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A methodology for simulating hydrogen sulphide generation in sewer network using EPA SWMM

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ABSTRACT

Predicting hydrogen sulphide concentration in sewer network through modelling tools will be beneficial for many stakeholders to design appropriate mitigation strategies. However, the hydrogen sulphide modelling in a sewer network is crucially dependent on the hydraulic modelling of the sewer. The establishment of precise hydrogen sulphide and hydraulic modelling however requires detailed and accurate information about the sewer network structure and the model parameters. This paper outlines a novel approach for the development of hydraulic and hydrogen sulphide modelling to predict the concentration of hydrogen sulphide in sewer network. The approach combines the calculation of wastewater generation and implementation of flow routing on the EPA SWMM 5.0 platform to allow hydrodynamic simulations. Dynamic wave routing is used for hydraulic simulations. It is considered to be the best approach to route existing/old sewer flow. The build-up of hydrogen sulphide model includes the empirical models of hydrogen sulphide generation and emission. Trial of the model was conducted to simulate a sewer network in Seoul, South Korea with some hypothetical data. Further analysis on the use of chemical dosing on the sewer pipe was also performed by the model. Promising results have been obtained through the model, however calibration and validation of the model is required. The presented methodology provides a possibility of the free platform SWMM to be used as a prediction tool of hydrogen sulphide generation.

Keywords: Chemical addition; Hydrogen sulphide; Sewer network; SWMM

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1. Introduction

Sewer pipe network is known to be the most susceptible pipe systems due to physical and biochemical transformation processes of wastewater during its transport to a wastewater treatment plant. It is becoming increasingly important for a city to develop an approach for preventive maintenance of its sewer pipes. Sewer modelling is one of the approaches that can be used to estimate the sewer pipe condition. The modelling output can be used to assess the critical pipe locations and relate them to high impact locations. Therefore, early action can be taken in order to minimise the defects.

Gas generation in sewer networks have long been an issue in the operation and maintenance of sewer systems. With the ever expanding population worldwide, the generation of wastewater is set to increase; as such proper mitigation strategies in controlling the production of sewer gas has become an integral part in the operation and maintenance of a sewer system. One of the most documented of these sewer gases is the production of hydrogen sulphide as it is one of the most detrimental gases in a sewer network [1]. This includes the bad odour that the gas emits, health issues that it imposes to the personnel exposed to it as well as the corrosion to sewer infrastructure that the gas induces.

The odour and human health-related problems that are directly associated with hydrogen sulphide in sewer networks are shown in Table 1. Further, the oxidation of hydrogen sulphide into sulphuric acid by the bacteria of genus *thiobacillus* damages the sewer assets. The oxidation that can corrode the pipe occurs in the pores of the concrete lining above the water surface in the sewer. Minor problem of concrete corrosion have been reported when the concentration of total sulphide in the wastewater was within the range of 0.1–0.5 mg S/L while severe concrete corrosion may occur at sulphide concentrations from 2.0 mg S/L [2].

As sewer networks vary in regard to hydraulic conditions as well as constituents within the wastewater, it is important to look in depth into those variations. As concentrations of hydrogen sulphide are dependent on wastewater constituents, it is imperative that the breakdown of the wastewater constituents that favour the hydrogen sulphide should be listed. The general conditions which favour hydrogen sulphide formation are the following: pH levels ranging from 5.5 to 8.5, temperatures between 24 and 42˚C as well as the hydraulic conditions experienced within the network [4]. With the aid of modelling tools, the formation and emission of sulphide into hydrogen sulphide gas can be determined and the locality of high generation of hydrogen sulphide gas can be found through hydraulic analysis.

Prevention methods that are used to protect assets such as manholes and concrete pipes may include the injection of oxygen; this improves the aerobic conditions of the system and stops the emission of sulphide into hydrogen sulphide totally. However, injecting oxygen may not be ideal if hydrogen sulphide has already been formed. In that situation other mitigation strategies such as adding chemicals have to be executed. In order to do so, it is important to know the location where high generation of hydrogen sulphide occurs. Thus, the location of chemical dosing could be determined by looking at the mapping of critical pipes. In this study, chemicals such as magnesium hydroxide, iron salts, calcium nitrate and sodium hydroxide were used to look at the efficiency of those chemicals in reducing the release of hydrogen sulphide gas into the air space of sewers.

This study further investigates the generation rates through the *Environmental Protection Agency's Strom Water Management Model 5.0 (SWMM)* to run various simulations by combining flow routing to perform hydrodynamic analyses with input data such as manholes, pipelines and catchment characteristics [5]. SWMM provides simulation of the hydrodynamic conditions of the catchment developed which provides the parameters required for the prediction of hydrogen sulphide generation rate. With the assistance of

Table 1
Odour and human health-related effects of hydrogen sulphide in the atmosphere [3]

Odour or human effect	Concentration in atmosphere (ppm)
Threshold odour limit	0.0001–0.002
Unpleasant and strong smell	0.5–30
Headache; nausea; eye, nose and throat irritation	10–50
Eye and respiratory injury	50–300
Life threatening	300–500
Immediate death	>700

the modelling tool SWMM, various parameters of a typical sewer network will indicate the optimal dosing location of chemicals in order to properly mitigate the consequences of hydrogen sulphide emission in a sewer network.

2. Mathematical modelling

2.1. Storm water Model Management (SWMM)

Flow routing in SWMM is governed by the conservation of mass and momentum equation for gradually varying, unsteady flow (i.e. the Saint Venant flow equation) [6]. There are three routing approaches to solve the Saint Venant equation: Steady Flow, Kinematic Wave and Dynamic Wave [6].

Steady Flow routing represents the simplest type of routing possible by assuming that within each computational time step flow is uniform and steady. To route the flow, it simply translates inflow hydrographs at the upstream end of the conduit to the downstream end, with no delay or change in shape. The Manning equation (Eq. (1)) is used to relate flow rate to flow area (or depth). Unfortunately, this form of routing is insensitive to the time step employed, and is really only appropriate for preliminary analysis using long-term continuous simulations.

$$Q = \frac{1}{n} \cdot R^{2/3} \cdot S_f^{1/2} \cdot A \tag{1}$$

(The definition of symbols that appear in the equations can be found in the abbreviations section).

Kinematic Wave Routing assumes uniform flow but unsteady state condition. This routing method solves the continuity equation along with a simplified form of momentum equation in each conduit (See Eqs. (2) and (3)). This routing is considered to be an efficient routing approach for long-term simulation, if the effects of backflow, entrance/exit losses, flow reversal or pressurised flow are not expected to occur in the simulation.

Dynamic Wave Routing takes into account the non-uniform and unsteady state condition. This routing solves the complete one-dimensional Saint Venant flow equation (Eq. (2)) and therefore produces the most theoretically accurate results. These consist of continuity and momentum equations for conduits and a volume continuity equation at nodes. With this form of routing, it is possible to represent all the effects that cannot be simulated in Kinematic Wave Routing.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{2}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + \underbrace{g \cdot A \frac{\partial H}{\partial x} + g \cdot A \cdot S_f + g \cdot A \cdot h_{\mathrm{L}}}_{\text{Kinematic wave}} = 0 \tag{3}$$

In the case of sanitary flow, many researchers model flow routing by using kinematic wave routing, as the sanitary sewer is assumed to have unsteady state flow and it is uniform across the pipe. This assumption is applicable to new sewer systems where the pipe bottom disturbances (e.g. sediment) are not yet formed and pipe defects are relatively small. In the case of "old sanitary sewer pipes" (existing sewer pipes), the sewer condition is completely different as the bottom of the pipes may be occupied by sediment or thick biofilms. Furthermore, pipe defects occur mostly due to pipe ageing and as a result cause pipe corrosion. All the above-mentioned causes make the kinematic wave routing method unreliable for modelling sanitary flow routing in "old sanitary sewer pipes". Dynamic wave routing is the best approach to the existing sewer flow route, since it takes into account varied and unsteady state flow.

2.2. Modelling the generation of hydrogen sulphide

The implementation of modelling tools is used to predict the generation and concentration of hydrogen sulphide by forecasting sulphide production and emission. The use of empirical equations to predict hydrogen sulphide formation may be advantageous to water authorities as it offers direct relationship between the hydrogen sulphide concentration and the input variables such as velocity, water depth, temperature and pH. Investigation of hydrogen sulphide formation has been conducted in the past, and several predictive empirical equations have been proposed as listed in Table 2.

The net rate of formation is not only determined by the rate of generation but also the rate of dissipation of hydrogen sulphide in the liquid phase. The dissipation rate of hydrogen sulphide is also a function of hydraulic parameters. The dissipation of hydrogen sulphide can be caused due to several processes such as biological and chemical oxidation, precipitation and emission to the sewer atmosphere. Empirical equations in Table 3 are the dissipation equations of hydrogen sulphide in the liquid phase more due to hydraulic action.

Table 2
Empirical equations of hydrogen sulphide generation

Equation	Reference
$r_a = 0.5 \times 10^{-3} \times v \times (C_{\mathrm{BOD}_{\mathrm{total}}})^{0.8} \times (C_{\mathrm{SO}_4^{2-}})^{0.4} \times 1.139^{(T-20)}$	[7]
$r_a = 0.228 \times 10^{-3} \times C_{\mathrm{BOD}_{\mathrm{Total}}} \times 1.07^{(T-20)}$	[12]
$r_a = 3.2 \times 10^{-4} \times (C_{\mathrm{BOD}_{\mathrm{total}}}) \times 1.07^{(T-20)}$	[9]
$r_a = k \times 10^{-3} \times (C_{\mathrm{BOD}_{\mathrm{Soluble}}} - 50)^{0.5} \times 1.07^{(T-20)}$	[13]

Table 3
Empirical equation of hydrogen sulphide dissipation

Equation	Reference
$r_b = 0.64 \times (S_f \times v)^{3/8} \times (C_t) \times d_{\mathrm{dm}}^{-1}$	[9]
$r_b = K \times \sqrt{\frac{\gamma \times v \times S_f}{\mu}} \times \frac{w}{A} \times 1.024^{(T-20)} \times \left(\frac{[C_T]_0}{1 + \left(\frac{K_{s1}}{10^{\mathrm{pH}}}\right) + \left(\frac{K_{s1} \times K_{s2}}{10^{(2 \times \mathrm{pH})}}\right)} - P_{\mathrm{PH_SS}} \times K_H \right)$	[8]

2.3. *Gas transfer*

The dissipation of hydrogen sulphide from the wastewater can be caused by many processes such as emission, oxidation or precipitation. The process of hydrogen sulphide oxidation and precipitation has less chance to occur unless there is a chemical introduced into the sewer. Most of the time, emission occurs, particularly in gravity sewer pipe networks. Emission process will change hydrogen sulphide in the wastewater to hydrogen sulphide gas that is released to sewer air space. The release of hydrogen sulphide to air space can be affected mainly by the hydraulic process. High slope and velocity is usually the main trigger of the hydrogen sulphide emission. However, the emission is also determined by the temperature and the pH of the wastewater. High temperature triggers more release of hydrogen sulphide, while high pH causes less hydrogen sulphide gas generation. High pH triggers more total dissolved sulphide that stays in disassociated form (HS^-, S^{2-}) rather than the molecular form of hydrogen sulphide.

The central point is the dissociation of H_2S expressed by the following equilibrium reactions in Eq. (4).

Air—water gas transfer:

$$H_2S_{(g)} \Leftrightarrow H_2S_{(aq)} \Leftrightarrow HS^- + H^+ \Leftrightarrow S^{2-} + 2H^+ \tag{4}$$

The $pK(= -\log K)$ values shown below are given at 20˚C and defined by the following equilibrium equations:

$$K_{a1} = \frac{C_{H^+} \times C_{HS^-}}{C_{H_2S_{(aq)}}} \tag{5}$$

$$K_{a2} = \frac{C_{H^+} \times C_{S^{2-}}}{C_{HS^-}} \tag{6}$$

where $pK_{a1} = 7.0$, $pK_{a2} = 14.0$.

At equilibrium conditions and at a constant total concentration of dissolved sulphide in the water phase, increase in pH value will reduce the partial pressure of H_2S in the atmosphere above the water surface. Therefore, when applying Henry's law (Eq. (7)), only the actually occurring molecular H_2S form should be taken into account.

$$p_A = H_A \times \chi_A \tag{7}$$

The Henry's constant is temperature dependent. The temperature dependency of the Henry's constant for H_2S can be described as:

$$\log \mathrm{H}_{\mathrm{H2S}} = 104.069 - (4423.11 \times T_K^{-1}) - (36.6296 \times \log T_K) + (0.01387 \times T_K) \tag{8}$$

To determine the ratio between the concentration of $H_2S_{(aq)}$ and HS^- at a given pH, Eq. (5) is reformulated to the equation shown below:

$$\mathrm{pH} = \mathrm{pK}_{a1} + \log \frac{C_{HS}^-}{C_{H_2S_{(aq)}}} \tag{9}$$

3. Methodology

3.1. Routing of wastewater and gas

In a sewer system with closed manholes, the transformation process is mainly driven by the drag of the flowing water. Drag forces depend on hydraulic parameters such as velocity and the water depth. In such case, it is very important to determine the major hydraulic variables that finally will be used to compute the hydrogen sulphide generation in wastewater. Two empirical equations to predict the generation and emission of hydrogen sulphide were used, thus the net sulphide generation can be calculated. Total dissolved sulphide generation was predicted by empirical equation of Pomeroy & Parkhurst [9] and hydrogen sulphide emission rate was predicted by empirical equation proposed by Lahav et al. [8]. The variable in these two equations are considered to cover all main parameters affecting the total generation of hydrogen sulphide. The hydrogen sulphide gas is predicted by using gas transfer equation (Eqs. (4)–(9)).

For this preliminary study, the input flow in the sewer nodes which represent the manholes in the sewer networks is derived from calculations; it was calculated as average daily flow. The sewer network catchment is based on the sewer catchment area in Seoul, South Korea as can be seen in Fig. 1. However, some of the data are purely hypothetical. Parameters such as the population, BOD loading rates, wastewater production per capita, diurnal pattern, wastewater pH and temperature are all hypothetical. Based on calculations using BOD loading rates of 45 g/d/person, it was found that the BOD concentration in all discharged nodes is equivalent to 300 mg/L. Table 4 illustrates the data that are required for the modelling.

EPA SWMM model is used to simulate the sewer hydraulics. All the inputs derived from the previous calculation were input into the SWMM model. The hydraulic process was routed for 24 h of duration at 5 minute intervals. The SWMM's simulation produces velocity, water depth and water surface slope as outputs. The outputs of SWMM's simulation were used for hydrogen sulphide modelling. The modelling of hydrogen sulphide was conducted by using an excel spread sheet that contains the extracted data of hydraulic modelling. The generation rate, emission rate, the net generation rate of total sulphide, emitted hydrogen sulphide in wastewater and hydrogen sulphide gas were calculated using the spread sheet. Net total sulphide generation rate is calculated by subtracting the total dissolved sulphide generation from the hydrogen sulphide emission rate. The diagram showing the modelling methodology for this study is illustrated in Fig. 2.

3.2. Modelling hydrogen sulphide generation under the influence of chemical addition

With the assistance of the modelling tool SWMM, various parameters of a typical sewer network will indicate the optimal dosing location of chemicals in order to properly mitigate the consequences of hydrogen sulphide emission in a sewer network. To model the formation of hydrogen sulphide under the influence of chemical dosing, the constant in the sulphide dissipation rate equation (Table 3) was varied based on the chemical used. The dissipation rate constants of different chemicals are listed in Table 5.

4. Results and discussion

4.1. Determination of critical pipes

As a first step, the catchment was analysed for locations having potential for high H_2S bulk water concentrations and for locations where much hydrogen sulphide gas could escape to the sewer atmosphere. The classification was made based on the calculation obtained from the excel spread sheet. The sewer pipe was classified to be critical if the hydrogen sulphide concentration was higher than 0.1 mg/L in the wastewater and the hydrogen sulphide gas is higher than 0.5 ppm. According to a study conducted by Hvitved Jacobsen et al. [2], if concentration of total dissolved sulphide in sewer pipe reaches 0.1 mg/L or higher, it indicates minor corrosion in the sewer pipes. Furthermore, the hydrogen sulphide gas concentration in sewer higher than 0.5 ppm triggers odour issues.

As seen in Fig. 3, there are several sewer pipes in the network that were identified as critical. The potential corrosion and odour particularly occur in the downstream pipes. As the downstream pipes have higher pipe diameters, the wastewater velocity is smaller and detention time becomes longer. These hydraulic factors have contributed to the high generation of total dissolved sulphide.

4.2. Assessing hydraulic properties and hydrogen sulphide generation rate

The formation of hydrogen sulphide in liquid phase is very much related to the hydraulic movement in sewer pipes. Through modelling, the investigation relating the hydraulic properties such as velocity and water depth with the formation rate of hydrogen sulphide can be carried out. This investigation could be a rapid predicting tool to estimate the magnitude of the formation of hydrogen sulphide.

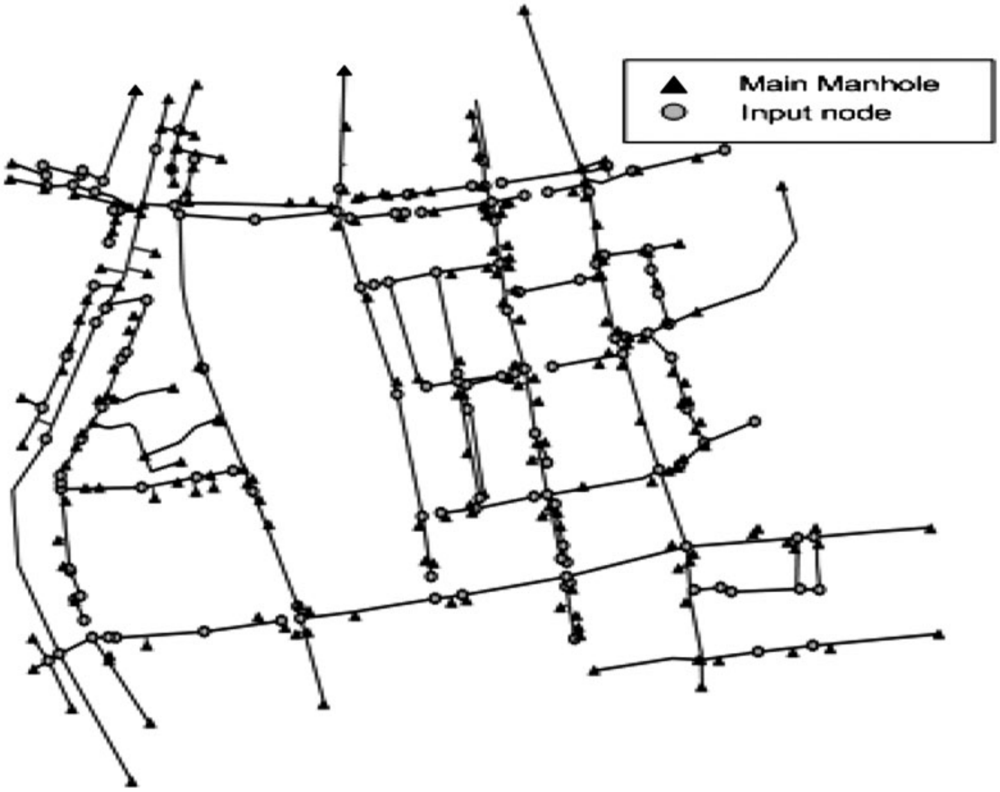

Fig. 1. Sewer network in study area.

Table 4
Preliminary data for modelling

Catchment characteristics	Manhole characteristics	Pipeline characteristics
Population	Invert elevation	Roughness coefficient
Dry weather flow (DWF) of total population of a catchment	Maximum water depth (distance from invert to ground surface)	Pipe length
	Average DWF	Sewer slope
	Diurnal pattern	Pipe diameter
	BOD loading rates and decay coefficients	

As depicted in Fig. 4, the generation rate of total dissolved sulphide is constant as the flow velocity increases. This is since the equation of Pomeroy and Parkhurst [9] does not consider the hydraulic properties in the generation of hydrogen sulphide. Furthermore, the emission rate increases when the flow velocity increases. As a result, the net total dissolved sulphide generation decreases as the velocity increases. Decreasing net generation rate means that the concentration of total dissolved sulphide in the wastewater will also decrease as the velocity increases. Study of flow velocity and dissolved sulphide generation has been conducted by Santry [10] which reported that velocity lesser than 0.8 m/s will correspond to higher total dissolved sulphide generation. This study confirmed the finding reported by Santry [10].

Fig. 5 illustrates the relationship between the water depth and the net generation rate of total dissolved sulphide. Similar to previous explanation, the net generation rate was obtained by subtracting the

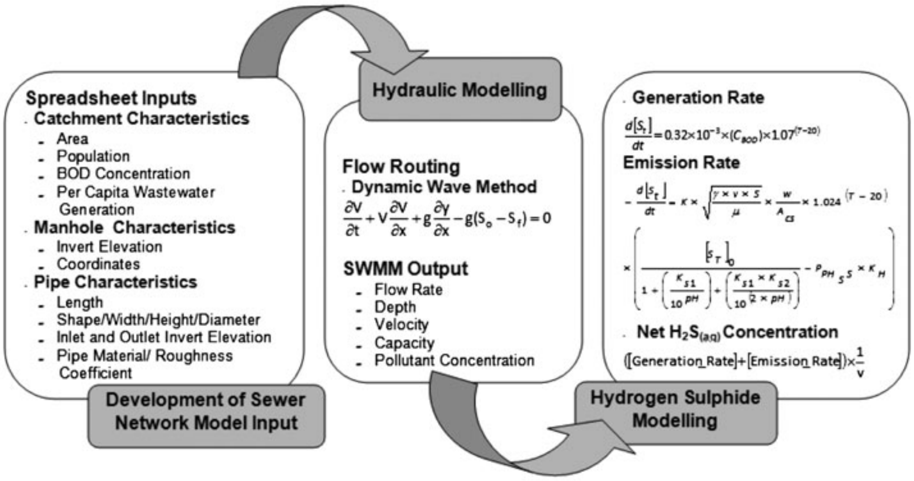

Fig. 2. Components of modelling.

Table 5
Dissipation rate constants (K) for different chemicals

Chemical addition	Dissipation rate constant (K)
No chemical	4×10^{-7}
Magnesium hydroxide	1×10^{-7}
Sodium hydroxide	9×10^{-8}
Calcium nitrate	5×10^{-7}
Ferric chloride	9×10^{-7}

generation rate from the emission rate. As the total dissolved sulphide generation rate does not include any hydraulic parameters, it shows constant trend when the water depth increases. On the other hand, the emission rate decreases when the water depth increases. As a result, the net total dissolved sulphide generation rate increases with the increase of water depth.

Thus, the modelling tool is not only a tool to identify the critical pipes but also can be used to evaluate the risk of net generation of hydrogen sulphide. This analysis helps to identify the necessity of further investigation of studies on sewer pipes.

4.3. Hydrogen sulphide gas generation

As discussed above, hydrogen sulphide gas generation causes problems related to odour and corrosion. The generation of hydrogen sulphide gas depends on pH, temperature and hydraulic characteristics [11]. pH determines which dissolved sulphide species will be present in the wastewater. Only hydrogen sulphide (H_2S) species can be transformed and released to sewer atmosphere while the other two species (HS^- and S^{2-}) will stay dissolved in the wastewater. Hydrogen sulphide species will exist in the wastewater if the pH is less than 9 with the highest generation occurring at pH less than 6. In this study, it was assumed that the pH of the wastewater was 7. Therefore, hydrogen sulphide will be present in the wastewater. However, no computation of hydrogen sulphide species was based on pH value conducted in this study, since here we assumed that all the hydrogen sulphide species were emitted to sewer atmosphere based on the emission rate equation. Dividing the emission rate by the velocity, the concentration of hydrogen sulphide emitted to sewer atmosphere can be found.

The other factor that affects hydrogen sulphide gas generation is sewer temperature. High temperature triggers more release of hydrogen sulphide to sewer atmosphere. Therefore, the emitted hydrogen sulphide concentration calculated from emission rate equation was corrected to an assumed temperature which is 20°C in this study.

Hydraulic properties determine the release of hydrogen sulphide based on whether there is any turbulence in the sewer flow or not. High velocity triggers more turbulence compared to low velocity. Therefore, even though the concentration of hydrogen sulphide is high in the wastewater it does not mean all the hydrogen sulphide will be released to sewer atmosphere. Based on the calculation, 43 pipes were identified having hydrogen sulphide concentration more or equal to 0.1 mg/L in the wastewater. However, out of 43 pipes, only 37 pipes were categorised as critical since these pipes have hydrogen sulphide concentration more than 0.5 ppm. The plot of hydrogen sulphide concentration and hydrogen sulphide gas for pipes that had hydrogen sulphide concentration higher than 0.1 mg/L is presented in Fig. 6.

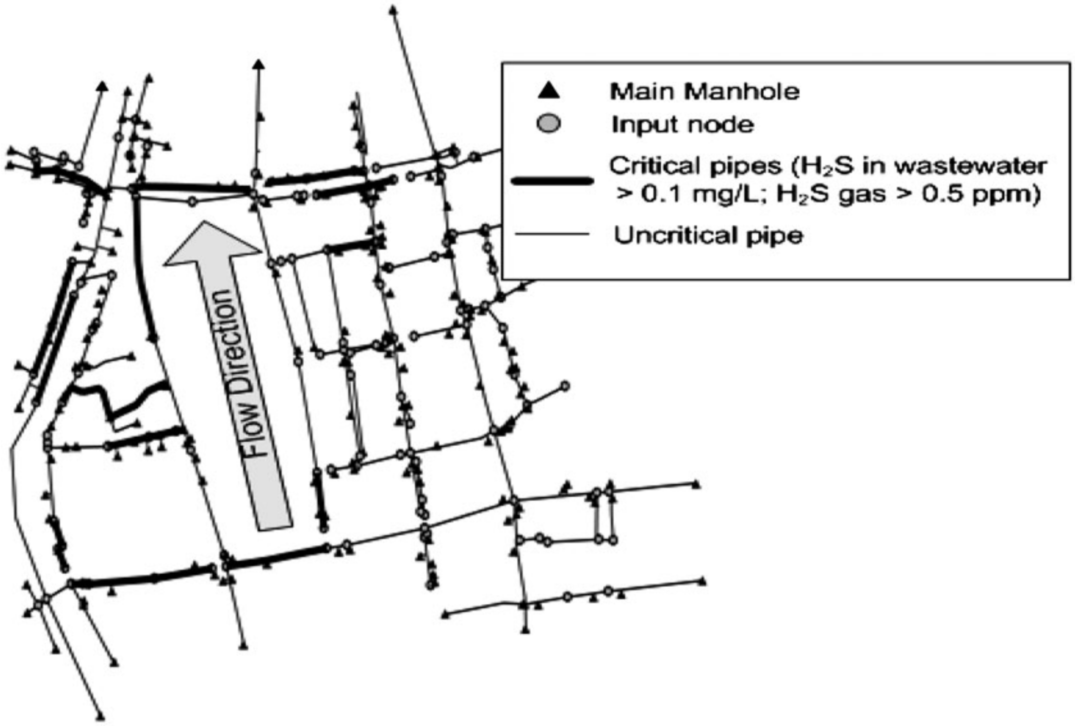

Fig. 3. Identification of critical pipes.

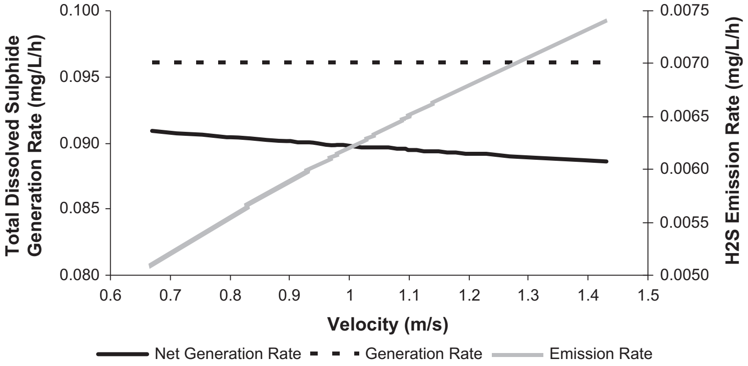

Fig. 4. Total dissolved sulphide generation rate, H_2S emission rate and net sulphide generation rate with flow velocity taken from a pipe that has the highest sulphide concentration.

As depicted in Fig. 6, the circle contains the pipes which have high hydrogen sulphide concentration but did not emit hydrogen sulphide gas. It is because those pipes had relatively flatter slope compared to other pipes.

4.4. Hydrogen sulphide formation under the influence of chemical addition

Having to know the location of critical pipes as well as the risk of the sewer pipes which could be exposed to hydrogen sulphide can help a water authority to spot the best location to mitigate the problem. However, it is important to know the best mitigation strategy that fits to the study area. This section compares the application of different chemicals to mitigate hydrogen sulphide problem in the studied sewer pipe. Five chemical mitigation strategies were applied to sewer network using the different dissipation rate constants. The net rate of generation of hydrogen sulphide for every chemical addition is plotted and compared. The plot is intended only to compare the net

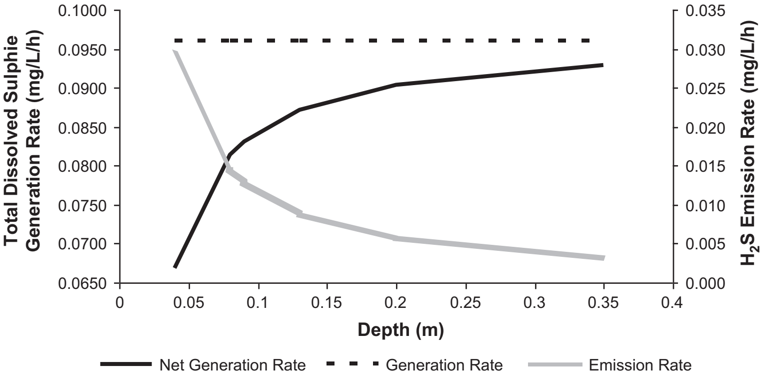

Fig. 5. Total dissolved sulphide generation rate, H_2S emission rate and net sulphide generation rate with water depth taken from a pipe that has the highest sulphide concentration.

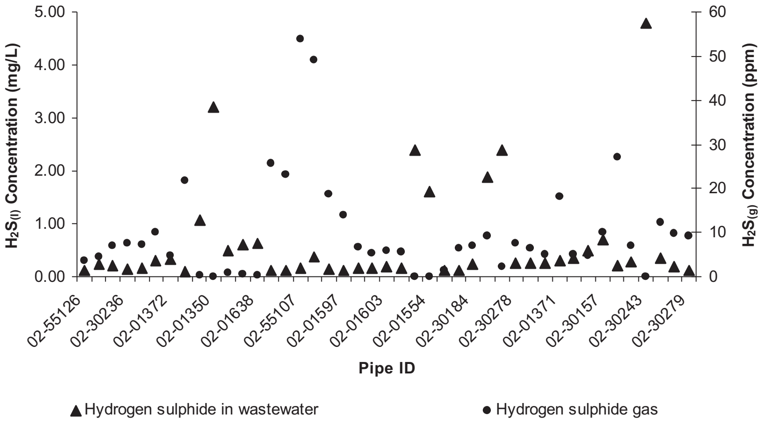

Fig. 6. Hydrogen sulphide concentration in wastewater and gas phase for sewer pipes that has hydrogen sulphide concentration > 0.1 mg/L.

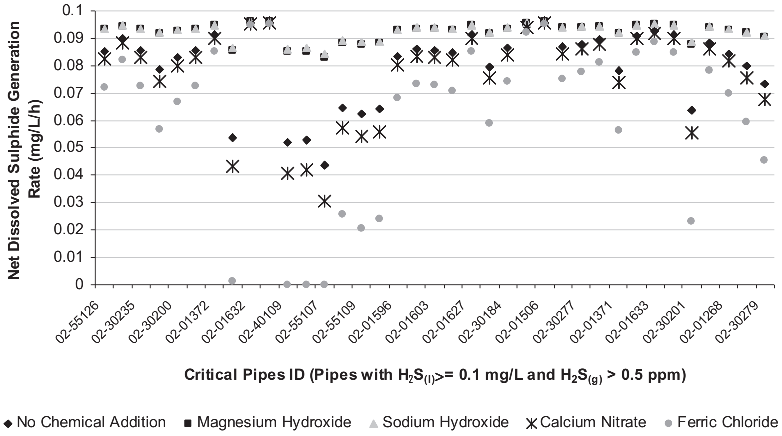

Fig. 7. Net sulphide generation rate in the critical pipes with and without chemical dosing.

rate of generation in the critical pipes. The lowest net generation rate is considered to be the best chemical option to be applied in the studied sewer pipe. As depicted in Fig. 7, iron salt is the best chemical to suppress the formation of hydrogen sulphide and calcium nitrate is the second best chemical to be applied.

However, a further cost analysis is needed to produce a thorough solution to the mitigation of hydrogen sulphide generation.

5. Conclusions

Modelling hydrogen sulphide formation in sewer network can be applied as a planning tool to identify problem areas in terms of odour and corrosion. The proposed modelling methodology was trialled using a sewer network data obtained from Seoul, South Korea with some hypothetical data. The model can help to identify critical pipes due to hydrogen sulphide generation (in wastewater and in gas phase). This study also derived a relationship between the important hydraulic parameters such as flow velocity and water depth with the generation rate and emission rate of hydrogen sulphide. The modelling of hydrogen sulphide gas was also conducted by considering the temperature correction and hydraulic properties of flow velocity and water depth. Finally mitigation strategies were implemented on the sewer network by dosing certain chemicals to the sewer network. The result of this study shows that the proposed tool can be of great assistance in planning and optimising of management efforts.

However, further study needs to be conducted to calibrate the modelling result with the real field data. On the other hand, it is necessary to refine the modelling procedure and integrate the modelling process of hydraulic and hydrogen sulphide computation into a single model. The simplification of the sewer process in the empirical equation is also one of the weaknesses that needs to be tackled in future research.

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Abbreviations

p_A — partial pressure of a compound A in the gas phase (atm)
χ_A — mole fraction of compound A in the liquid phase (mol/mol)
H_A — Henry's law constant for A (atm)
T_K — temperature (°K)
K_{a1} — equilibrium constant pH (H_2S and HS^-)
K_{a2} — equilibrium constant pH (HS^- and S^{2-})
C — concentration (mg/L)
R — hydraulic radius (m)
A — area (m^2)
n — Manning constant
S_f — water surface slope
Q — flow rate (m^3/s)
H — head (m)
x — pipe length (m)
h_L — head loss (m)
r_a — sulphide generation rate (mg/L/h)
r_b — sulphide dissipation rate (mg/L/h)
v — velocity (m/s)
T — temperature (°C)
w — width of exposed water surface (m)

References

[1] G. Boon, Septicity in sewers: Causes consequences and containment, Water & Environ. J. 6 (1992) 79–90.
[2] T. Hvitved-Jacobsen, J. Vollertsen, J.S. Matos, The sewer as a bioreactor-A dry weather approach, Water Sci. Technol. 45 (2002) 11–24.
[3] T. Hvitved-Jacobsen, J. Vollertsen, A.H. Nielsen, Sewer Processes: Microbial and Chemical Process Engineering of Sewer Networks, vol. 2, Taylor & Francis, Boca Raton, FL, 2013.
[4] P.H. Nielsen, T. Hvitved-Jacobsen, Effect of sulfate and organic matter on the hydrogen sulfide formation in biofilms of filled sanitary sewers, J. Water Pollution Control Fed. 60 (1988) 627–34.
[5] L.A. Rossman, Storm Water Management Model-User's Manual, ver 5, U.S. E.P.A, Cincinnati, OH, 2010.
[6] L.A. Rossman, Quality Assurance Report for Dynamic Flow Routing, U.S. E.P.A, Cincinnati, OH, 2006.
[7] D.K.B. Thistlethwayte, The control of sulphides in sewerage systems. Butterworth, Sydney, 1972.
[8] O. Lahav, A. Sagiv, E. Friedler, A different approach for predicting H_2S(g) emission rates in gravity sewers, Water Res. 40 (2006) 259–266.
[9] R.D. Pomeroy, J.D. Parkhurst, The forecasting of sulfide buildup rates in sewers, Prog. Water Technol. 9 (1977) 621–628.
[10] I.W. Santry, Hydrogen sulfide in sewers, J. Water Pollut. Control Fed. 35 (1963) 1580–1588.
[11] T. Hvitved-Jacobsen, J. Vollertsen, Odour formation in sewer networks, in: R.M. Stuetz, F.B. Frechen (Eds.), Odours in Wastewater Treatment – Measurement, Modelling and Control, I.W.A Publishing (2001) 33–65.
[12] A.G. Boon, A.R. Lister, Formation of sulphide in a rising-main sewer and its prevention by injection of oxygen, Progress in Water Technol. 7 (1975) 289–300.
[13] P.H. Nielsen, K. Raunkjaer, T. Hvitved-Jacobsen, Sulfide production and wastewater quality in pressure mains, Water Sci. Technol. 37 (1998) 97–104.