping stations, if chemical dosing is not properly controlled, some wastewater slugs could reach the discharge point without receiving adequate chemical dosing, leading to poor sulfide control. On the other hand, other slugs could receive excessive dosing, entailing a waste of chemicals. In this respect online dynamic control would allow preventing undiluted wastewater slugs to reach the control point (discharge point) without dosing and avoiding excessive dilution of the chemical to ensure a suitable concentration/pH at the discharge point. Over the course of Activity 3, efforts have focused on two different strategies to online control the operation of SPS receiving chemical dosing to ensure suitable odour and corrosion management.

3.4 Field-site validation of the control algorithms

3.4.1 Introduction

Online control algorithms for the optimized dosing of the main chemicals for sulfide control used by the Australian water industry (magnesium hydroxide, nitrate, oxygen and iron salts) have been developed on paper, and successfully tested using the SeweX model. Furthermore, these control algorithms were tested in field conditions to ensure their validity. These were done in four case studies detailed as below.

3.4.2 Case study 1: Mg(OH)₂ dosing at Queensbury SPS

3.4.2.1 Introduction

Hydrogen sulfide (H₂S) is generated in the liquid phase of sewer systems under anaerobic conditions by sulfate reducing bacteria (SRB) (Hvitved-Jacobsen 2002; Melbourne and Metropolitan Board of Works, 1989). H₂S can be transferred from the liquid to the gas phase in gravity sewers and manholes, where headspace exists (Boon 1995), inducing sewer corrosion which can dramatically reduce the life-span of sewer pipes (WERF 2007). It also causes odour nuisances and has serious health concerns due to its toxicity (Boon 1995; Knight and Presnell 2005). The control of hydrogen sulfide in sewer systems is thus one of the main challenges for water utilities worldwide.

There are currently several methods to control this problem, with chemical dosing being the most widely used. According to a recent survey conducted among the major water utilities in Australia, magnesium hydroxide is used at more dosing sites than any other chemicals (Ganigüé et al. 2011). Mg(OH)₂ reduces hydrogen sulfide transfer from the liquid to the gas phase by increasing the pH of the sewage (Gutierrez et al. 2009). Generally, H₂S is present in the liquid phase at an equilibrium of two key sulfide species, namely H₂S and HS⁻. The rise of pH shifts the equilibrium, reducing the concentration of volatile H₂S in the liquid phase and hence preventing its release to the sewer atmosphere. The maximum pH achievable by Mg(OH)₂ dosing is 9.0–9.2 due to its limited solubility in water (WERF 2007). At such pH levels, the percentage of H₂S in the liquid is less than 1%. Gutierrez et al. (2009) revealed a further, previously unrecognised benefit of the use of Mg(OH)₂ for sulfide control. Long-term elevation of sewage pH to 8.6–9.0 diminishes SRB activity by 30%–50%, thus reducing sulfide formation in addition to reducing its transfer. An elevated pH at 8.6 – 9.0 also prevents the formation of methane in sewers (Gutierrez et al. 2009). Methane is a greenhouse gas with a global warming potential 21–23 times higher than carbon dioxide (IPCC 2006).

The way chemical dosing is conducted has not only a major influence on the effectiveness of the chemical on sulfide control, but also significant implications to operational cost. Controlling chemical dosing in rising main sewers, to which chemicals are typically added (Ganigüé et al. 2011), is very challenging due to the plug-flow behaviour of a sewer system (Schutze et al. 2004). According to the same industrial survey (Ganigüé et al. 2011), flow-paced or profiled dosing strategies are used at the majority of the Mg(OH)₂ dosing sites, which are commonly based on empirical guidelines developed through experience (de Haas et al. 2008). However, these could lead to over or under dosage as sewers have a very dynamic behaviour, with sewage flow and characteristics showing large variations throughout the day, week and year. This is especially critical for sewage pH, which exhibits very strong dynamics, typically fluctuating from 6.5 to 8.5 (Sharma et al., 2013). Additionally, rain water inflow and

infiltration may dilute sewage and decrease its hydraulic retention time within the pipe, dramatically reducing the amount of chemical required for suitable sulfide control. In theory, on-line dosing control has great potential benefits, allowing improved control performance and a reduction of chemical costs (Sharma and Yuan 2009). However, up to date there has been no reported attempt of on-line control of chemical dosing for sulfide mitigation in sewers.

The present article describes the development of the first on-line control algorithm for optimised chemical dosing in sewers. The conceptual design of the control is described in detail, and its benefits are demonstrated through detailed simulation studies and a 2-month field trial.

3.4.2.2 CONTROL DESIGN

Mg(OH)₂ dosing location

The main aim of magnesium hydroxide dosing for sulfide control is to raise sewage pH to reduce sulfide transfer from the liquid to the gas phase. Ideally, the dosing control has to guarantee stable sewage pH close to the desired set-point at the discharge point of rising main sewer pipes, with the lowest chemical consumption. The optimal dosing location will largely depend on specific conditions of each system. Dosing Mg(OH)₂ at the discharge point would be simpler than other locations in terms of control. However, a dosing location at the beginning of the pipe has several advantages as: i) It minimizes sulfide transfer during the transport (e.g. through air valves), preventing possible odour complaints along the pipe; ii) It decreases sulfide production and stops methane generation, as high pH levels (8.6-9.0) are detrimental to their activity (Gutierrez et al. 2009); and iii) The reduction on the biological activity also likely decreases sewage acidification due to fermentative processes (Gutierrez et al. 2009), reducing the amount of magnesium hydroxide required for control. Therefore, in this study we designed a control algorithm with the assumption that Mg(OH)₂ is to be added at a sewage pumping station, although it could be easily adapted to other dosing locations.

Mg(OH)₂ dosing control design

Overall control structure

The Mg(OH)₂ dosage needs to increase the sewage pH at the dosing location to the desired set-point, and also to neutralise the pH decline during sewage transport caused by sewage acidification. The proposed control algorithm, presented in **Figure 3-41**, comprises three components. The first one determines the amount of Mg(OH)₂ to be dosed in the wet well to raise the pH to the desired set-point, based on the pH measurement in the wet well. Secondly, a feedforward loop will predict the extra amount of Mg(OH)₂ required to balance the net proton production during the sewage transport, based on the hydraulic retention time (HRT) of each sewage slug. In this case, Mg(OH)₂ will be dosed by a second dosing pump at the beginning of the pipe. Finally, a feedback loop will adjust the dosing of the second component based on the overall long-term performance of the control.

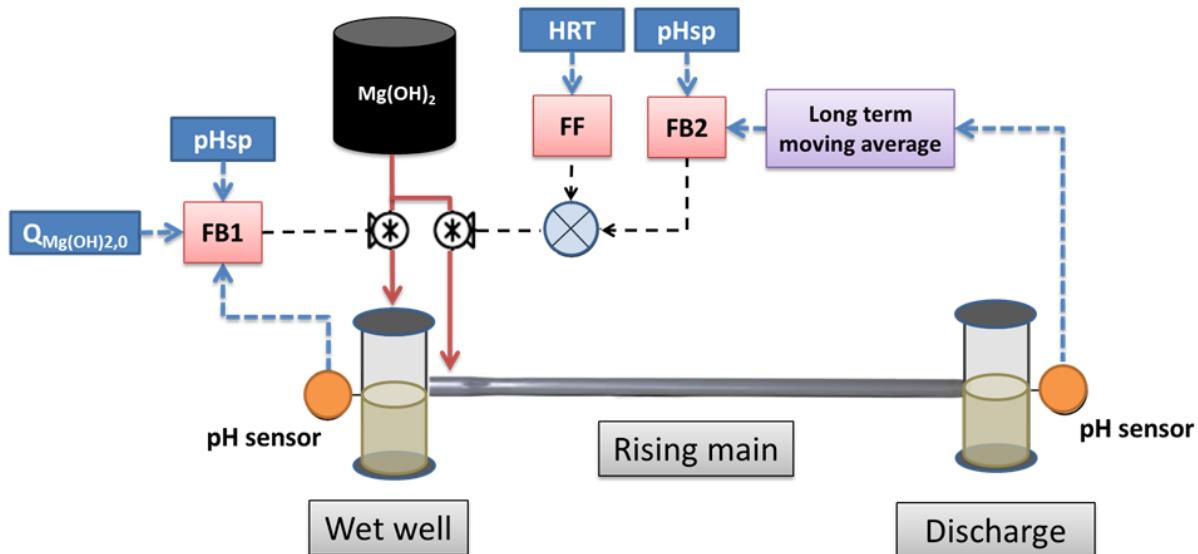


Figure 3-41. Mg(OH)₂ on-line dosing control scheme. $Q_{\text{Mg(OH)}_2,0}$: Nominal constant Mg(OH)₂ dosing rate; pHsp: pH set-point; FF: feedforward control; FB: feedback control

Feedback 1 (FB1)

The amount of Mg(OH)₂ to be dosed to raise the pH to a desired control set-point is dependent mainly on the sewage pH and its buffer capacity. Wastewater composition is variable throughout the day, resulting in dynamic pH and sewage buffer capacity (Sharma et al. 2013). Sewage pH can be measured on-line using robust and affordable sensors. In this light, the proposed methodology for Component 1 is to dose Mg(OH)₂ into the wet well based on the signal from a pH sensor. Dosing is controlled by a feedback loop, which adjusts the dosing rate based on the error between the real-time on-line pH measurements in the wet well and the control set-point through the use of e.g. a PID control algorithm. The controller equation of FB1 is presented in Equation 1.

$$Q_{\text{Mg(OH)}_2,\text{FB1}} = Q_{\text{Mg(OH)}_2,0} + k_{\text{FB1}} * (\text{pH}_{\text{sp}} - \text{pH}_{\text{ww}}) \quad (1)$$

Where $Q_{\text{Mg(OH)}_2,\text{FB1}}$ is the Mg(OH)₂ dosing rate into the wet well (kg/d), $Q_{\text{Mg(OH)}_2,0}$ the Mg(OH)₂ nominal constant dosing rate (kg/d), k_{FB1} the feedback constant (kg/d pH unit), pH_{sp} the pH control set-point at the wet well and pH_{ww} the sewage pH in the wet well.

Proper mixing of the chemical with the sewage is critical for an effective control. This can be achieved by setting up a mixing device/recirculation pump in the wet well.

Feedforward (FF)

As stated before, bio-transformations take place while sewage travels along the pipe, with net proton production expected, which results in a pH decline. To overcome this, an additional amount of Mg(OH)₂ should be dosed to each sewage slug pumped into the pipe to ensure the pH at discharge (i.e. end of the pipe) meets the set-point.

Sewage acidification occurs during its transport mainly due to organic matter fermentation and sulfide production. It depends on many factors, but the most important are the hydraulic retention time (HRT) of the sewage in the pipe and the Area to Volume ratio of the pipe (A/V = 2/R, where R is the radius of pipe). Sewage acidification usually follows a linear relationship with HRT, with longer retention times resulting in higher net proton productions during sewage transport. However, acidification will be limited at long retention times due to substrate availability. Similarly, as the bio-processes in a sewer pipe are primarily biofilm-mediated (Guisasola et al., 2008), a smaller A/V ratio will lead to a higher net proton production rate.

For a given pipe with a known A/V ratio, we propose the following equation to describe the dependency of proton production on the HRT (Equation 2):

$$\Delta[H^+] = a * HRT^b \quad (2)$$

where $\Delta[H^+]$ is the net proton production, in mol/m³, HRT the hydraulic retention time of the sewage in hours, and a and b are model parameters requiring calibration.

Therefore, if the HRT of a sewage slug is known, the additional amount of magnesium hydroxide required to balance pH decrease due to the biological activity can be estimated. The controller equation of the feedforward loop is designed as:

$$Q_{Mg(OH)_2_FF} = f Q_{sewage} \Delta[H^+] \quad (3)$$

where $Q_{Mg(OH)_2_FF}$ is the Mg(OH)₂ dosing rate of the feedforward loop (kg/d), f (= 0.029 kg/mol) is a factor to convert moles of protons to kg of Mg(OH)₂, Q_{sewage} is the flow of sewage into the rising main (m³/d) and $\Delta[H^+]$ is the net proton production in mol/m³.

However, sewer systems have a plug-flow behaviour, and hence the HRT of a sewage slug entering the pipe is governed by the future sewage flow that ‘pushes’ this slug through the pipe. In this light, the HRT of the slug is not known at the time when the feedforward dosing is carried out, and therefore has to be predicted. The prediction of HRT can be achieved using an Auto-Regressive Moving-Average (ARMA) model, which have been successfully applied to the prediction of future flows in sewers several hours ahead (Chen et al., 2014). In cases where the system has a very stable daily flow pattern with no significant rainwater infiltration, typical daily profiles can be used to estimate the sewage HRT at anytime of a day.

Feedback 2 (FB2)

The first two components constitute the core of the control algorithm and overall have a feedforward nature because the control action is determined based on the measurement of perturbations rather than the current output of the controlled variable (in this case pH at the discharge point). Although effective and efficient, feedforward controllers are subject to a certain degree of uncertainty due to for example modelling errors and/or unknown disturbance (Stephanopoulos, 1984). To prevent this, another feedback loop can be included as the third component of the control algorithm. The objective of this loop is to correct long-term control error, which is the difference between the long-term averaged sewage pH at the discharge point and the set-point, rather than the instantaneous control error. Indeed, due to the plug flow nature of sewer systems, the pH measurement at the discharge point cannot be directly used as an input for this feedback loop due to the transport delay. Instead, we propose to use the weighted moving average of the pH at the discharge point, with the more recent pH measurements being

given a higher weight. The calculation of the moving average pH (pH_{ave}) is presented in the following equation (Equation 4):

$$pH_{ave}(n) = \alpha * pH_n + (1 - \alpha) * pH_{ave}(n - 1) \quad (4)$$

where $pH_{ave}(n)$ is the weighted average pH at the present time, $pH_{ave}(n - 1)$ is the weighted average pH at the previous sampling time, pH_n is the measured pH at the present time, and α is a weighting factor ($0 < \alpha < 1$) to be tuned. The weighting factor α is important since it determines whether the feedback signal relies more on the recent pH measurements or historical data.

The control objective is to reduce the error between a set-point and the feedback signal. A proportional controller is employed here, correcting the dosing of the FF component (Equation 5):

$$Q_{Mg(OH)_2_FF+FB2} = Q_{Mg(OH)_2_FF} + k_{FB2} * (pH_{sp} - pH_{ave}) \quad (5)$$

where $Q_{Mg(OH)_2_FF+FB2}$ is the $Mg(OH)_2$ dosing rate into the rising main (kg/d), k_{FB2} the feedback constant of FB2 (kg/d pH unit), pH_{sp} the pH control set-point at the discharge point and pH_{ave} the average pH calculated based on Equation 4.

3.4.2.3 MATERIALS AND METHODS

The Queensbury pumping station and rising main

Field studies were conducted at the Queensbury SPS operated by South Australian Water (Adelaide, Australia). The rising main has a total length of 5290 m and a pipe diameter of 600 mm. The SPS receives sewage from different sewer systems located upstream, with a total average dry weather flow of 12 ML/d and an average hydraulic retention time of sewage in the pipe of 4 hours. To control sulfide emissions, $Mg(OH)_2$ is dosed at the beginning of the rising main, straight after the SPS pump, according to a pre-defined daily dosing profile, with the chemical dosing rate being proportional to the sewage flow and 4 different dosing levels throughout the day (see Figure S1 for further details). The aim of the dosing is to maintain the pH at discharge above 8.55. Flow meters and pH meters are located at the pumping station and the discharge point. Local signals are hardwired to the local PLC, whereas data from sensors located at the discharge are made available through a Remote Telemetry Units (RTU).

Control field trials

The validation of the control algorithm was conducted in a 2-months field trial. During the first month, $Mg(OH)_2$ was dosed according to the pre-defined profile dosing whereas dosing was controlled according to the proposed algorithm during the second month. An external PLC system (Opto22, USA) was installed at the Queensbury SPS to on-line control the dosing of $Mg(OH)_2$. The control required as inputs the pH measurement at the wet well and the sewage flow. The sensor signal data was pre-processed to remove outliers and to ensure its quality, and subsequently used to calculate the dosing rate, which governed the operation of a Variable Speed Drive (SVD) $Mg(OH)_2$ pump. The system was connected to a laptop with internet access through a wireless router, allowing remote access via 3G network for data download and control fine-tuning.

Due to technical constraints of the trial site, the control algorithm had to be adapted. According to the theoretical control design, Mg(OH)₂ should be dosed both into the wet well and at the beginning of the pipe. However, chemical dosing in the Queensbury SPS is conducted directly into the main. We adapted the FB1 control algorithm such that the amount of alkali required to reach a target pH in the wet well (FB1) was calculated based on the buffer capacity of sewage, which was determined offline by acid-base titration experiments over a 24 hour period prior to the implementation of the controller. Sewage samples from the wet well were collected on an hourly basis for 24 hours and titrated in duplicate using an automatic titration device consisting of a pH sensor and a micro-pump, which delivered 47.5 µL of NaOH solution (0.065N) per pump stroke. Initially, 30 mL of sewage sample were placed in the titration device, and the micropump was started for continuous addition of a NaOH (0.065N) solution up to a pH of 11. A computer, to which the pH sensor and the micropump were connected, controlled the progress of the titration and recorded both the volume of NaOH solution added and the pH. Titration curves were obtained by plotting pH against the volume of the NaOH solution added. The 48 buffering capacity curves are presented in Figure S2 of Supplementary Information. Experimental results clearly showed that buffer capacity of the sewage between pH 7.5 and 9 was very similar throughout the day. Given this, and for simplicity, an average buffer capacity curve (Figure S2) was used for the control trial. It is important to keep in mind that rainwater infiltration may reduce the sewage buffering capacity. Nevertheless, the analysis of one-year historical flow data from the Queensbury SPS (data not shown) did not reveal any significant changes in the daily flow pattern during wet weather events, validating this assumption.

In a similar way, samples at the discharge of the rising main were also collected every 30-60 minutes (covering a range of HRT from 2 to 8 hours) to investigate the sewage acidification during its transport. These were titrated to pH 9.2 following the methodology described above. The net proton production (in mol/m³) was calculated as the amount of base required to raise the pH of a given volume of sewage to the pH set-point, multiplied by its normality. Equation 2 was fitted to experimental data using SigmaPlot 11 (Systat software, Germany), obtaining the model parameters, standard errors and 95% confidence regions.

The calculation of sewage acidification and the amount of additional Mg(OH)₂ to neutralize it (FF) is dependent on sewage HRT. Considering the negligible effect of rain events on the Queensbury SPS flow, on-line prediction of the retention time of a sewage slug entering the pipe was judged unnecessary, and a typical daily HRT profile was used for the control implementation. This profile was generated through the analysis of historical flow data, and is presented in Figure S3 of Supplementary Information. Longer retention times (6 – 7 hours) were observed during early morning due to the low sewage flow during night time (4000-5000 m³/d), whereas HRT dropped to 2-3 hours around midday and stayed at that level until the evening, when water usage in households and industries diminishes.

Finally, the FB controller (FB2) was not implemented in this trial due to the limited calculation power and storage capacity of the PLC used.

Desktop simulation studies

Model development and calibration

Simulations studies were carried out to test the effectiveness of the fully implemented controller and evaluate the contributions of each component to the overall control performance. For that, the Queensbury SPS and rising main were modelled using SeweX, a dynamic mathematical model for the simulation of the physical, chemical and biological processes in

sewer systems (Sharma et al., 2008c). The model predicts the time and spatial variations of the main wastewater quality parameters in the liquid and gas phases by taking into account the biochemical processes (carbon, sulfur and nitrogen conversions under aerobic, anaerobic and anoxic conditions) occurring in sewer biofilms and in the bulk liquid, chemical processes and equilibria (e.g. sulfide oxidation, precipitation reactions, and acid-base systems) and physical processes (such as liquid-gas mass transfer). The pH prediction is achieved based on charge balances (Sharma et al. 2013). As its inputs, the model requires the sewer system characteristics (network layout, pipe sizes, lengths and slopes), wastewater composition and hydraulic data.

The Queensbury model was calibrated using data obtained during a sampling campaign, with Mg(OH)₂ being dosed according to a pre-defined profile at the time. Field samples were collected from the wet well and discharge manhole on an hourly basis, for 24 hours. Part of each sample was filtered immediately using 0.20 µm filters (Millipore, USA) and then transferred to 5 separate vials for the analysis of soluble inorganic sulfur species, soluble nitrogen and phosphorus compounds, volatile fatty acids (VFA), soluble chemical oxygen demand (COD) and soluble total inorganic carbon (TIC). The rest was stored for total COD analysis and sewage titration. Sample vials were stored in an icebox to prevent degradation and transported to an analytical laboratory at The University of Queensland, where they were stored in fridges at 4 °C until analysed. During the model calibration, sewage characteristics at the wet well were used as inputs for the model. Model outputs were compared with data collected during the sampling campaign, and model parameters were manually fine-tuned to obtain a good model fit. A comprehensive description of the model calibration procedure and the calibration results, are presented in Supplementary Information section (Section S.1 and Figure S4).

Long-term performance of the different control components

The performance of the different components of the on-line control was assessed in a scenario analysis using the calibrated Queensbury model. For this, four different scenarios were defined: i) No chemical dosing; ii) Mg(OH)₂ dosing based on FB1 on-line control; iii) Mg(OH)₂ dosing based on FB1+FF on-line control; and iv) Mg(OH)₂ dosing based on FB1+FF+FB2 on-line control. Simulations were run for 60 days, and the aim of the on-line dosing control was to maintain a pH of 8.55 at the discharge point.

Control performance under wet weather conditions

As discussed in sub-section 3.2, the sewer network in which Queensbury SPS is located is highly impervious to rainwater infiltration. However, this may not be true for all sewer systems, as shown by Chen and co-workers who observed, in different sewer systems, a significant increase of sewage flows following rain and storm events (Chen et al. 2014). Infiltration of rain and storm run-off in sewer systems shortens sewage retention time, and dilutes the sewage, thus reducing the requirements for Mg(OH)₂ dosing during those periods. The performance of the control (FB1+FF) under wet weather conditions was assessed in a 7-day simulation (Scenario A). The sewage characteristics and flow to the Queensbury SPS were modified based on the same infiltration pattern observed at the UC09 SPS of Gold Coast, Australia (Chen et al., 2014). Baseline flow was multiplied by a correction factor obtained by comparing the UC09 typical dry-weather and wet-weather flows, which are depicted in Figure S5. Sewage composition was modified assuming that the increase in sewage flow was due to rainwater infiltration, which diluted sewage composition according to the previous infiltration factor. The composition of run-off water assumed in this scenario, adapted from Mohammed et al. (2011),

is shown in Table S1. Finally, the benefits of integrating future flow prediction to FF were also evaluated (Scenario B).

Analytical methods

Liquid samples for total dissolved sulfide analysis were preserved using a sulfide anti-oxidant buffer (SAOB) according to the procedure described by Keller-Lehmann et al. (2006) and subsequently analyzed using an ion chromatograph equipped with an UV detector (Dionex ICS-2000). Ammonia and phosphate concentrations in the samples were measured using a Lachat QuikChem8000 Flow Injection Analyzer (FIA, Lachat Instrument, Milwaukee, WI). Total and Soluble COD was measured from unfiltered and filtered sewage samples respectively, following the closed reflux colorimetric method 5220D of standard methods (APHA 1998) using a spectrophotometer Merck CSB spectroquant model SQ300 (25–1500 mg COD/L range). VFAs were measured by gas chromatography (GC) (PerkinElmer, Inc.). Filtered sample (0.9 mL) was transferred into a GC vial to which 0.1 mL of formic acid was added. Measured values were converted to COD using the theoretical chemical oxygen demands of each VFA. Dissolved Inorganic Carbon was analyzed using a multi N/C 2100 Total Organic Carbon (TOC) analyzer (Analytik Jena, Germany) equipped with a Focus Radiation NDIR-Detector.

3.4.2.4 RESULTS AND DISCUSSION

Field trial results

Titration data obtained during the sampling campaign was used to calibrate the acidification model proposed in Equation 2. Experimental net proton production as a function of HRT is depicted in **Figure 3-42**, together with the acidification model fit, the 95% confidence region, and the parameter values.

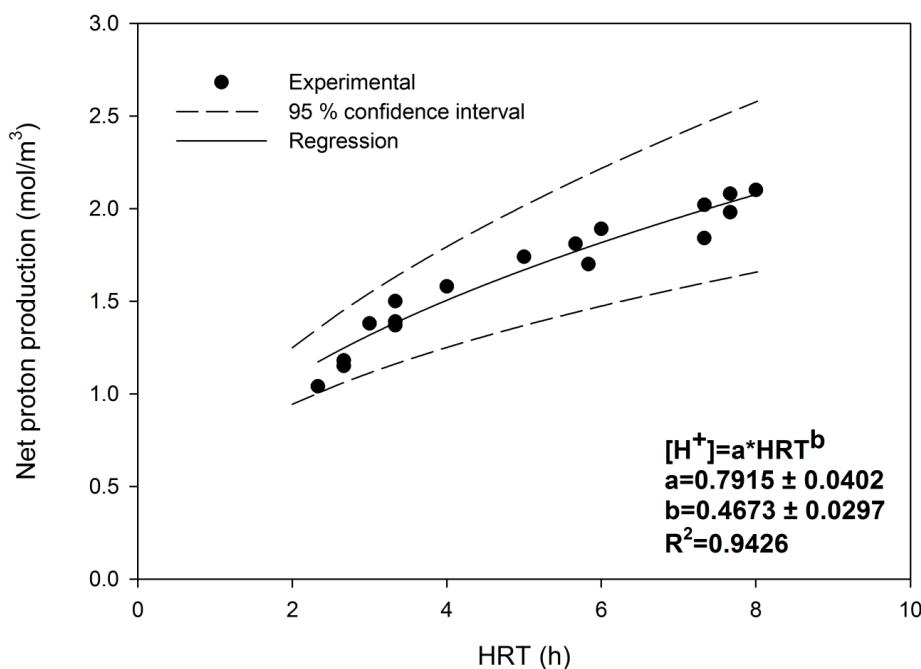


Figure 3-42. Net proton production as a function of HRT, model fit and the 95% confidence region.

Experimental results confirmed that, in the HRT range tested, net proton production during sewage transport increased with transport time following a power function. The proposed acidification model (Equation 2) was capable of describing sewage acidification with good accuracy (confirmed by the high regression coefficient, $R^2 = 0.9426$) and low uncertainty, especially at short HRT. Therefore, this curve can be used to determine the additional amount of Mg(OH)₂ to be dosed for a given system, if HRT of each sewage slug is known.

The Queensbury system was monitored for a month prior to the trial to assess the performance of the existing dosing profile, which aims to keep pH above 8.55, and establish a baseline to compare the on-line control performance with. Given the maximum total dissolved sulfide concentration at the discharge point measured during the sampling campaign (around 10 mgS/L), a pH set-point of 8.55 at the discharge point would keep the molecular H₂S in the liquid phase below 0.25 mgS/L. The on-line control (FB1+FF) was subsequently tested for a period of one month to achieve the same targeted pH level of 8.55. **Figure 3-43A** shows the pH at the discharge of the Queensbury rising main during the baseline period with the existing profiled dosing (days -30 to 0) and on-line control trial (days 0 to 30). Additionally the average 5 percentile for the two periods is also presented as a discontinuous line. It is necessary to note that Mg(OH)₂ was not dosed during some periods due to technical problems with the chemical dosing pump. To gain deeper insights of the performance and benefits of the control, the pH profiles at the discharge and the corresponding Mg(OH)₂ dosing rates for both the profiled and on-line controlled dosing over a 24 hours period are presented in **Figure 3-43B** and **Figure 3-43C**, respectively.

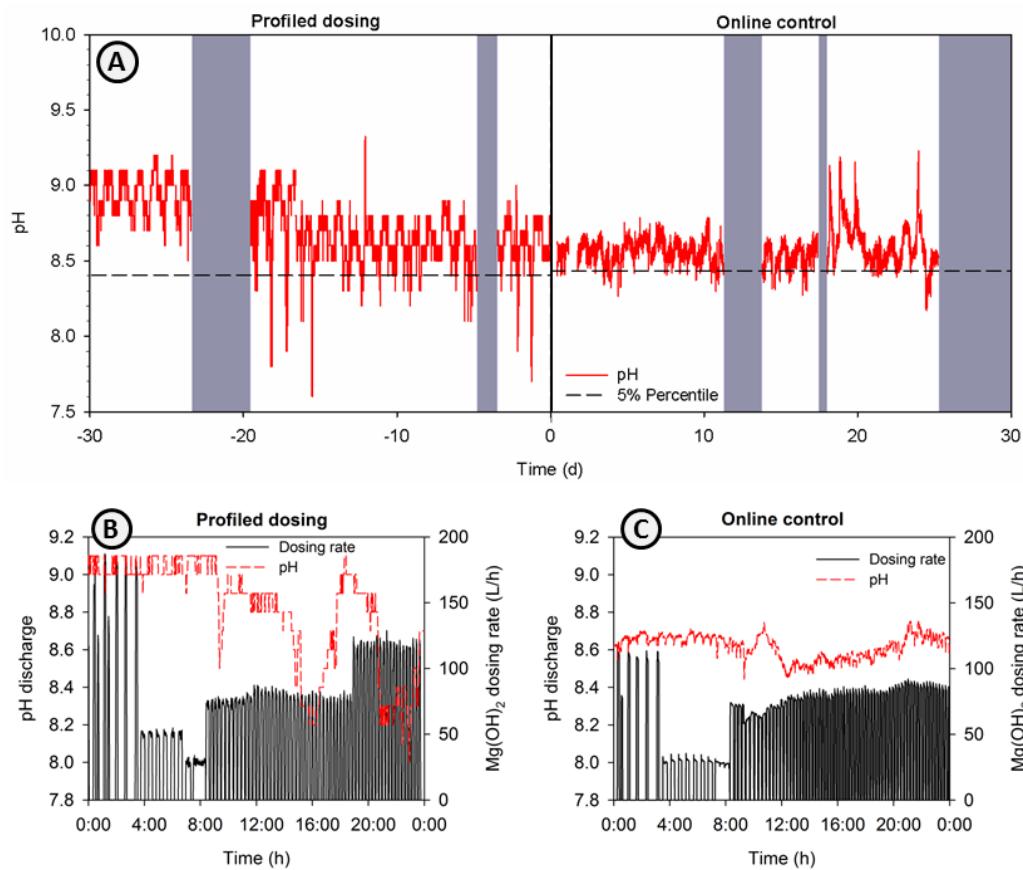


Figure 3-43. A) Sewage pH at the discharge point and the 5 percentile of the pH at the discharge throughout the trial. The shaded areas indicate periods without chemical dosing due

to technical problems; B) The Mg(OH)₂ dosing rate with the profiled dosing, along with the resulting pH profile during a 24-hours period; C) The Mg(OH)₂ dosing rate with the on-line control dosing, along with the resulting pH profile, during a 24-hours period.

As can be seen in Figure 3-43.A, the Mg(OH)₂ on-line dosing strategy was capable of controlling pH at discharge in a more stable and accurate way ($\text{pH } 8.59 \pm 0.10$) in comparison to the pre-defined profiled dosing, which exhibited larger pH fluctuations (between 8.5 and 9.2), with an average pH of 8.73 ± 0.21 . The main reason for such a large fluctuation throughout a day, which can be clearly observed in Figure 3-43.B, is hypothesized to be the change in wastewater characteristics, which was not taken into account by the profiled control. The 5 percentile value of the two control strategies was very similar, being 8.40 and 8.44, respectively, although the Mg(OH)₂ dosing rate of the on-line control was significantly lower (Figure 3-43.C), with the subsequent reduction in chemical usage. To estimate the potential economic benefits of the on-line control, the annual Mg(OH)₂ dosing for Queensbury SPS was calculated based on the results of the trial, being $370 \text{ m}^3 \text{ Mg(OH)}_2/\text{year}$ for the profiled dosing and $320 \text{ m}^3 \text{ Mg(OH)}_2/\text{year}$ for the on-line controlled dosing. The on-line control could thus achieve a 13% reduction in chemical consumption. Assuming an Mg(OH)₂ unitary cost of \$590/tonne (Ganigu éet al. 2011), the decrease in the dosing rate could entail an annual saving of \$41,000 for the site, or \$10 per ML of sewage.

Desktop assessment of the on-line control algorithm performance

Queensbury long-term performance

To assess the performance of the different components of the on-line control, four different scenarios were simulated for a period of 60 days using the calibrated Queensbury SPS model. The pH at the discharge of each of the scenarios for the full 60 days period is presented in Figure S6 of Supplementary information, and the key results of the simulation are summarized in **Table 3-4**. As FB2 requires a full week of operation to compute the moving average, the average pH at the discharge point and the annual Mg(OH)₂ dosing were calculated for the period 7-60 days.

Table 3-4. Summary of scenario analysis, including average pH at discharge and annual chemical consumption.

Scenario	Average pH \pm SD	Annual Mg(OH) ₂ dosing (m ³ /year)
No dosing	6.70 ± 0.13	0
FB1	7.24 ± 0.27	120.7
FB1 + FF	8.58 ± 0.23	282.12
FB1 + FF + FB2	8.55 ± 0.24	275.6

Results of the simulation study show that, despite the FB1 component increased the pH of the sewage to pH 8.55 at the inlet of the rising main, pH dropped dramatically during the transport to values of 7.24 ± 0.27 . The inclusion of the FF component allowed compensating for the net acidification of sewage during its transport, reaching pH at discharge of 8.58 ± 0.23 , with a slight offset from the desired set-point. This additional dosing increased the chemical dosing by two-

falls. Finally, FB2 corrected the dosing of FF based on the long-term moving average of pH at discharge, fine tuning the dosing to achieve the desired pH set-point.

Additionally, Figure 3-44 shows the pH profile throughout a representative day for the different scenarios, together with the dosing resulting from FB1, FF and FB2.

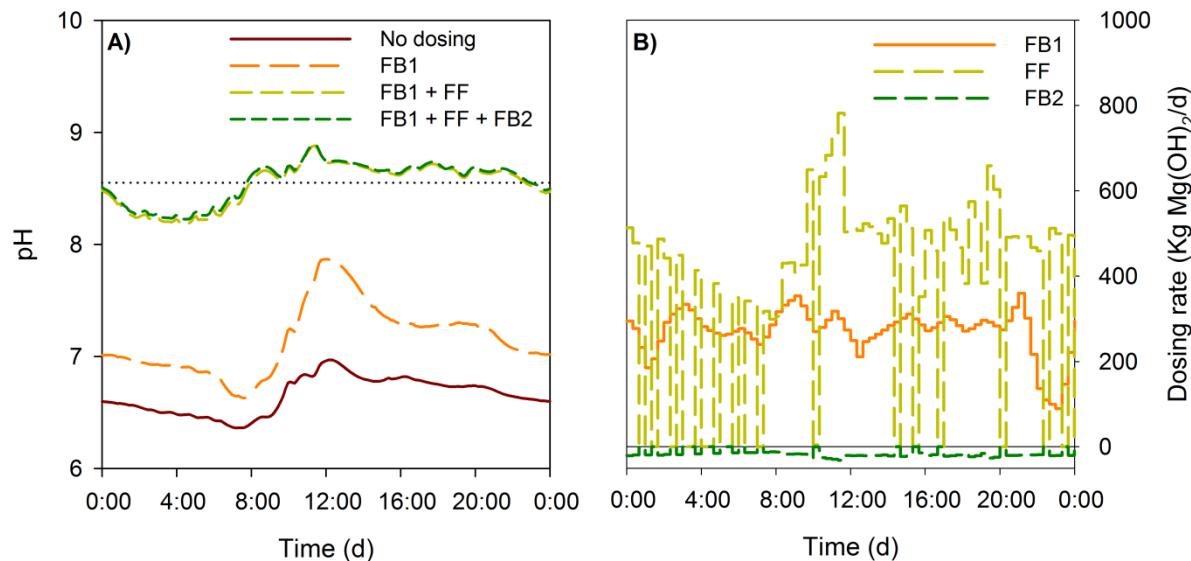


Figure 3-44. Simulated results: A) The pH at the discharge point of the rising main for different dosing scenarios; and B) Dosing rates calculated by different components of the control algorithm. The dosing profiles resulting from FF and FB2 were intermittent, as Mg(OH)₂ dosing occurred only when the sewage pump was on.

Figure 3-44A shows that pH at the discharge was highly dynamic throughout a day, strongly linked to the sewage HRT (see Figure S3 for further details). In all scenarios, the pH was generally lower during early morning due to the higher HRT of sewage (and therefore a higher degree of acidification), whereas pH increased at 10-12 am (coinciding with the lowest HRT), and remained at that level until late evening. Such a pH variation is also clearly visible in the FB1 scenario. In this light, even though the initial pH of all sewage pumped from the wet well to the rising main was 8.55, there was about 1 pH unit difference between pH at discharge in the early morning (pH 6.65 at 7 am) and in midday (pH 7.86 at 12 pm). The dosing of an additional amount of Mg(OH)₂ to compensate for the net proton production during sewage transport was capable of dampening such an effect, and minimizing the pH fluctuation. The pH during early morning was still slightly below the set-point, likely due to a slight under-prediction of proton production by the acidification model.

Regarding the dosing rates (**Figure 3-44B**), the Mg(OH)₂ dosing by component FB1 was continuous during the day due to the continuous flow of wastewater into the wet well. Dosing rate decreased from about 300 kg Mg(OH)₂/d to 90 kg Mg(OH)₂/d due to the decrease in sewage flow. On the contrary, dosing by FF was linked to the operation of the SPS, and only took place when pumps were turned on and sewage was being pumped into the rising main. The highest dosing rate by FF (between 500-740 kg Mg(OH)₂/d) was observed around midday due to the high sewage flow rate (around 600 m³/h), even though the dosing requirement per unit volume of sewage was the lowest due to the short HRT (1.2 mol/m³ of sewage). Finally, FB2 resulted in a negative dosing rate, which slightly reduced the dosing rate required the FF component, accompanied by a slightly decreased sewage pH (Table 1).

Impact of wet weather conditions on the performance of the on-line control

The performance of the on-line control algorithm under wet weather conditions is assessed through a simulation study, with results presented in **Figure 3-45**.

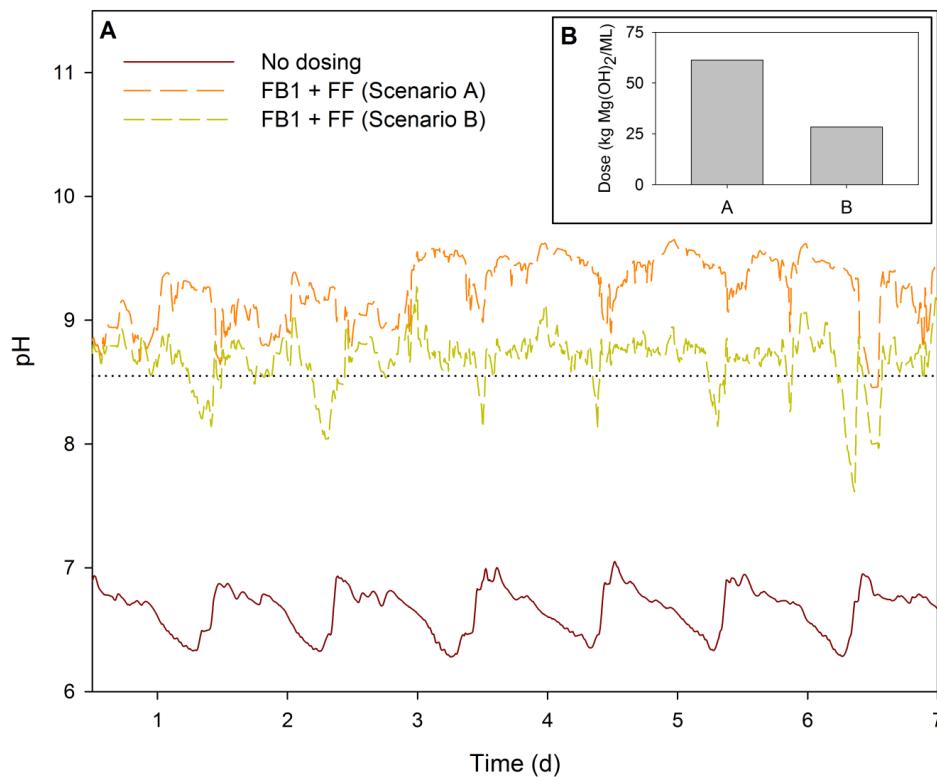


Figure 3-45. A) Simulated pH at the discharge under wet weather conditions, without chemical dosing and with dosing controlled by FB1 and FF. For the FF component, two scenarios are considered with HRT being assumed (Scenario A) and predicted (Scenario B), respectively. B) Mg(OH)₂ dosage for the two scenarios.

The on-line control algorithm (FB1+FF) with the prediction of the sewage net acidification relying on dry weather HRT (Scenario A) was capable of controlling pH at discharge above the desired set-point. However, the shorter HRTs of sewage under wet-weather conditions and the decrease in the buffering capacity of sewage after dilution by the low-strength rain water, led to an Mg(OH)₂ overdosing (pH at discharge consistently above 9). To reduce Mg(OH)₂ wastage, a second scenario (Scenario B) was simulated by considering the predicted HRT of the sewage using a black box ARMA model (Chen et al., 2014). Besides, the dosage of FF was also corrected based on the ratio between sewage and infiltrated run-off. This was calculated based on the increase of flow at a given moment, in comparison with the typical dry weather flow at the time of the day. Such a factor allowed correcting the decrease of buffering capacity of sewage due to the mix with low-strength rainwater run-off. The on-line control in this case was capable of controlling pH at the discharge at pH 8.67 ± 0.21 , very close to the desired set-point of 8.55.

Figure 3-45B depicts the chemical dosage (in kg Mg(OH)₂ per ML of sewage) added to the sewage in Scenarios A and B. The Mg(OH)₂ addition resulting from FB1 was similar in the

two cases; however, a substantial chemical saving was achieved with FF component when HRT is predicted in real-time than being assumed with the total dosage was cut from 61.3 (Scenario A) to 28.3 kg Mg(OH)₂/ML (Scenario B).

Implications and future work

The present work describes for the first time the development of an algorithm for the on-line control of chemical dosing for sulfide mitigation in sewers. This control is resilient to changes in wastewater composition (which affect the buffer capacity) and flow. Due to its simplicity and low capital investment (requires only two pH sensors), it can be easily implemented in new chemical dosing stations. Besides, as already proven in the case study, its flexibility allows for the incorporation of such a scheme in already existing Mg(OH)₂ dosing systems with minor modifications. However, care needs to be taken that adjustments on the algorithm do not compromise its performance. For instance, during the field trial validation, a typical HRT profile was used instead of HRT predicted in real-time. Such an assumption was done based on the grounds that the SPS had a fairly stable hydraulic pattern, without significant changes along the year, even during wet weather. However, as demonstrated in the wet-weather scenario analysis, HRT should be predicted on-line in sewer systems with significant rainwater infiltration. Whether this is necessary or not for a given system can be determined by the in-depth analysis of historical flow data. As proven by Chen and co-workers, on-line HRT prediction can be done based on flow measurements using a black-box model (Chen et al. 2014).

Another option to potentially optimise the proposed on-line control is to define a time-varying pH set-point profile throughout the day based on the dissolved sulfide levels. During the sampling campaign, sulfide concentration at the discharge of the rising main ranged from 6 to 10 mgS/L (see Figure S4). In this study, the control goal during the entire trial was to keep pH at 8.55 to ensure that, even at the highest dissolved sulfide concentrations (i.e. 10 mgS/L), H₂S levels in the liquid phase would be controlled below 0.25 mgS/L. However, at a dissolved sulfide concentration of 6 mgS/L, a pH of 8.35 would be sufficient to control the concentration of H₂S in the liquid phase below the target of 0.25 mgS/L, thus reducing the amount of Mg(OH)₂ dosed. The implementation of an advanced control with dynamic adjustment of the pH set-point would require the real-time estimation of dissolved sulfide levels at the discharge point, which adds an extra layer of complexity to the control. As demonstrated in Sharma et al. (2008), at relatively short HRT (e.g. below 8 hours) and non-limiting substrate conditions, there exists a linear relationship between HRT and the dissolved sulfide concentration in a sewer rising main. Provided that, as already discussed, HRT can be reliably estimated using ARMA models (Chen et al. 2014), concentrations of the dissolved sulfide concentration at the discharge could be predicted based on flow measurements. This approach requires further investigation.

3.4.2.5 CONCLUSIONS

Chemical dosing is widely applied for sulfide control in sewers. However, on-line control of the dosing rate has not applied to date. In practice, the chemical dosing rate is either kept at a constant level or paced with the sewage flow rate. A three-component on-line control algorithm for the optimised dosing of Mg(OH)₂ was developed and validated with both simulation studies and a field trial. The results showed that on-line chemical dosing control should be adopted, which can result in not only significant savings in chemical consumption, but also a more consistent system performance. Due to the plug-flow nature of sewer pipes, feedforward control should play an important role in the control design. The sewage flow rate variation is

an important disturbance to be considered in the control design. For sewers with its flow rate significantly influenced by rains, the sewage flow rate should be predicted on-line to support the controller design.o be added.

3.4.3 Case study 2: Nitrate dosing at Clifton Springs SPS

3.4.3.1 Background

The validation of the control algorithm for nitrate dosing was undertaken in collaboration with Barwon Water at Clifton Springs SPS #3, a rising main pipe with a length of 1900 m, a pipe diameter of 250 mm, an average dry weather flow of 0.8 ML/d.



Figure 3-46. The map of the sewer networks for Clifton Springs SPS #3.

As shown in Figure 3-48, the hydraulic retention time in the rising main pipe ranges between 1 to 7 hr, with an average HRT of 3.2 hr. During 5 am to 9 pm, the HRT is around 2 hr due to frequent pumping events at the Clifton Springs #3 SPS. The sewage pH is around 7.8 ± 0.4 , with high end after 7 AM and the low end during early morning time. The high pH is likely related to the ammonia and the low pH is due to the proton production during periods with long HRT. The sewage temperature is around 19 °C.

3.4.3.2 Baseline monitoring

An intensive sampling campaign was conducted at Clifton Springs #3 to verify that sulfide concentration at the dosing site was negligible, but also to assess the performance of the current dosing system. Monitoring was conducted over two consecutive days to capture the variability

of wastewater characteristics and control performance throughout the day. Grab samples were collected from both Clifton Springs #3 wet well and discharge manhole on an hourly basis for the analysis of sulfur compounds, greenhouse gases (GHG) and NH₄⁺, PO₄³⁻, NO₂⁻/NO₃⁻. Additionally, an OdaLog online gas sensor was installed in the discharge manhole for a period of 24 hours, allowing the continuous monitoring of the concentration of H₂S and CH₄ in the gas phase. In order to assess the performance of the current dosing system, wastewater flow and nitrate dosing telemetry data were also obtained to compliment the analytical results.

The concentration of TDS in the wet well is presented in **Figure 3-47**. As can be seen, the amount of sulfide in the sewage at the wet well was during the whole day below 1 mgS-TDS/L. This confirms that the sewage had not experienced significant sulfate reduction during the transport from households to the SPS. Next, the concentrations of TDS and NO_x⁻ (nitrate plus nitrite) at discharge are presented in **Figure 3-48**, together with the hydraulic retention time of the sewage and the nitrate dosage received.

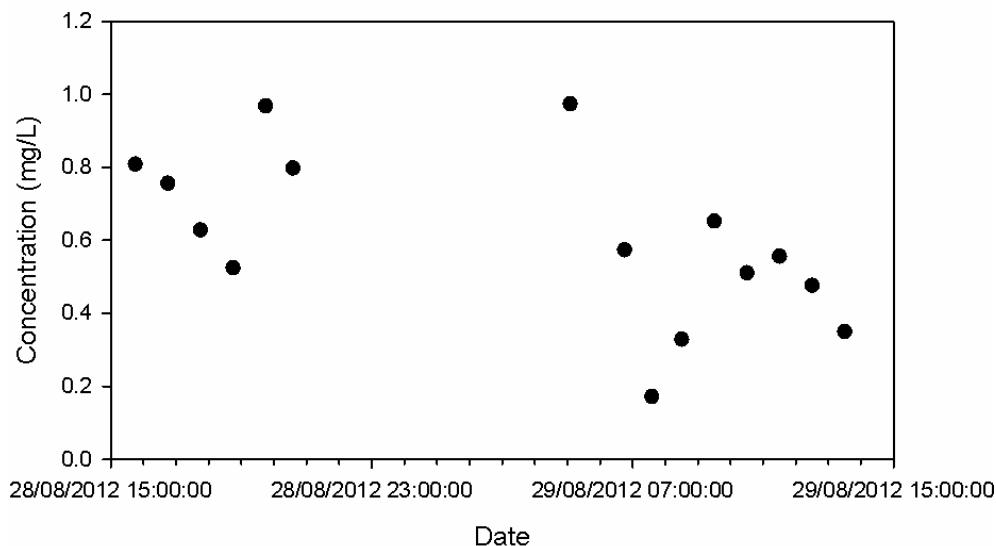


Figure 3-47. Concentration of TDS in the wet well of Clifton Spring SPS#3.

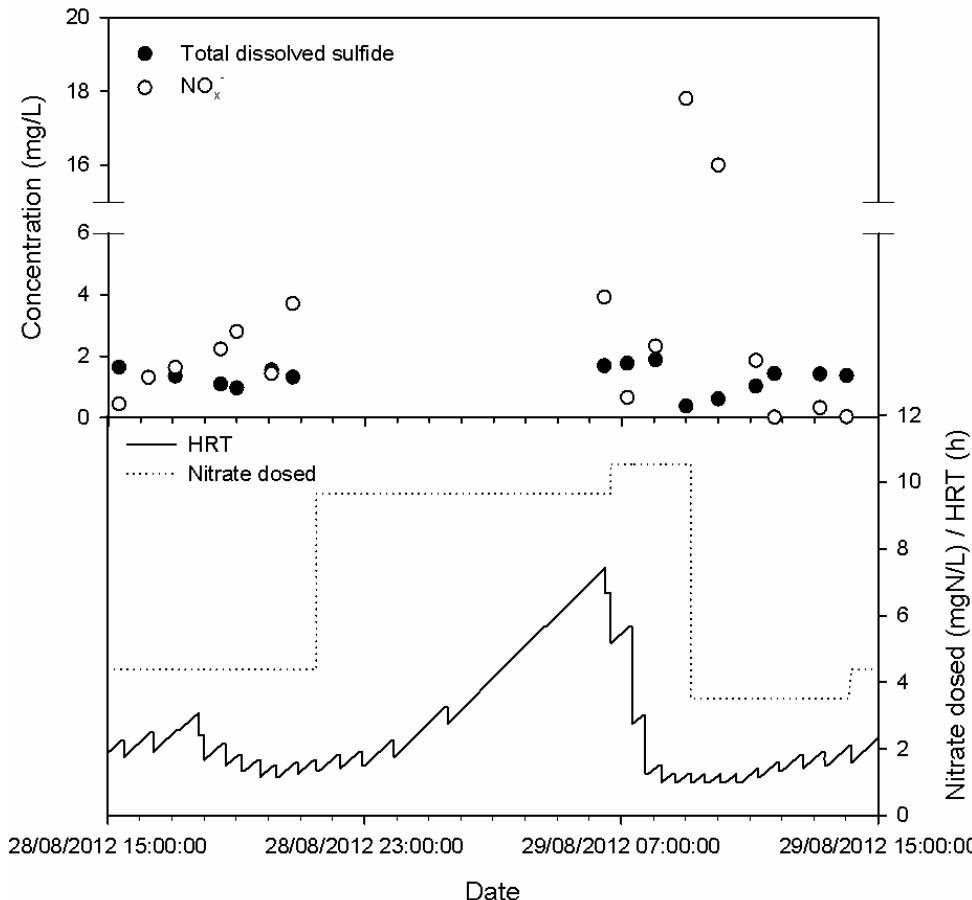


Figure 3-48. Top: Concentration of TDS and NO_x^- at discharge. Bottom: HRT of the sewage and nitrate dose.

During the period between 2:00PM and 9:00PM TDS at discharge was 1-2 mgS/L, whereas nitrate was around 2-4 mgN/L. Similar concentrations were observed during the morning-midday period (5:00AM-3:00PM), although from 8AM until 10AM sulfide level at discharge was very close to zero. This coincided with high NO_x^- concentration at discharge, pointing out that over that period, the control may be overdosing $\text{Ca}(\text{NO}_3)_2$.

A S::CAN unit was installed at the discharge manhole to monitor the dissolved sulfide concentration in the sewage. As shown in **Figure 3-49** and **Table 3-5**, total dissolved sulfide was well controlled with nitrate dosed according to a daily profile. The average sulfide was less than 0.1 mgS/L, although few spikes of sulfide around 1 mgS/L were observed, mainly during late morning at short HRTs. However, the data also indicated that very likely nitrate was overdosed during the morning time, leading to residual nitrate reaching 10 mgN/L in the discharge. This observation implies that optimization is needed for the dosing profile.

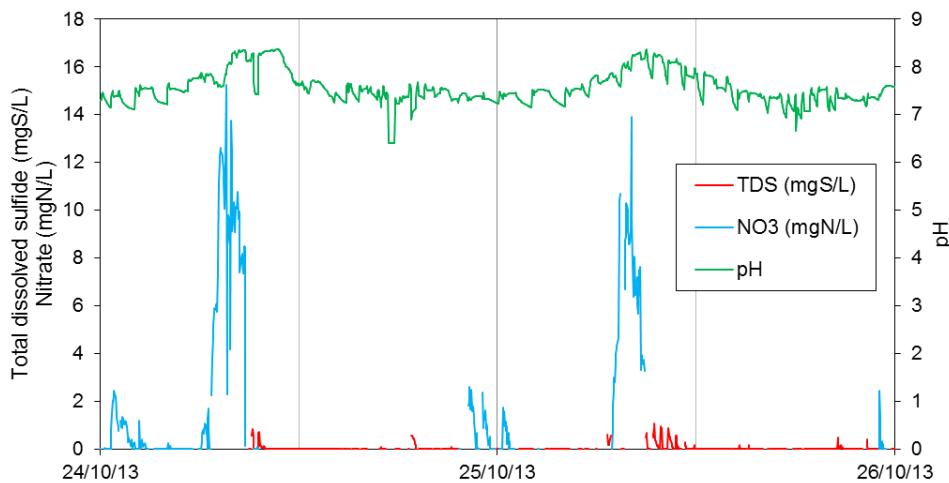


Figure 3-49. Profiles of total dissolved sulfide, nitrate and pH at the discharge manhole with profiled dosing.

Table 3-5. The monitored pH, sulfide, and nitrate levels in the Clifton Spring SPS 3# discharge manhole for the existing nitrate dosing.

	Average	SD	90%ile
pH	7.36	0.48	8.00
Sulfide	0.08	0.24	0.33
Nitrate	0.38	2.55	4.79

Previously, the H₂S gaseous concentration in the discharge manhole was monitored without nitrate dosing and after the profiled dosing (Figure 3-50). The TDS data correlates well with the H₂S profiles in the sewer gas. During most time of the day, both TDS and H₂S were found to be zero. In contrast, H₂S was found to be 40-50 ppm without nitrate dosing. Thus, the TDS monitoring using S::CAN, together with an Odalog H₂S gas sensor, is sufficient for the long term monitoring of dosing performance.

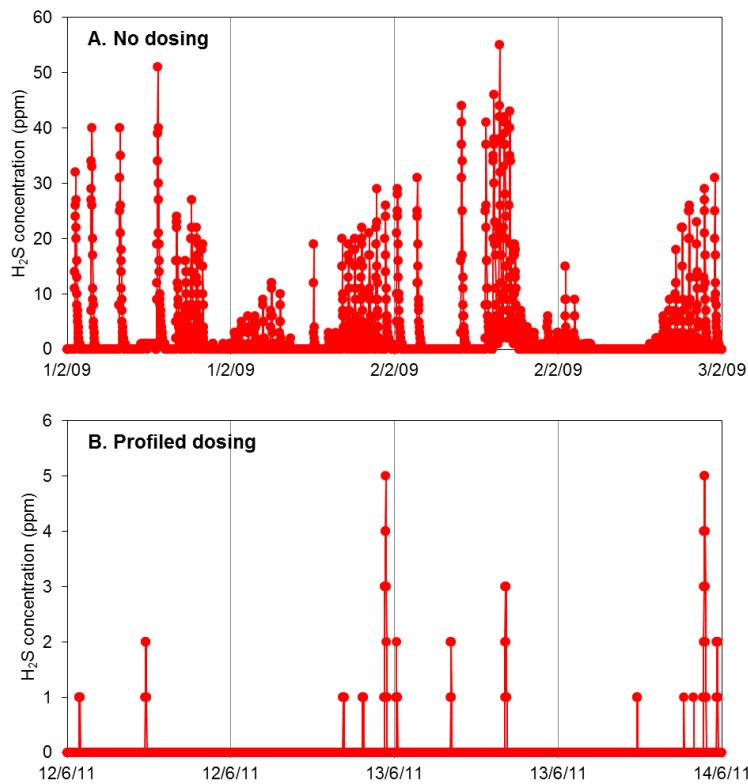


Figure 3-50. H₂S gaseous concentration in the Clifton Springs SPS #3 discharge manhole without dosing and with the profiled dosing of nitrate.

3.4.3.3 Optimization of dosing profiles

Ca(NO₃)₂ was dosed directly into the outlet pipe from the SPS according to a profiled flow-paced control to mitigate sulfide corrosion and odours. Optimized profiles for the nitrate dosing were generated according to the control strategies discussed in previous reports. In brief, nitrate dosage is designed to satisfy two consumption processes: the oxidation of sulfide produced upstream and the heterotrophic organic matter oxidation during the transport time between the dosing site and the discharge point/control point. A correction factor was also applied to account for the effects of quiescent periods caused by pumping operational patterns.

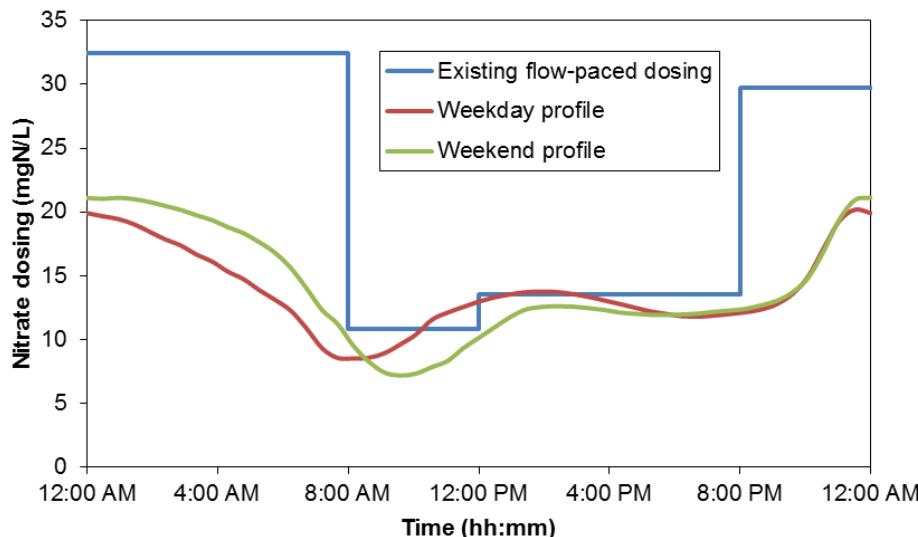


Figure 3-51. The existing flow-paced dosing profile and the optimized dosing profiles for weekdays and weekends, respectively.

The optimized profiles were firstly compared to the existing profile for the daily dosing volume of nitrate, based on the typical wastewater flow and pumping pattern. It was found that the daily dosing volume optimized profiles were lower than existing profile by saving nitrate of 33% and 13%, for weekdays and weekends respectively. The overall chemical saving was estimated to be 27% in comparison to the existing profile. Furthermore, the actual chemical saving and performance of the optimized profiles were validated by implementing the profiles.

Table 3-6. Comparison of existing profile with the optimized profiles in terms of chemical dosage and saving.

	Daily dosing volume (L)	Estimated saving (%)
Existing profile	70.0	-
Optimized profile (weekdays)	46.7	33
Optimized profile (weekends)	60.9	13
Optimized profile (weekly)	355.3	27

3.4.3.3 Performance of optimized nitrate dosing profiles

To monitor the performance of nitrate dosing, a S::CAN unit and an Odalog H₂S sensor were installed at the discharge manhole to monitor the dissolved sulfide concentration in the sewage, and the gaseous H₂S concentration. In addition, the chemical usage was recorded for both the existing profile and the optimized profiles.

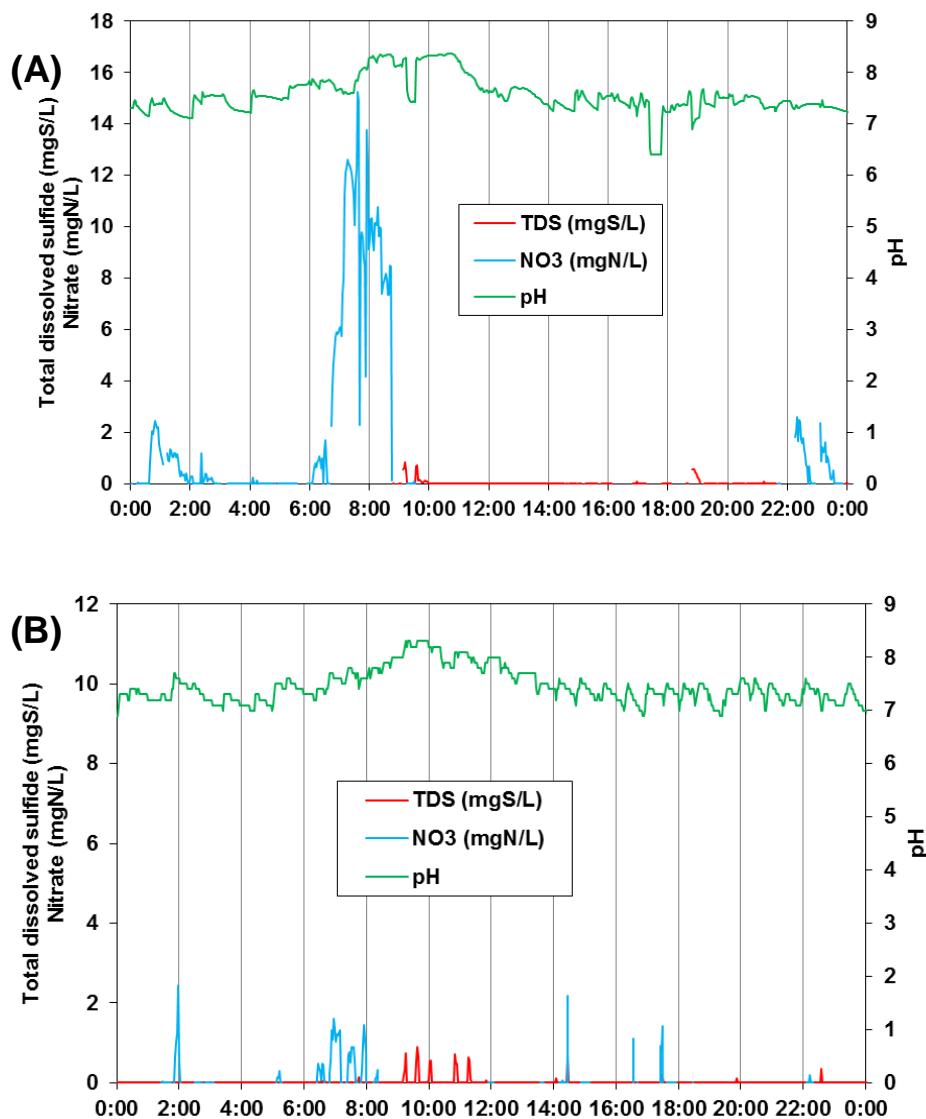


Figure 3-52. Total dissolved sulfide and nitrate concentration in the Clifton Springs SPS #3 discharge manhole for the existing dosing profile (A) and the optimized dosing profiles (B).

As shown in **Figure 3-52** and **Table 3-7**, the optimized profiles achieved comparable control of total dissolved sulfide as that of existing profile. The average sulfide was improved from 0.2 to 0.1 mgS/L, although there were a few spikes of sulfide around 1 mgS/L mainly at short HRT during late morning. For existing profile, the data also indicated that very likely nitrate was overdosed during the morning time, leading to residual nitrate reaching 14 mgN/L in the discharge. The overdosing of nitrate was reduced greatly with the optimized profiles, with residual nitrate less than 2 mgN/L. The average nitrate at discharge was reduced from 1.9 to 0.1 mgN/L, implying a saving of chemical.

Table 3-7. The monitored pH, sulfide, and nitrate levels in the Clifton Spring SPS 3# discharge manhole.

	Max	Average	SD	Median	99%ile
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	pH	8.8	7.5	0.4	7.4	8.5
Existed profile	Sulfide	8.3	0.2	0.5	0.0	2.3
	Nitrate	15.7	1.9	3.0	0.3	12.5
Optimized profile	pH	8.4	7.3	0.4	7.3	8.2
	Sulfide	4.7	0.1	0.4	0.0	1.7
	Nitrate	9.7	0.1	0.5	0.0	2.4

The actual daily chemical consumption was also recorded and compared. **Figure 3-53** shows that optimized profile has saved an average of 42% chemical during the trial period. This saving percentage was higher than the theoretical estimation (27%), possibly due to the flow fluctuation. Collectively, the optimized profile was demonstrated to control hydrogen sulfide to the same level with less chemical consumption.

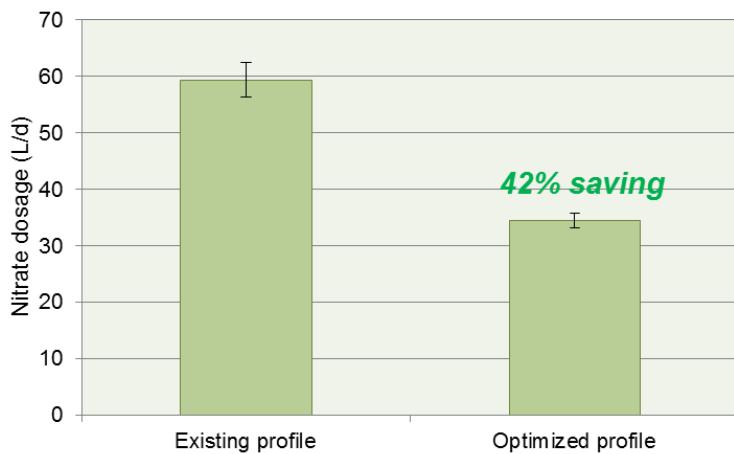


Figure 3-53. Daily consumption of nitrate for existing and optimized profile, respectively.

3.4.4 Case study 3: Iron salts dosing at Bellambi SPS

3.4.4.1 Background

The validation of the online control algorithm for the optimised dosing of iron salts was conducted at Bellambi SPS (SWC). The rising main, which conveys wastewater from the SPS to Wollongong WWTP, has a total length of 9930 metres and a pipe diameter of 603/750 mm. The average dry weather flow is around 21ML/d, yielding an average hydraulic retention time around 4 hours (Figure 3-54).

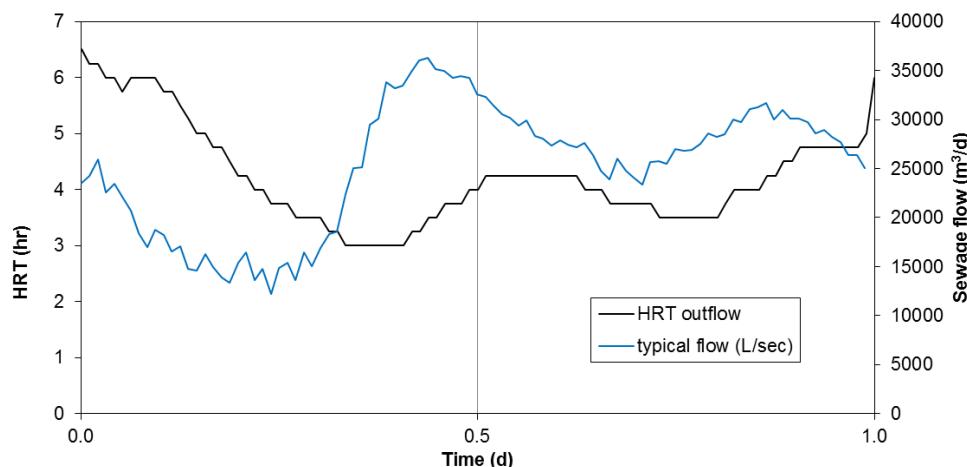


Figure 3-54. Sewage flow rate and daily hydraulic retention time for the Bellambi SPS rising main pipe.

Two sensors were installed at the beginning (Bellambi SPS) and end (Wollongong STP) of the rising main. The system was monitored over a period of six days, three without chemical dosing and three with ferrous dosing. Next, the concentration of TDS at the beginning and end of the pipe are depicted in Figure 3-55. Please note that the monitoring period without chemical dosing was affected by rainfall, and the accumulated rainfall data is also presented.

The results of the monitoring campaign show that sulfide concentration at the inlet of Bellambi SPS is very low, below 0.5mgS/L, and hence does not need to be taken into consideration in the calculation of the dosing requirements by the online control algorithm. Regarding the discharge location, currently with the iron dosing in place sulfide concentration is most of the time below 0.5 mgS/L, which is the control objective of SWC. If no chemicals were dosed to control sulfide, this concentration would rise to 2-5 mgS/L, depending on the HRT. Finally, it is important to highlight that on the period without chemical dosing, sulfide concentration at discharge significantly decreased during and after the rain episode. This is due to the infiltration of rainwater that: i) increases the flow/decreases the sewage HRT, decreasing the sulfide produced; and ii) dilutes the sewage composition with rainwater, limiting the available substrate for SRB growth, potentially negatively affecting the production of sulfide. In areas with frequent rain episodes, these phenomena can play a critical role, reducing the amount of sulfide produced during those periods. If chemicals are dosed on a flow-paced fashion with pre-defined profiles, these can lead to significant chemical overdosing. However, if controlling the dosing through an online control, these periods are an opportunity for savings in chemical dosing, if sulfide produced along the pipe is properly estimated.

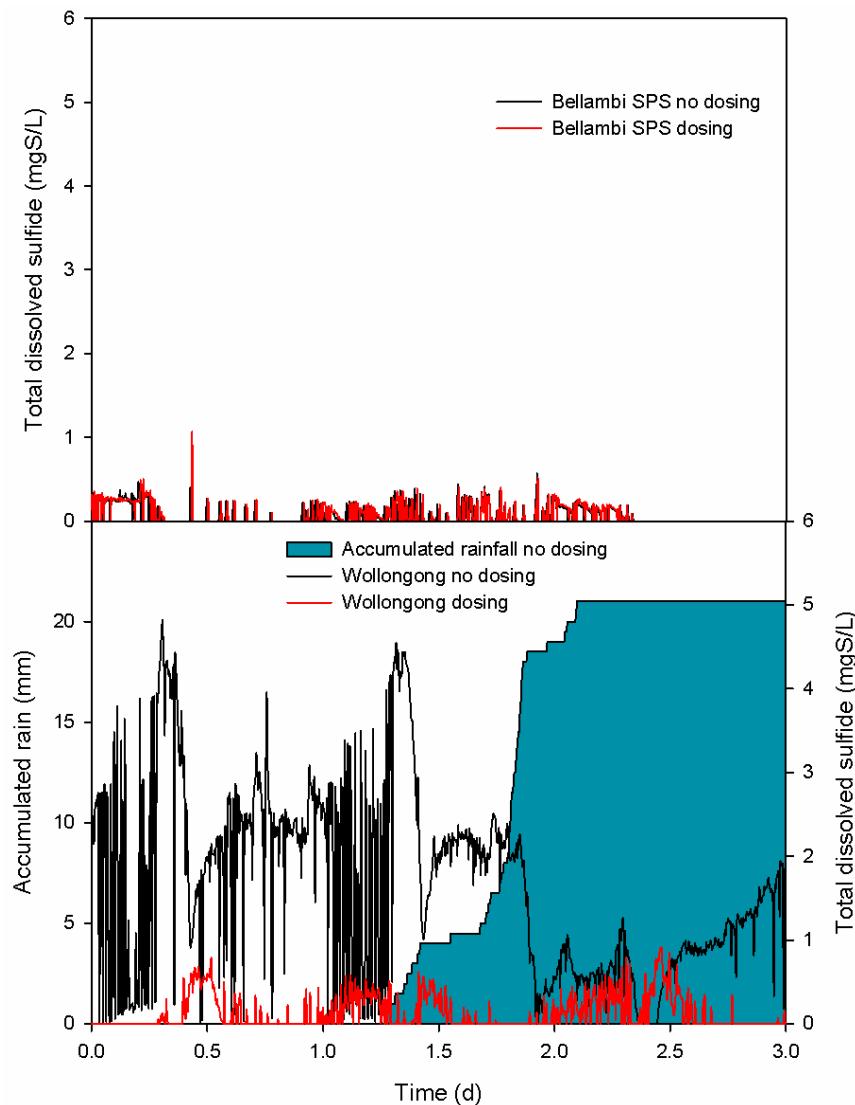


Figure 3-55. Top: TDS at the inlet with and without chemical dosing; Bottom: TDS at the end of the pipe with and without chemical dosing, and accumulated rainfall during the period without iron dosing.

To control the sulfide at the discharge to Wollongong WWTP, iron is dosed at the Bellambi pumping station according to a pre-defined profile. As shown in Figure 3-56, the average concentration of total dissolved sulfide was reduced down to 0.1 mgS/L from 1.6 mgS/L without iron dosing, while the sewage pH was not changed, remaining around 7.4 ± 0.2 .

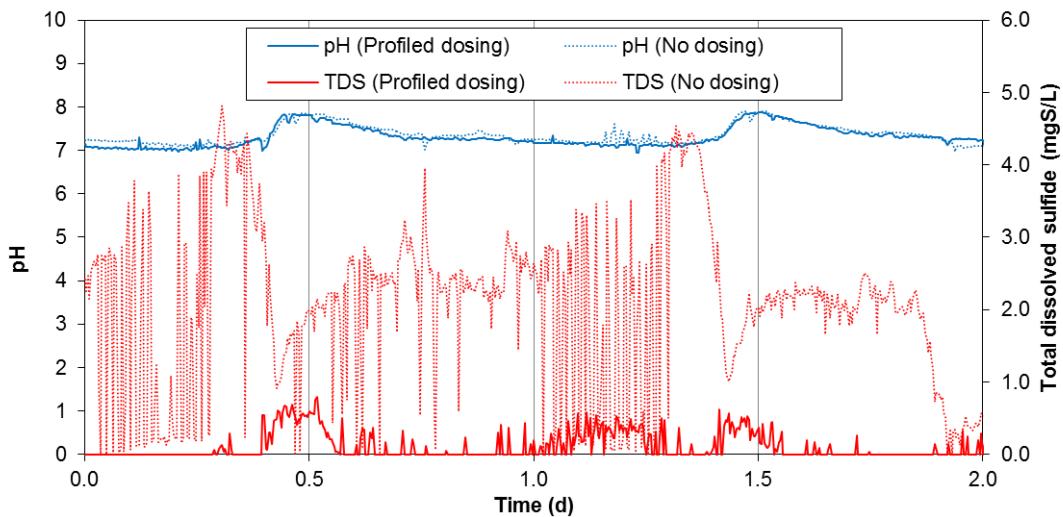


Figure 3-56. The profiles of total dissolved sulfide and pH at the discharge of Bellambi rising main without iron dosing and with profiled dosing of iron.

3.4.4.2 Bellambi SPS simulation study

To illustrate the benefits of the proposed control algorithm, both in terms of sulfide control and reduction of chemical dosing, the outcomes of an online control were assessed in a simulation study and compared to two other scenarios: i) no chemical dosing and ii) iron salts being dosed according to a pre-defined profile.

Online control algorithm.

Considering that the iron salts dosing at Bellambi takes places at the SPS, and assuming that TDS in the wet well is negligible, the online control algorithm has to estimate the total dissolved sulfide produced during the transport of the sewage. There is a linear relationship between the hydraulic retention time (HRT) of the sewage in the pipe and the amount of sulfide produced. In this respect, sulfide levels at discharge can be estimated through the HRT, which can be predicted using an Auto Regressive (AR) model (previously calibrated and validated).

During rain events, rainwater may infiltrate in sewer systems, increasing the sewage flow and diluting the composition of the main physical-chemical parameters. This has critical implications for the calculation of the dosing requirements. Firstly, the higher flow will lead to shorter HRT and hence less sulfide produced. The AR model can predict with reasonable accuracy the increase on the flow due to rainwater infiltration and based on that estimate the HRT of the sewage in the pipe. Moreover, under heavy rain the dilution of the concentration of sulfate and readily biodegradable organic matter (i.e. acetate), substrates of sulfate reducing bacteria (SRB), may limit the SRB reaction rate. To take into account the nonlinear reduction on the amount of sulfide generated a correction factor was added to the control algorithm to correct SRB activity at short HRT (HRT lower than 3 hours). This is illustrated in Figure 3-57.

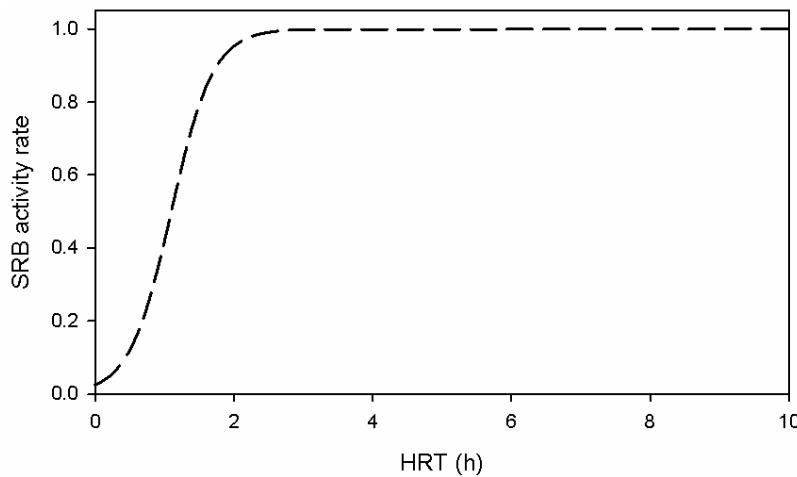


Figure 3-57. Non-linear SRB activity rate correction at short HRT due to substrate limitation.

pH at discharge is also an important parameter to consider when aiming to optimise iron salts dosing, as this governs speciation of S²⁻/HS⁻/H₂S. The lower the pH, the less S²⁻ in equilibrium in the liquid phase, requiring higher Fe²⁺ concentrations to reach the point where FeS precipitates.

Provided that the control goal at Bellambi SPS is to achieve a TDS around 0.5 mgS/L and pH at discharge is usually above 7, in this case the impact of pH is minor and for the sake of simplicity it was not considered in the calculation of the dosing requirements.

AR future flow prediction.

As a starting point, SP5 team was provided with a year of flow historical data, with a resolution of 15 minutes. Figure 3-58 depicts the Bellambi SPS historical data flow over a period of 200 days. Based on this data, future flow was predicted using the previously developed AR model. Results for 1 hour, 3 hour and 6 hour ahead predictions under dry weather and wet weather conditions are presented in Figure 3-59, and confirm the good prediction capability of the model.

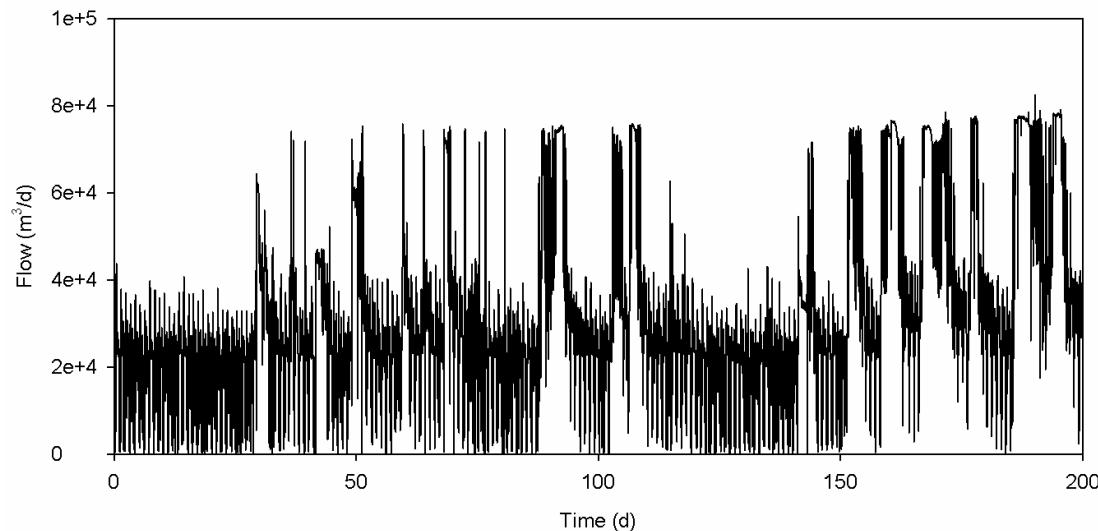


Figure 3-58. Historical flow data of Bellambi SPS.

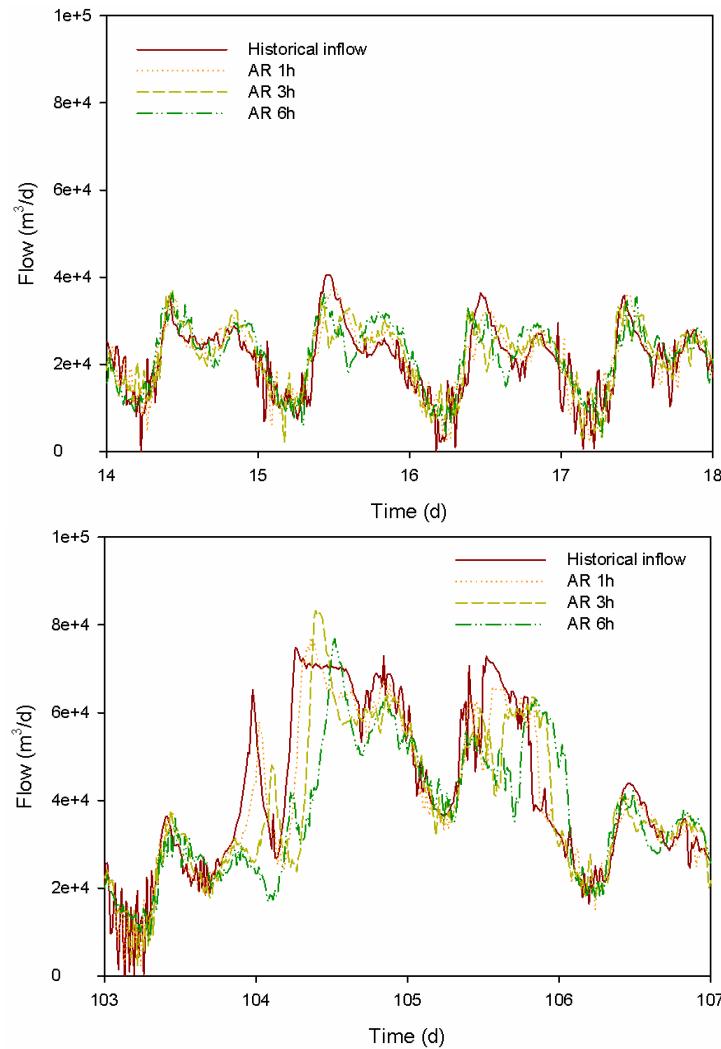


Figure 3-59. Historical and predicted inflow to Bellambi SPS wet well (Top: dry weather conditions; Bottom: wet weather conditions).

Simulation study.

The Bellambi system was modelled using SeweX model and the performance of the online control algorithm was assessed in a simulation study. The system was simulated for 200 days, with changing weather conditions. pH of the wastewater in the wet well ranged from 7 to 8.5, following a typical daily pattern. Regarding the wastewater composition, and for the sake of simplicity, the concentration of all the parameters was assumed constant during dry weather conditions. However, during rain events, this composition was adjusted to account for the sewage dilution due to rainwater infiltration. The amount of rainwater infiltrated was estimated by comparing the actual SPS flow with the typical dry weather flow profile, and the sewage characteristics were corrected based on that. Finally, apart from the online control, two other scenarios were also simulated using the same conditions, the first one without chemical dosing, and the second one with the current profiled dosing used at Bellambi SPS. Next, Figure 3-60 presents the concentration of total dissolve sulfide (TDS) at the discharge of the rising main for each of the scenarios.

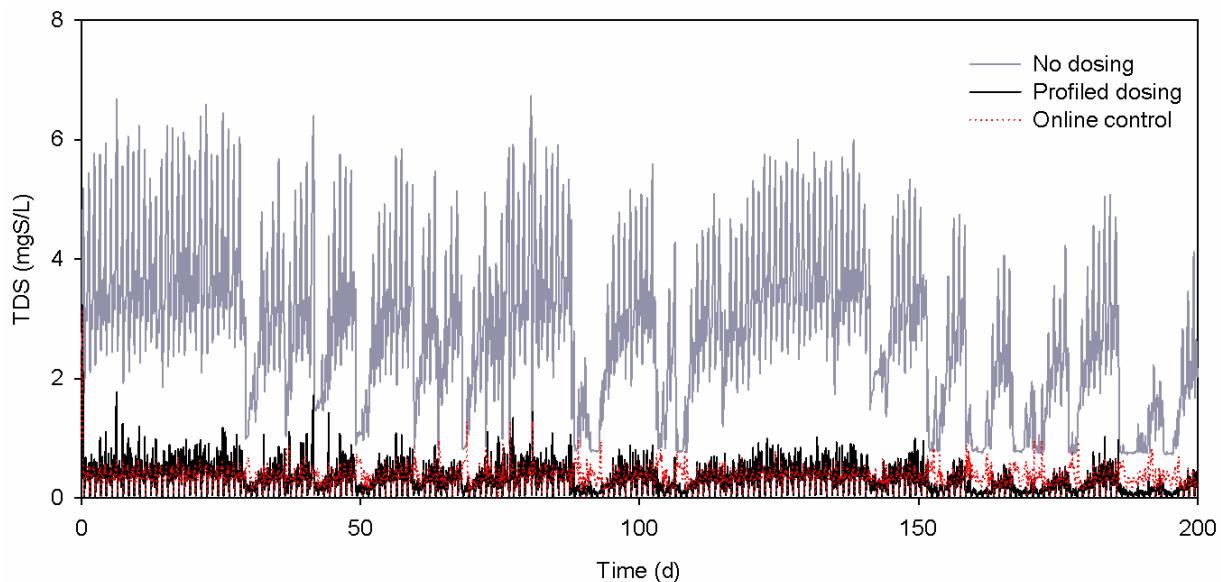


Figure 3-60. Simulated TDS discharge under three different scenarios: i) no dosing, ii) Fe³⁺ profiled dosing, and iii) Fe³⁺ online dosing.

During the whole 200-day period both profiled dosing and online control were able to control sulfide at discharge very close to the control goal (0.5 mgS/L). The average TDS at discharge and the average Fe³⁺ daily dosing rate for each scenario were calculated and are presented in Table 3-8. Results clearly show that online control was capable of achieving a similar degree of sulfide control, reducing the chemical dosing by 20%.

Table 3-8. Total dissolved sulfide at discharge and average daily dosing for the three scenarios.

	No dosing	Profile dosing	Online dosing
Average TDS discharge (mgS/L)	2.18 ± 1.18	0.31 ± 0.24	0.35 ± 0.16
Average daily dosing (KgFe ³⁺ /d)	-	73.45	57.20

To gain a deeper insight, TDS profiles for each of the scenarios under dry weather and wet weather conditions are presented in Figure 3-61.

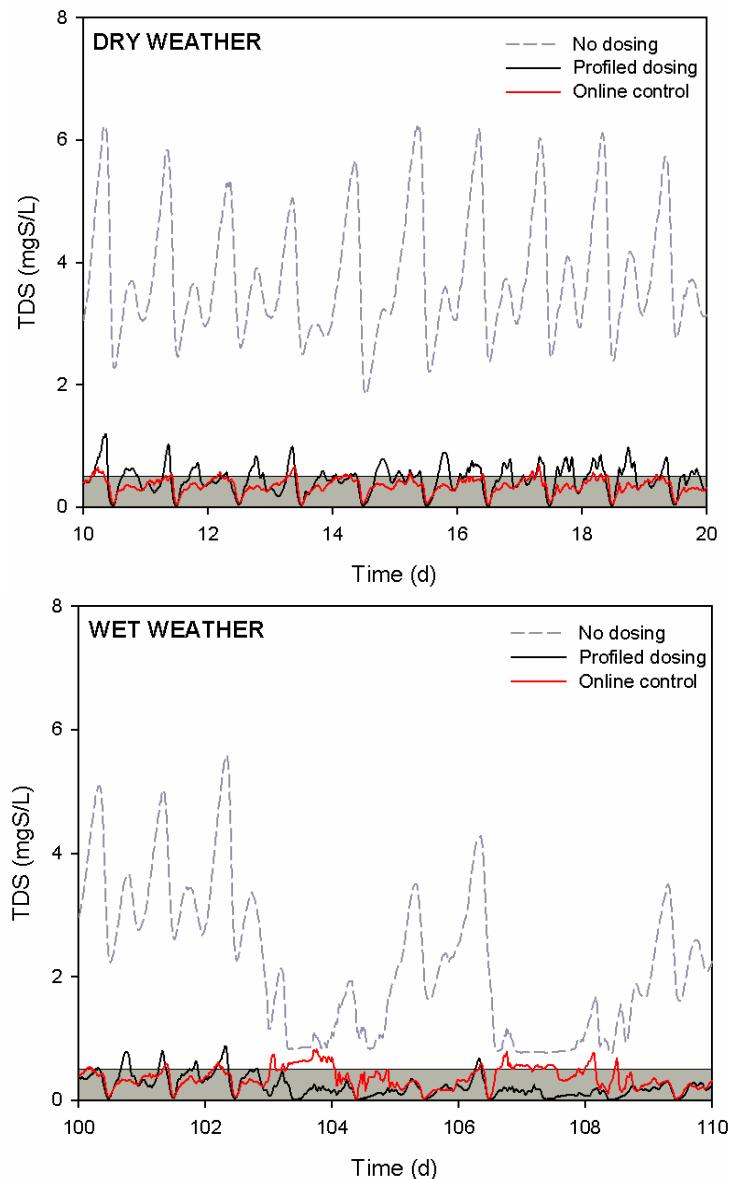


Figure 3-61. Simulated TDS discharge in dry weather (top) and wet weather (bottom) conditions under three different scenarios: i) no dosing, ii) Fe³⁺ profiled dosing, and iii) Fe³⁺ online dosing.

These graphs clearly show that under dry weather conditions both controls performed well and on a similar way. However, during wet weather conditions the infiltration of rainwater significantly reduced the amount of sulfide produced within the pipe. According to the simulation results, in these conditions the online control was capable of predicting sulfide production closely and hence outperform the profiled dosing.

3.4.4.3 Implementation and performance of online control at Bellambi SPS

The feed forward control algorithm utilizing AR model, validated previously, was implemented by SWC into the PLC controlling the iron dosing. The new control was online since 18 September and data of sewage flow, pH and total dissolved sulfide were analysed to evaluate its control performance. Figure 3-62 shows diurnal fluctuation of sewage flow, with an average around 20.8 ML/day. This flow rate is comparable to that during the profiled dosing and no dosing periods.

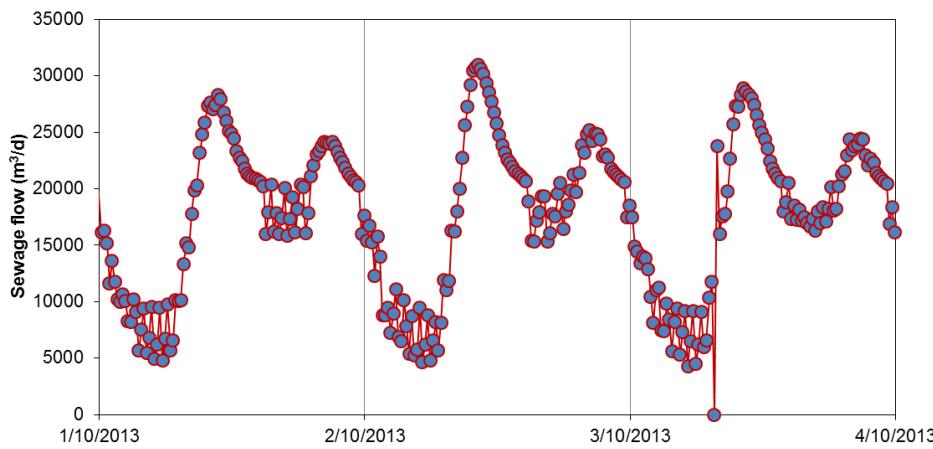


Figure 3-62. Sewage flow during the trial of the new AR model based feed-forward control.

Figure 3-63 shows the typical daily profiles of total dissolved sulfide and pH during the trial period. It is clear that the feed-forward control achieved comparable control of sulfide as the existing profiled dosing. More importantly, Table 3-9 shows about 26% chemical saving for the same level of sulfide control.

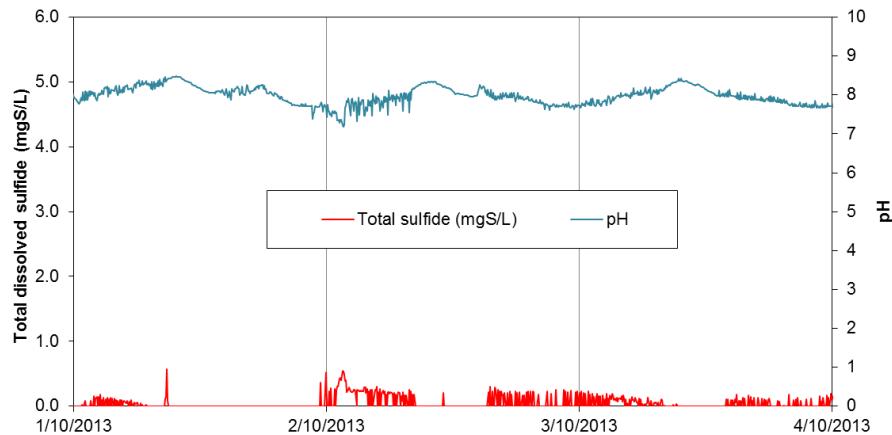


Figure 3-63. Typical profiles of total dissolved sulfide and pH during the trial of feed-forward control.

Table 3-9. Comparison of sewage parameters at Wollongong WWTP inlet among three scenarios: profiled dosing, feed-forward dosing and no dosing.

Parameters	No dosing	Profiled dosing	Feed-forward dosing
Sewage flow (ML/d)	21	20.9	20.9
pH	7.4 ±0.2	7.3 ±0.2	7.4 ±0.2
Average TDS (mgS/L)	1.65	0.13	0.07
90% TDS (mgS/L)	3.08	0.46	0.23
Iron dosage (L/day)	0	433	318

By comparing the daily dosing profiles for profiled and feed-forward dosing, it is clear that both controls applied similar dosage between 0:00 AM to 9:00 AM. Feed-forward dosed slightly higher iron between 9:00 AM to 2:00 PM. However, profiled dosing strategy obviously overdosed iron between 2:00 PM and midnight. Overall, the improved dosing profile using online AR model achieved sulfide control with lower iron dosage.

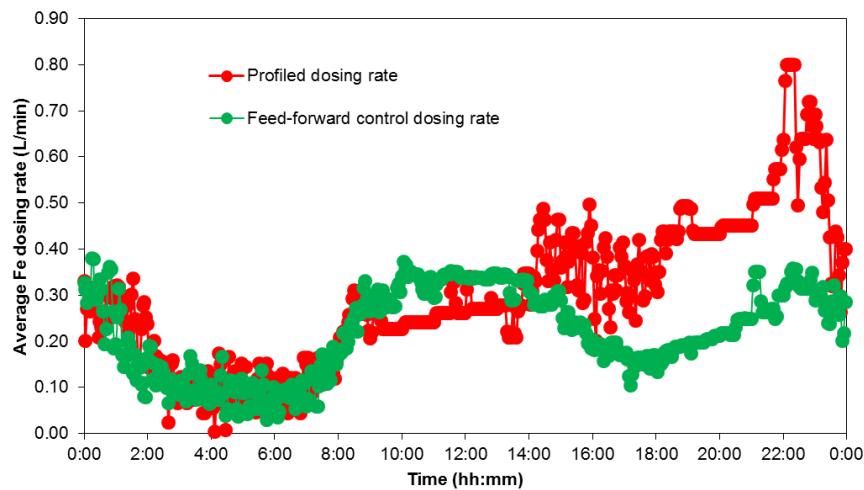


Figure 3-64. Daily average of Fe dosing rate for the profiled dosing and feed-forward online control.

4. PRACTICAL OUTCOMES AND CONCLUSIONS

The research outcomes of the present sub-project provide Australian water utilities with new tools for cost-effective control of sulfide in sewers, in addition to insights to the practical management of sewer systems and further implications. The following is a brief summary and conclusions.

- The most widely used chemicals have been identified through an Australia-wide industry survey. These chemicals have been extensively tested by water industry and also in the sister subprojects of SP5. Thus, the four chemicals comprise a bank of safe options for the potential sulfide control projects. It must also be realized that many emerging chemicals, like free nitrous acid, may achieve effective control at low cost and environmental footprints. In addition, the control for FNA dosing is relatively easier than other chemicals. This implies FNA dosing can attain reliability without hefty investment on on-line sensors and controllers.
- This project has demonstrated that the conventional dosing schemes might over-dose chemicals based on sewage flow or predefined profiles. Optimized control saves chemical and improves reliability of the sulfide control. The combination of feed-forward and feed-back schemes can achieve adequate performance. When feedback control is not practical, feed-forward control can still work satisfactorily. The selection of control systems depends on many factors including the system complexity and maintenance requirement. The most non-intrusive approach can be done through the implementation of an optimized dosing profile based upon typical flow, HRT and sulfide concentrations.

5. RECOMMENDATIONS FOR FUTURE RESEARCH

SP5 successfully identified commonly used chemicals for sulfide control in sewers. Based upon that, optimal dosing control strategies were designed using theoretical analysis and mathematical modelling during the 5 years of investigation. Also, a network wide control scheme was proposed to help the management of big sewer catchments.

The project, due to the limitation of resources, did not consider the possible cases for dosing multiple chemicals to achieve synergistic efficiency. For example, magnesium hydroxide can be used to contain sulfide in sewage when it flows through pipes in the upstream. Iron salts can be dosed at a downstream point to precipitate all sulfide. The benefits are the higher pH promotes the iron sulfide precipitation. There are of course other combinations depending on the requirements of sulfide control and the availability of the chemicals. Future research might explore the possible combinations and their merits.

Iron salts, magnesium hydroxide, nitrate and oxygen are the most commonly used chemicals for sulfide control. Fundamental understanding of the mechanisms involved in sulfide control with these chemicals has been gained in this project. On-line control algorithms have been developed for single sewer pipes (rising mains or gravity sewers), and successfully demonstrated through real-life case studies. The control algorithms ensure consistent sulfide control performance throughout the pipe with chemical consumption kept to a minimum. In the case studies, 15-45% savings in chemical consumption were achieved. However, sewer corrosion and odour problems are rarely limited to a single pipe but typically distributed across of a network consisting of many interconnected pipes and sewage pumping stations (SPSs). Sewage flow in a sewer network is highly dynamic. The intermittent operation of SPSs result in ‘sewage slugs’ dominated by or even solely attributed to certain sewage streams. This makes network-wide sulfide control with a limited number of chemical dosing units in the network a highly challenging task. Indeed, there is currently a lack of suitable methodologies to support such control designs.

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