Influence of ventilation in H₂S exposure and emissions from a gravity sewer
Rita Ventura Matos, Filipa Ferreira and José Saldanha Matos

ABSTRACT
This study was carried out to evaluate the effect of natural ventilation and intermittent pumping events in hydrogen sulfide and methane dynamics, in terms of system operation and risk of gas exposure. Work was conducted in a full scale gravity sewer downstream of pumping stations, in Portugal. Different ventilation rates and locations were assessed, as well as H₂S removal rates and potential exposure risk, through the opening of distinct manhole covers. Increased ventilation, resulting from opening of one manhole cover, saw a 38% increase in average pipe air velocity peaks, doubling the estimated rate of air turnovers per day, accompanied by an increase of nearly 20% in H₂S average removal rate. Simultaneous opening of two manhole covers induced similar airflow rates through the vent stack, but different rates throughout the pipe. H₂S removal rates were also found to differ, according to location of open manholes, but also initial H₂S headspace concentration. Under more unfavourable conditions, natural ventilation did not suffice in attaining recommended safety concentrations, regardless of number and location of open manhole covers. H₂S concentrations above defined thresholds were verified for all studied setups. Headspace oxygen concentrations below an 18.5% asphyxiation threshold also occasionally occurred, even at manholes immediately downstream of ventilation point.

Key words | hydrogen sulfide exposure, intermittent pumping, odour, sewer ventilation

HIGHLIGHTS
- The study assesses field data regarding the effect of ventilation and pumping in gas movement in sewers, which is lacking in the literature.
- Under unfavourable conditions, natural ventilation did not suffice in attaining recommended safety concentrations.

INTRODUCTION
The challenges associated with the presence of noxious gas compounds in sewer headspace have been the subject of much research in past decades, especially hydrogen sulfide (H₂S), due to its toxicity, odour and infrastructure corrosion potential (Zhang et al. 2012). In fact, occupational health risks and worker incidents resulting from exposure to H₂S in sewers have been well documented in the literature, and are still a serious concern (Christia-Lotter et al. 2007; Yalamanchili & Smith 2008). Its effects on human health depend on the duration and dosage of such exposure, and may range from simple eye irritation, headache and nausea (at concentrations of up to 50–100 ppm) to respiratory arrest or even instant death for H₂S contents of over 700 ppm (Matos 1992; WHO 2000).

When carrying out operation and maintenance (O&M) activities in a sewer system, workers are subjected to a number of increased hazards and safety and health risks, often originating accidents and compensation claims. These dangers are severely aggravated in confined structures, such as flow retention organs, tanks or pumping stations (PS), which are often poorly ventilated (Yeh et al. 2010). This has led to the creation and improvement of...
regulatory frameworks and guidelines on safety practices and methods, such as the standard on Occupational Health and Safety Assessment Series (OHSAS 18001) or the European Commission Directive 2009/64/EU. These regulations include specific guidelines for personal protective equipment (PPE) use for wastewater workers, as well as recommendations on maximum exposure limits to H2S (ranging from 5 to 10 ppm in a work shift, to a maximum 50 ppm of instant exposure). Nonetheless, it has been shown recently (Wright 2018), that workers often present some reluctance in wearing PPE. In that study, several wastewater utility workers were surveyed in the USA, and even though only 2.5% of workers responded they did not know about occupational hazards/events that can cause injuries or health harm, 23.4% still indicated they do not wear PPE in their routine operations. In fact, the eventual lack of awareness among utility workers and confidentiality of accident reports (Malakahmad et al. 2012), coupled with rapid changing conditions in sewer atmospheres, complicate the process of accurate risk assessment in those situations, and more data and work on that subject are essential.

Another important process related to H2S is the microbiologically induced sewer corrosion, which occurs with H2S adsorption to unweathered concrete surfaces, followed by its oxidation to sulfuric acid (H2SO4), under highly moist environments of over 85% relative humidity, (Thistlethwaite 1972). H2SO4 is capable of quickly reacting with the alkaline minerals present in the mix. This process yields highly expansible by-products (etrangite and gypsum), thought to be responsible for cracking and structural fails (Wells & Melchers 2013), which may even originate partial or total system collapses. In addition, H2S is also an odorous compound, responsible for many foul odour related complaints to wastewater utilities.

On the other hand, the study of methane (CH4) generation in sewers has gained interest in recent years, and as such, efforts are being made to quantify and model CH4 generation and emission from sewers, seeing as it can be a significant greenhouse gas (GHG) source, often overlooked in national inventories (Foley & Lant 2009; Guisasola et al. 2009; Ren et al. 2015; Sun et al. 2018). CH4 has a global warming potential 23 times higher than that of carbon dioxide over a 100 year horizon (IPCC 2001). Besides its negative environmental impacts, CH4 also presents a risk for human health, and especially for utility workers, since it is explosive in concentrations over 5%. Moreover, in light of climate change scenarios, aggravated temperatures and increased water scarcity, production of H2S and CH4 in sewer systems can arguably be expected to increase.

Sewer ventilation largely influences gas concentration and movement in wastewater collection systems (Ward et al. 2011). It mostly affects advective transport, time of H2S contact with sewer walls, relative humidity (R.H.) content, air-water mass transfer processes, and H2S oxidation rates. Adequate headspace ventilation is therefore essential, first and foremost to attain safety conditions for workers carrying out inspections and regular works, but also in attaining R.H. contents below a certain threshold (usually considered below 85% according to Thistlethwaite (1992)), which inhibits the onset of the corrosion process. One expeditious way used to refer to natural sewer ventilation is the number of turnovers per day (TPD), as a measure of air renewal rates within the sewer headspace.

Sewer ventilation is mostly affected by wind speed, temperature, pressure differentials and water velocity (Ward et al. 2011). As such, gas phase renewal rates can significantly vary with sewer dimension, the number of openings and flow regime. Air TPD, induced by natural ventilation in gravity sewers, has been observed in the ranges of 0.09–0.13 in sewers of 1.5 m and 0.45 m of diameter, respectively (Pescod & Price 1981, 1982). High air turnovers are expected in pipes with over 1.0 m diameter, while low air turnovers are expected in long sewers of less than 0.3 m in diameter, due to increased headspace volume as the sewer length increases (Pescod & Price 1981). Forced ventilation has been used at specific locations to ensure the safety of workers, for example near PS, at rates of 25–50 TPD (Pomeroy 1945; Tata et al. 2003). Nonetheless, criteria for designing general ventilation systems are still mostly based on ‘rules of thumb’, without a solid scientific background (Hurse & Ochre 2008), and a more thorough knowledge is required on the subject.

Air renewal rates are essential to understanding gas phase transport and removal in sewers. This has been investigated by Nielsen et al. (2012) in a pilot-scale sewer reactor, where H2S removal, by adsorption and oxidation by corroding concrete surfaces, was observed to increase with the increasing airflow rates. In another study, Sun et al. (2015) compared sulfide uptake rates (SUR) of concrete sewer walls exposed to constant average H2S concentrations (baseline), to those exposed to pulsed peaks of high loads of H2S. They found that fluctuations in corrosion rates existed when sewers were exposed to intermittent gas concentrations. The SUR increased greatly when exposed to high H2S loadings, then immediately decreased by about 7–50% of the baseline SUR. The SUR would eventually go up after several hours, but were always lower than the baseline SUR overall. The authors suggest a combination of factors is
probably responsible for those findings, namely a temporary storage of elemental sulfur in the corrosion layer and inhibition of sulfide oxidizing bacteria at high $H_2S$ levels and temporary acid surge.

However, many of the studies found in the literature regarding in-sewer $H_2S$ focus on steady-state gravity flows, on reducing or preventing the impact of corrosion in sewer infrastructure. Data from full scale operational systems is still insufficient in the literature, especially under rapid changing flow conditions, and is fundamental for an efficient system operation and design, as well as to obtain accurate removal rates and protection measures for workers. As such, this study was conducted in a full scale gravity sewer, downstream of several PS, with the following objectives:

- Assess the effect of increased ventilation in $H_2S$ removal rates and gas TPD.
- Evaluate the implications of these dynamics in terms of O&M activities and risk of gas exposure.

**METHODS**

**Case study description**

A gravity sewer of the Rua das Flores–Meco wastewater system (Portugal) was used as a guiding case study for the work herein presented. This network is located in the vicinity of a bathing area (Meco beach), 35 km south of Lisbon, where the effluent is transported by a sequence of rising mains, gravity sewers and inverted siphons. Several odour related complaints have been reported to utilities, mostly due to the presence of ventilation stacks at several locations (Figure 1). The studied sewer reach consists of a 290 m long trunk sewer with seven manholes, with 630 mm outer diameter (555 mm inner diameter), and an average slope of 2.2%, receiving intermittent discharges from several PS. There is a 6 m vertical ventilation stack at the upstream manhole, for pressure relieving purposes. The downstream end of the pipe is connected to a full flowing pipe.

**Field monitoring and sampling**

Continuous monitoring of several gas phase parameters was carried out, namely air velocity ($\pm 0.03 \text{ m s}^{-1}$), pressure ($\pm 0.05 \text{ Pa}$), temperature ($\pm 0.3 ^\circ \text{C}$), R.H. ($\pm 2\%$), $H_2S$ ($\pm 0.1 \text{ ppm}$), $CH_4$ ($\pm 0.01\%$) and $O_2$ ($\pm 0.01\%$) concentrations, at the venting stack and at different manholes (two at a time), for a total of 7 days. Three sets of multi-parameter probes (Testo 435-4) and multi-gas detectors (Ventis MX4) were used, and data logging intervals were set for 30 seconds. Probes were placed at pipe centroid height, to obtain mean values as much as possible, and to ensure they would not get submerged.

Grab samples were also collected for liquid phase quality monitoring. For this purpose, acrylic manhole covers were made, with a 10 cm orifice to allow cables to pass through. The orifices were sealed with tape during monitoring. During setups where all covers were closed, samples were collected with an automatic sampler, whereas during setups with open manhole covers they were collected using a bucket (see Table 1 for setup description).

Monitored parameters comprised dissolved oxygen (DO), wastewater temperature ($T_{ww}$), pH, total chemical oxygen demand (COD$_T$), and total and dissolved sulfide concentration ($S_T$ and $S_D$). DO ($\pm 0.2 \text{ mg l}^{-1}$), $T_{ww}$ ($\pm 0.15 ^\circ \text{C}$) and pH ($\pm 0.2$ units) were measured on site with a multi-parameter probe, YSI 556 MPS. COD was determined according to APHA method 5520 D (closed reflux colorimetric method) (Eaton et al. 1998), by using Spectroquant® testing kits with a measuring range of 25–1500 mg O$_2$ l$^{-1}$. Samples subject to $S_D$ determination were left to settle in full 0.5 litre closed bottles, before filtration of the clarified fraction using 1 μm pore filters. Sulfide content (expressed in mg HS$^{-1}$ l$^{-1}$) was determined according to APHA method 4500-S2 (Eaton et al. 1998). Preservation of samples for sulfide analysis was carried out by adding a zinc acetate solution.

Wastewater flow, velocity and depth were monitored, by an ultrasonic flow meter (POA Nivus) placed in the first pipe stretch, upstream of manhole C-2, logging data with 1 minute intervals (smallest available time step). The equipment was set up for continuous flow measurement, during one full week in May 2018, simultaneously with data collection and sampling. However, a malfunction in the data logger caused no flow data to be retrieved during that period; therefore additional work was carried out in June 2018, when data logging was fully operational.

In order to evaluate the combined effect of intermittent flows and ventilation in O&M activities, five setups were defined (M1 to M5), with a different number of open manhole covers (0, 1 and 2) and at different locations. It is worth noting that some of the covers had been sealed by the population. Worst-case scenarios refer to atmospheric conditions which are more favourable to sulfide generation (i.e. longer dry weather periods and higher temperatures), and best-case scenarios otherwise.
Figure 1 | (a) Schematics of Meco wastewater system; (b) Rua das Flores trunk sewer profile (Q: wastewater flow).

Table 1 | Monitoring design carried out at Meco case study

<table>
<thead>
<tr>
<th>Setup ID</th>
<th>Description</th>
<th>Date</th>
<th>Vent stack</th>
<th>Manholes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>Pre-campaign</td>
<td>12.12.2017</td>
<td>O(^\ast)</td>
<td>X (\times) X (\times) X X X X X</td>
</tr>
<tr>
<td>M1</td>
<td>Baseline: best case</td>
<td>08.06.2018</td>
<td>O(^\ast)</td>
<td>X X (\times) X X X (\times) X X</td>
</tr>
<tr>
<td>M2</td>
<td>Baseline: worst case</td>
<td>a: 16.05.2018</td>
<td>O(^\ast)</td>
<td>X X (\times) X X X (\times) X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b: 17.05.2018</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c: 18.05.2018</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>d: 07.06.2018</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>1 open manholes</td>
<td>17.05.2018</td>
<td>O(^\ast)</td>
<td>X O (\times) X X X (\times) X X</td>
</tr>
<tr>
<td>M4</td>
<td>2 open manholes (TM downstream)</td>
<td>a: 22.05.2018</td>
<td>O(^\ast)</td>
<td>X O (\times) O (\times) X X X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b: 22.05.2018</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M5</td>
<td>2 open manholes (TM upstream)</td>
<td>a: 22.05.2018</td>
<td>O(^\ast)</td>
<td>X O (\times) O (\times) X X X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b: 08.06.2018</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend: X \(\times\) – closed, O – open; TM – target manhole.
\(^\ast\)Monitored location.
Target manhole (TM) was defined as the location where O&M activities would occur (C-2 for all setups except for M4b, where it was C-3), whereas the complementary manhole (CM) was defined as the other manhole where monitoring was being carried out (C-2, C-3 or C-5). The rationale behind this was to evaluate the impact on the concentration of headspace gas of (a) an increased number of open manhole covers and (b) the location (upstream versus downstream) and distance of openings to TM. The impact of such setups was evaluated in terms of:

- headspace ventilation, namely airflow rate and velocity at pipe (v_air.pipe) and at the vent stack;
- estimated number of TPD at the first pipe stretch (C-1 to C-2) and average H2S removal rates at the upstream manhole (C-2);
- average duration per hour above or below established exposure thresholds and time required to attain minimum concentrations.

Air velocity was measured directly on site and used to calculate airflow rates, taking into account the available pipe headspace (non-wetted cross-section) and venting stack cross-section. It should be noted that air velocities result from a single point measurement (at pipe centroid). These were assumed to represent the average air velocity within the pipe, even though this constitutes an approximation, given that headspace velocities vary with distance to the wastewater surface and pipe walls (Pescod & Price 1982). Ideally, pipe traversing could be carried out; however, this is often not feasible in underground smaller pipes of difficult access. Notwithstanding, since for all setups of this study probe height and location were the same, comparison of results between them is valid.

### Data analysis

Data analysis started with fault detection, by eliminating errors (no data, error readings and negative values for concentration), visual graph evaluation and assessment of extreme values for potential outlier detection.

For headspace airflow rates and estimated TPD, seeing as two different connections contribute with flow to this gravity reach, some pumping events were selected, so as to constitute typical individual intermittent pumping flows. These were selected based on the observation of wastewater depths, velocities and gas concentration curves. The number of observations (pumping events) chosen for each setup varied from six to eight.

### RESULTS AND DISCUSSION

#### Overview of wastewater quality

Overall, the conditions were optimal for the release and emission of H2S to the atmosphere, with very low DO concentrations, abundant COD and neutral to slightly basic pH values. During May, 11 samples were collected and analysed, and the following mean (±standard error of the mean, SEM) values were obtained:

- **COD**: 517.3 ± 80.7 mg O2 l⁻¹, **Sr**: 4.6 ± 0.7 mg HS⁻¹ l⁻¹, **SD**: 3.7 ± 1.0 mg HS⁻¹ l⁻¹, **pH**: 8.2 ± 0.05, **T_ww**: 22.3 ± 0.6 °C and **DO**: 0.4 ± 0.04 mg O2 l⁻¹.

Diurnal wastewater flowrates in the two monitoring periods of June ranged from 1.3 to 89.1 l s⁻¹ (averaging 29.2 l s⁻¹ ± 1.1, SEM). During this time, two samples were collected at the onset and end of each day, except for COD with one sample only, due to bottle bursting, with the following results:

- **COD**: 567.4 mg O2 l⁻¹, **Sr**: 4.0 ± 1.0 mg HS⁻¹ l⁻¹, **pH**: 7.4 ± 0.3, **T_ww**: 20.1 ± 0.4 °C and **DO**: 0.6 ± 0.09 mg O2 l⁻¹.

#### Ventilation analysis

During baseline, gas peaks of both H2S and CH4, as well as air velocities exiting the vent stack, were always higher than those measured inside the pipe at both manholes. This may be explained by the proximity of the venting stack to the most upstream manhole of the gravity pipe.

H2S removal curves after each pumping event were always much steeper at C-2 than at C-5, where it never attained the minimum concentrations verified upstream (Figure 2). Regarding pressure differences between manhole inverts and the outside atmosphere, the verified trend is the same for both manholes, although lower pressure-difference (dP) peaks were observed at C-5. The observed pressure gradients induced by pumping events peaked at 100 Pa, and were significantly higher than those measured in other systems, for much smaller inflows (Matos et al. 2019).

The opening of one manhole cover resulted in a clear increase in headspace temperature, accompanied by the decrease of R.H. during the first hour after the opening of C-2. Headspace temperature at this manhole was roughly 22 °C at 12h25 (before the opening) and increased to over 24 °C at 13h00. Similarly, the R.H. peaked at 83% with pumping events before 12h25, while at 13h00 it peaked at
Figure 2 | Variation of headspace parameters at the three monitored locations of the gravity sewer, during 17.05.2018. For each chart, lighter tone lines indicate all measured data and the darker overlying lines refer to a 10 minute moving average. Vertical lines indicate time of passage from baseline (M2) to M3 (one open manholes cover at C-2).
75%. However, these observations coincide with the maximum outside temperatures (as measured in the venting stack). With the gradual temperature decrease throughout the day, headspace temperature and R.H. approximated to baseline values. This suggests that for this setup, outside temperature also played a relevant effect in bringing R.H. values down, rather than the increased ventilation rate alone.

Distance to point of ventilation is also quite relevant. While a slight increase in temperature was observed (1°C increase from 12h25 to 13h00) at C-5 (located 194 m from the venting stack and 146 m from C-2), the effect in R.H. decrease was hardly observed (keeping relatively constant at 88%).

There is a slight reduction in the average concentration of H₂S emitted through the venting stack and present at C-2, while there is an increasing trend of H₂S accumulation at C-5. This is thought to be due to the effect of the full flowing pipe downstream of C-7, which might inhibit air entering the system at C-2 from moving upstream. The same cannot be said about CH₄ concentration, since it was not initially present at the venting stack as it was at both manholes. However, after opening of the manholes cover it was detected at the venting stack and at manhole C-5. At this downstream location, the initial CH₄ concentration increase rapidly decreased after a short while. This may be due to the different densities of both gases (H₂S and CH₄) and the effect of the larger sewer diameter, which may have allowed for some uneven gas dispersion (it should be kept in mind that there was only one probe located at a single height). In fact, when looking at the behaviour of O₂, it can be seen that it follows the opposite trend of CH₄ at the venting stack and at C-2, as expected, since it is known that CH₄ displaces O₂. However at C-5 it continuously decreases after the manholes opening. This supports the idea of gas accumulation near the downstream end. Another aspect is that the overall CH₄ concentration was not very high, and therefore the scale may amplify these effects.

The opening of two manhole covers (setups M4 and M5) made it possible to observe the effect not only of increased ventilation, but also of distance to ventilation location. In fact, the effects of simultaneously opening C-1 and C-2 manholes covers or of opening C-2 and C-3 differ. As a result of the open manholes covers, air velocities within the pipe (at manhole C-2) increased to an average 0.21 m s⁻¹ (± 0.011, SEM) during M4a and to an average 0.31 m s⁻¹ (± 0.016, SEM) during M4b and M5. Expectedly, that increase was not verified at C-5.

The opening of C-1 and C-2 saw a decrease in average C-2 headspace temperature from 23.1°C (±1.2, standard deviation (SD)) to 21.7°C (±1.3, SD) and from 23.9°C (±0.5, SD) to 22.4°C (±1.3 SD) at C-3, even though diurnal outside temperature did not change much (20.9°C ± 0.4, SD). This, coupled with the increased ventilation rates, had a visible effect on the decrease of headspace R.H. at C-2 (to an average 70.8% ± 11.4, SD), but not at C-3 where it remained relatively constant (at roughly 83.5% ± 7.9, SD). This implies that the airflow rates induced by the two most upstream open manholes (at a distance of less than 50 m) and venting stack were not sufficient to significantly reduce R.H. levels at C-3, nearing average values optimal for the onset of corrosion processes. However, opening of manholes at C-2 and C-3 resulted in a more accentuated drop at C-2, to an average 63.0% (±0.34, SEM), even though headspace temperature was lower (20.1 ± 0.04, SEM).

The increased headspace natural ventilation which results from the opening of manholes will influence gas turnovers within the sewer. The TPD at the case study site was calculated based on the headspace air velocity and retention time inside the pipe (Table 2), according to:

\[
\text{TPD} = 24 \left( \frac{60 Q_{\text{air}}}{xs \times d} \right) \times n_{\text{p}} \times t_{\text{peak}}
\]

where,

- TPD – gas turnovers per day (1/day)
- \(Q_{\text{air}}\) – average airflow rate between manholes (m³/s)
- \(xs\) – average headspace cross-section between manholes (m²)
- \(d\) – distance between manholes (m)
- \(n_{\text{p}}\) – number of pump starts per hour (1/hour)
- \(t_{\text{peak}}\) – average gas wave peak duration (min).

During all pumping events, there is a period of 3–4 minutes in the wastewater hydrograph where flow

<table>
<thead>
<tr>
<th>Setup ID</th>
<th>Events (n)</th>
<th>Measured (v_{\text{air, pipe}}) (m s⁻¹)</th>
<th>Average peak duration per event (min)</th>
<th>Gas retention time from C-1 to C-2 (min)</th>
<th>TPD (C-1 to C-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>6</td>
<td>0.002 ± 0.002</td>
<td>3.7</td>
<td>480.4</td>
<td>0.7</td>
</tr>
<tr>
<td>M2</td>
<td>8</td>
<td>0.05 ± 0.02</td>
<td>2.8</td>
<td>16.8</td>
<td>16</td>
</tr>
<tr>
<td>M3</td>
<td>6</td>
<td>0.08 ± 0.03</td>
<td>4.2</td>
<td>11.5</td>
<td>35</td>
</tr>
<tr>
<td>M4</td>
<td>6</td>
<td>0.05 ± 0.01</td>
<td>2.8</td>
<td>16.7</td>
<td>16</td>
</tr>
<tr>
<td>M5</td>
<td>8</td>
<td>0.21 ± 0.08</td>
<td>4.0</td>
<td>4.2</td>
<td>88</td>
</tr>
</tbody>
</table>
conditions approximate to steady state; that is, flow velocities inside the pipe are relatively constant at their maximum value. It was assumed that during this period, headspace sewer pressurization was at its maximum (assumption supported by data), thus causing out-gassing through the venting stack, and the overall direction of the air velocity vector is towards the downstream direction. All values presented in Table 2 refer to that period, where quasi-steady conditions prevail. Estimation of the number of TPD was based on the assumption that most of the air renewal inside the pipe occurs during those peak flow periods (with four pumping events per hour), seeing as headspace air velocities were much higher at those occasions and close to zero otherwise. However, this constitutes a simplification, as during the ascending and descending parts of the hydrograph some ventilation may also occur (even if at a smaller scale).

The average maximum wastewater depth at that peak discharge was 0.112 ± 0.002 m, corresponding to an average maximum velocity of 1.50 ± 0.047 m s⁻¹. At this wastewater depth, the headspace cross-section (non-wetted area) is 0.21 m².

Setups M1 and M2 both refer to the situation of normal system operation (baseline); however, the measured pipe velocities differ considerably. This may be due to different atmospheric conditions, but also due to possible measurement interferences (possible anemometer displacement with passing wastewater flow). M2 includes measurements carried out during three different days and the obtained air velocities (0.05 m s⁻¹) are more in accordance with literature data. In this situation, with an average number of four pump starts per hour, the expected TPD is 16, or in other words, it requires 1.5 hours for complete air renewal at the pipe stretch between manholes C-1 and C-2.

Thistlethwayte (1972) found that natural ventilation in small diameter networks with several connections and air inlets/outlets could lead to up to 4 air TPD, while in larger and more confined systems that number could be lower than 1. Total length of the sewer pipe and number of connections (capable of providing air exchanges) will naturally influence this parameter. As such, the predicted turnovers at the studied pipe, which were obtained for a small sewer segment of 55 m, are in fact quite low, even if a venting stack is present.

With the opening of one manhole cover (C-2) during setup M3, the pressure difference between sewer headspace and outside atmosphere is drastically reduced. Instead, airflow rates in the pipe increase (to about 1.5 times that of M2) and the expected TPD more than doubles. The opening of two manhole covers (M4 and M5) induces different rates through the pipe. It seems the opening of C-1 and C-2 (M4) induces lower airflow rates at C-2 (than during M5), probably due to air emissions at C-1. Also, the lag time between pumping and measured headspace effects increases towards downstream. These results indicate that not only ventilation rates, but also distance to TM and rising main, will influence transport and emission (to the exterior) of pollutants within the sewer.

This analysis can become more complex given that air is compressible and manholes may act as air reservoirs, to some extent. In addition, the uncontrollable exterior weather conditions may also influence density and pressure gradients, which in turn have an impact on sewer gas movement and emission, thus contributing to the difficulty in simulating such processes.

Matias et al. (2018) compared field measurements against predictive modelling results of headspace air velocity and H₂S gas concentration in a small gravity sewer downstream of a pumping station, using two modelling tools, namely AEROSEPT.V02 and WATS. The authors found differences in model results, with WATS returning higher H₂S concentration values in the upstream part of the system, while AEROSEPT.V02 indicated a larger number of pipes should present concentrations above 10–30 ppm. Another major difference in that study refers to pipe air velocity, with field measurements ranging from 0.05 to 0.06 m s⁻¹, while model results were in the 0.19 to 0.22 m s⁻¹ range. These results led the authors to acknowledge the difficulty in taking turbulence into account when predicting H₂S gas concentrations, which reinforces the results of this study.

**H₂S gas removal rates**

Another important aspect refers to the influence of ventilation in H₂S removal rates. Table 3 shows average maximum and minimum H₂S concentrations, time required to reach minimum concentrations and average removal rates obtained at the three manholes.

During baseline operation, average maximum H₂S concentration inside the sewer, per pumping event, is quite similar along the length of the pipe (38.2 ± 2.2 ppm at C-2 and 37.4 ± 2.5 ppm at C-5 during M2). However, when monitoring equipment was installed at consecutive manholes C-2 and C-3, the measured difference between peaks was higher (56.3 ± 1.5 versus 31.0 ± 1.3 ppm). Minimum concentrations and the time required to attain them also vary between C-2 and C-5. For example, it took on average 5.4 ± 0.4 minutes for a drop in H₂S concentration from

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**Table 2:**

<table>
<thead>
<tr>
<th>Manhole</th>
<th>Maximum Wastewater Depth (m)</th>
<th>Average Maximum Velocity (m s⁻¹)</th>
<th>Estimated TPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1</td>
<td>0.112 ± 0.002</td>
<td>1.50 ± 0.047</td>
<td>16</td>
</tr>
<tr>
<td>C-2</td>
<td>0.21</td>
<td>0.05</td>
<td>1.5</td>
</tr>
<tr>
<td>C-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3:**

<table>
<thead>
<tr>
<th>Manhole</th>
<th>Average Maximum Concentration (ppm)</th>
<th>Time to Min Concentration (min)</th>
<th>Removal Rate (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1</td>
<td>38.2 ± 2.2</td>
<td>5.4 ± 0.4</td>
<td>0.19</td>
</tr>
<tr>
<td>C-2</td>
<td>37.4 ± 2.5</td>
<td>5.4 ± 0.4</td>
<td>0.22</td>
</tr>
<tr>
<td>C-3</td>
<td>56.3 ± 1.5</td>
<td>5.4 ± 0.4</td>
<td>0.22</td>
</tr>
<tr>
<td>C-4</td>
<td>31.0 ± 1.3</td>
<td>5.4 ± 0.4</td>
<td>0.19</td>
</tr>
<tr>
<td>C-5</td>
<td>30.0 ± 1.2</td>
<td>5.4 ± 0.4</td>
<td>0.19</td>
</tr>
</tbody>
</table>
Table 3 | Average H₂S removal rate (ppm min⁻¹)

<table>
<thead>
<tr>
<th>Setup ID</th>
<th>H₂S max. (ppm)</th>
<th>H₂S min. (ppm)</th>
<th>Time to H₂S min. (min)</th>
<th>Average H₂S removal rate (ppm min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 (n=3)</td>
<td>10.4 ± 0.4</td>
<td>6.3 ± 0.7</td>
<td>1.0 ± 0.0</td>
<td>1.0 ± 0.0</td>
</tr>
<tr>
<td>M2 (n=50)</td>
<td>38.2 ± 2.2</td>
<td>22.3 ± 0.5</td>
<td>2.2 ± 0.0</td>
<td>2.2 ± 0.0</td>
</tr>
<tr>
<td>C-2</td>
<td>36.3 ± 1.2</td>
<td>21.0 ± 0.9</td>
<td>1.5 ± 0.0</td>
<td>1.5 ± 0.0</td>
</tr>
<tr>
<td>C-3</td>
<td>24.8 ± 1.2</td>
<td>14.0 ± 0.9</td>
<td>1.2 ± 0.0</td>
<td>1.2 ± 0.0</td>
</tr>
<tr>
<td>C-5</td>
<td>20.5 ± 1.5</td>
<td>0.0 ± 0.0</td>
<td>0.5 ± 0.0</td>
<td>0.5 ± 0.0</td>
</tr>
<tr>
<td>M3 (n=7)</td>
<td>55.5 ± 8.1</td>
<td>29.6 ± 0.4</td>
<td>1.0 ± 0.0</td>
<td>1.0 ± 0.0</td>
</tr>
<tr>
<td>M4 (n=6)</td>
<td>9.5 ± 0.4</td>
<td>0.0 ± 0.0</td>
<td>0.3 ± 0.0</td>
<td>0.3 ± 0.0</td>
</tr>
<tr>
<td>M5 (n=6)</td>
<td>9.5 ± 0.4</td>
<td>0.0 ± 0.0</td>
<td>0.3 ± 0.0</td>
<td>0.3 ± 0.0</td>
</tr>
</tbody>
</table>

The main mechanisms responsible for H₂S removal at a gravity sewer include adsorption and oxidation, often regarded as equally important factors in gas build-up and removal within the sewer. However, during M5 (open C-1 and C-2 manholes covers), a 1.5-fold increase in average maximum airflow rate, resulted in a 1.5 times increase of H₂S removal at C-2, while at C-5, that removal rate dropped to half of the one verified during baseline. The higher gas concentration injections in the aforementioned study by Nielsen et al. (2012) (when compared to H₂S peaks at the Meco location), along with the forced constant airflow rates and the smaller pipe diameter of their reactor, make difficult a direct comparison between H₂S removal rates in both studies.
To better illustrate this discussion, Figure 3 depicts H₂S removal under different setups at manhole C-2 (headspace H₂S concentration during M1 was very low and therefore not included in the figure).

Higher air velocities cause increased gas advection further downstream, which in turn induce conflicting results. On one hand, there is a smaller contact time between sewer surfaces and H₂S, which may potentially decrease surface corrosion. On the other hand, a potentially longer sewer extension subjected to H₂S exposure and a thinner air/pipe layer may aggravate those effects. This demonstrates the complexity of processes related to H₂S-induced sewer corrosion and toxicity, especially under intermittent conditions such as those downstream of pump stations, and can be even more intricate considering how downstream pressurization may affect gas movement towards the opposite direction (and expected contact times with sewer walls).

In a 2015 study, Vollertsen and co-workers conducted extensive measuring campaigns to target sewer odour problems in San Francisco and assess whether a conceptual model (WATS) could reproduce the measured concentrations of H₂S gas in the sewer atmosphere, among other wastewater parameters (Vollertsen et al. 2015). Even though the model could replicate the general variability of the analysed parameters, H₂S gas samples presented statistically significant differences from model results. The authors discuss the influence of systematic errors, such as the effect of H₂S gas logger placement in the accurate representation of gas flows and concentrations, seeing as H₂S is not homogenously distributed in a sewer headspace. Another aspect is related to uncertainty and how rapid changing conditions, which induce high variability, may not have been accurately included in the model. These considerations are in accordance with the findings of this study, which attest to the need for dynamic ventilation models, in addition to the steady-state H₂S models that are used for global optimization of sewer corrosion problems.

In terms of engineering practice, this data is also quite relevant for ventilation system design. For instance, an average maximum airflow rate of 0.016 m³ s⁻¹ (M3) at the upstream section of the pipe (C-2) did not seem sufficient to attain a minimum H₂S threshold (below 10 ppm), nor R.H. contents below 85%, at a downstream location distanced 154 m (C-5). The opening of two manholes, caused maximum flowrates of 0.011 m³ s⁻¹ and 0.045 m³ s⁻¹, apparently sufficient for a more significant removal of H₂S to below 10 ppm at both C-2 and C-5 manholes, however, most likely due to increased gas exchanges with the outside atmosphere. In systems prone to anaerobic conditions and H₂S ventilation, design of ventilation systems at discharge locations should be carried out taking into consideration
the effects of pressure gradients in gas emissions to the outside atmosphere, especially at locations near existing populations.

**System maintenance and potential risk of gas exposure**

Knowledge of concentration levels of harmful substances and duration of exposure to them is essential for accurate risk assessment. In addition, it is also relevant to assess the average time it takes for H$_2$S minimum concentrations to be attained.

In order to estimate the impact of the analysed setups in terms of potential exposure risk to utility workers, a comparison between setups was made regarding duration of exposure above or below concentration thresholds. Because not all the setups had exactly the same monitoring duration, results are presented as average hourly durations above or below the defined thresholds. These thresholds were defined based on the different exposure recommendations (for example OHSA, or the Commission Directive no. 2009/161/EU) for instantaneous exposure or full working shifts. O$_2$ concentrations below 18.5% are known to lead to asphyxiation, while a concentration over 23% generates flammable/explosive atmospheres. While the latter is not realistically expected to occur in sewers with natural ventilation only (such as the present case study), it was included for reference.

Figure 4 depicts the comparison of average duration above or below the defined thresholds for H$_2$S and O$_2$ at target and complementary manholes. Only observations where the CM was always closed were included, for comparison purposes. Observed CH$_4$ concentration was never above the 5% explosion threshold, and was therefore not included in the analysis.

Under normal operation (M1 and M2) all manhole covers are closed. During M1, the difference between C-2 (TM) and C-5 (CM) in terms of average hourly durations above defined H$_2$S thresholds is not significant (due to the low concentrations measured throughout the sewer). However, during M2 average hourly durations above thresholds

![Figure 4](https://iwaponline.com/wst/article-pdf/81/10/2043/716100/wst081102043.pdf)
are much more significant at C-5. For example, at that manhole concentrations were above 10 ppm on average 74.4% of the time, while at C-2 it was only 35.6% of the time. Shorter durations above 50 ppm were observed (4.1% and 5.7% for TM and CM, respectively).

Headspace oxygen concentrations were never below the 18.5% asphyxiation threshold at TM C-2. However, at C-5 headspace oxygen concentrations below the 18.5% threshold were observed for 7.8% and 14.7% of the time (M1 and M2 setups, respectively). This attests to the importance of ventilation at the exact location where exposure to (M1 and M2 setups, respectively). This attests to the importance of ventilation at the exact location where exposure to risk is foreseen to occur.

Setup M5 refers to the opening of manholes cover at C-2. Even so, at that manhole (TM), average hourly H2S concentrations above 10 ppm were still observed for 23.6% of the time (14.2 minutes per hour), and above 20 ppm for 8.2% (4.9 minutes per hour). This indicates that the opening of a single cover (and increased opportunity for air exchanges with the atmosphere) may not be sufficient to ensure proper sewer ventilation and safe H2S exposure levels, when performing any task or activity at a certain manhole. Expectedly, this is more aggravated at the CM (C-5), where concentrations above 10 ppm were observed 64.5% of the time (38.7 minutes per hour), and 37.4% above 20 ppm (22.5 minutes per hour). The horizontal distance of 154 m between C-5 and the open manholes cover at C-2 (natural ventilation point) resulted in an average increase of 24.5 minutes per hour over 10 ppm, and of 17.6 minutes per hour over 20 ppm.

M4 refers to the situation where the TM is the downstream manhole of two consecutive open manholes (C-1 and C-2). For this situation, for comparison purposes with other setups, only a closed manhole was considered as the CM (setup M4a). Exposure to lower concentrations of H2S (<20 ppm), was overall slightly lower at the open manhole (TM), even though not expressively different from the CM, located only 47.7 m downstream. Short durations of H2S concentration above 50 ppm were observed at C-2 (average 0.7 minutes per hour), which were not detected at the following manhole.

Opening of manholes C-2 and C-3 (setup M5) resulted in the lowest overall exposures, practically negligible at TM (C-2) and only 5.7% above the 10 ppm threshold at the CM (C-5). This may be explained by increased in-gassing at the TM, but also because of much lower overall concentrations in one of the monitoring periods.

Even though CH4 concentrations in this study were not found to be threatening (i.e. above 5% explosion threshold), its emission to the atmosphere from sewer systems may still be relevant in terms of GHG emissions and inventories. To this extent, the limited literature on the mechanisms of biological oxidation mechanisms of CH4 suggests this topic should be further investigated in the future.

This exploratory experiment allows some insight into the effect of distance to the point of ventilation and number and location of open manholes. This was observed not only in terms of gas movement within the sewer and odorous emissions to the atmosphere, but especially in terms of risk exposure of utility workers, in particular when considering that many are still non-compliant with PPE usage in routine operations.

**CONCLUSIONS**

This study allowed perception of the effect of intermittent flows and increased natural ventilation in airflow rates at the venting stack and gravity sewer, as well as the potential exposure risk to sewer gas (H2S, CH4 and low concentrations of O2).

With the opening of one manhole cover (C-2) the expected TPD more than doubles (when compared to standard operation). An increase in average pipe air velocity peaks from 0.05 m s⁻¹ to 0.08 m s⁻¹ was also observed, accompanied by an increase in the H2S average removal rates of roughly 20%. The opening of two manhole covers (M4 and M5) induces similar airflow rates through the vent stack, but different rates through the pipe. It should be noted that the lag time between pumping and measured headspace effects increases towards downstream. H2S removal rates were also found to differ. The opening of manholes C-2 and C-3 resulted in lower average removal rates (of 2.88 ppm min⁻¹), however this was also largely influenced by the lower H2S headspace concentration verified during this setup. On the other hand, the opening of manholes C-1 and C-2 resulted in an increase of 40% of H2S removal (when compared to baseline), but this setup also presented higher initial H2S concentrations.

These results indicate that not only ventilation rates, but also distance to TM and rising main, will influence transport and emission (to the exterior) of sewer gas pollutants. Naturally, setups which result in higher airflow rates inside the pipe generally caused higher removal rates, especially at C-2. However, that was not always the case at C-5, where the increased ventilation rates at the upstream section resulted in considerably lower removal rates at that downstream manhole (for example during M5), due to gas build-up.
In terms of potential risk, the time to attain minimum H$_2$S concentrations and the duration of potential exposure to concentrations above recommended thresholds were also evaluated for the different setups and distances to point of ventilation. It was observed that under certain more unfavourable conditions, natural ventilation may not suffice for attaining recommended safety concentrations (regardless of number and location of open manhole covers).

The study constitutes a preliminary assessment in terms of environmental aspects and potential risk assessment, which shed some light into the complexity of aerodynamics of sewer systems. Comprehensive field studies such as this one, while adding great value by providing full scale real data, are more limited in time and resources, thus originating smaller data sets. The relatively short length of the full scale gravity pipe, and restrictions in terms of number of open manholes, due to some covers being sealed, as well as in ventilation control due to the height of the stack, caused some limitations in the extent of the possible setups under analysis. Further design options should be explored in terms of increased number of open manholes and durations of each opening, as a further step in evaluating exposure risks, ventilation needs and odour release potential.

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