INVESTIGATION OF GAS- AND LIQUID-PHASE SEWER ENVIRONMENTAL FACTORS LEADING TO MICROBIALLY-INDUCED CONCRETE CORROSION

By

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Abstract

INVESTIGATION OF GAS- AND LIQUID-PHASE SEWER ENVIRONMENTAL FACTORS LEADING TO MICROBIALLY-INDUCED CONCRETE CORROSION

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Sewer systems are a principal element of infrastructure in modern cities, accounting for massive amounts of public investments made over many decades and can be considered as an asset of the nation. Many concrete manholes in the sewer system are deteriorating due to the attack of sulfuric acid produced by microorganisms in a process termed as Microbial Induced Concrete Corrosion (MICC). The life span of concrete sewer elements significantly reduces from 100 years to 30–50 years, in extreme cases even down to 10 years. The primary aim of this study is to enhance the understanding of the correlation between gas-phase hydrogen sulfide (H_2S) concentrations, which lead to MICC, and sewer environmental factors, including dissolved oxygen (DO), biochemical oxygen demand (BOD_5), sulfide, sulfate, temperature, and pH. In addition, the effects of seasonal variations on H_2S concentrations and the impact of manhole categories including the depth, velocity, turbulence and drop are also studied.

For 130 manholes in the City of Arlington, Texas, the wastewater characteristics in the gas phase such as temperature, relative humidity and hydrogen sulfide were measured *in-situ* using various instruments and the liquid phase parameters like dissolved oxygen (DO), pH and temperature were also measured in-situ. The samples for measuring the biochemical oxygen demand (BOD_5), sulfate, total and dissolved sulfide were collected in-situ and were analyzed in the laboratory using standard methodology. The sewer system characteristics like slope and velocity were obtained from the city.

In each manhole studied, H_2S concentration, liquid phase temperature, and liquid phase pH showed similar hourly trends in consecutive days of sampling. The trend in rise and fall of concentration of these parameters over time showed slight variations depending on the manhole's location and category. The manholes with hydraulic jump generated the highest average H_2S concentration, and the lowest was observed in manholes with subcritical flow in upstream and downstream. The average liquid phase temperature was always greater than the ambient temperature inside a manhole, with a variation of 3°F on an average. In all the manholes studied for seasonal variation, the concentration of hydrogen sulfide was found to be maximum during the summer, when the temperature was elevated. Due to involvement of multiple parameters affecting each factor, no strong linear correlations were obtained between the factors studied.

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Chapter 1

INTRODUCTION

1.1 Background

Sewer systems are a principal element of infrastructure in modern cities, accounting for massive amounts of public investments made over many decades and can be considered as an asset of the nation. There are around 550,000 km of concrete pipes in the USA (Romanova et al., 2014). The total asset value of these networks is estimated to be about one trillion dollars in the USA and $100 billion in Australia (Koch et al., 2002).

Many concrete manholes are deteriorating faster due to the production of sulfuric acid by microorganisms in a process termed Microbial Induced Concrete Corrosion (MICC) and are not meeting their expected design life. The life span significantly reduces from 100 years to 30–50 years, in extreme cases, the life span even down to 10 years. (Jensen, 2009). The production, emission and build-up of hydrogen sulfide gas in manholes is identified as a major cause of corrosion. Improved living conditions due to industrialization and urbanization have led to the increased use of hot water and sulfur-containing detergents in households and the presence of toxic metals and chemicals from industrial discharges, leading to increased corrosion (Romanova et al., 2014).

Corrosion of manholes in the sewer system is a global issue with not only great economic relevance but also significant environmental health and safety issues in regions having warmer climates. Corrosion causes loss of concrete mass and deteriorates the structural capacity, leading to cracking of sewer pipes and ultimately structural collapse. Corrosion of manholes on roads can create safety risks from manhole lids dropping down through the structure or sewers overflowing. (Pollak, 2017).

The restoration and replacement of deteriorated sewers is expensive. Millions of dollars are being spent globally on the maintenance of the sewer networks. £104 billion is the estimated cost for replacing the sewer mains in the UK (Romanova et al., 2014). When the estimated rehabilitation cost of concrete sewer pipes was €100 million in Germany (Kaempfer et al., 1998), £4 million per year was the estimated cost of sewer corrosion in Belgium (Vincke et al., 2002). In the USA alone, sewer asset loss around $14 billion per annum is expected due to the corrosion of sewer pipes ((Koch et al., 2002). Failures in the aging infrastructure is expected to increase this cost (Sydney et al., 1996; US EPA, 1991).In order to maintain a satisfactory working of the existing wastewater infrastructure in the United States, an expenditure of 390 billion dollars within the next 20 years was projected by USEPA in 2002(Gutiérrez-Padilla et al., 2010). Coatings to remedy corroded manhole concrete can cost $10 to $30 per square foot of coverage, depending on whether the corrosion has caused the walls to be structurally deficient (Jurgens, 2014).

1.2 Manhole: An Overview

A manhole is a vertical shaft with a removable cover that provides access to a sewer or storm water drain from the ground surface. These are generally located where there is a junction of two or more sewer or storm water lines, at locations where the size or diameter of sewer or storm water line changes, locations where the direction or alignment of sewer line changes and when the grade or slope of the sewer line changes.

The principal purposes of a manhole are:

1. Facilitating inspection, cleaning and removal of obstructions in the sewer pipeline.
2. Allowing the escape of gases, thereby enhancing the ventilation of the sewage system.
3. Assisting to ensure that the sewer or storm water line is laid in convenient lengths.
4. Allowing the authorities to join two or more sewer pipes and change the direction of flow (Fibertech, 2019)

Manholes can typically be classified into three categories based on the depth of manhole. They are shallow, normal, and deep manholes. The manhole chosen for a specific location depends on factors like sewer line size, and the major purpose that is to be served by manhole.

1. Shallow manholes are generally located in the beginning of a sewer line, where the sewage flow is mostly light. Shallow manholes are typically two to three feet deep.
2. Normal manholes are about 150 centimeters or five feet deep with a heavy manhole lid that is usually square or rectangular in shape.
3. Deep manholes have depth greater than 150 cm (five feet) and have a heavy cover at the top. The size of manhole is gradually increased, and there is a facility for going down, such as a built-in ladder.

Manholes manufactured using a variety of materials are available in the market these days. Based on the shape and the purpose it serves, it may vary from bricks, precast concrete, plastic, to fiberglass. Brick manholes were common in early construction but are not permitted for new construction. Traditionally, precast concrete was used for manufacturing manholes. These precast manholes are formed in segments and are then assembled on site. Several studies show that in ideal conditions, they can last for up to 100 years. Deterioration of structural capacity of these manholes due to hydrogen sulfide corrosion, leads to cracking in the interior parts of sewer pipes which ultimately results in the collapse of the structure. The restoration and replacement of corroded sewers is expensive and time consuming. Plastic manholes manufactured using polyethylene is durable and highly resistant to corrosion. Frequent maintenance and rehabilitations are not required as plastic do not degrade with time like the precast concrete manholes. They are environmental-friendly and do not pose a risk of contaminating the ground that they are installed. Advantages of fiberglass and plastic polyethylene models over traditional concrete manholes has increased their popularity in the recent years. While fiberglass manholes exceed against concrete manholes in almost every respect, they are costlier to purchase. However, installation costs for fiberglass manholes are lower and maintenance is virtually eliminated. (Open Channel Flow, 2019)

1.3 Thesis Objectives

Many researches have been done in the area of corrosion of concrete manholes and pipes but many of these lack reliable field data and interaction between key parameters which is being considered here. The laboratory studies have focused on the corrosion mechanisms related to MICC, but it is almost impossible to reproduce field environmental conditions of MICC in the lab. In this study over 130 manholes in the City of Arlington, Texas, with varying manhole categories were studied and samples and data were collected, which gives us a better insight on various parameters and their contribution to the corrosion of manholes. There are several factors affecting sulfide generation, volatilization, and corrosion of concrete manholes and pipes:

1. Wastewater Characteristics: dissolved oxygen (DO), presence of sulfur compounds, biochemical oxygen demand (BOD_5), temperature, and pH;
2. Sewer System Characteristics: slope and velocity, turbulence, whether the pipe is flowing full, accumulated grit and debris, sewer pipe materials, concrete alkalinity.

Reduced life span of sewer structures is creating asset loss worth billions of USD every year and the maintenance and rehabilitation cost is also extremely high. The lack of reliable field data and difficulty in reproducing the exact field environmental conditions in laboratory, motivated this detailed study on factors leading to the generation and volatilization of H_2S, the key player of MICC causing deterioration of manhole and sewer pipelines. The problem addressed in this research is investigating the factors causing a rise in the generation and volatilization of H_2S, leading to MICC and understanding how hourly trends and seasonal variations affect these sewer environmental factors.

The overall goal of this research was to create better awareness about the main factor, driving the other sewer environmental parameters leading to increased generation and volatilization of H_2S leading to MICC and to suggest ways to reduce the generation and volatilization of H_2S in manholes. This study aims to improve the understanding of the correlation between hydrogen sulfide (H_2S) concentrations and sewer environmental factors, including dissolved oxygen (DO), biochemical oxygen demand (BOD_5), sulfide, sulfate, temperature, and pH. Patterns in daily variations of H_2S concentration, gas temperature, DO, pH, and liquid-phase temperature in manholes are investigated. In addition, the effects of seasonal variations on H_2S concentrations and the impact of manhole categories including the depth, slope, velocity, turbulence and drop are also studied. Finally, the impact of H_2S concentrations, along with gas-phase oxygen, relative humidity, and temperature, on MICC is investigated. Over 130 manholes were investigated to study the relation between various liquid and gas phase parameters leading to H_2S generation and volatilization in the manholes. The following were the expectations we had at the initial stage of this study.

1. It was expected to see highest H_2S concentrations from about 4 p.m. to 12 a.m., due to high late afternoon temperatures, and low overnight flow rates.

2. At a given temperature, manhole categories (based on drop, pipe diameter, flow, bends and multiple inlets) generating greater turbulence in sewer environment will lead to greater volatilization of H_2S gas in manholes.
3. Higher the temperature, lower will be the concentrations of gases oxygen (DO) and H_2S in the liquid phase.
4. Greater BOD will deplete DO in the liquid phase, leading to greater liquid-phase sulfide production and greater H_2S levels.
5. Greater sulfate in the liquid phase will lead to greater liquid-phase sulfide production and gas-phase H_2S.
6. The lower the pH, the more H_2S will volatilize into the gas phase.

1.4 Thesis outline

The rest of the thesis is outlined as follows:

1. Chapter two reviews the literature on corrosion of manholes due to hydrogen sulfide gas.
2. Chapter three describes the methodologies and procedure for onsite data collection as well as for the analysis of samples in laboratory, to address the objectives of the investigation.
3. Chapter four discusses about the data analysis and the findings of this research study.
4. Chapter five summarizes the findings and conclusions of this study and also provides future recommendations.

Chapter 2

LITERATURE REVIEW

2.1 Microbially induced concrete corrosion (MICC)

One of the initial researches on concrete sewer corrosion in USA dates to 1900 (Olmstead & Hamlin, 1900). Though the study concluded sulfuric acid as the root cause of corrosion, the relation between sulfuric acid and hydrogen sulfide was not established. The physiochemical and biological processes leading to the corrosion of sewer pipe have been studied since 1940 and a set of representative knowledge associated with microbiologically-induced concrete corrosion (MICC) has been gained over years (Parker, 1945, 1947, 1951). Acid-producing autotrophic microbial community that colonizes in the concrete surfaces of the sewer pipes, dissolves the cement (calcium carbonate binder) leading to microbial induced concrete corrosion. (Davis et al., 1998).

2.2 Mechanism of MICC

Fresh concretes surface in the sewer pipes have pH of 12, which is strongly alkaline, preventing the microbial activities leading to corrosion (Sand et al., 1987). However, CO_2 and H_2S that builds up in the sewer system gradually reduces the pH of the alkaline surface by carbonation of concrete surface and neutralization of hydrogen sulfide (Zhang et al., 2008; Nielsen et al.; 2005). Fresh domestic sewage entering a sewage system is usually free of sulfide (ASCE, 2007). Anaerobic bacteria colonize the slime layer formed in the submerged parts of sewer pipelines lacking dissolved oxygen. Under anaerobic conditions these bacteria utilize the oxygen chemically bound in sulfate (SO_4^{2-}), which is a common anion in water and wastewater (released by hydrolysis of sulfur-bearing proteins). The bacteria thus reduce the sulfate to sulfide ion (S^{2-}). These sulfide ions then combine with hydrogen in water to form hydrogen sulfide (USEPA, 1992). Figure 2.1 represents the schematic diagram of the first phase of MICC in a concrete sewer pipe.

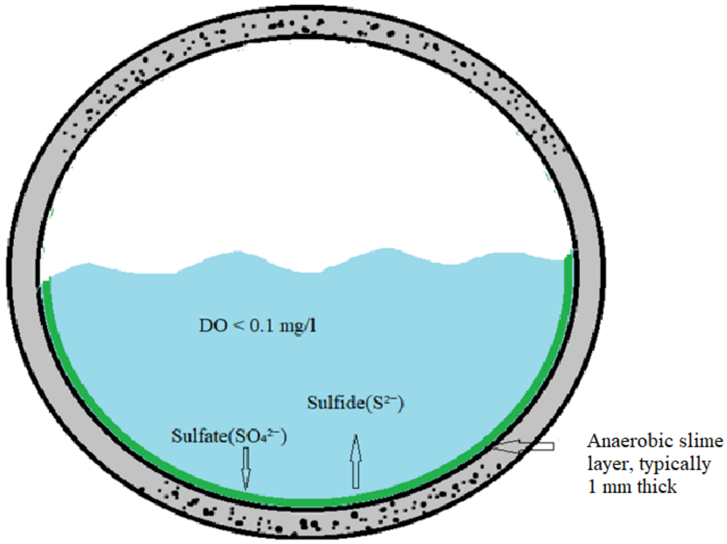
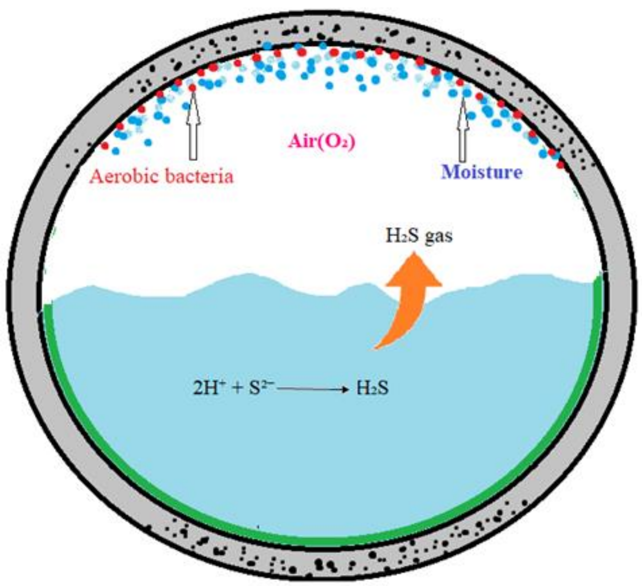


Figure 2-1: Sulfide formation

The rate of sulfide production in the slime layer depends on various environmental factors including concentration of organic content (BOD), concentration of dissolved oxygen in wastewater, temperature, wastewater velocity (higher velocity means more turbulence, which increases dissolved oxygen), wetted perimeter of pipe (greater liquid surface area exposed to the gas phase increases dissolved oxygen) (ASCE, 2007). In regions with temperate climates, the hydrogen sulfide produced under anaerobic conditions, mainly prevails in force mains. Hydrogen sulfide is released into the sewer atmosphere when the waste water is discharged from a force main into a partly filled gravity sewer (Jensen et al., 2009).

Hydrogen sulfide dissociates to dissolved hydrogen sulfide gas (H_2S), hydrosulfide ion (HS^-), and sulfide ion (S^{2-}) depending on pH of the waste water. The distribution is approximately 50%H_2S gas and 50 % HS^-, when the pH is neutral. When the pH reduces by a single unit to 6, the distribution becomes approximately 90% dissolved hydrogen sulfide gas and 10% hydrosulfide ion. Figure 2.2 shows the schematic diagram of H_2S gas formation in concrete sewer pipelines. The only form of sulfide that can be release from the wastewater to the atmosphere, causing odor and corrosion of concrete is dissolved H_2S gas (USEPA, 1992). Hydrogen sulfide gas is a colorless but extremely odorous. Concentrations as low as

0.00047 ppm can be easily detected by human sense of smell. H_2S gas can cause queasiness, headache and conjunctivitis in concentrations as low as 10 ppm. Exposure to concentrations above 100 ppm can cause serious inhalation problems and harm the sense of smell, along with the burning of eye and respiratory tract. At a higher concentration, greater than 300 ppm, death can occur within a few minutes (ASCE, 2007).



b) H_2S formed in wastewater is released as H_2S gas to sewer atmostphere.

Figure 2-2: H_2S gas formation

The release of H_2S from solution is accelerated by structures like drops and sharp bends in gravity sewers, creating turbulent conditions (Jensen et al., 2009). The H_2S gas released combines with the moisture on the non-submerged surfaces of pipe and is biologically oxidized by aerobic *Thiobacillus* bacteria to sulfuric acid (H_2SO_4), which causes corrosion of the concrete (Wei et al., 2010; USEPA, 1992). Figure 2.3 shows the phase 3 of chemical processes involved in the corrosion of concrete sewers.

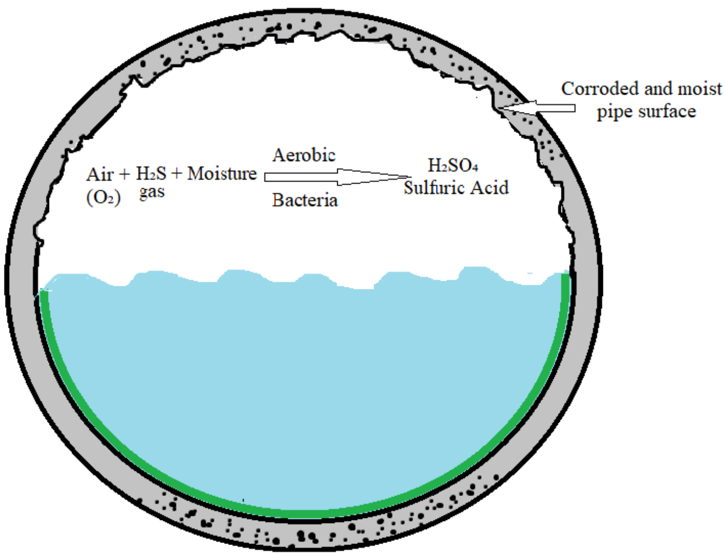
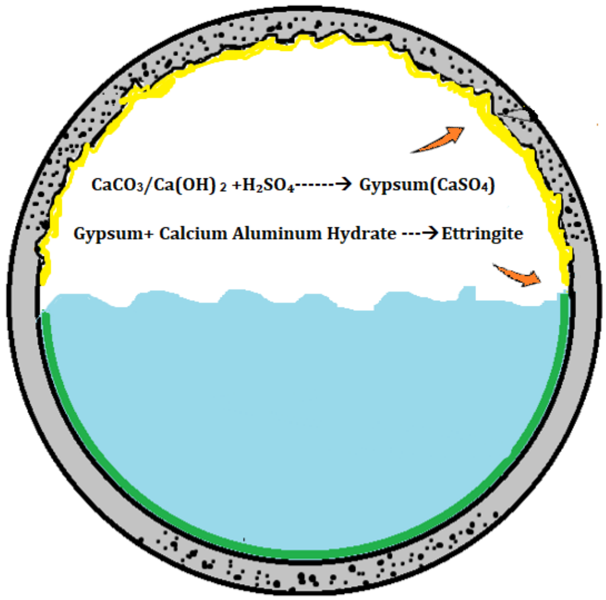


Figure 2-3: Sulfuric acid formation

Fresh concrete has an alkaline surface pH whereas weathered concrete has a slightly acidic surface pH (around 6). When concrete is subject to active sulfuric acid corrosion, it may have a surface pH of 1 to 3. The sulfuric acid reacts with the calcium silicate, calcium carbonate ($CaCO_3$), and portlandite or calcium hydroxide ($Ca(OH)_2$) in the cement to form calcium sulfate, or gypsum ($CaSO_4$), a soft corrosion product. Gypsum then reacts with calcium aluminum hydrate to form ettringite. Both gypsum and ettringite are highly expansive minerals, which generates internal cracking at the concrete interface enhancing the corrosion development (Monteny et al., 2000; Parande et al., 2006). The swelling of concrete in the initial stages of corrosion makes it difficult to measure the loss of concrete due to corrosion (USEPA, 1992). Figure 2.4 shows the final phase of chemical processes involved in the corrosion of concrete sewers. With the removal of the deteriorated materials by sewage flow, the concrete corrosion accelerates (Mori et al., 1992).



d)Gypsum and Ettringite cause internal cracking resulting in corrosion of the concrete surface

Figure 2-4: Corrosion of concrete surface

Direct oxidation of hydrogen sulfide to elemental sulfur may occur in presence of abundant atmospheric oxygen or other oxidant, resulting in variation in the shades of the yellow color on the surface of corroded concrete. Due to the availability of abundant atmospheric oxygen near the manhole cover, yellow color is observed in manholes with high hydrogen sulfide concentrations (ASCE, 2007). The hydrogen sulfide corrosion can cause severe damage to manholes, concrete pipes and even force mains. Corrosion of manholes on roads can create safety hazards from manhole lids falling through the structure, streets giving way, or sewers flowing beyond their capacity (Pollak, 2017).

Many innovations and technological advancements are utilized to minimize the effects of corrosion in concrete sewers. Using chemicals like salts of nitrates or iron to reduce H_2S generation in the sewer pipelines (Gutierrez et al., 2008; Jiang et al., 2011; Jiang et al., 2013; Zhang et al., 2009). Use of corrosion resistant concrete in new manhole construction and for repairing the corroded surfaces of existing manholes are some of the other technologies used (Hewayde et al., 2007; De Muynck et al., 2009; Haile et al., 2010; Alexander et al., 2011). Use of alternate materials like fiberglass and plastic polyethylene to build manholes and sewer pipelines is also gaining popularity, as they have many advantages over traditional precast concrete.

The rate of concrete loss is dependent upon several factors, of which hydrogen sulfide gas concentration is only one. Comprehensive understanding of the correlations between the rate of corrosion and various sewer environmental factors such as the H_2S concentration, temperature and relative humidity are critical to assess and improve the corrosion control strategies.

2.3 Factors affecting hydrogen sulfide generation

Sulfide generation is a biochemical process which occurs in submerged portions of a sanitary sewer. Factors which increase hydrogen sulfide generation in the liquid phase include:

- Low dissolved oxygen:

The biofilm formed from the slimy layer of bacteria and inert solids, below the water level, becomes thick enough to resist the penetration of dissolved oxygen and develops an anoxic zone. At low DO levels (0.1-1.0 mg/l), the anaerobic bacteria utilize oxygen from sulfate ion, which is a common component of wastewater, to oxidize organic matter and form sulfide. This sulfide further reacts with hydrogen in water to form hydrogen sulfide (ASCE, 1989). Higher sulfide generation occurs in force mains, which flow full with very little oxygen (ASCE, 1995).

- High Biochemical Oxygen Demand (BOD):

BOD is the amount of oxygen utilized in the biological metabolism of biodegradable organic compounds (ASCE, 1989). High BOD encourages microbial growth and depletes DO concentration leading to increased sulfide generation in proportion to BOD concentration (USEPA, 1992).

- High wastewater sulfate content:

In wastewater, sulfate is generally released by the hydrolysis of sulfur-bearing proteins. The higher the sulfate content in the wastewater, the more likely the formation of H_2S.

- High temperatures:

High temperature increases microbial growth rate, which in turn increases the rate of sulfide production in the liquid. Also, as temperature increases, oxygen becomes less soluble in the liquid phase, resulting in low dissolved oxygen (USEPA, 1991).

- Low velocities:

In sewers flowing less than full, low velocities will result in greater generation of sulfides. As the velocity of flow decreases, grits and organic solids settle, leading to high BOD levels, which lead to H_2S formation (ASCE, 1989; ASCE, 1995). In addition, the long retention times associated with low flow velocities give aerobic bacteria more time to consume all available DO, creating anaerobic conditions Also, low velocities allow growth of a thicker slime layer, in which the anaerobic bacteria which form hydrogen sulfide reside (ASCE, 1989).

- Low Slopes:

Sewer systems having low slopes generally have low reaeration rates, which leads to low dissolved oxygen, generating more hydrogen sulfide. Also, with low slopes, solid and grit deposition on the bottom of pipes will be higher, which in turn aids higher generation of hydrogen sulfide (USEPA, 1992).

- Low turbulence:

Turbulence improves the oxygenation of wastewater flowing through the sewer system, reducing the production of hydrogen sulfide (ASCE, 1989). Lower turbulence will decrease the degree of reaeration, which aids higher generation of hydrogen sulfide. Table 2.1 shows the factors affecting the hydrogen sulfide generation.

Table 2.1. Factors affecting hydrogen sulfide generation

Parameter	**Level leading to H_2S formation**	**Reference**
DO	<1 mg/L	ASCE, 1989
BOD	>250 mg/L	ASCE, 2007
Sulfate	Higher the sulfate level, the greater the H_2S formation	ASCE, 1995
Temperature	Generally > 15ºC	ASCE, 2009
Flow Velocity	Rule of thumb: < 2 ft/sec for pipe flowing full*	ASCE, 1989
Slope	Low	USEPA, 1992
Turbulence	Low	ASCE, 1989

*Actually, depends on BOD and flow geometry (cross-sectional area and surface width of flow)

2.4 Factors affecting volatilization of H_2S from the liquid to the gas phase

Factors which favor volatilization of H_2S from the liquid to the gas phase, include:

- Concentration of liquid-phase hydrogen sulfide:

Dissolved hydrogen sulfide is the only form of sulfide that can be released from wastewater to the atmosphere as H_2S gas. The higher the concentration of H_2S in liquid phase, the higher the rate of volatilization.

- High turbulence:

Although low turbulence favors hydrogen sulfide formation in the liquid phase, high turbulence causes stripping of H_2S into the gas phase. So, the higher the turbulence, the higher the volatilization.

- Steep slopes and high flow velocities:

Steep slopes will tend to increase flow velocities and turbulence. Slope changes that produce hydraulic jumps, abrupt changes in flow direction (angle points), and short radius curves also tend to increase H_2S volatilization (Kienow and Kienow, 1991)

- High temperatures:

As temperature increases, its volatilization into the gas phase increases, due to changes in Henry's law constant with temperature.

- Low pH:

Low pH of sewage (<6) favors a shift to dissolved H_2S gas (as opposed to dissociated H^+ and HS^- or S^{2-}); low pH thus leads to increased volatilization (ASCE, 1995).

Table 2.2 shows the factors affecting hydrogen sulfide volatilization

Table 2.2. Factors affecting hydrogen sulfide volatilization

Parameter	**Level leading to H_2S volatilization**	**Reference**
Liquid-phase H_2S concentration	0.1 mg/L or lower (dissolved)	EPA, 1992
Turbulence	High	
Slope	High	
Flow Velocity	High	
Temperature	High	
pH	<6 (around 90% of sulfide is in the form of H_2S at pH = 6)	EPA, 1992

2.5 Factors affecting sulfuric acid formation and concrete corrosion

Once in the gas phase, H_2S can adsorb onto concrete surfaces, where it can be biologically converted into sulfuric acid by *Thiobacilli* and other aerobic acidogenic sulfur-oxidizing microbes. Factors affecting sulfuric acid formation and corrosion are listed in Table 3. Generally, H_2S concentrations > 2 to 5 ppm have the potential to cause corrosion, depending on the physical conditions of the sewer (ASCE, 2007). The sulfuric acid reduces the wall moisture pH values to the 1-2 range, and reacts with the calcium silicate, calcium carbonate ($CaCO_3$), and portlandite or calcium hydroxide ($Ca(OH)_2$) in the cement to form calcium sulfate, or gypsum ($CaSO_4$), according to equations 1-3 below (ASCE, 2007):

$$H_2SO_4 + CaSi \rightarrow CaSO_4 + Si + 2H^+ \qquad (1)$$

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2CO_3 \qquad (2)$$

$$H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4 + 2H_2O \qquad (3)$$

Gypsum then reacts with calcium aluminum hydrate to form ettringite. Both gypsum and ettringite are highly expansive and can cause cracking at the concrete interface (O'Connell et al., 2010; Jiang et al., 2014;

Kienow and Kienow, 1991). High alkalinity of concrete can reduce the rate of corrosion due to volatilized H_2S. Table 2.3 shows the factors affecting sulfuric acid formation the level leading to corrosion.

Table 2.3. Factors affecting sulfuric acid formation and corrosion

Parameter	**Level leading to sulfuric acid formation and corrosion**	**Reference**
Gas-phase H_2S concentration	>2 ppm	ASCE, 2007
Relative humidity	>80%	EPA, 1991
Oxygen concentration	High	EPA, 1991
pH	pH < 3 is an indicator of active corrosion; pH <2 is an indicator of severe corrosion	EPA, 1991
Temperature	High	EPA, 1991

2.6 Summary of Literature Review

Article: Determining the long-term effects of H_2S concentration, relative humidity and air temperature on concrete sewer corrosion **Authors:** Jiang, G., Keller, J., & Bond, P. L		
Aim /Experimental condition	**Factors considered**	**Conclusion**
Investigated the long-term effects of H_2S concentration, relative humidity and air temperature over 3.5 years under controlled conditions simulating the sewer environment.	• H_2S concentration • Air temperature • Relative humidity	• H_2S is found to be a key factor influencing the rate of concrete corrosion during long-term exposure to sewer conditions. • Increased corrosion rates were observed in coupons located in gas-phase subjected to high relative humidity, whereas corrosion rates were lower in coupons that were partially submerged in the waste water. • Strong effects of temperature on pH, sulfate and corrosion loss were not observed.
Article: Influence and Interaction of Temperature, H_2S and pH on Concrete Sewer Pipe Corrosion **Authors**: Anna Romanova, Mojtaba Mahmoodian, Morteza A. Alani		
Aim /Experimental condition	**Factors considered**	**Conclusion**
Samples were collected from two manholes in Kent, UK for period of two months to establish a relation between parameters	• Liquid phase pH., • Liquid phase and ambient temperatures, • Hydrogen sulfide	• Liquid phase pH values do not have a direct influence on hydrogen sulfate concentration. • On average liquid phase temperature was found to be higher by 3.5°C than the ambient temperature. Both temperatures followed over-all trend of the temperature outside the manhole.

		• When the hourly temperature patterns remained discrete for each manhole, general daily trend was similar and was governed by the domestic and industrial use as well as discharges from rising mains and pumping stations. • During periods with low temperature and low waste water activity, the concentration of H_2S was found to peak and was found to have a 10h shift in general pattern.
Article: Prediction of sulphide build-up in filled sewer pipes **Authors**: Amir M. Alani; Asaad Faramarzi; Mojtaba Mahmoodian; Kong Fah Tee		
Aim /Experimental condition	**Factors considered**	**Conclusion**
To model and predict the sulfide build-up for steady state condition in filled sewer pipes.	• Diameter of pipe • Temperature of the waste water (°C), • Hydraulic radius • COD	• The results showed that the sulfide build-up raises by increasing [COD], temperature, detention time and/or stream velocity. • The sewer diameter was found to have an inverse effect on sulfide build-up.
Article: Microbial mediated deterioration of reinforced concrete structures **Authors**: Shiping Wei, Mauricio Sanchez, David Trejo, Chris Gillis		
Aim /Experimental condition	**Factors considered**	**Conclusion**
To investigate the microbial populations in deteriorated bridge concrete above the water level and in adjacent soils.	• Microbial populations	• A positive correlation between the total bacterial cell number and the level of deterioration was obtained.

Article: Biogenic sulfuric acid attack on different types of commercially produced concrete sewer pipes **Author**: Ma. Guadalupe, D. Gutiérrez Padilla, Angela Bielefeldt, Serguei Ovtchinnikov, Mark Hernandez, Joann Silverstein		
Aim /Experimental condition	**Factors considered**	**Conclusion**
To study degradation of low- and high-quality concrete in environments simulating sewer pipes with and without bacteria in laboratory	• pH • Sulfate formation • Loss of material by weight	• The rate of corrosion of the (Low-w/c) concrete in the simulated MICC conditions was significantly lower than the (High-w/c) concrete. • The correlation between pH and the bacterial activity, were in accordance with the hypothetical mechanism for the microbially induced concrete corrosion.
Article: Microbiologically induced concrete corrosion: A case study from a combined sewer network **Author**: C. Grengg, F. Mittermayr, A. Baldermann, M.E. Böttcher, A. Leis, G. Koraimann, P. Grunert, M. Dietzel		
Aim /Experimental condition	**Factors considered**	**Conclusion**
Investigation of a deteriorated concrete sewer system to study the intricate reaction mechanisms and controlling parameters for progressing MICC.	• Retention times • pH	• Long retention times of the wastewater leads to high microbial activity and abundant sulfate reduction, enhancing H_2S degassing and H_2SO_4 production. • H_2SO_4 accumulation in the interstitial solutions of the concrete resulted in pH values between 0.7 and 3.1
Article: Corrosion of concrete sewers—The kinetics of hydrogen sulfide oxidation **Author**: Vollertsen, Jes, et al.		

Aim /Experimental condition	Factors considered	Conclusion
To study hydrogen sulfide induced concrete corrosion in sewer reactors operated with a free water surface to impersonate gravity sewer conditions.	• Intermittent hydrogen sulfide loads	• Absorption and oxidation of H_2S is faster compared to H_2S release from the sewage in a gravity sewer. • Hydrogen sulfide was found to be oxidized by corroding concrete at rates comparable to that of submerged sewer biofilms. • Corrosion of concrete surfaces was observed within a few months after upstart, with surface pH values falling below 1–2. • The heaviest corrosion attack was found to occur close to the water line.

Article: Evaluation of concrete corrosion after short- and long-term exposure to chemically and microbially generated sulfuric acid

Author: Bettina Huber, Harald Hilbig, Jörg E. Drewes, Elisabeth Müller

Aim /Experimental condition	Factors considered	Conclusion
Portland-cement based concrete samples were incubated for 28 days in microbially derived H_2SO_4 (pH 1.3–2.4) and chemically generated H_2SO_4 (pH 1.0 - 2.0) to investigate the potential differences between the two acid attacks and the corrosion behavior over time was also evaluated.	• visual inspections • Weight loss • Calcium leaching	• In the corrosion solutions similar pH values, sulfate and calcium concentrations were measured indicating comparable corrosion conditions. • The process of concrete corrosion is not a linear over time and multiple factors were found to influence the degradation process

Article: Hydrogen sulfide induced concrete corrosion of sewer networks **Author**: Jensen, Henriette Stokbro		
Aim /Experimental condition	**Factors considered**	**Conclusion**
To study the mechanisms and kinetics of H_2S uptake on to the concrete surfaces and the H_2S oxidation within the corroded concrete	• Corrosion products from heavily corroded concrete surfaces.	• Uptake of hydrogen sulfide on to concrete surface was found to be faster compared to release of H_2S to sewer atmosphere from the wastewater.

Article: Identification of controlling factors for the initiation of corrosion of fresh concrete sewers **Author**: Jiang, G., Sun, X., Keller, J., & Bond, P. L.		
Aim /Experimental condition	**Factors considered**	**Conclusion**
A long-term (4.5 year) study in purpose-built corrosion chambers to identify the controlling factors for initiation of corrosion on fresh concrete sewers.	• Gas phase concentration of H_2S • Relative humidity • Gas temperature.	• During the initiation stage sulfide oxidation rate was found to be the limiting factor rather than the H_2S concentration, whereas in long-term sulfide corrosion higher H_2S concentrations were increasing the corrosion rates. • Humidity provides moisture to the concrete surface, which is important for both the initiation and active corrosion stages via vapor condensation. • Higher temperature reduced the corrosion initiation time due to its positive impact on reaction kinetics.

Article: Interactions of nutrients, moisture and pH on microbial corrosion of concrete sewer pipes **Authors:** Tadahiro Mori, Tsuguhiro Nonaka, Kazue Tazaki, Minako Koga, Yasuo Hikosaka, Shuji Noda		
Aim /Experimental condition	**Factors considered**	**Conclusion**
To investigate the effects of nutrients, moisture and pH on microbial corrosion of concrete sewer pipes and mortar specimen.	• Nutrients • Moisture • pH	• Heavy corrosion of concrete was found to occur near the water level and was found to reduces as the distance from water level increased. The necessary level of oxygen, moisture and nutrients must be available to cause maximum corrosion. • Depending on the pH two main corrosion products, gypsum and ettringite were formed. At pH level less than 3 gypsum was formed on the surface of the mortar specimen whereas at pH level was greater than 3 ettringite was formed inside the specimen.
Article: In-situ evaluation of predictive models for H_2S gas emission and the performance of optimal dosage of suppressing chemicals in a laboratory-scale sewer **Authors:** Abdikheibari, S., Song, H. M., Cho, J. I., Kim, S. J., Gwon, S. C., Park, K., & Jegatheesan, V.		
Aim /Experimental condition	**Factors considered**	**Conclusion**
To quantify H_2S gas emission from a simulated sewer system, with slopes varying between 0.5% and 1.5%, under the dosing of certain mitigating chemicals.	• Slope • Hydrogen sulfide gas emission	• Steeper slopes led to quick release of the H_2S gas in the gas phase. • NaOH and $Mg(OH)_2$ were the best candidates to suppress the H_2S gas generation. • Keeping the sewer networks in aerobic condition would decrease emissions chemically as well as biologically.

Article: An observation-based model for corrosion of concrete sewers under aggressive conditions **Author**: T. Wells, R.E. Melchers		
Aim /Experimental condition	**Factors considered**	**Conclusion**
Developing a mathematical model to predict the rate of corrosion in concrete pipe as a function of exposure time and environmental /operating conditions.	• H_2S level • Temperature • Relative Humidity • Instantaneous corrosion rate	• The pH of fresh concrete reduces rapidly during the initial exposure period; however, corrosion rates were found to be low. • With further reduction in pH, the concrete deterioration begins and a mass loss around 24 mm is observed after 2 years. The old concrete corrodes almost at constant rate during this period. • The corrosion product layer was found to have had negligible influence on corrosion losses.

Although many researches have been done in the area of corrosion of concrete sewers and pipe lines, fewer researches were done in the area of corrosion of manholes. Many of these researches lack reliable field data and interaction between key parameters which is being considered here. The laboratory studies focused on the corrosion mechanisms related to MICC, but it is almost impossible to reproduce field environmental conditions of MICC in the lab. In the study conducted by Romanova et al., samples were collected from two manholes in Kent, UK for a period of two months to find the relation between the parameters like liquid phase pH, liquid phase and ambient temperatures and Hydrogen sulfide. Although the study concluded that the liquid phase pH values do not have a direct influence on hydrogen sulfate concentration and on average the liquid phase temperature is greater by 3.5°C than the gas temperature inside manhole, the relation of parameters humidity, Dissolved Oxygen (DO), and flow rate were not investigated. The conclusions were made from the study of 2 manholes for a period of 2 months, which is comparatively a short period of time and data. Also the study did not establish the relation of manhole categories, seasonal variations and liquid phase characteristics with the hydrogen sulfide corrosion rates.

In this study over 130 manholes in the City of Arlington, Texas, with varying manhole categories were studied over 4 seasons (fall 2017, spring 2018, summer 2018 and fall 2018) and samples and data were collected which gives us a better insight on various parameters and their contribution in the corrosion of manholes. There are several factors affecting sulfide generation, volatilization, and corrosion of concrete manholes and pipes. This study aims to enhance the understanding of the correlation between hydrogen sulfide (H_2S) concentrations and sewer environmental factors, including dissolved oxygen (DO), biochemical oxygen demand (BOD_5), temperature, and pH. In addition, the effects of seasonal variations and impact of manhole categories including the depth, slope, velocity, turbulence and drop are also studied. The study aims to determine how the corrosion rates are affected by these key environmental factors.

Chapter 3

METHODOLOGY

In this study over 130 manholes with varying manhole categories were studied. Samples and data were collected to enhance our insight about various parameters and their contribution to the corrosion concrete manholes. This study aims to enhance the understanding of the correlation between hydrogen sulfide (H_2S) concentrations and sewer environmental factors, including dissolved oxygen (DO), biochemical oxygen demand (BOD_5), temperature, and pH. In addition, the effects of seasonal variations and impact of manhole categories including the depth, slope, velocity, turbulence and drop are also studied. Finally, the impact of H_2S concentrations, along with gas-phase oxygen, relative humidity, and temperature, on MICC is investigated.

Table 3.1 shows the frequency and measurement methods for gas- and liquid-phase parameters that influence MICC rates. The wastewater characteristics in the gas phase such as temperature, relative humidity, oxygen and hydrogen sulfide were measured *in-situ* using various instruments and the liquid phase parameters like dissolved oxygen (DO), temperature, and pH were also measured in-situ. The samples for measuring the biochemical oxygen demand (BOD_5), sulfate, total and dissolved sulfide are collected from in-situ and were analyzed in the laboratory. The sewer system characteristics like slope, velocity, and turbulence were obtained from the city.

Table 3.1. Frequency and measurement methods of gas-phase and liquid-phase parameters that influence MICC rates.

Category	Specific Parameters	Measuring Instruments/ Method	Frequency of Measurement
Gas-phase	Hydrogen sulfide (H_2S) (midway between the liquid surface and the top of the manhole shaft)	OdaLog SL 50 (App-Tek International)	Continuous for 48 hours
	Relative humidity	Kestrel® DROP™	Continuous for 48 hours
	Temperature	Kestrel® DROP™	Continuous for 48 hours
	Oxygen	ToxiRAE Pro	20 minutes
Liquid-phase	Temperature	Aqua Troll/ Hanna	Continuous for 48 hours
	pH		
	Dissolved oxygen (DO)		
	Biochemical oxygen demand (BOD_5), dissolved	ISCO to collect sample/lab analysis using Standard Method 5210 B	Hourly
	Sulfide, total and dissolved	ISCO to collect sample/lab analysis EPA Method 9034-Titrimetric procedure	Hourly
	Sulfate	ISCO to collect sample/lab analysis using 10227 Spectrophotometer	Hourly
	Velocity	Obtained from city	24 hours

3.1: Equipment Used

3.1.1: OdaLog

OdaLog SL 50 (App-Tek International) is used to measure the gas-phase hydrogen sulfide concentration in the manholes. The OdaLog shown in Figure 3.1 uses an electrochemical sensor to detect levels of a specific gas in parts per million (ppm). The sensor consists of electrolyte and electrodes packaged in a small container with a diffusion barrier which the gas passes through. A subsequent chemical reaction causes current flow within the sensor to change in relation to the level of gas passing through the diffusion barrier. This current output is then interpreted within the OdaLog, displayed on the LCD (in ppm) and recorded in the OdaLog's data-logging chip. The OdaLog was placed at the midway between the liquid surface and the top of the manhole shaft and the H_2S concentration was measured every minute for 48 hours.

Figure 3-1 OdaLog

3.1.2: Kestrel® DROP™

The gas-phase parameters relative humidity and temperature inside the manhole were measured with the aid of Kestrel® DROP™. It connects wirelessly to the Kestrel® Connect App to view logged data on smart devices. In the manhole, kestrel was dropped to the midway between the liquid surface and the top of the manhole shaft for measuring the parameters every minute continuously for 48 hours. The image of the instrument is shown in Figure 3.2.

Figure 3-2: Kestrel Drop

3.1.3: ToxiRAE Pro O_2 Sensor

ToxiRAE Pro O_2 Sensor is used to determine the gas-phase oxygen concentrations in the manhole. The concentration of oxygen in manhole is usually lower than the normal concentration of oxygen at the ground surface above manhole. The depth of a manhole plays an important role; as the depth of manhole increases, the concentration of oxygen decreases. The instrument shown in Figure 3.3 is usually dropped midway of manhole depth to obtain measurement. The electrochemical sensor used in the ToxiRAE Pro has a range of 0 to 30% oxygen by volume and response time of 15 sec. Sensors embody physio-chemical processes, which slow down when cooled and speed up when heated. It can efficiently work in temperature ranging from -20° C to 50° C and pressure range of atmospheric pressure ±10%.

Figure 3-3: ToxiRAE Pro O2 Sensor

3.1.4: Aqua Troll 600 Sonde

The Aqua TROLL 600 Sonde, shown in Figure 3.4, is one of the instruments that was used to measure the liquid-phase parameters temperature, pH and dissolved oxygen. The sensors that are placed in the Aqua Troll are replaceable. Turbidity sensors, barometer, ammonium, chloride, nitrate and conductivity sensors can also be installed, replacing any of the existing sensors. The Aqua TROLL 600 connects wirelessly via Bluetooth to the VuSitu Mobile App or can connect to Win-Situ 5 Software using cable or Bluetooth.

The Aqua TROLL 600 Sonde can operate at temperatures ranging from -5 to 50° C. During sampling the instrument is immersed in water and the sensors measure the respective parameters in every 1 minute continuously for 48 hours. The data is stored and can be downloaded via an internal removable micro SD card or wirelessly via Bluetooth. Calibrations are simplified through auto detection of calibration solution and auto stabilization. Calibration frequency for pH sensors is 10 to 12 weeks, for RDO sensors is 12 months and temperature sensor is calibrated only when required by user protocol.

Figure 3-4: Aqua Troll

3.1.5: Hanna

The Hanna HI98194 meter, shown in Figure 3.5, is one of the instruments that was used to measure the liquid-phase parameters like temperature, pH and dissolved oxygen. It has a multi-sensor probe, which allows the measurement of key parameters including pH, conductivity, DO, and temperature. The sensors have color-coded caps and the sockets are identified with colored triangles, corresponding to the colors of the sensors (pH - red; EC - blue; D.O. - white). The multiparameter probe transmits readings digitally to the meter, where data points can be displayed and logged. HI98194 meter can operate at temperature ranging from -5 to 50° C. Figure3.4 shows the image of instrument. During sampling the instrument is immersed in water and the sensors measure the respective parameters in every minute continuously for 48 hours. The 6 parameters that were measured in the field included Temp. [°F], pH, mV [pH], Pressure. [atm], D.O. [%] and D.O. [mg/L].

Figure 3-5: Hanna

3.1.6: ISCO 6712 Portable Sampler

The samples for measuring the liquid phase parameters such as biochemical oxygen demand (BOD), total and dissolved sulfide and sulfate concentration are collected from the manholes using an ISCO 6712 Portable Sampler shown in Figure 3.6. The length of the tubing can be adjusted according to the depth of the manhole. The samples are collected for a duration of 48 hours. The compact sampler has 24 sampling bottles, each of volume 500 ml, and collects the sample in an orderly sequence, depending on the way it is programmed. In this study 125 ml of the sewage sample was collected every 1 hr. After installation of the auto sampler in manhole, bottles 1 and 2 will collect the samples for first 4 hours. Then the sampler handle automatically moves towards bottle 3 and 4, where the sample is collected for the next 4 hours. These samples are analyzed in laboratory for the liquid phase parameters like BOD, total and dissolved sulfide and sulfate. The samples in the odd numbed bottles are used for total and dissolved sulfide analysis and samples from even numbered bottles are used for BOD and sulfate. 5 ml of preservatives (zinc acetate and NaOH) are added to the odd numbered bottles to avoid the conversion of sulfide to sulfate after the sample collection.

Ice: Dry ice is added if the outside temperature is above 78ºF, to keep the samples cold for 48 hours. The 78ºF temperature was determined from preliminary testing of the ISCO. If the temperature is less than 78ºF, normal ice is used to keep the samples cold for 48 hours. Preliminary testing determined that a portion of the normal ice will remain unmelted after 48 hours of the temperature is 78ºF or less.

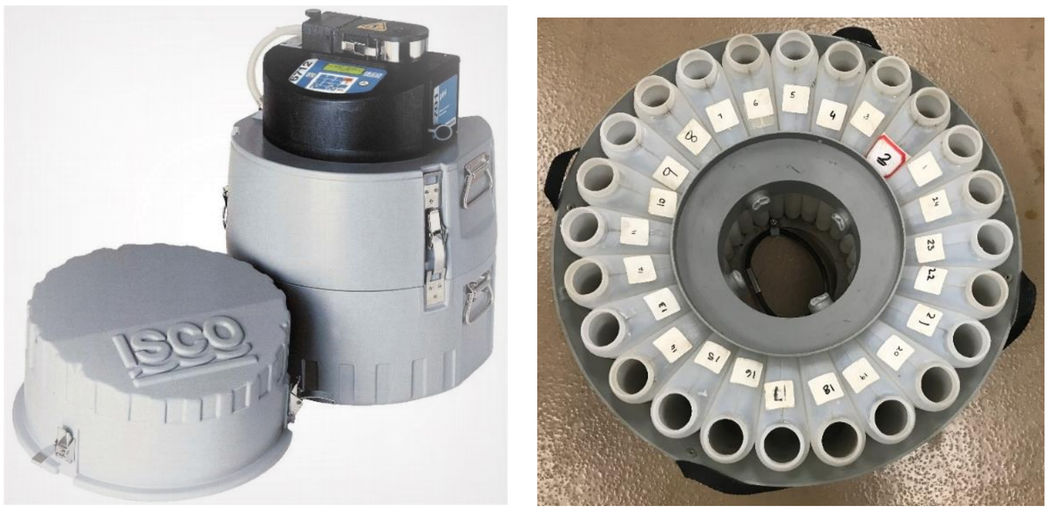


Figure 3-6: (a) ISCO,(b) Sampling bottles

3.2: Laboratory analysis

3.2.1: BOD analysis: 5210 B

The relative oxygen requirements of wastewater is determined by an empirical test having standardized laboratory procedures called the biochemical oxygen demand (BOD) test. The method consists of filling an airtight BOD bottle of specified size (300ml) with (2 ml sample and 298 ml distilled water) diluted sample to overflowing and incubating it at the specified temperature for 5 days. The BOD concentration in most wastewaters exceeds the concentration of dissolved oxygen (DO) available in an air-saturated sample. The samples contain enough organic substance to support bacterial growth. The buffer solution is added to aerated water to ensure that, the pH of the incubated sample remains in a range suitable for bacterial growth. Figure 3.7 shows the buffer solution (BOD pillow) being added to the aeration tank.

Dissolved oxygen is measured initially and after incubation, and the BOD is computed from the difference between initial and final DO. Because the initial DO is determined shortly after the dilution is made, all oxygen uptake occurring after this measurement is included in the BOD measurement. The standard method 5210 B for BOD analysis, adopted from *Standard Methods for the Examination of Water and Wastewater*, was followed in the laboratory. Figure 3.8 shows the measuring of BOD in the incubated samples.

(a) (b)

Figure 3-7 (a) Adding BOD Pillow and (b) Measuring BOD.

3.2.2: Sulfate

The sulfate in the sample is analyzed with the aid of Spectrophotometer DR2800 and Turbidimetric method 10227 using TNT 864 or TNT 865 reagent set kits. The TNT 864 reagent set kit shown in Figure 3.9 can measure the sulfate in the range of 40-150 mg/L and TNT 865 reagent set kit can measure a range of 150-900 mg/L. The samples for the analysis are collected using ISCO. The sample is filtered to remove any solid particles in it and 2 ml of the filtered sample is added to the TNT 864 vial. A spoon full of reagent A is added to the vial and the vial is capped and shaken for a minute by inverting the vial. After 30 seconds, the vial is inserted in the cell holder of Spectrophotometer DR2800 as shown in Figure 3.10. The spectrophotometer reads the barcode and shows the sulfate concentration. Sulfate ions in the sample react with barium chloride in aqueous solution in the vial and form a precipitate of barium sulfate. The resulting turbidity is measured photometrically at 890 nm on Spectrophotometer DR2800.

(a) (b)

Figure 3-8 (a) TNT vials and (b) Spectrophotometer DR 2800.

3.2.3: Sulfide

EPA Method 9034-Titrimetric procedure for acid-soluble and acid insoluble sulfides was followed to determine the sulfide concentration in the samples collected using sampling instrument ISCO. The soluble and insoluble sulfide are separated by filtrating the sample using glass filter papers. Figure 3.11(a) shows the filtration set up. The filtrate is used to measure the soluble sulfide, and solids on filter paper are used to measure insoluble sulfide in the sample. Standard titrimetric procedure is followed, and more details can be obtained from the users manuals. Figure 3.11(b) shows the titration setup. The sulfide is oxidized to sulfur by adding a known excess amount of iodine. The excess iodine is determined by titration with a standard solution of sodium thiosulfate until the blue iodine starch complex disappears. Sodium thiosulfate is used for quantitation and duplicates are done for every sample.

.

(a) (b)

Figure 3-9 (a) Filtration of sample (b) Titration of samples

Chapter 4

RESULTS AND DISCUSSION

4.1 Hourly variation of liquid and gas phase parameters

Gas phase parameters like H_2S concentration, ambient temperature, relative humidity and liquid phase parameters like pH, DO, liquid phase temperature with time were plotted for 48-60 hours to find how their concentration varied depending on time. Figures 4.1, 4.2 and 4.3 show samples of plots showing the hourly variation of the liquid and gas phase parameters in manholes. Specific observations about the figures will be made in the following sections.

Observations are made with the assumption that during the early hours in the morning (5 am – 10 am), the wastewater generated contains urine, feces, water and toilet paper from toilet flushing and the water from showers containing soap or toiletry products which are generally high in organic content, and the flow is generally high. During the day time (11 am - 6 pm), when people are mostly in schools and offices, the generation and flow of sewage in pipe line is moderate or low. During this time period, the wastewater with higher sulfate content from toiletry products and proteins generated at households is now in the municipal sewer system. Around 6-8 pm, the temperature is still warm, and people are back from offices. Around 7-8 pm, the generation of wastewater might start increasing as household activities like cooking, using washing machines and dish washers, showers, baths, sinks will be resumed. The increased flow will lead to turbulence, which causes stripping of H_2S gas from the wastewater. Thus, the concentration of H_2S gas increases after 10 pm.

Human lifestyle is expected to influence the generation of sewage from the residential areas. For example, in an area where the residents tend to cook more food at home, the chances of more food waste entering the sewage stream through sinks are higher. Similarly, if more people tends to wash hair during nights, sulfide-containing shampoo and other toiletry products will enter the stream during night time rather than during day time.

H09MH0072

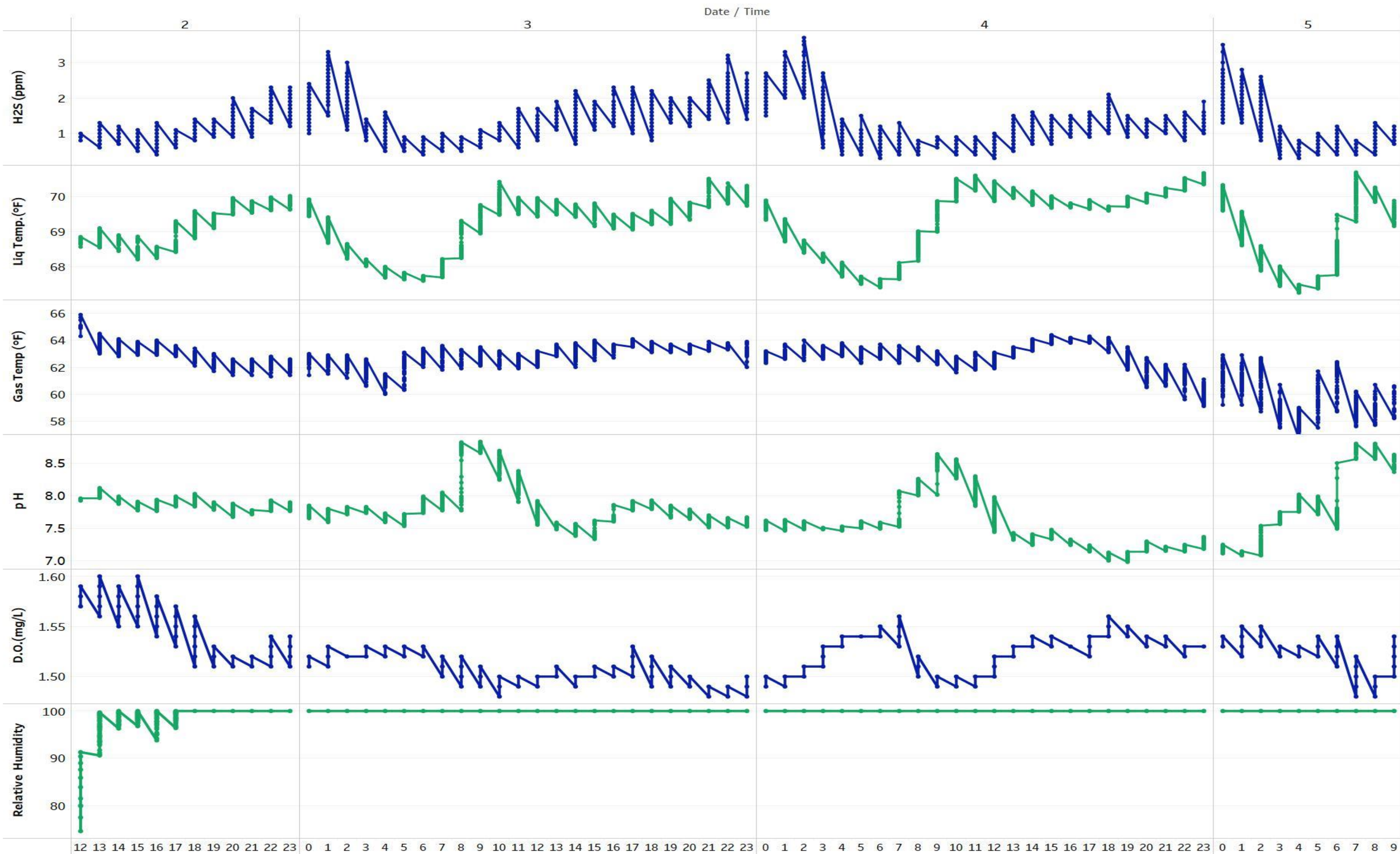


Figure 4-1: Hourly variation of liquid- and gas-phase parameters of manhole H09MH0072

J08MH0181

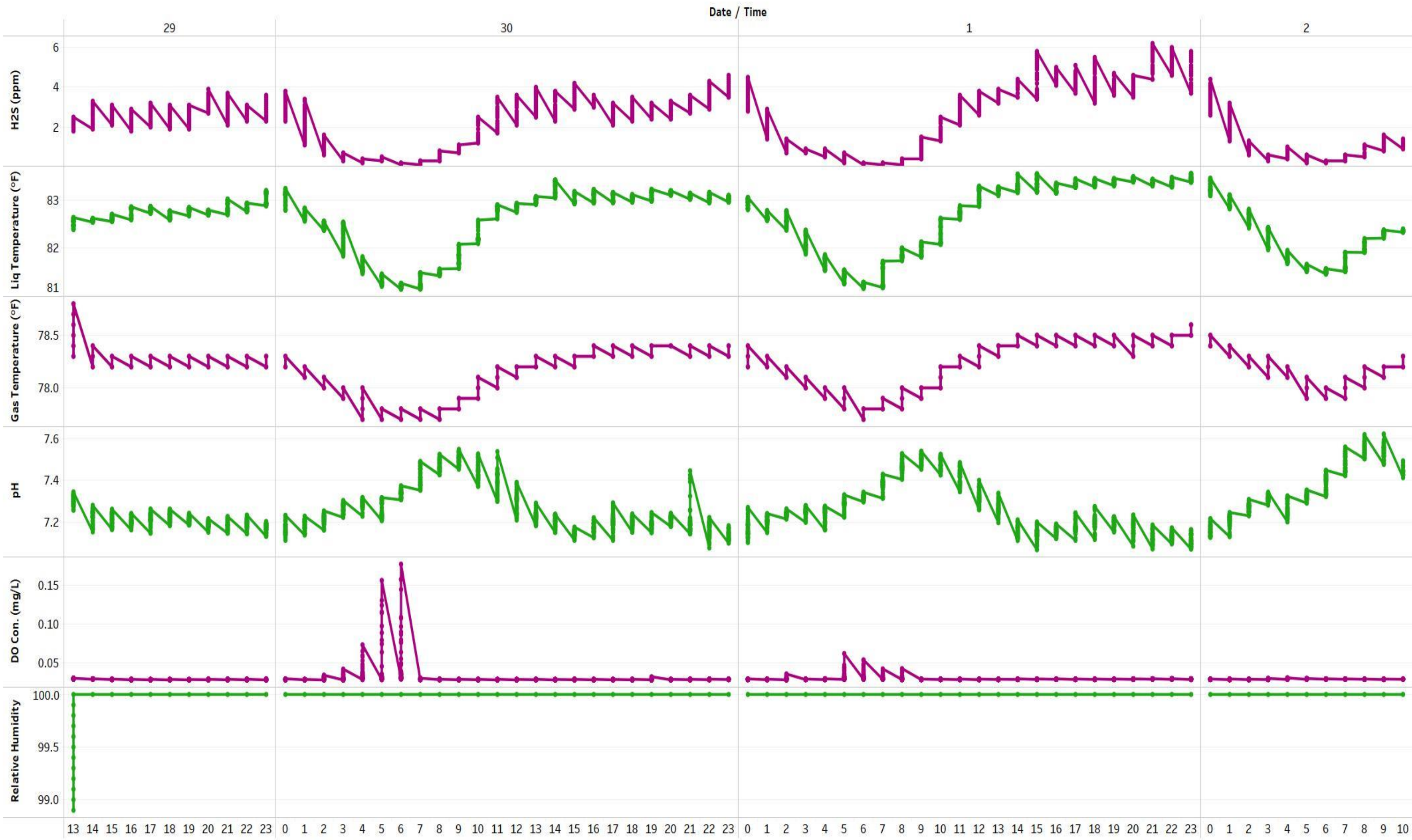


Figure 4-2: Hourly variation of liquid- and gas-phase parameters of manhole J08MH0181

I08MH0180

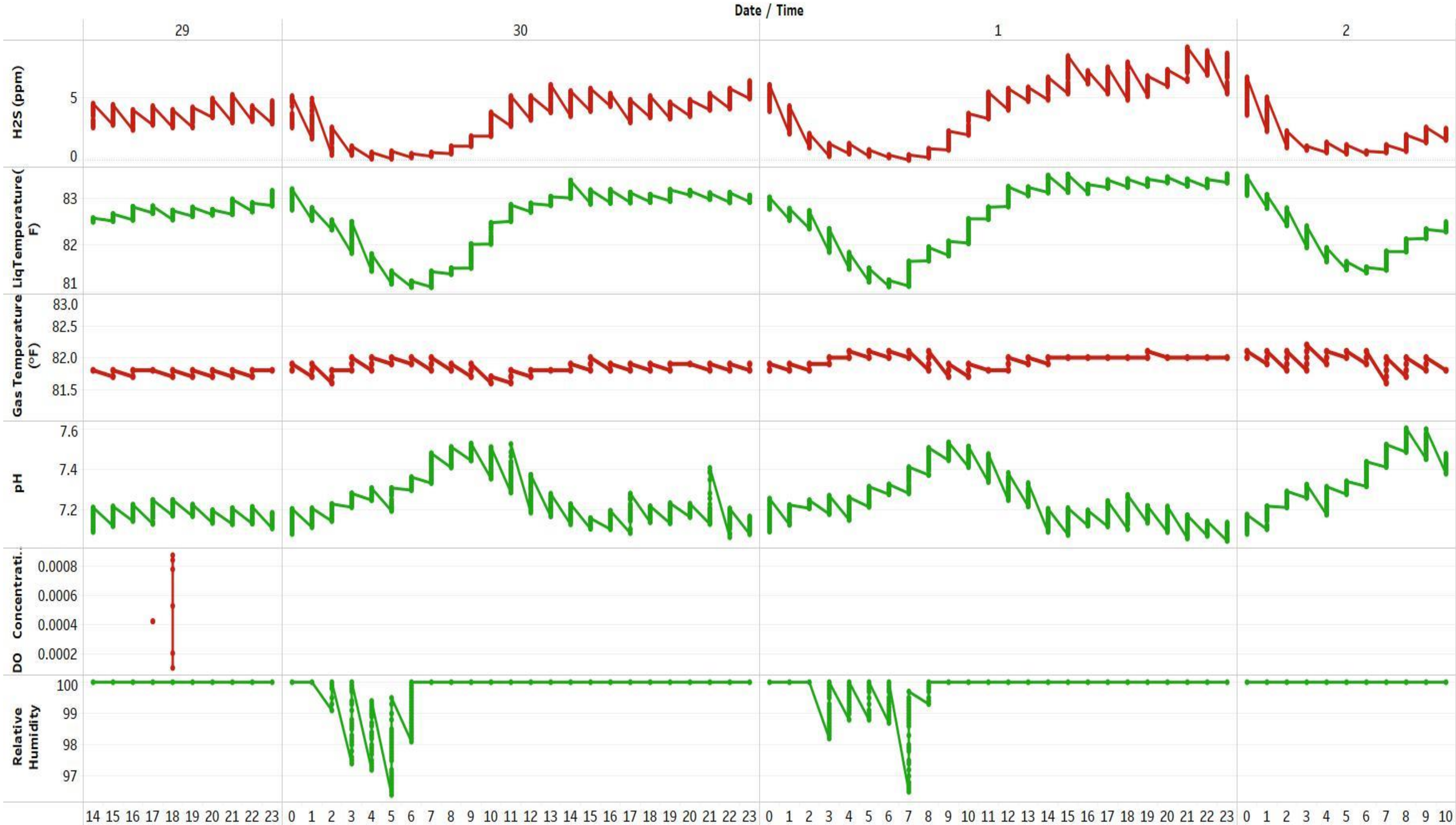
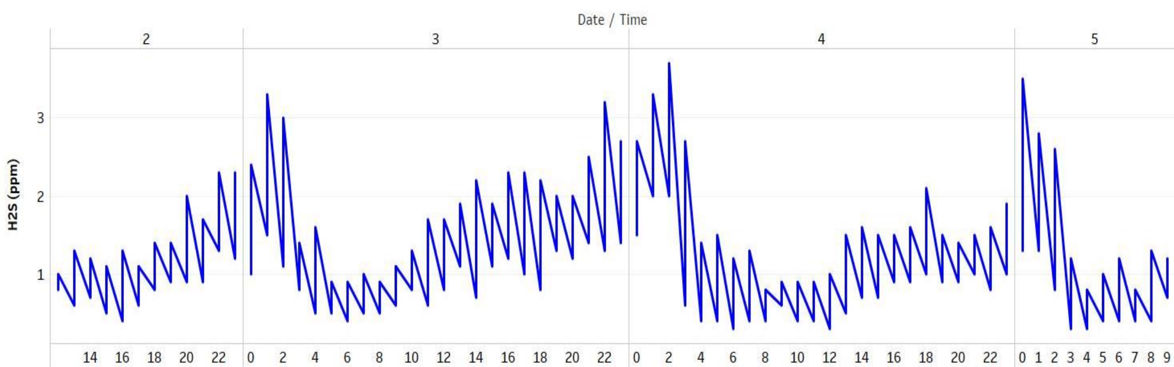


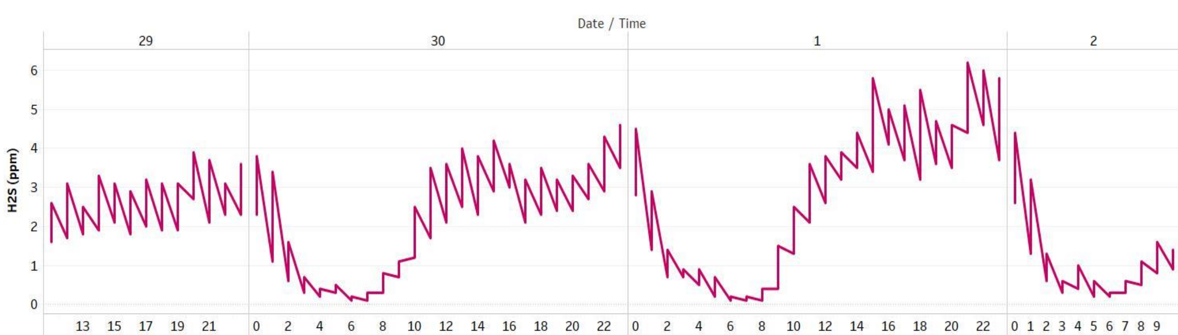
Figure 4-3: Hourly variation of liquid- and gas-phase parameters of manhole I08MH0180

4.1.1: H_2S concentration

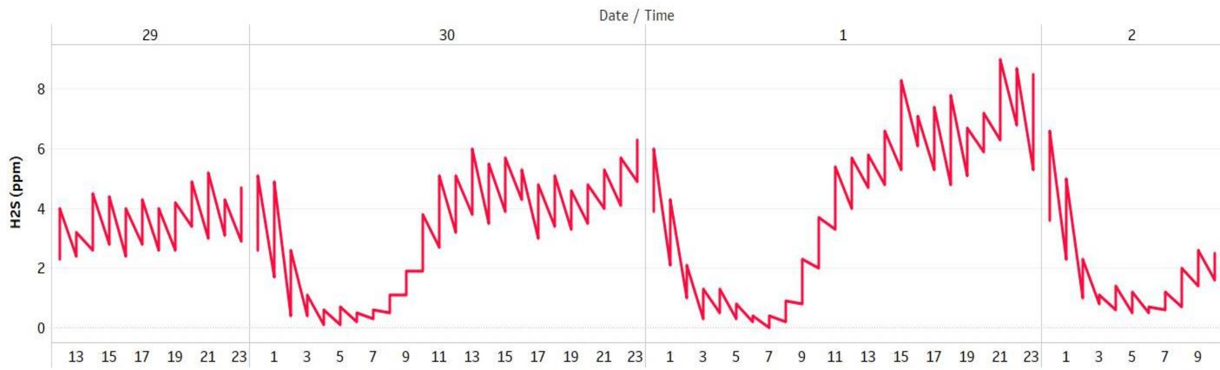
Figure 4.4 shows hourly variations of H_2S in the 3 manholes for which data was shown in the previous section. In the manholes studied, the concentration of H_2S gas was typically found to be least during the early hours of the day (2 am - 10 am), with the least H_2S concentration measured during 8-9 am. This is observed in Figure 4.4(a), (b) and (c) as the trough in the plots and the trend is repeated on all days, during which the measurements were taken. During 2-6 am, the household activities and sewage generation is bare minimum, generating less flow through the sanitary sewer pipelines. Lower flow velocity leads to lower turbulence, which might increase the organic solid deposition in the pipelines enhancing the growth of sulfate reducing bacteria. However, in the early hours of the day, the available organic and sulfate content in the liquid phase is extremely low, which reduces the chances of sulfide generation in liquid phase. Also due to lower turbulence, the volatilization of available H_2S in liquid phase to gas phase will be minimized. This is likely the reason for observing low H_2S gas concentration during 2-6 am.



(a)



(b)



(C)

Figure 4-4 Hourly variation of H_2S gas in manholes (a) H09MH0072 (b) J08MH0181 (c) I08MH0180

Figure 4.5 shows plot of flow velocity vs time for 3 sample manholes. During 6-10 am, the flow through the sewer pipeline is maximum due to increased household activities. Sulfate which is naturally present in domestic water enters the sanitary sewer system, along with human excreta and sulfur containing soap or toiletry products during this period. Anaerobic conditions are essential for the bacteria to reduce sulfate and generate sulfide, which will then form H_2S. However, the flow velocity is found to increase during this time period, according to modeled velocity data provided by the City of Arlington, as shown in Figure 4.5. As the velocity increases, turbulence and reaeration rate increases. As the DO increases, the rate of generation of sulfide in the liquid phase decreases, leading to reduced concentration of H_2S gas in the manholes. The low ambient temperature during 2-10 am is likely also a factor causing the low concentration of H_2S gas.

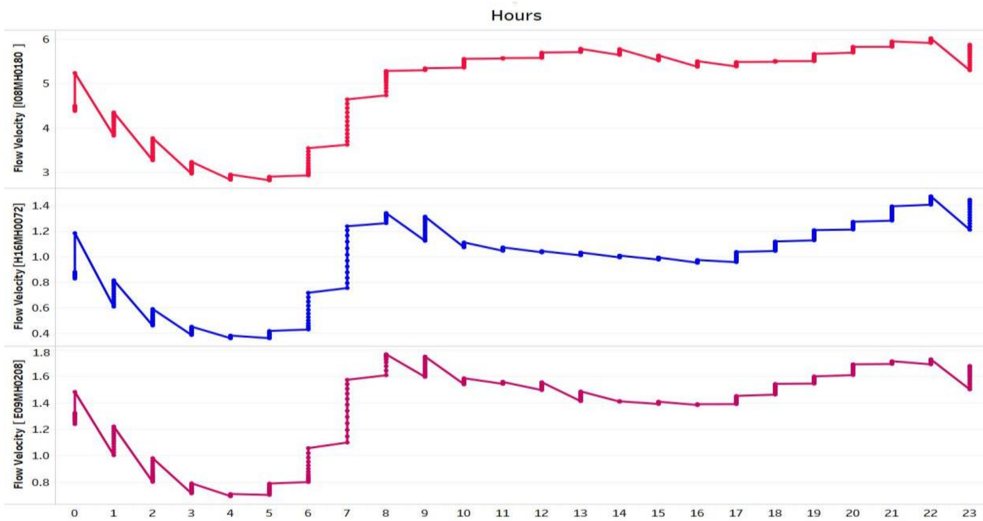
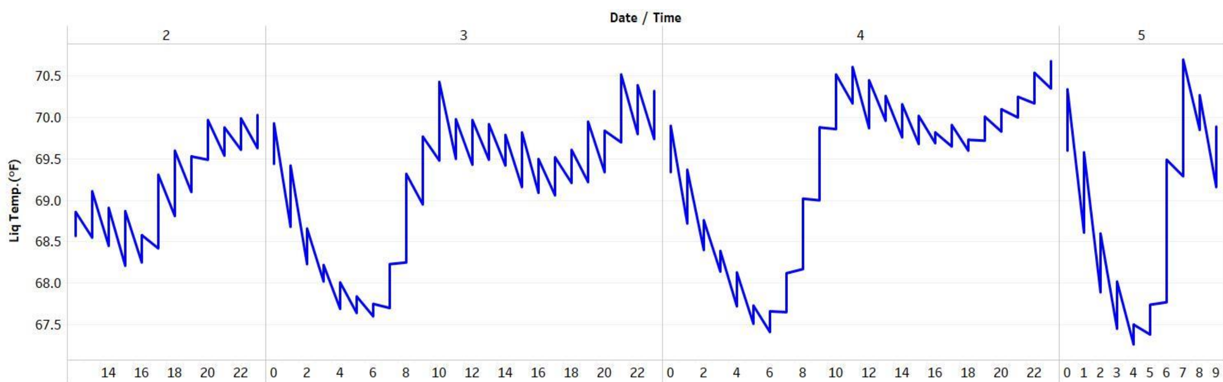


Figure 4-5: Hourly variation of flow velocity

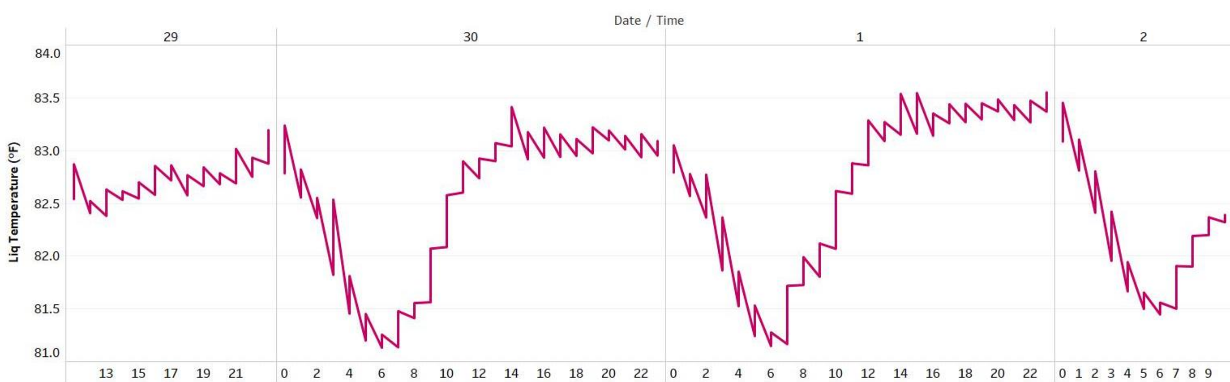
The concentration of H_2S gas in the manholes studied was found to peak during the final hours of the day and early mornings (8 pm - 1 am). The liquid phase concentration of sulfide is maximum around this period, according to lab analyses. This could be because the moderate or low flow in sewer system during the day time (11 am- 6 pm) increases the retention time of grit and organic solid waste which have entered the system during the early hours of the day. The lower flow velocity also creates low turbulence, leading to lower reaeration rates in the waste water in sewer pipelines. The limited reaeration in the wastewater will lead to lower DO in the system. Lower velocity allows the growth of a thick slime layer, where the anaerobic bacteria reside (Grengg et al., 2015). The temperature remaining the highest during this period of the day and low concentration of DO in sewage water causes the anaerobic bacteria to utilize the oxygen from sulfate and oxidize the organic matter, generating higher concentration of H_2S in liquid phase. Volatilization of H_2S might be taking place during this time due to decreased pH, but the rate of volatilization is found to be lower due to reduced turbulence. As the household activities resume, the flow increases around 7-8 pm. Increased flow velocity increases the turbulence, which leads to stripping of the H_2S in liquid phase to gas phase. This is likely the reason of the increased concentration of H_2S gas in the sewer atmosphere after 8 pm. The general trend is repeated in almost all manholes studied, in all the days the measurements were taken.

4.1.2: Liquid phase temperature

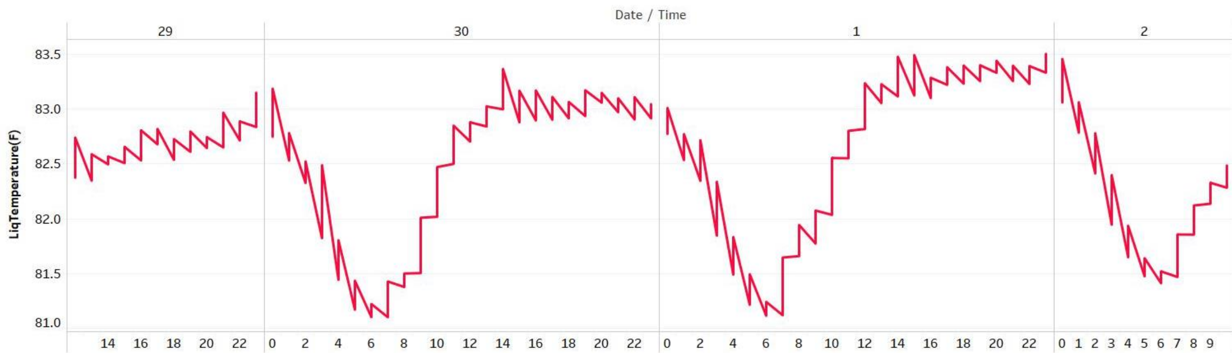
Figure 4.6 shows the hourly variation in liquid phase temperature for the 3 manholes for which data was shown earlier in Section 4.1. The liquid phase temperature or liquid phase temperature generally follows an hourly trend similar to that of H_2S concentration. The liquid phase temperature is found to have a declining trend during 2-6 am. This could typically be because of the reduced water usage in the houses due to reduced household activities during this time period. A lower volume of wastewater will have a higher surface area-to-volume ratio and will cool more quickly. This could also be affected by the air temperature outside the manhole, which is generally the lowest temperature experienced during a day.



(a)



(b)



(c)

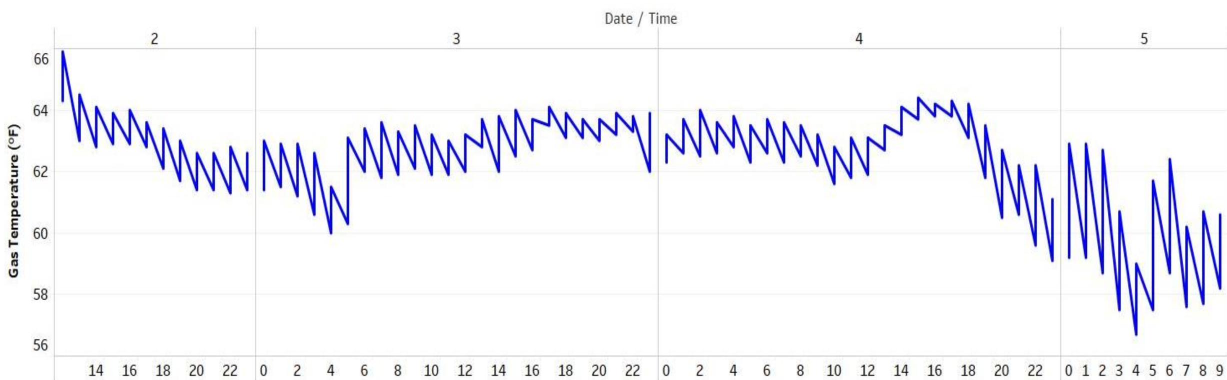
Figure 4-6 Hourly variation of liquid phase temperature in manholes (a) H09MH0072 (b) J08MH0181 (c) I08MH0180

The liquid phase temperature is found to follow an increasing trend after 6 am and found to peak around 11 am. In Figure 4.6 (a, b and c) the graph trends to rise after 6 am. The increased use of warm water during the morning for bathing and other daily ablutions might be the reason of increased eff luent temperature during this period. The liquid phase temperature is found to continue the increased levels even after 11am. Although the water usage reduces after 10 am, the increase in external temperature might be a reason for the elevated liquid phase temperature during 11 am – 6 pm. The increased microbial activity in the anaerobic conditions in sewer system generates exothermic reactions, resulting in increased liquid phase temperature.

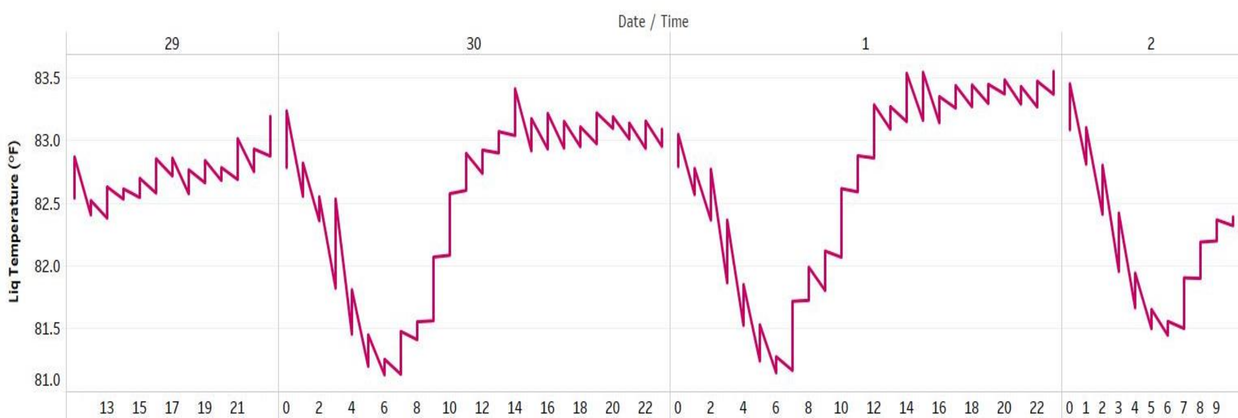
After 6 pm, though the temperature outside the manhole reduces, increased warm water usage in households helps in keeping the elevated liquid phase temperature. The generation of H_2S gas is exothermic. As the H_2S gas generation is found to increase after 10 pm, the increase in the liquid phase temperature after 10 pm can be justified.

4.1.3: Gas temperature

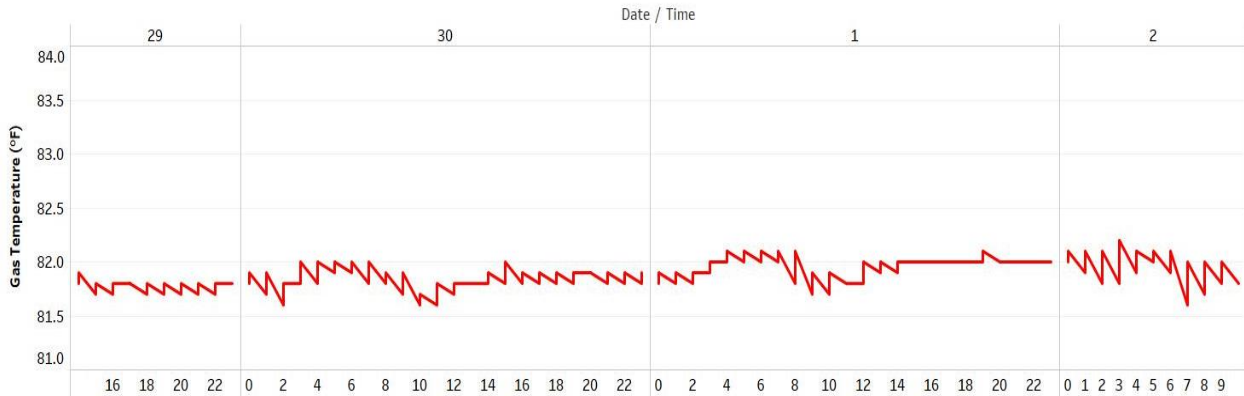
Figure 4.7 shows the hourly variation in gas temperature for the 3 manholes for which data was shown earlier in Section 4.1. It is observed that the gas temperature is lower than the liquid phase temperature in all the cases studied. H09MH0072 was measured during spring, when the temperature was lower, while J08MH0181 and I08MH0180 were measured during summer. Though the gas temperature was found to be least during 2-6 am, a significant decline is not observed in manhole H09MH0072. The gas temperature of manhole H09MH0072 could have a greater influence of ambient temperature as the depth of manhole is 12 feet, which means that the point of measurement of gas temperature was only 6 feet below the ground surface. It was surprising to not see significant changes in gas temperature in manhole I08MH0180 as seen in manhole J08MH0181 which were both of more than 21 feet depth. The gas temperature increased after 8 am and was found to peak around 12 pm, when the ambient temperature was also high. The gas temperature stayed almost stagnant till 12 am, and then showed a decline, as shown by the liquid phase temperature discussed in Section 4.1.2.



(a)



(b)

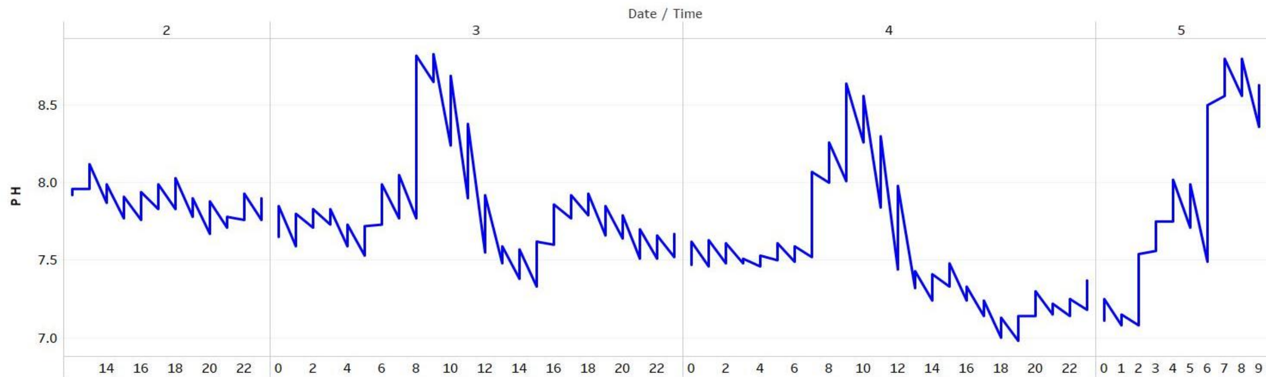


(c)

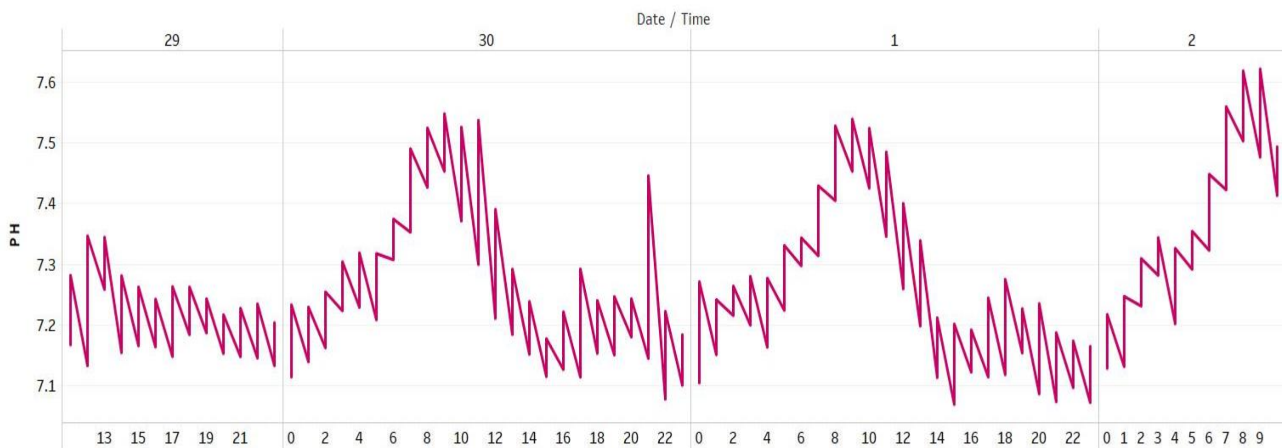
Figure 4-7 Hourly variation of gas temperature in manholes (a) H09MH0072 (b) J08MH0181 (c) I08MH0180

4.1.4: Liquid phase pH

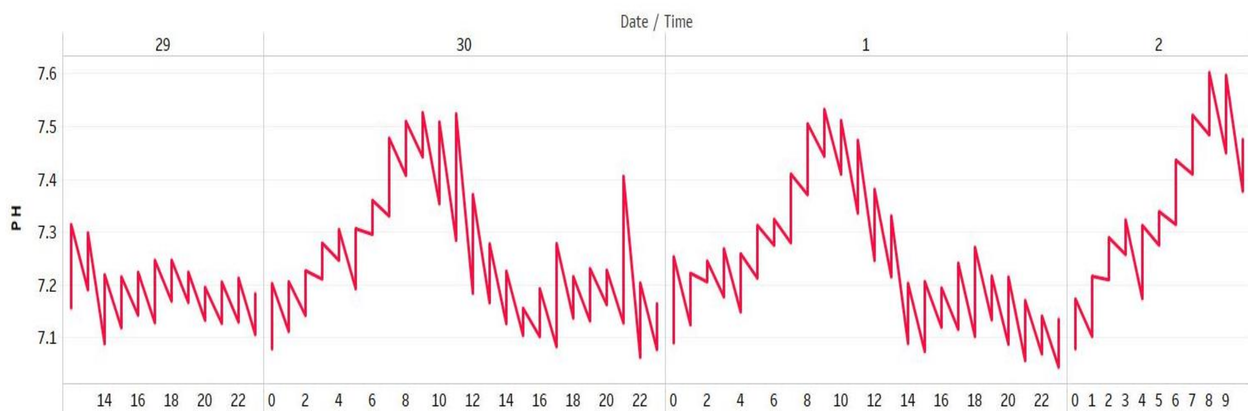
From the Figure 4.8(a, b and c) showing the hourly variation of pH for the 3 manholes for which data was shown earlier in Section 4.1, it is observed that pH varies inversely with the other parameters like H_2S concentration and liquid phase temperature. The pH of the fresh sewage is in the range 5.5 to 8.0, which is slightly more than the pH of water supplied to the community(Characteristics Of Sewage And Overview of Treatment Methods, 2019). This is thought to be because of the copious amounts of fats carried in the sanitary sewage water. Fecal pH is generally found to be neutral, with a median value of pH 6.6 and a range of mean pH values of 5.3–7.5. The pH of fresh urine is largely neutral with a median of pH 6.2, with a range of mean pH values of 5.5-7.0 (Rose et al., 2015). In our study the pH of the liquid phase varied within the range of 6.0 – 8.5, the maximum value observed during 5-9 am. This might typically be due to the increased use of toiletry products for daily ablutions and increased flow of sanitary waste in the sewer system during this period. The toiletry products like soaps and body wash are generally alkaline, varying from 8 to 13 depending on the brands. pH is found to follow a decreasing trend after 9 am, and when the sewage generation remains low during 11 am – 6 pm, the pH remains almost constant in that lower pH value. This is thought to be influenced by the decomposition of organic matter in the sewer system, which may lower the pH due to anaerobic reactions that form acids.



(a)



(b)

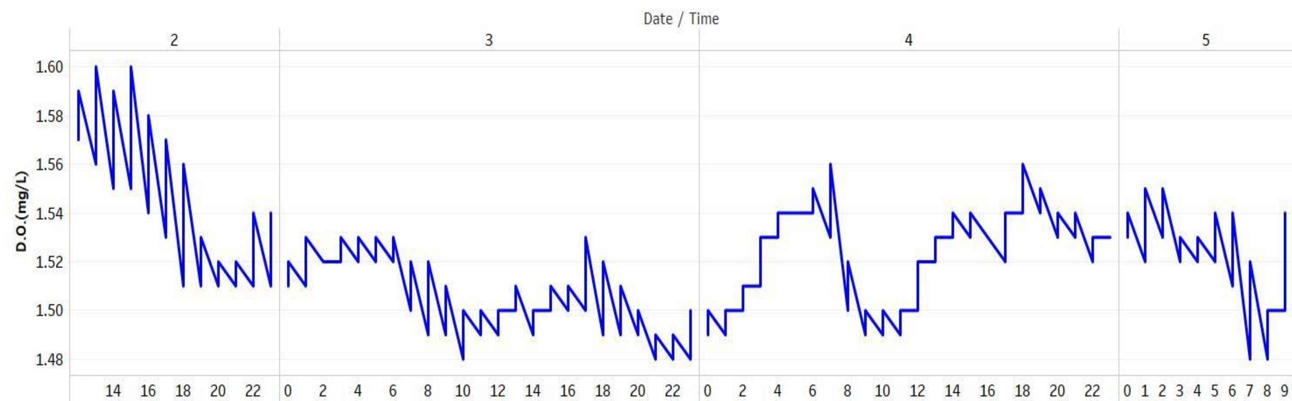


(c)

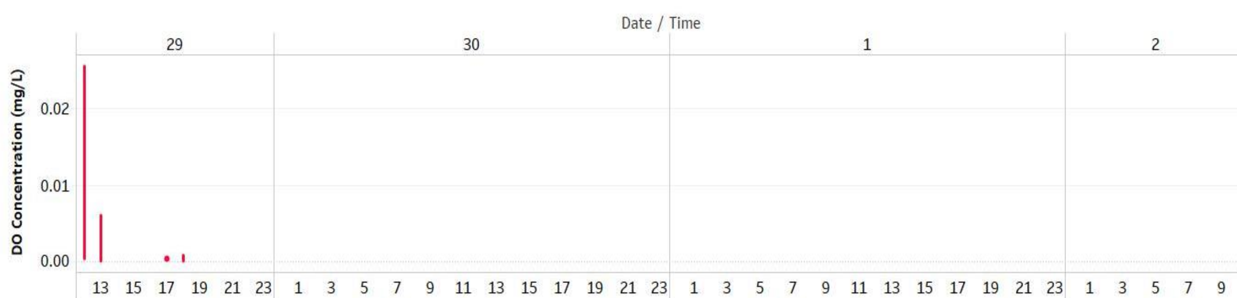
Figure 4-8: Hourly variation of pH in manholes (a) H09MH0072 (b) J08MH0181 (c) I08MH0180

4.1.5: Dissolved Oxygen

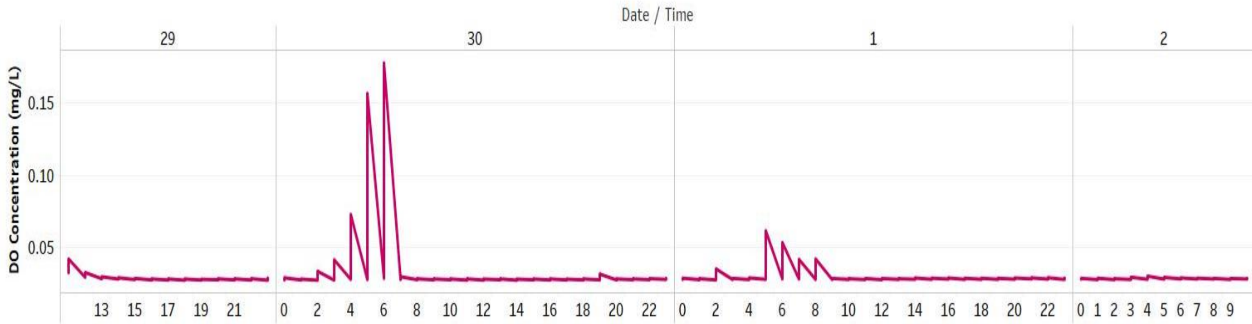
Figure 4.9 shows the hourly variation in dissolved oxygen concentration for the 3 manholes for which data was shown earlier in Section 4.1. The hourly variation of the DO in the wastewater is found to follow an inverse trend compared to that shown by H_2S concentration and liquid phase temperature. When the flow in the sewer system is found to increase, the DO shows a rise in level, whereas when the flow rate is lower, the DO level is remains lower. From observing the hourly trend, the DO concentration is comparatively higher during (2 am - 10 am), with the peak around 6-7 am. The higher flow velocity of wastewater might have led to higher reaeration rates in the sewage, which causes increased DO in wastewater. According to Henry's law, the solubility of gas decreases as temperature increases. So, at higher temperature, the DO concentration is expected to be lower, if no reaeration occurs due to increased flow velocity or turbulence. In some manholes the DO level remained almost zero during some period during the day and in some manholes the DO measurements were not recorded. This might be because the DO level was too low for the instrument to detect.



(a)



(b)



(c)

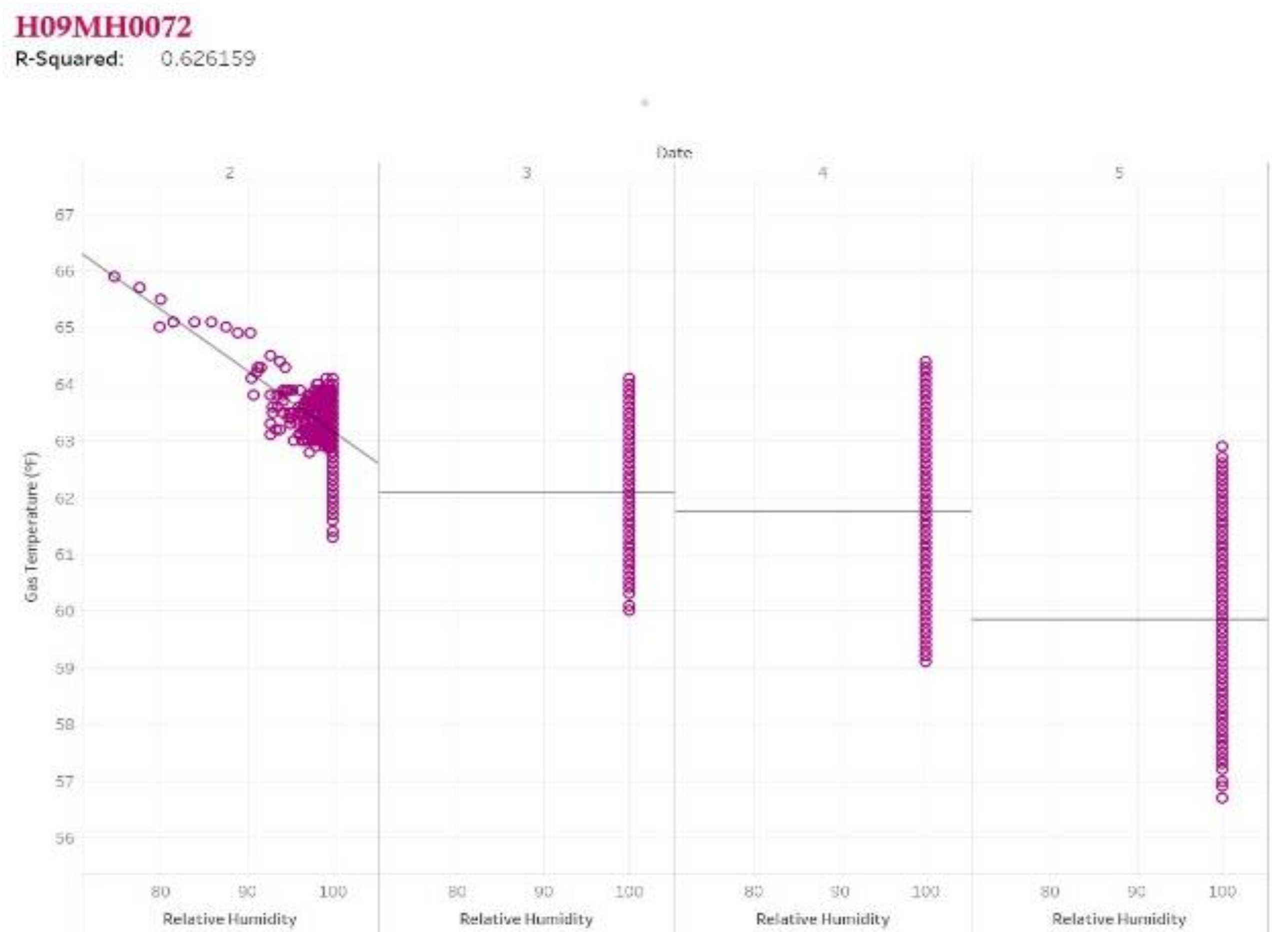
Figure 4-9: Hourly variation of DO in manholes (a) H09MH0072 (b) J08MH0181 (c) I08MH0180

4.1.6: Relative Humidity

As per USEPA, relative humidity greater than 80% leads to sulfuric acid formation and corrosion of concrete pipes (EPA, 1991). Figures 4.10 to 4.14 show the trends obtained by plotting relative humidity vs. gas temperature for each day's monitored hours. Trends are shown for the 3 manholes discussed in 4.1 above, as well as for two additional manholes that showed different trends.

In the initial hours after the installation of instruments in manhole, reflected in the data for the first day, the relative humidity recorded in the instruments was usually low, and then increased as the time passed. This is expected to be the result of interaction and mixing of air inside manhole with the air above the manhole, when the manhole lid was removed for the installation of equipment inside the manhole. During the first day (left-most plot in each series in Fig. 4.10 (a) to (e), the expected trend of an increase in relative humidity with decrease in temperature is shown (warm air can hold more water vapor than cool air; when the temperature rises, the relative humidity falls if no moisture is added to air).

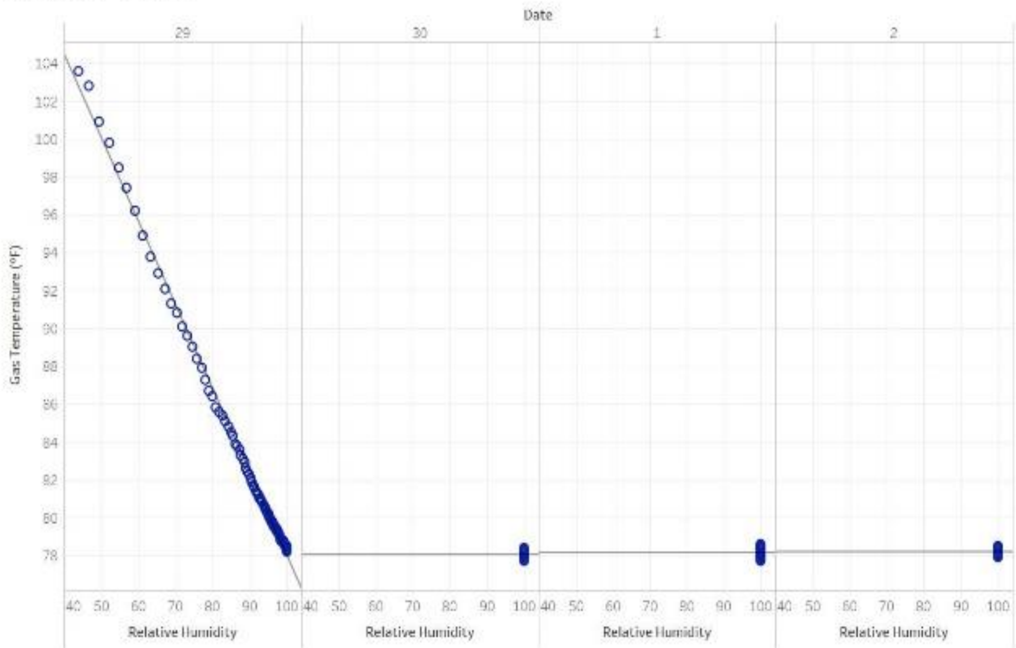
For subsequent days 2, 3 and 4, the relative humidity remained at 100% during most of the time. In the second plot from the left on Fig. 4.10 (b), the relative humidity actually increased with an increase in temperature. This might be because of addition of moisture into the air due to evaporation inside manhole. In Figure 4.10 (c), we can see that in all 4 days of sampling, the relative humidity decreased as temperature increased. The trend obtained is in compliance with our expected trend. Though the manhole was measure in summer, when the evaporation rates are higher, the relative humidity was found to fall. This could be related to the manhole category and depth of manhole. The manhole H10MH0004 does not have drops, which could reduce the amount of moisture content mixing with the air. Also, when the manhole is deep (~ 40’), the measurements taken by instrument which is dropped at the midway of manhole depth might not be affected by the moisture. This could possibly be the reason for such a trend.



(a)

J08MH0181

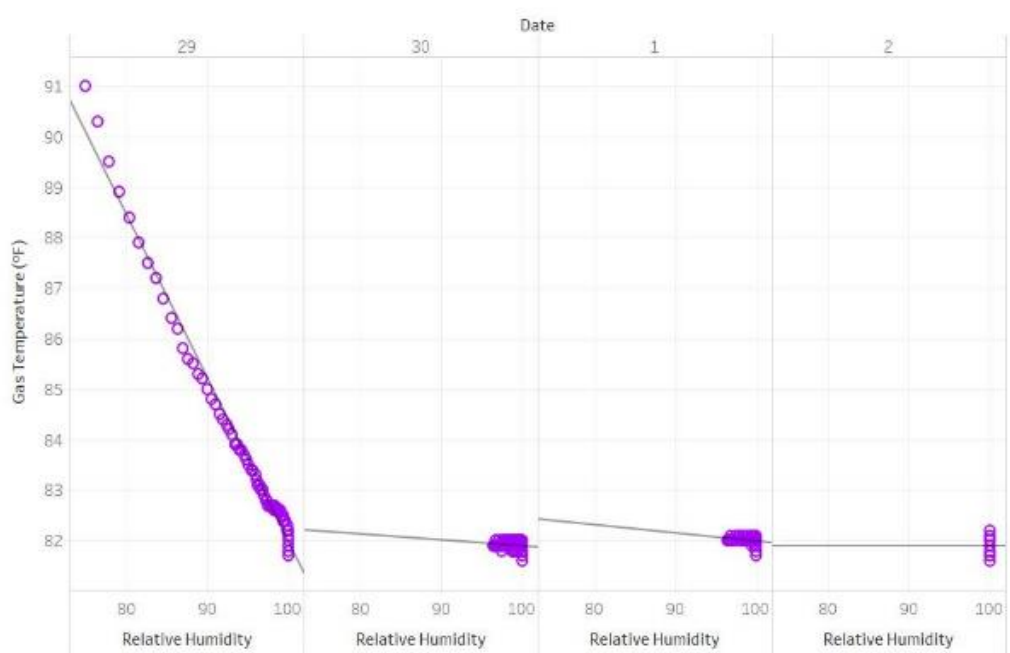
R-Squared: 0.99734



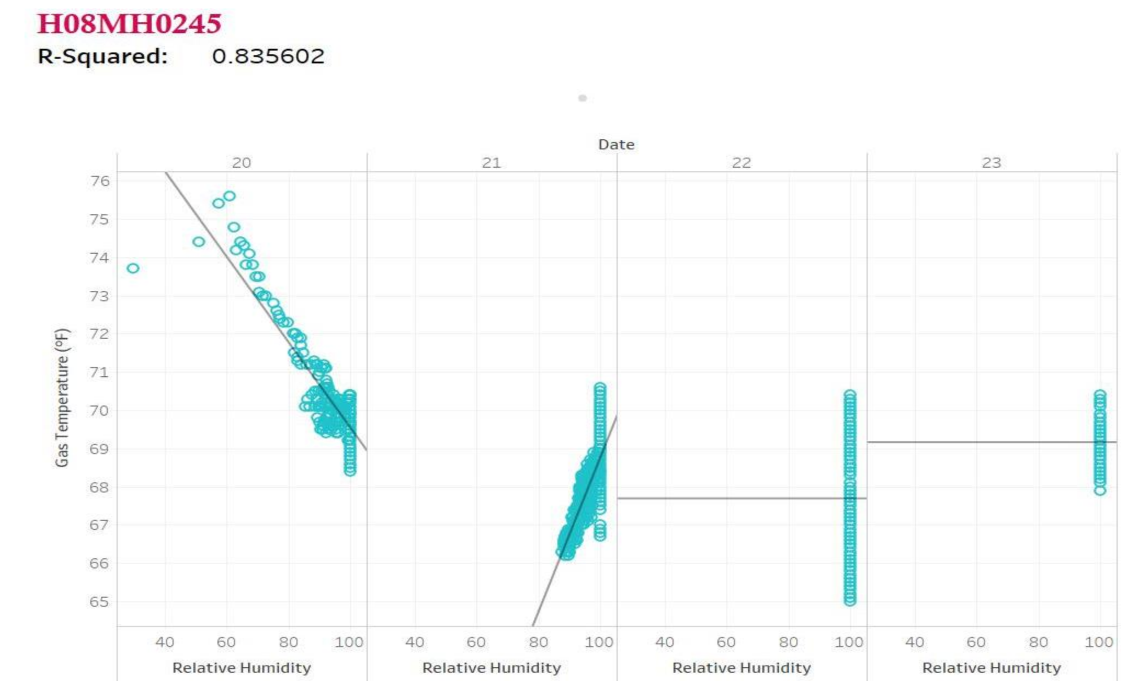
(b)

I08MH0180

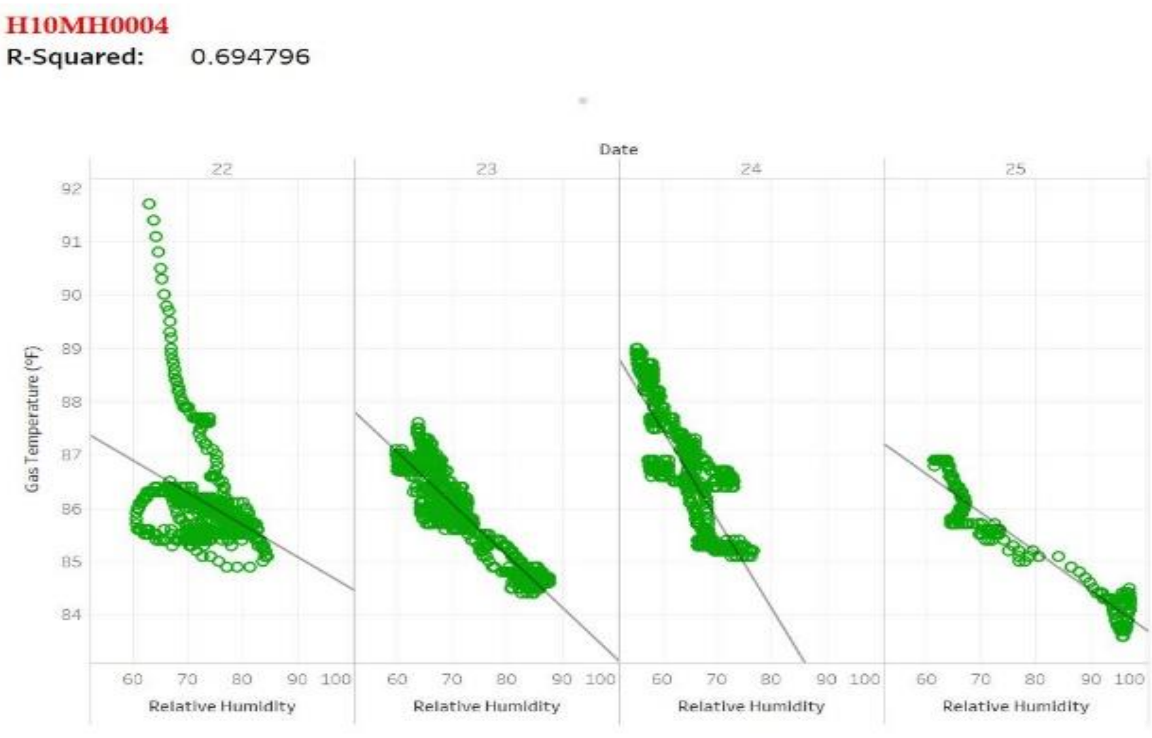
R-Squared: 0.990971



(c)



(d)



(e)

Figure 4-10: Relative humidity vs gas temperature (a) H09MH0072 (b) J08MH0181 (c) I08MH0180 (d) sample plot 1 (e) sample plot 2

4.2: Manhole category and average H_2S concentration

Manholes can be categorized based on their features like drop height, type of flow, number of inlets, presence of bends. The hydrogen sulfide concentration in manholes are also found to be affected by these features. The average H_2S concentration in over 130 manholes of various manhole categories are plotted in Figure 4.13. Each category is discussed in more detail below.

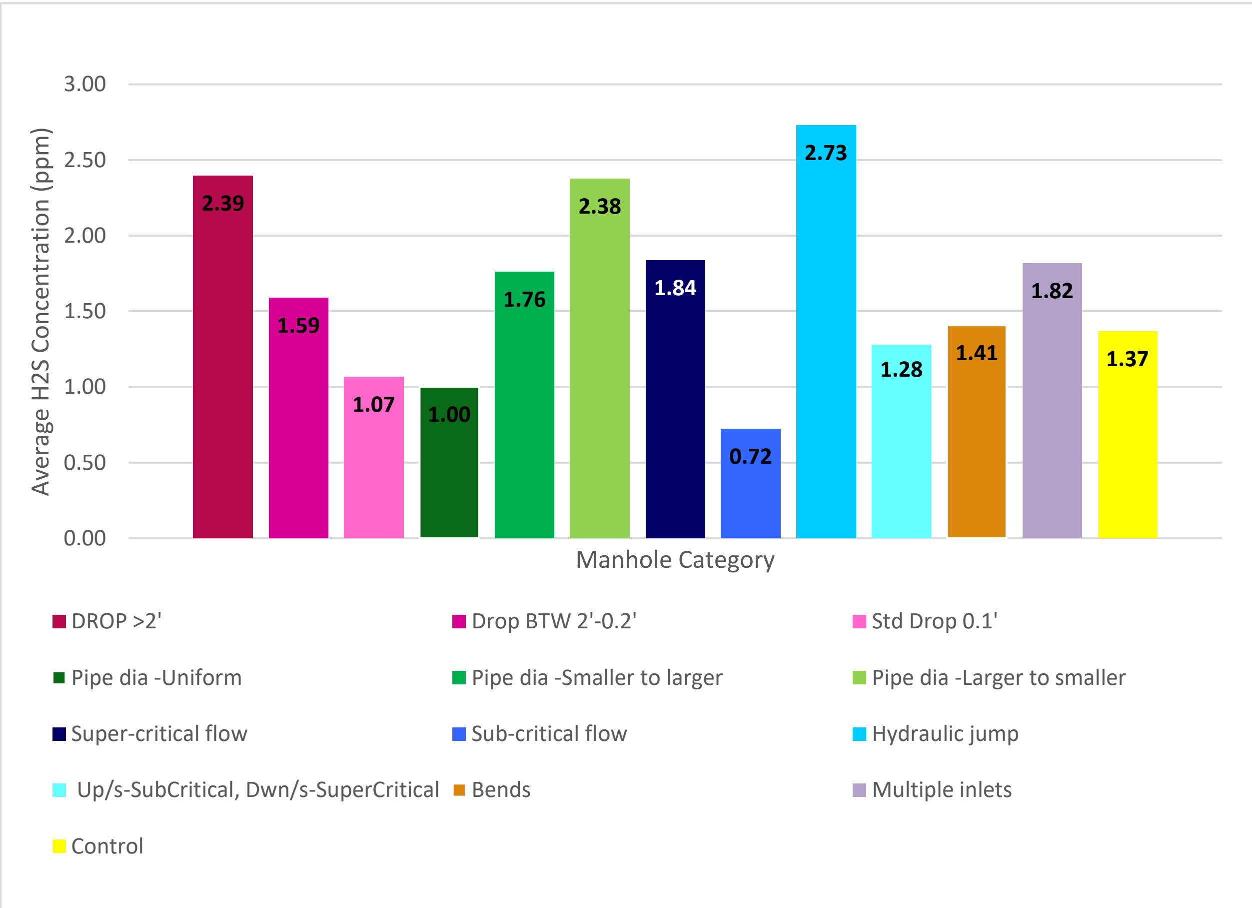


Figure 4-11: Average H_2S concentration for various categories of manholes

4.2.1: Drop

The drop structures are used in sewer system to guide the flow from a shallow sewer pipeline to a deeper sewer pipeline through a vertical shaft. The sewage water is allowed to fall freely by gravity, to the deeper pipeline, which then carries the sewage to downstream to the treatment plant. When the sewage water falls through the drop, air in the manhole mixes with the water, which increases the DO level in water. The turbulence created during the fall also leads to stripping of H_2S from liquid to gas phase. Figure 4.14 shows the schematic diagram of stripping of H_2S gas in manhole due to drop >2'.

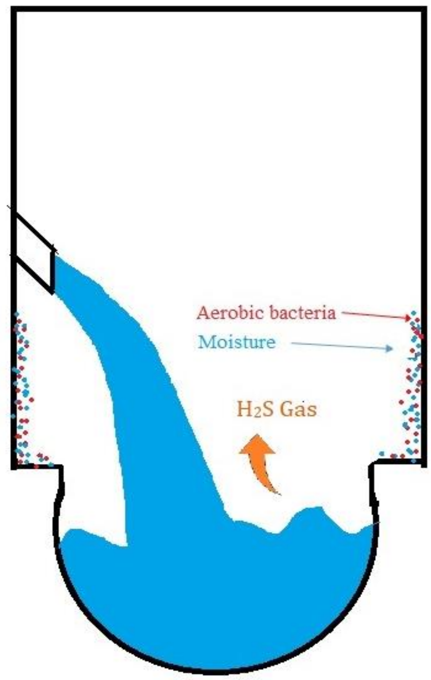


Figure 4-12: Stripping of H_2S gas in manhole due to drop >2'

In the manholes studied, 3 distinct categories of drops were observed: drops >2', drops between 0.20'- 2' and standard drops of 0.1'. From Figure 4.13 (drops shown in red, orange, and pink), it is observed that the average H_2S concentration is the highest in manholes with drops greater than 2'. The concentration of H_2S demonstrates a declining trend as the height of drop decreases. This is due to the decrease in volatilization of H_2S from liquid to gas phase as the turbulence decreased proportional to the decrease in height of drop.

4.2.2: Pipe Diameter

When designing a sanitary sewer system, the diameter of sewer pipe is selected in such a way to obtain a flow velocity sufficient to minimize the settling of grit and organic solids in the pipelines. Depending on the diameter of the upstream and downstream pipes, 3 different categories are seen surrounding manholes: uniform diameter, diameter changing from small to larger, and diameter changing from larger to smaller size. From Figure 4.13 (different pipe diameter categories shown in green), it is observed that the manholes with uniform diameter in upstream and downstream pipe line have the lowest average H_2S concentration (1 ppm) among the 3 categorical manholes based on diameter. This is because the disturbance is least in the manhole as the pipe diameter remains uniform, creating the least amount of turbulence. When the pipe diameter changes from larger to smaller, the flow area decreases and the velocity of liquid at that flow rate increases. The average H_2S concentration is the highest (2.38 ppm) for the manholes with larger pipe diameter on upstream and smaller diameter in downstream. This could be due to turbulence created when the fluid enters a smaller diameter pipe and velocity increases. The average H_2S concentration was found to be intermediate (1.76 ppm average), for manholes with smaller diameter pipe in upstream and larger diameter pipe downstream. When diameter changes from smaller to larger, the flow area increases and flow velocity decreases. This change creates some turbulence, but not as much as when the flow velocity increases.

4.2.3: Flow Category

In the sewer system, the sewage water is transported from the point of generation to the treatment plant through the pipelines buried with a gradient, which are designed to take advantage of gravity flow. The flow through the sewer pipe might be supercritical or subcritical depending on the slope of the pipeline. Gravity sewers are generally designed to maintain subcritical flow conditions in the pipeline so as to reduce the turbulence leading to volatilization of H_2S in sewer system. There are exceptions like natural topography and ground conditions where supercritical flow might be inevitable.

Supercritical flow is characterized by high velocity, low depth of flow, and steep bottom slope whereas subcritical flow is characterized by low velocity, high depth of flow, and small bottom slope. As shown in Fig. 4.13, the average H_2S concentration for supercritical flow was 1.84 ppm, and for subcritical flow was 0.72 ppm, much lower than supercritical flow. When the flow is supercritical, the higher velocity leads to greater stripping of H_2S from liquid to gas phase. In manhole where upstream has subcritical flow and downstream has super critical flow, the average H_2S concentration is found to be 1.28 ppm, which is intermediate between the value for subcritical flow (0.72 ppm) and supercritical flow (1.84 ppm).

A hydraulic jump is the phenomenon that occurs when a sudden change in flow from supercritical to subcritical occurs. A hydraulic jump creates high turbulence, which leads to volatilization of H_2S from liquid phase where significant concentration of sulfide is already present in waste water sewer system. As shown in Fig. 4.12 (different flow categories shown in blue), the average H_2S concentration is maximum in manholes which have a hydraulic jump.

4.2.4: Bends and Multiple Inlets

Figure 4.15 shows examples of manholes with multiple inlets (a) and bends (b). Bend structures are used in sewer pipelines when a change in direction of flow is required. The angle of bend in manholes varies depending on the direction in which pipes are laid in upstream and downstream. In our study, a wide range of bends varying from 90° to 170° was observed. In manholes which had a single inlet and outlet, guided bends were installed in places where there was a change in direction of flow. Sharp bends are source of turbulence in sewer system. In flows where a significant concentration of sulfide is already present in wastewater, turbulence can result in sulfide release, causing concrete corrosion in manholes and sewer pipelines.

(a) (b)

Figure 4-13 (a) Manhole with multiple inlets (b) Manhole with bends.

When multiple inlets are present in a manhole, flows from different inlets collide, generating higher turbulence at the point of contact. Turbulence being a cause of H_2S volatilization in sewer systems, the average H_2S concentration is higher in manholes with multiple inlets.

In Fig. 4.13, the average H_2S concentration for control category manholes is plotted to compare to the average concentration in manholes with bends and multiple inlets. The control manholes do not have drops or bends: They have uniform diameter and single inlet. The average H_2S concentration in control manholes was 1.37 ppm. When bends were present in manholes, the average H_2S concentration increased slightly to 1.41 ppm, and when multiple inlets were present in manholes, the average H_2S concentration increased to 1.81 ppm.

4.3: Relation between liquid phase temperature and gas temperature.

Figure 4.16 shows the average liquid phase temperature (liquid phase temperature) and gas phase temperature inside each of 130 manholes. The manholes are arranged according to the season in which they were measured. The average liquid phase and average gas-phase temperature calculated for various seasons are tabulated in Table 4.1. The main observations are noted below.

Table 4-1: Average liquid phase and gas-phase temperature in different seasons

Season	**Average liquid phase temperature (°F)**	**Average gas-phase temperature (°F)**	**Variation between average liquid phase and average gas-phase temperature**
Fall 2017	78.13	76.05	2.08
Spring 2018	68.15	61.90	6.25
Summer 2018	81.54	80.90	0.64
Fall 2018	78.83	76.98	1.85

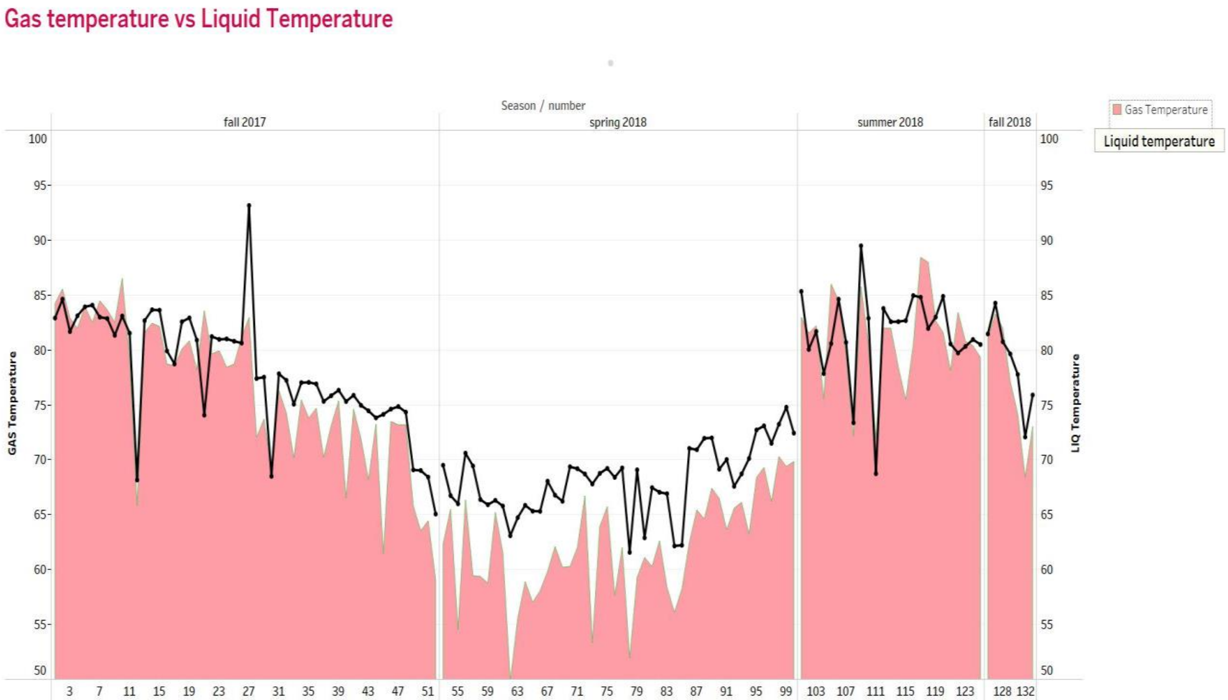


Figure 4-14: Variation of liquid phase temperature and gas phase temperature over seasons

1. In the study it was observed that the average liquid phase temperature is always greater than the gas-phase temperature inside a manhole. For the 3 seasons (spring, summer and fall), difference between the liquid phase temperature and gas-phase temperature inside manhole varies by 3° on an average. This result is similar to the findings of Romanova (2014), which found that the average liquid phase temperature was higher by 3.5°F than the gas-phase temperature for 2 manholes studied for a period of 2 months.
2. The liquid phase and gas-phase temperature were lowest during the spring season. The difference between average liquid phase and average gas-phase temperature was also maximum (6°F) during the spring season. The larger difference may be due to the colder atmospheric temperatures of air outside the manhole in spring.
3. In summer the average liquid phase and average gas-phase temperature highest among 3 seasons, and the difference between average liquid phase and average gas-phase temperature

was found to be the least (0.6°F). The higher temperature in both liquid and gas phase is due to an increased air temperature outside manhole during the summer.

4. In fall of both 2017 and 2018, the average liquid phase temperature remained 78°F and the average gas-phase temperature remained around 76°F. The variation of average liquid phase and average gas-phase temperature during fall 2017 and fall 2018 were 2.08 and 1.85, respectively. The fall 2018 had less data points compared to the fall 2017, which could potentially be a reason for the slight variations in the readings.

Figure 4.17 shows the linear relationship between gas-phase and liquid phase temperature. A linear trend was obtained for each season and for the overall data points, which had R^2 value of 0.89.

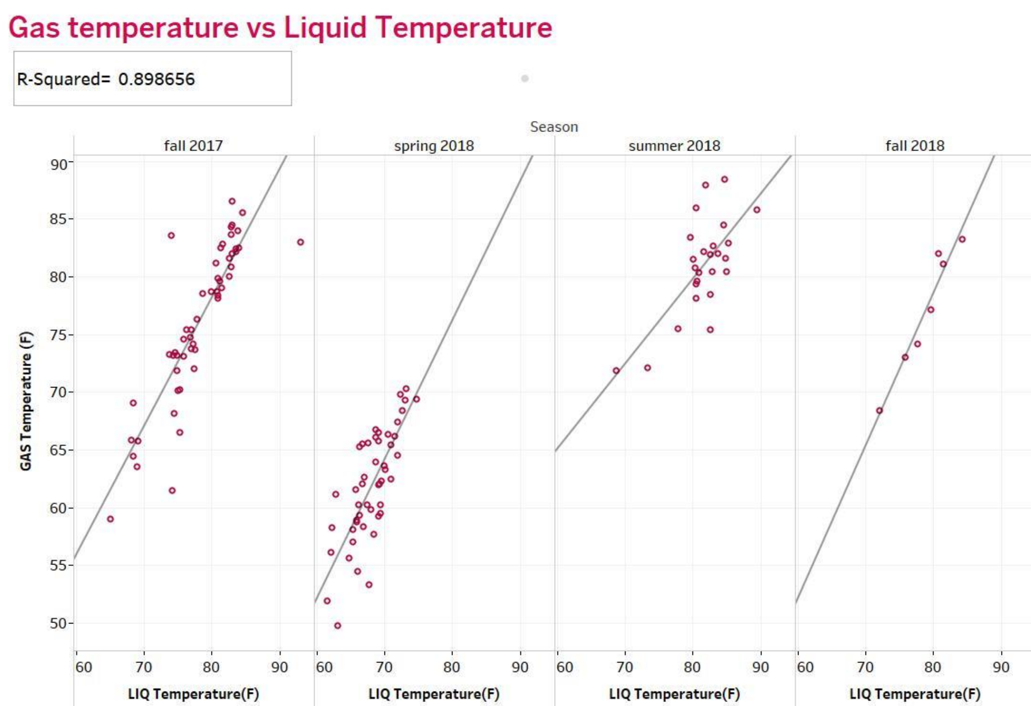


Figure 4-15: Trend line graph for liquid phase temperature and gas phase temperature

4.4: Relation between average relative humidity and gas-phase temperature

Figure 4.18 shows the average relative humidity and gas-phase temperature inside each of 130 manholes. The manholes are arranged according to the season in which they were measured. Figure 4.19 shows average relative humidity vs. gas-phase temperature for the 130 manholes, arranged according to season. There is essentially no correlation, because for most of the data, the relative humidity was measured as 100% (as discussed in Section 4.1.6).

Average Relative humidity vs Avg Gas phase temperature

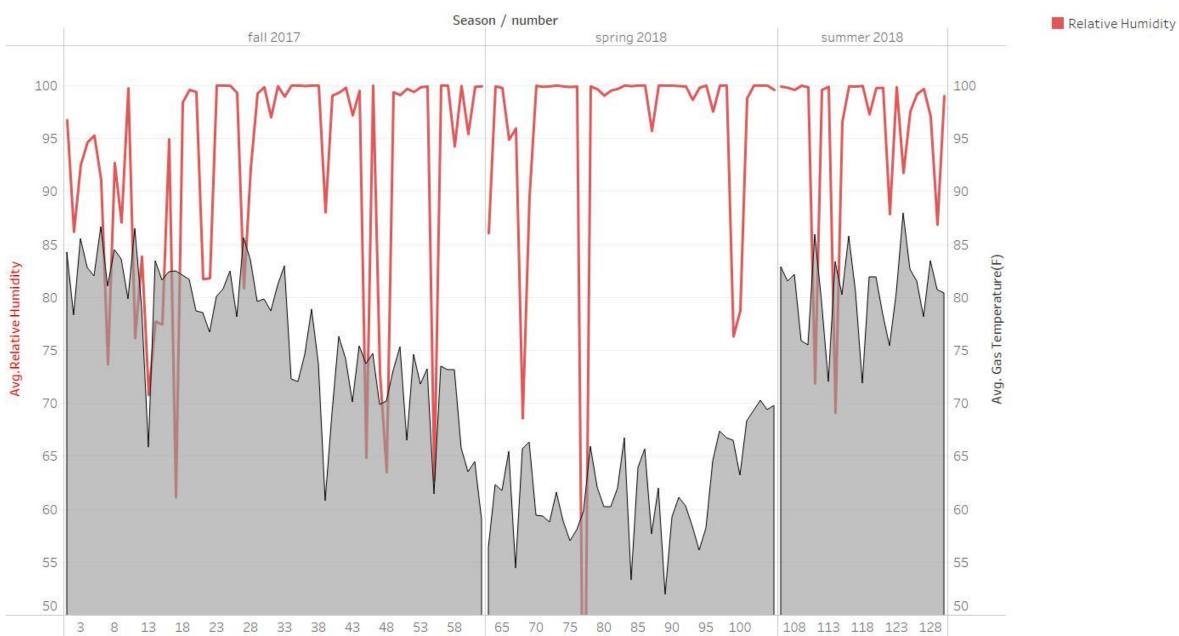


Figure 4-16: Variation of average relative humidity and gas phase temperature over seasons

Average Relative humidity vs Avg Gas phase temperature

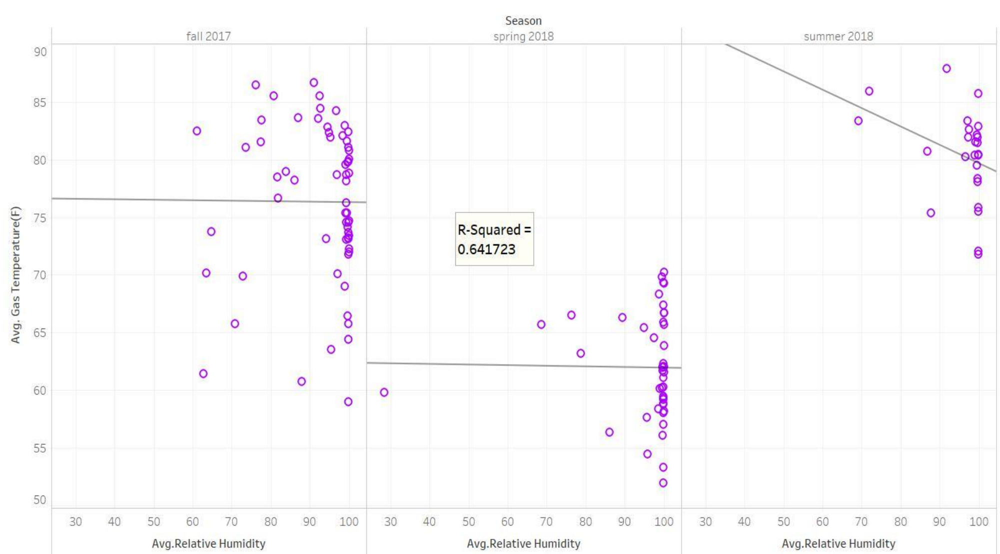


Figure 4-17: Trend line graph for average relative humidity and gas phase temperature

Table 4.2 shows the average relative humidity and average gas phase temperature measured during various seasons. Evaporation in summer is high, which adds moisture to the atmosphere in manholes. This could possibly be the reason why the relative humidity did not show much decrease in summer even when the average ambient temperature was high.

Table 4-2: Average relative humidity and average gas temperature during various seasons

Season	**Average relative humidity**	**Average gas phase temperature(°F)**
Fall 2017	92.15	76.35
Spring 2018	95.47	61.98
Summer 2018	96.77	80.27

4.5: Relation between average DO and factors affecting it

Dissolved oxygen is the amount of free gaseous oxygen dissolved in water. The amount of DO in sewage water is affected by multiple factors. Dissolved oxygen concentrations are constantly affected by diffusion, reaeration, and decomposition of organic matter in the liquid phase. To find the existence of correlation between the average DO and the factors affecting the DO levels in waste water, the data from over 130 manholes were analyzed.

4.5.1: Average liquid phase temperature and average DO in the liquid phase

Fig. 4.18 shows the average liquid phase temperature vs. the average DO concentration in the liquid phase for the 130 manholes analyzed. No correlation is observed (R^2=0.18). At higher liquid phase temperature, the average DO concentration in liquid phase is found to be lower. Despite the scattering of points in Figure 4.20, there is for all seasons a distinctive downward trend in DO with increasing gas temperature. According to Henry's law, the solubility of oxygen decreases as temperature increases. Table 4.3 shows the average DO and average liquid phase temperature during fall, spring and summer seasons.

The effects of seasonal variation can also be observed in Figure 4.20. During summer when temperature is higher, DO concentration is found to be very low (0-1 mg/L). During the fall when the temperature is slowly declining from higher to lower temperature, scattered points are observed. In the spring season when the temperature is lowest among the 3 seasons considered, the average DO concentration in liquid phase is highest.

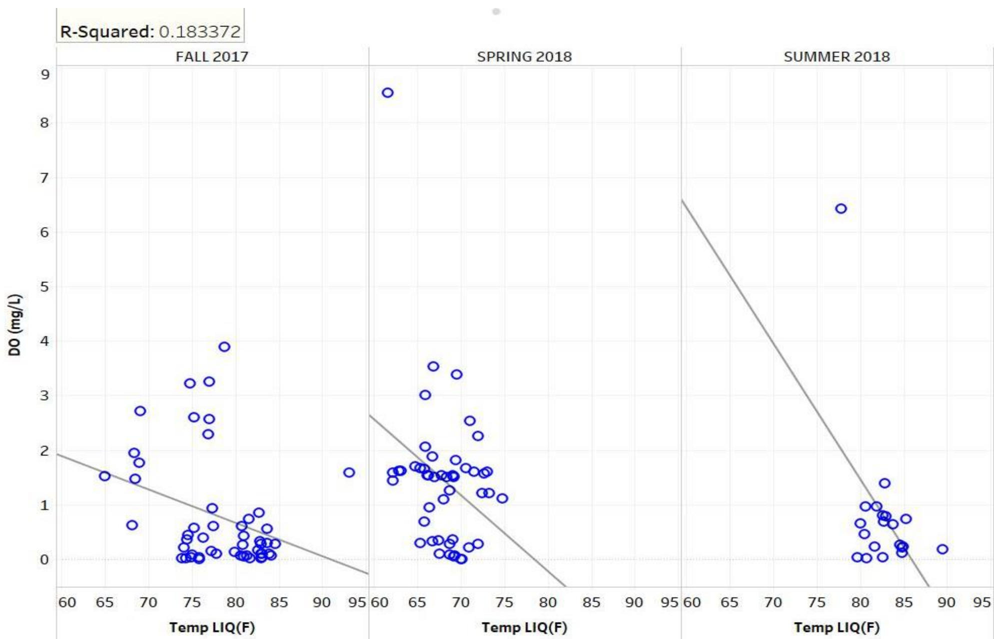


Figure 4-18: Trend line graph for liquid phase temperature and DO concentration

Table 4-3: Average DO and average liquid phase temperature during various seasons

Season	Average DO (mg/L)	Average liquid phase temperature (°F)
Fall 2017	0.91	78.1
Spring 2018	1.4	68.15
Summer 2018	0.66	81.5

4.5.2: Average gas-phase temperature and average DO in the liquid phase

Fig. 4.19 shows the average gas-phase temperature in the manhole vs. the average DO concentration in the liquid phase for the 130 manholes analyzed. No strong correlation is observed (R^2=0.19). At higher temperature the average DO concentration was found to be lower than the average DO concentration in the liquid phase when the temperature was lower. Despite the resultant scattering of points in Figure 4.19, there is a distinctive increase in DO concentration when gas temperature decreases. As the liquid phase and gas-phase temperature are found to follow a general trend (as per our result in 4.3), their relationship with DO in liquid phase also shows a similar trend.

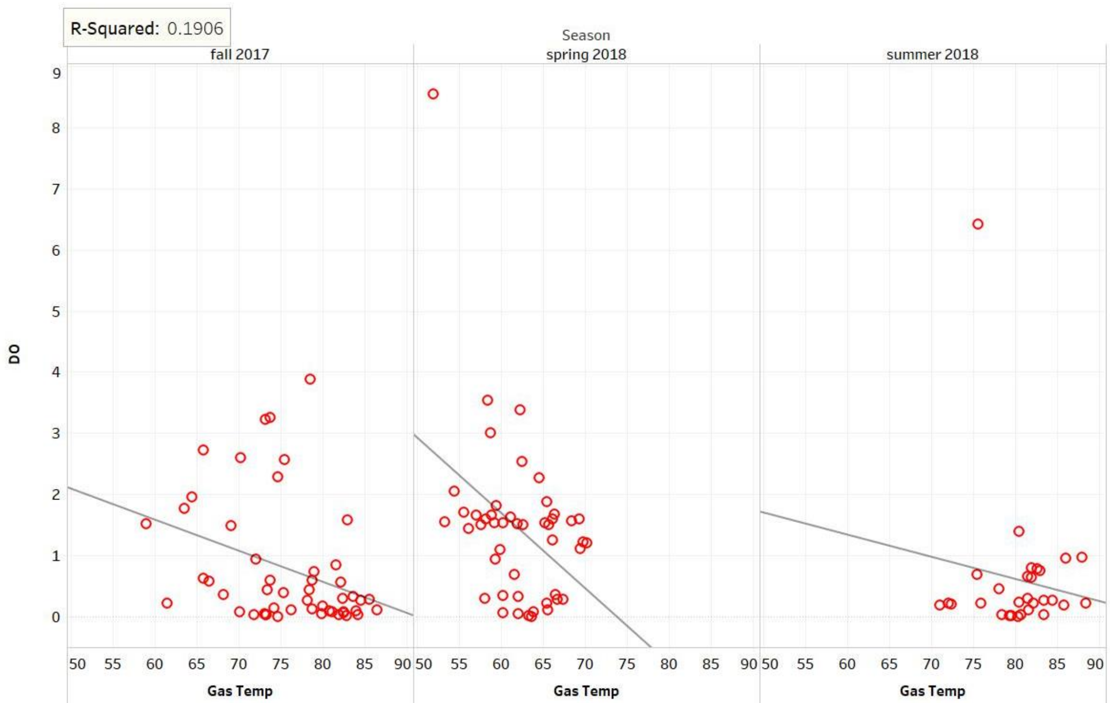


Figure 4-19: Trend line graph for Gas temperature and DO concentration

4.5.3: Relation between average DO and Average BOD

The average BOD concentration was found to be higher in fall and was found to be least in summer. High BOD, or high oxygen demand, should result in low DO concentrations. The graphs generally show this, but the correlation is very weak. This is probably due to the fact that temperature exerts more influence over DO concentration (as described in the preceding sections) than BOD. Figure 4.22 shows the trend line graph for average DO and average BOD.

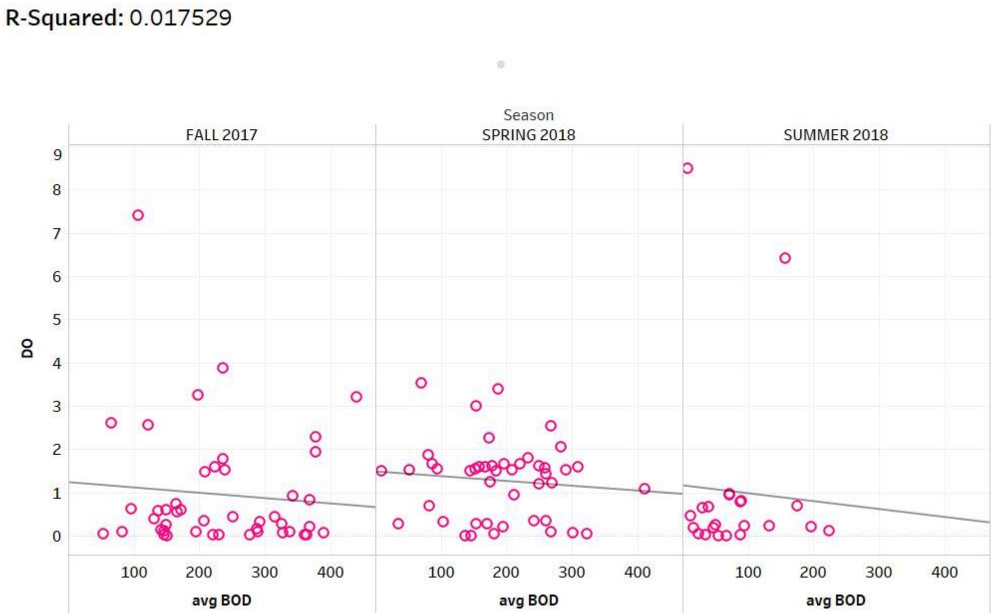


Figure 4-20: Trend line graph for average DO and average BOD

4.6: Relation between average H_2S concentration and factors affecting it

H_2S concentration inside the manhole is influenced by factors like liquid phase temperature, pH, liquid-phase sulfate, turbulence, liquid-phase sulfide, slope, and flow velocity. The factors liquid phase temperature, pH, liquid-phase sulfate, and liquid-phase sulfide were analyzed to check the existence of linear relationship between them and gas-phase H_2S. Table 4.4 shows the average H_2S concentration during various seasons.

Table 4-4: Average H_2S concentration during various seasons

Season	**Average H_2S concentration(ppm)**
fall 2017	1.40
spring 2018	1.02
summer 2018	3.94

4.6.1: Average H_2S concentration and liquid phase temperature

On plotting the hourly variation of H_2S concentration and the liquid phase temperature (Figure 4.1 - 4.3), they were found to follow the same trend with time. When the liquid temperature rises, the concentration of H_2S in the manhole was found to increase. So, it was expected to see a correlation between the average H_2S concentration and liquid phase temperature. However, as shown in Fig. 4.21, a strong correlation or trend was not obtained when H_2S was plotted vs. liquid phase temperature by season. The involvement of multiple factors in the generation of H_2S gas in the sewer system could be a reason for not seeing a correlation between these factors.

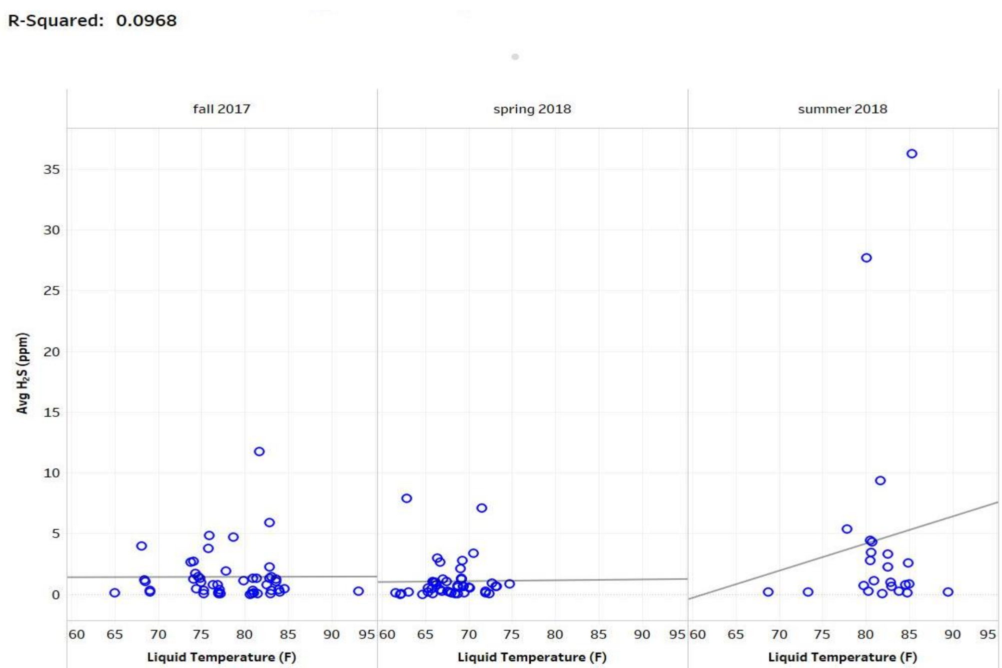


Figure 4-21: Relation between H_2S concentration and liquid phase temperature

4.6.2: Average H_2S concentration and average pH

Depending on the pH the sulfide in sewage water can dissociate into H_2S, HS^- and S^{2-}. At neutral pH the distribution is approximately 50% H_2S and 50% HS^-. When the pH drops to 6 the distribution is approximately 90% H_2S and 10% HS^-. However, a linear co-relation was not obtained between the average H_2S concentration and average pH in different seasons. Figure 4.22 shows that only in summer the expected trend was seen. Determining a linear correlation might be difficult here because of involvement of factors like DO, sulfate concentration in sewer water and microbial activity in the generation of sulfide from the sulfate in the liquid phase.

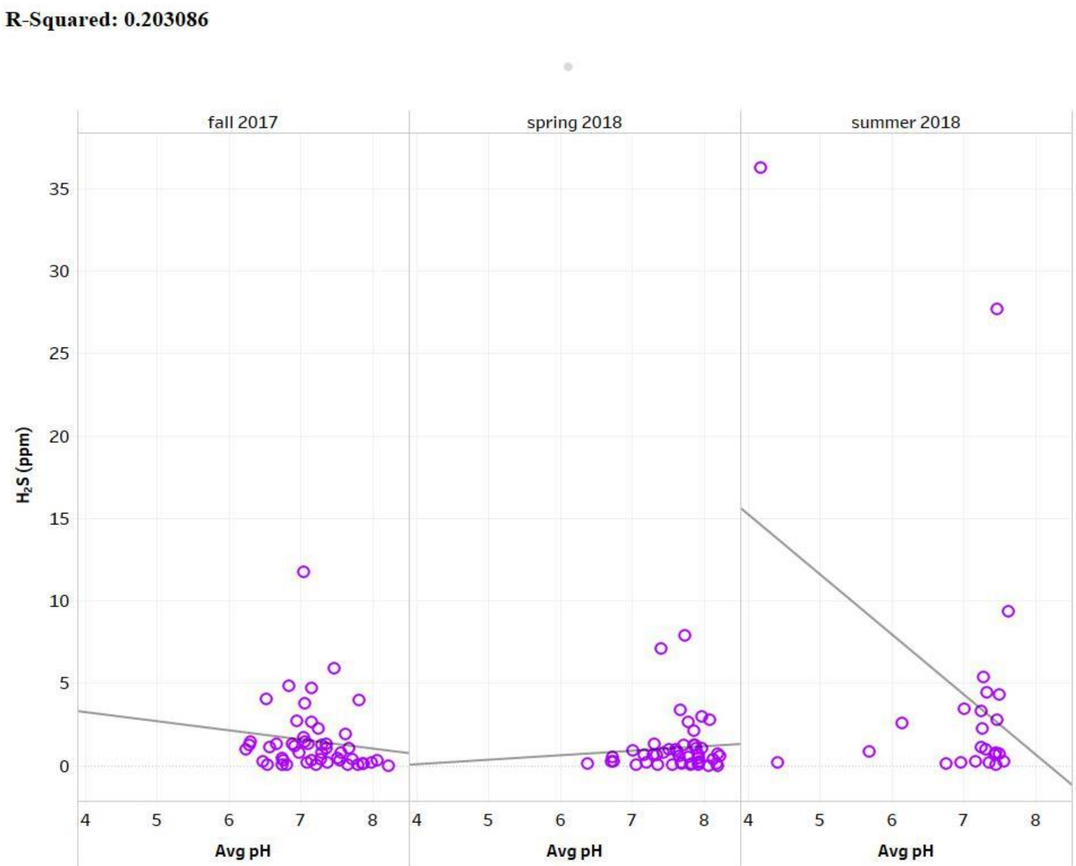


Figure 4-22: Relation between H_2S concentration and average pH

4.6.3: Average H_2S concentration and average sulfate

Figure 4.23 shows H_2S concentration vs. liquid-phase sulfate by season. When the average sulfate content is high in liquid phase, it is expected to generate more hydrogen sulfide in liquid phase. The greater the concentration of sulfate in liquid phase, the more sulfide anaerobic bacteria can generate by reducing the sulfate in the water. However, the volatilization of H_2S into the gas phase from liquid phase is dependent on multiple factors like pH, temperature, turbulence, and flow velocity. This could possibly be the reason for not seeing a correlation in Figure 4.23.

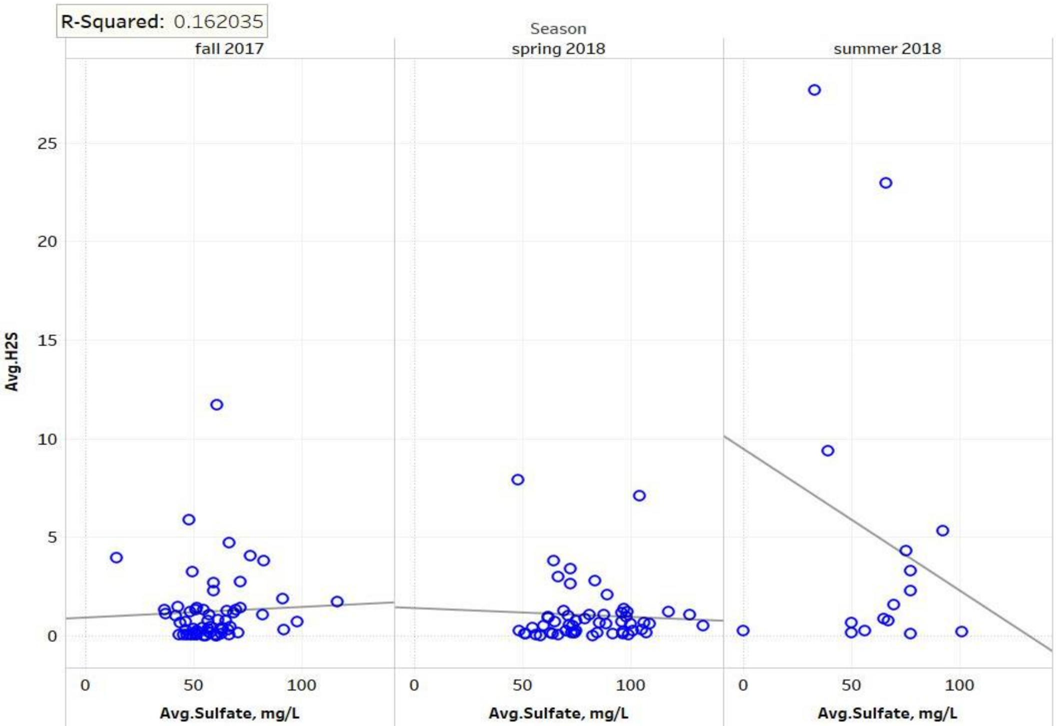


Figure 4-23: Relation between average H_2S concentration and average Sulfate in liquid

4.6.4: Average H_2S and average liquid-phase sulfide concentration

The liquid-phase sulfide concentration is another factor which influences H_2S concentration in the sewer system. The liquid-phase sulfide is volatilized into H_2S gas. Figure 4.24 shows average gas-phase H_2S concentration vs. liquid-phase sulfide. In summer the concentration of sulfide in the liquid phase is found to stay stagnant around 300 mg/L, which is lower than the sulfide concentration in fall and spring seasons. This shift could be related to the elevated temperature during summer. H_2S being poorly soluble in water, will volatilize into the headspace of the sewer based on Henry's Law, leaving behind less concentration of sulfide in liquid phase. In fall and spring, the data points are distributed as the temperature is also fluctuating during these seasons. As provided in Table 4.4, average H_2S concentration is found to be highest during the summer.

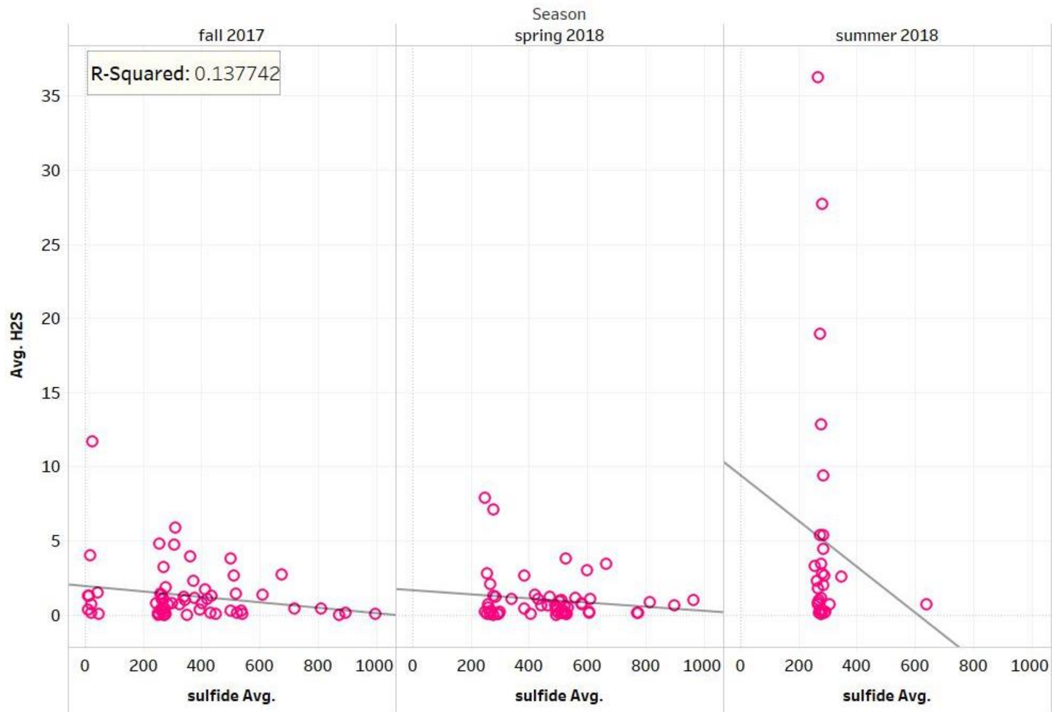


Figure 4-24: Relation between average H_2S concentration and average Sulfide in liquid

4.7: Relation between liquid-phase sulfide concentration and factors affecting it

4.7.1: Relation between average DO and average sulfide in liquid phase

Fig. 4.25 shows the average DO vs. average sulfide in the liquid phase for the 130 manholes analyzed. It would be expected that sulfide would increase as DO decreases: as DO availability decreases, bacteria start using chemically-bound oxygen in sulfate, which produces sulfide. However, Fig. 4.25 does not show this expected trend. This is probably due to the fact that factors besides DO, including wastewater sulfate concentration and liquid-phase temperature, can also influence sulfide. It may also be because chemically-bound sulfate does not begin to be used until DO reaches zero, meaning that a correlation between DO and sulfide levels would not be observed.

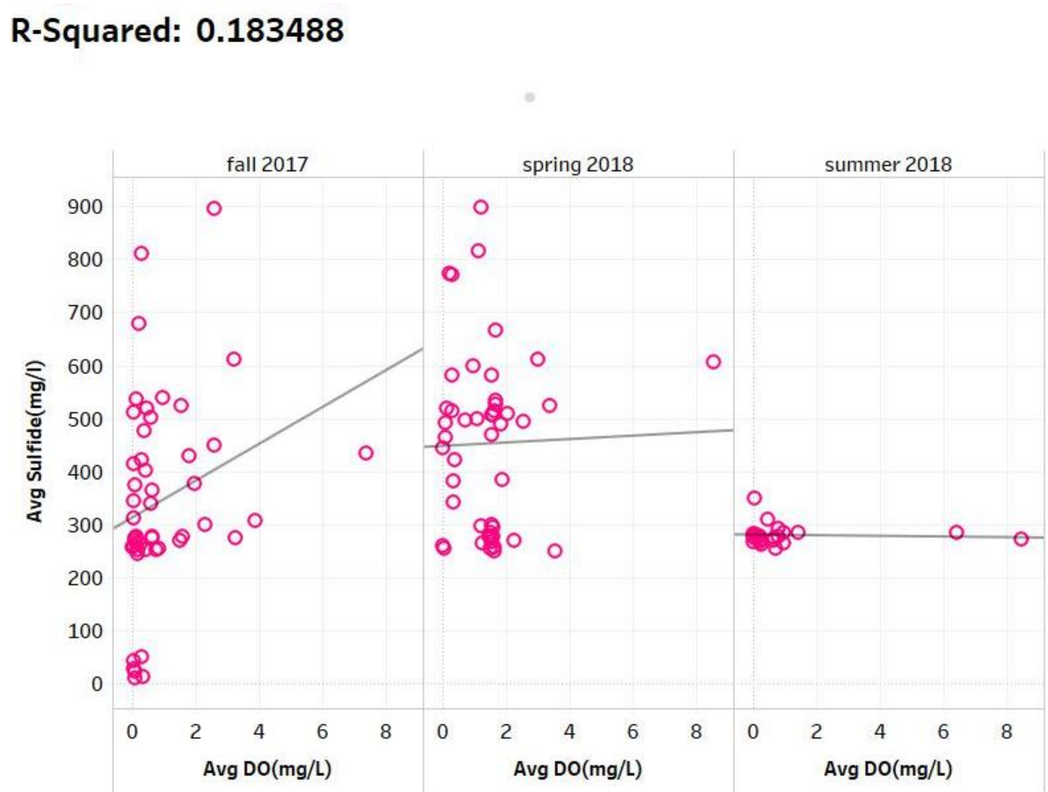


Figure 4-25: Relation between DO concentration and the sulfide content in liquid phase.

In summer the average sulfide concentration is found to remain clustered around 300 mg/L and the DO concentration is mostly below 1 mg/L. During summer when the temperature is generally higher than other seasons, volatilization of sulfide from liquid to gas phase increases. This is because increased temperature causes an increase in the kinetic energy of the molecules, resulting in increased motion of these molecules. This results in the breaking of intermolecular bonds and the gas molecule escapes from solution. Thus, as the temperature increases, the solubility of a gas decreases, according to Henry's law. This could be the reason of lower concentration of sulfide in liquid phase in summer.

During the fall and spring seasons, when the temperature is transitioning from higher to lower levels and vice versa, the sulfide concentration has more spread. This would be consistent with the sulfide trends varying with temperature according to Henry's law. The DO values also show more spread during spring and fall.

4.7.2: Relation between average BOD and average sulfide in liquid phase

Figure 4.26 shows BOD measured at various manholes as a function of liquid-phase sulfide, by season. BOD is the amount of oxygen utilized in the biological metabolism of biodegradable organic compounds (ASCE, 1989). BOD is often considered as an indicator of high organic content in a sample. Hence higher BOD indicates more source of organic compounds for generation of sulfide in sewage. High BOD boosts the microbial growth which depletes the DO concentration in sewage resulting in an increased sulfide generation in proportion to BOD concentration. The expected trend is observed in spring, when the temperature remains lowest among the 3 seasons considered.

In summer when the temperature is very high, greater generation of sulfide because of the increased metabolism of bacteria is expected. However, as shown in Figure 4.26, the concentration of sulfide in the liquid phase is found to stay stagnant around 300 mg/L, which is lower than the sulfide concentration in fall and spring seasons. This shift could be related to the elevated temperature during summer. H_2S being poorly soluble in water, will volatilize into the headspace of the sewer based on Henry's Law, leaving behind less concentration of sulfide in liquid phase. Somewhat greater H_2S concentrations in the gas-phase were found in summer, according to Figure 4.22.

In fall when the temperature transforms from warm to cold, the plot between average sulfide and average BOD is found to be scattered. The higher sulfate content observed might be during the colder days, when the volatilization is lower.

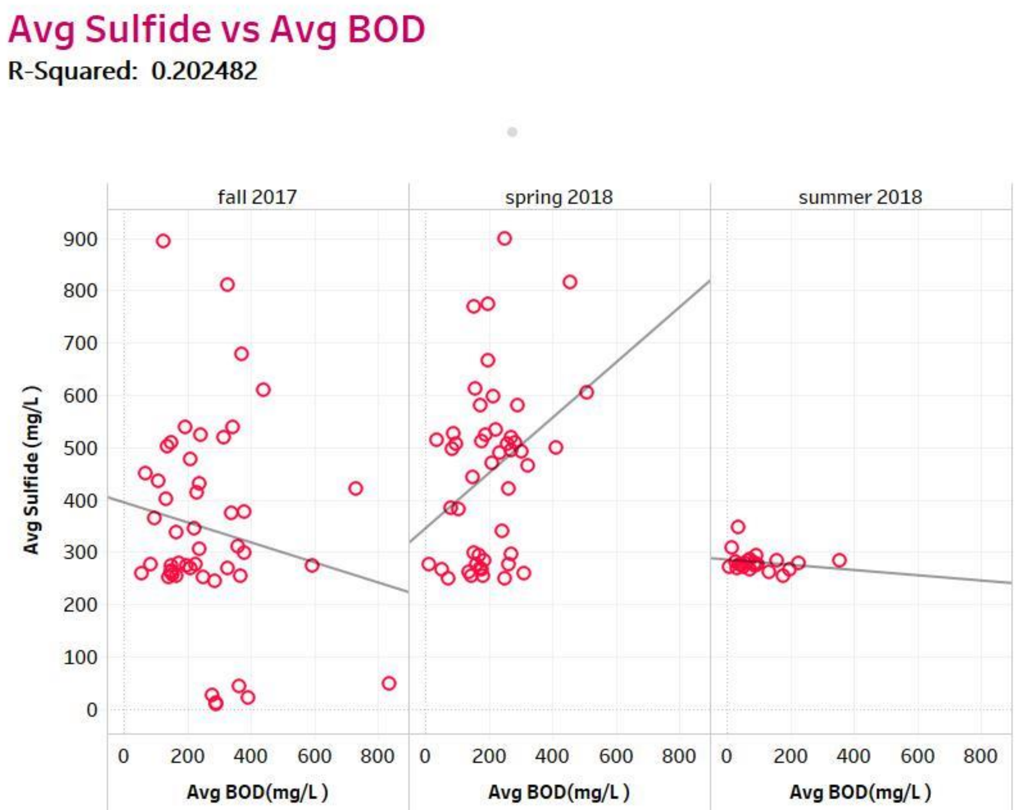


Figure 4-26: Relation between BOD and the sulfide content in liquid phase.

4.7.3: Relation between average liquid phase temperature and average sulfide in liquid phase

Figure 4.27 shows data for liquid-phase sulfide vs. liquid phase temperature by season. High temperatures increase microbial growth rates, which in turn increases the rate of sulfide production in the liquid. The expected trend is observed only in the spring season.

In summer, when the temperature is mostly above 80°F, the sulfide concentration in liquid phase is found to stay constant around 300 mg/L. The volatilization of sulfide in liquid phase to H_2S gas in the elevated temperature could possibly be the reason of lower sulfide content seen in the liquid phase. In Figure 4.27 a cluster of data points around 300mg/L in seen summer. Similar cluster is observed in fall, when the temperature remained warm. At lower temperature, the sulfide concentration in liquid phase was found to be high.

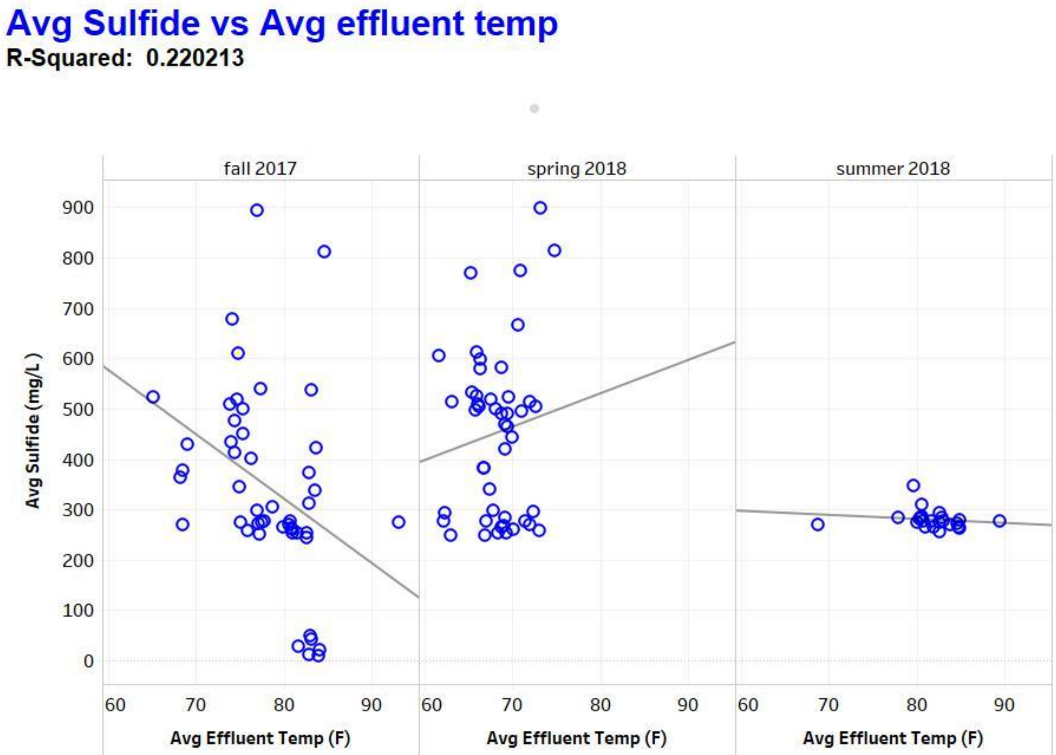


Figure 4-27: Relation between liquid phase temperature and the sulfide content in liquid phase.

4.8: Relation between seasonal variation and hydrogen sulfide concentration in manholes.

10 manholes were investigated in the 3 seasons for over 50 hours each to study the variation in H_2S concentration inside manhole. The liquid phase temperature and H_2S concentration inside manholes were measured in the 3 consecutive seasons fall, spring and summer. In all the manholes studied, the concentration of H_2S was found to be highest during the summer season. The higher temperature in summer is expected to be the reason for the increased H_2S concentration in manholes. Figure 5.28 and figure 5.29 shows the samples of the graphs that shows how the H_2S concentration varied in fall, spring and summer

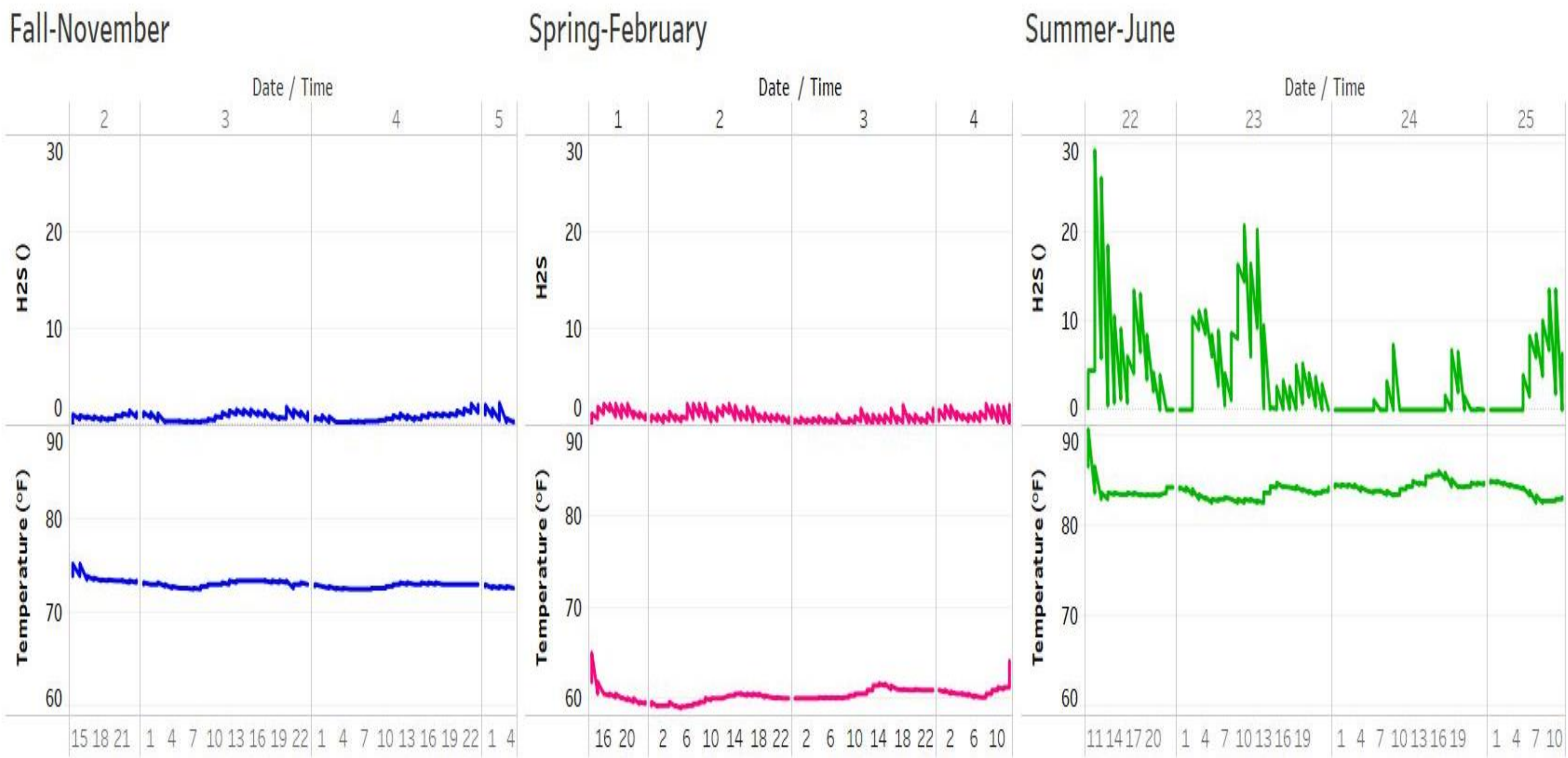


Figure 4-28: Relation between liquid phase temperature and the H_2S concentration-sample plot 1.

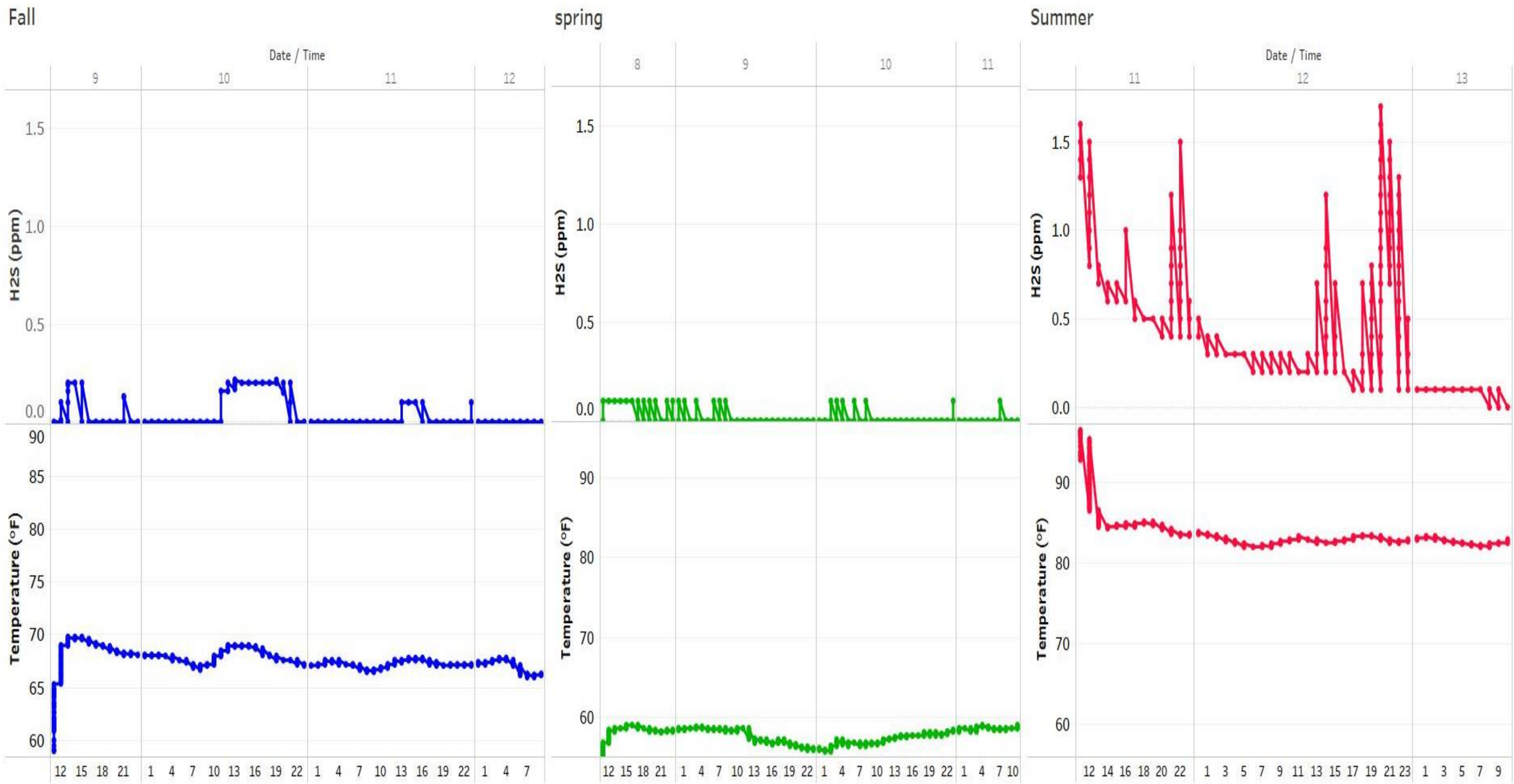


Figure 4-29: Relation between liquid phase temperature and the H_2S concentration-sample plot 2

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Findings

The corrosion of manholes is one of the most challenging problems regarding sewer operation and maintenance for many cities. Multiple factors are involved in generation and volatilization of hydrogen sulfide, causing corrosion of manholes. Having a better understanding of the significance of each factor and their relationships will enable researchers in developing a model that can predict the corrosion in manholes. This study aimed at finding the relation between various factors affecting H_2S generation in the liquid phase, volatilization from liquid to gas phase. To investigate the influence of each contributing parameter, a comprehensive analysis was carried out.

- As shown in the data plotted, H_2S concentration, liquid-phase temperature, and liquid-phase pH in some cases showed similar hourly trends in consecutive days of sampling. The trend in rise and fall of concentration of these parameters over time showed slight variations depending on the manhole's location and category.
- The manhole categories play a significant role in H_2S generation. In categorical manholes, the manholes with hydraulic jump generated the highest average H_2S concentration, followed by manholes with drops. The lowest concentration of H_2S was observed in manholes with subcritical flow in upstream and downstream. This was followed by manholes with uniform pipe diameter in upstream and downstream.
- In the study we found that in general, the average liquid-phase temperature is always greater than the ambient temperature inside a manhole. In the 3 seasons considered (spring, summer and fall), the liquid-phase temperature and ambient temperature inside manhole varies by 3°F on an average. The liquid-phase and ambient temperature were least during the spring season and maximum during summer season. A linear trend was obtained between the liquid-phase and ambient temperature.

- As the temperature increased, the hydrogen sulfide concentration showed slight increase but a linear trend was not obtained. In all the manholes studied for seasonal variation, the concentration of hydrogen sulfide was found to be maximum during the summer, when the temperature was elevated.
- The parameters like liquid-phase temperature, gas temperature and BOD were plotted against DO to study their influence on liquid-phase DO concentration. Both liquid-phase temperature and gas temperature were found to have no strong correlation with DO. No correlation was found between DO and BOD, either.
- Influence of factors like liquid-phase temperature, pH, liquid-phase sulfate and liquid-phase sulfide on the gas-phase H_2S concentration were studied. No strong correlations were observed between H_2S concentration and the factors considered. Involvement of multiple parameters influencing the factors is expected to be the reason for this.
- The relation between average sulfide concentration in the liquid-phase and factors affecting it, like average liquid-phase temperature, average BOD and DO concentrations were studied. Due to involvement of multiple parameters affecting these factors, no strong correlations were obtained between average sulfide concentration in the liquid-phase and the factors.

5.2 Conclusions

- Though multiple factors are involved in this process , temperature is found to be the main factor driving most of the other contributing factors as well.
- To reduce H_2S generation, the newly installed sewer pipes should be with uniform diameter when possible and slopes should aid subcritical flow.
- Manhole structures like drops>2’ and multiple inlets should be minimized

5.3 Future Recommendations

- Further research is needed to determine the how the seasonal variations are affecting the parameters in a manhole. All liquid and gas phase parameters should be measured for a set of manholes in all 4 seasons, the fall, winter, spring and summer, to compare to get a better idea on how seasonal variation affects H_2S generation in manholes.
- Since multiple factors are involved in generation and volatilization of H_2S, multiple linear regression analysis could be used to determine the contribution of each predictor variable in variation of the response variable.
- Measurement of redox potential can indicate how much oxidizing capacity the sewage contains or lacks.
- Studying precipitation data, to determine if any of the data collected was impacted by rainfall, can further improve the results of the study.
- Using the data and results, a model can be built to determine the corrosion rates in manhole.

References

1. Romanova, A., Mahmoodian, M., & Alani, M. A. (2014). Influence and interaction of temperature, H_2S and pH on concrete sewer pipe corrosion. International Journal of Civil, Architectural, Structural, Urban Science and Engineering, 8(6), 592-595.

2. Koch, G. H., Brongers, M. P., Thompson, N. G., Virmani, Y. P., & Payer, J. H. (2002). Corrosion cost and preventive strategies in the United States (No. FHWA-RD-01-156,).

3. Jensen, H. S., Nielsen, A. H., Lens, P. N. L., Hvitved-Jacobsen, T., & Vollertsen, J. (2009). Hydrogen sulphide removal from corroding concrete: Comparison between surface removal rates and biomass activity. Environmental technology, 30(12), 1291-1296.

4. Pollak, Denis. “A Vital Component Ignored.” The Water Spot Newsletter, Nevada Water Environment Association, Silver State Water Environment News. Available at https://nvwea.org/sswe-newsletters-detail/2667-a-vital-component-ignored, accessed 1/2017

5. Kaempfer, W., & Berndt, M. (1998, September). Polymer modified mortar with high resistance to acid to corrosion by biogenic sulfuric acid. In Proceedings of the IXth ICPIC Congress, Bologna, Italy, 14th (pp. 681-687).

6. Vincke, E., Van Wanseele, E., Monteny, J., Beeldens, A., De Belie, N., Taerwe, L. & Verstraete, W. (2002). Influence of polymer addition on biogenic sulfuric acid attack of concrete. International biodeterioration & biodegradation, 49(4), 283-292

7. Koch, g. H. (2002). Historic congressional study: corrosion costs and preventive strategies in the United States (no. Fhwa-rd-01-156).

8. Sydney, R., Esfandi, E., & Surapaneni, S. (1996). Control concrete sewer corrosion via the crown spray process. Water environment research, 68(3), 338-347.

9. U.S. Environmental Protection Agency (EPA), Office of Water. (1991). *Hydrogen Sulfide Corrosion in Wastewater Collection and Treatment Systems: Report to Congress*. 430/09-91-009

10. Gutiérrez-Padilla, M. G. D., Bielefeldt, A., Ovtchinnikov, S., Hernandez, M., & Silverstein, J. (2010). Biogenic sulfuric acid attack on different types of commercially produced concrete sewer pipes. Cement and Concrete Research, 40(2), 293-301.

11. Jurgens, John. 2014. "Manhole Makeover." Civil + Structural Engineer. Available at http://csengineermag.com, accessed 1/17.

12. Fibertechinc. "Manholes: The ultimate Resource" Available at https://fibertechinc.net/rhino-manholes/manholes-ultimate-resource/ , accessed 10/18.

13. Engineering Articles "Manhole." Available at http://www.engineeringarticles.org/manhole/, accessed 10/18.

14. Olmstead, W., & Hamlin, H. (1900). Converting portions of the Los Angeles outfall sewer into a septic tank. Engineering news, 44(19), 317-318.

15. Parker, C. D. (1945). The corrosion of concrete: 1. The isolation of a species of bacterium associated with the corrosion of concrete exposed to atmospheres containing hydrogen sulphide. Australian journal of experimental biology and medical science, 23(2), 81-90.

16. Parker, C. D. (1945). The corrosion of concrete: 2. The function of *thiobacillus concretivorus* (nov. Spec.) In the corrosion of concrete exposed to atmospheres containing hydrogen sulphide. Australian journal of experimental biology and medical science, 23(2), 91-98.

17. Parker, C. D. (1947). Species of sulphur bacteria associated with the corrosion of concrete. *Nature*, *159*(4039), 439.

18. Parker, C. D. (1951). Mechanics of corrosion of concrete sewers by hydrogen sulfide. *Sewage and Industrial Wastes*, 1477-1485.

19. Davis, J. L., Nica, D., Shields, K., & Roberts, D. J. (1998). Analysis of concrete from corroded sewer pipe. International biodeterioration & biodegradation, 42(1), 75-84.

20. Sand, W. (1987). Biotest system for rapid evaluation of concrete resistance to sulfur-oxidizing bacteria. Materials Performance, 26(3), 14-17.

21. Zhang, L., De Schryver, P., De Gusseme, B., De Muynck, W., Boon, N., & Verstraete, W. (2008). Chemical and biological technologies for hydrogen sulfide emission control in sewer systems: a review. Water research, 42(1-2), 1-12.

22. Nielsen, A. H., Lens, P., Vollertsen, J., & Hvitved-Jacobsen, T. (2005). Sulfide–iron interactions in domestic wastewater from a gravity sewer. Water research, 39(12), 2747-2755.

23. American Society of Civil Engineers (ASCE)/Water Environment Federation (WEF). 2007. Gravity Sanitary Sewer Design and Construction, Second Edition. ASCE Manuals and Reports on Engineering Practice No. 60, WEF Manual of Practice No. FD-5. Paul Bizier, Ed. American Society of Civil Engineers, Reston, VA.

24. U.S. Environmental Protection Agency (EPA), Office of Water, Office of Wastewater Enforcement and Compliance. 1992. Detection, Control, and Correction of Hydrogen Sulfide Corrosion in Existing Wastewater Systems. EPA 832-R-92-001.

25. Wei, S., Sanchez, M., Trejo, D., & Gillis, C. (2010). Microbial mediated deterioration of reinforced concrete structures. International biodeterioration & biodegradation, 64(8), 748-754.

26. Monteny, J., Vincke, E., Beeldens, A., De Belie, N., Taerwe, L., Van Gemert, D., & Verstraete, W. (2000). Chemical, microbiological, and in situ test methods for biogenic sulfuric acid corrosion of concrete. Cement and Concrete Research, 30(4), 623-634.

27. Parande, A. K., Ramsamy, P. L., Ethirajan, S., Rao, C. R. K., & Palanisamy, N. (2006, March). Deterioration of reinforced concrete in sewer environments. In Proceedings of the Institution of Civil Engineers-Municipal Engineer (Vol. 159, No. 1, pp. 11-20). Thomas Telford Ltd.

28. Mori, T., Nonaka, T., Tazaki, K., Koga, M., Hikosaka, Y., & Noda, S. (1992). Interactions of nutrients, moisture and pH on microbial corrosion of concrete sewer pipes. Water research, 26(1), 29-37.

29. Gutierrez, O., Mohanakrishnan, J., Sharma, K. R., Meyer, R. L., Keller, J., & Yuan, Z. (2008). Evaluation of oxygen injection as a means of controlling sulfide production in a sewer system. Water research, 42(17), 4549-4561.

30. Jiang, G., Gutierrez, O., Sharma, K. R., Keller, J., & Yuan, Z. (2011). Optimization of intermittent, simultaneous dosage of nitrite and hydrochloric acid to control sulfide and methane productions in sewers. Water research, 45(18), 6163-6172.

31. Jiang, G., Sharma, K. R., & Yuan, Z. (2013). Effects of nitrate dosing on methanogenic activity in a sulfide-producing sewer biofilm reactor. Water research, 47(5), 1783-1792.

32. Zhang, L., De Schryver, P., De Gusseme, B., De Muynck, W., Boon, N., & Verstraete, W. (2008). Chemical and biological technologies for hydrogen sulfide emission control in sewer systems: a review. Water research, 42(1-2), 1-12.

33. Hewayde, E. H., Nakhla, G. F., Allouche, E. N., & Mohan, P. K. (2007). Beneficial impact of coatings on biological generation of sulfide in concrete sewer pipes. Structures & Infrastructure Engineering, 3(3), 267-277.

34. De Muynck, W., De Belie, N., & Verstraete, W. (2009). Effectiveness of admixtures, surface treatments and antimicrobial compounds against biogenic sulfuric acid corrosion of concrete. Cement and Concrete Composites, 31(3), 163-170.

35. Haile, T., Nakhla, G., Allouche, E., & Vaidya, S. (2010). Evaluation of the bactericidal characteristics of nano-copper oxide or functionalized zeolite coating for bio-corrosion control in concrete sewer pipes. Corrosion Science, 52(1), 45-53.

36. Alexander, M. G., & Fourie, C. (2011). Performance of sewer pipe concrete mixtures with portland and calcium aluminate cements subject to mineral and biogenic acid attack. Materials and structures, 44(1), 313-330.

37. U.S. Environmental Protection Agency (EPA), Office of Water. 1991. Hydrogen Sulfide Corrosion in Wastewater Collection and Treatment Systems: Report to Congress. 430/09-91-009.

38. American Society of Civil Engineers (ASCE)/Water Environment Federation (WEF). 1995. Odor Control in Wastewater Treatment Plants. ASCE Manuals and Reports on Engineering Practice No. 82, WEF Manual of Practice No. 22. American Society of Civil Engineers, New York, Water Environment Federation, Alexandria, VA.

39. American Society of Civil Engineers (ASCE). 2009. Manhole Inspection and Rehabilitation, Second Edition. ASCE Manuals and Reports on Engineering Practice 92. Joanne Hughes, Ed. American Society of Civil Engineers, Reston, VA

40. Grengg, C., Mittermayr, F., Baldermann, A., Böttcher, M. E., Leis, A., Koraimann, G., & Dietzel, M. (2015). Microbiologically induced concrete corrosion: A case study from a combined sewer network. Cement and concrete research, 77, 16-25.

41. Rose, C., Parker, A., Jefferson, B., & Cartmell, E. (2015). The characterization of feces and urine: a review of the literature to inform advanced treatment technology. Critical reviews in environmental science and technology, 45(17), 1827-1879.

42. NPTLE "Characteristics of sewage and overview of treatment methods", available at https://nptel.ac.in/courses/105105048/M13L16.pdf , accessed 1/19.

Biographical Information

Aiswarya Acharath Mohanakrishnan graduated with bachelor's degree in Civil Engineering from University of Calicut, Kerala, India in April 2016. Growing up seeing her Mother who is a Teacher, she was always passionate about teaching right from her school days. After graduation she got married in May 2016 to Mr. Prasad Ariyandath and moved to the United States. His interest and support in fulfilling her dream and making her independent made it possible for her to join for graduate studies at University of Texas at Arlington in August 2017. She started as a graduate research volunteer under Dr. Melanie L. Sattler for the City of Arlington project on manhole corrosion in November 2017 and later on started her research work on the same project. She received the Outstanding Civil Engineering Masters Student Award for academic excellence in April 2019 and graduated with her master's degree in Civil Engineering from UTA in May 2019.

Aiswarya's research interests include sustainability and solid waste management, landfill design and monitoring, wastewater treatment designs, and renewable energy.