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# Preliminary Hydrogen Sulfide Emission Factors and Emission Models for Wastewater Treatment Plant Headworks

A Dissertation

Submitted to the Graduate Faculty of the  
University of New Orleans  
in partial fulfillment of the  
requirements for the degree of

Doctor of Philosophy  
in  
Engineering and Applied Science

by  
Amitdyuti Sengupta  
Bachelor of Engineering, Nagpur University 2004  
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May 2014

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## Abstract

Generation of hydrogen sulfide ( $H_2S$ ) is a common phenomenon from wastewater collection, transport, and treatment processes. Impacts of  $H_2S$  emissions from wastewater include corrosion and reduction in the service life of wastewater infrastructure, odor nuisance in the community, and health impacts on wastewater operations and maintenance personnel (Nielsen, et al. WEFTEC 2006).

Conventional odor control studies performed by municipalities to design their individual odor/corrosion control strategies largely depend on establishing a dilution to detection threshold (D/T) ratio and ascertaining the recognition threshold (R/T) for air samples collected from the study area. These conventional odor studies based on grab samples using R/T and D/T technique using a few days of data have a number of limitations and potentially lead to inaccurate conclusions. However,  $H_2S$  emission studies using continuous air monitoring is expensive and time consuming.

The objective of this research is to understand the feasibility of utilizing emission factors as a tool to predict hydrogen sulfide emissions from headworks of four different Jefferson Parish, Louisiana wastewater treatment plants (WWTP). Proposed model(s) developed for predicting  $H_2S$  emission factors that depend on wastewater parameters should be convenient for the municipalities to use as the data required is monitored routinely. Use of  $H_2S$  emission models should assist rapid identification of  $H_2S$  emission hot spots, optimize  $H_2S$  control strategies, predict potential health risks, prevent community odor nuisance, and ascertain infrastructure corrosion.

This dissertation attempts to; i) develop a research methodology, ii) identify instruments required, iii) generate emission factor ranges and compare their sensitivity to wastewater parameters, iv) generate preliminary empirical emission models based on flow treated, population serviced and area served by a treatment plant for each sampling location and v) provide a roadmap for future research opportunities to refine the models generated as part of this dissertation.

Key words: emission model, emission factor, emission ranges, hydrogen sulfide, odor control, air quality, wastewater treatment.



## 1.0 Introduction/Background

Formation and release of hydrogen sulfide (H<sub>2</sub>S) gas from municipal wastewater is a well-recognized problem that has significant impacts on wastewater infrastructure. Impacts of generation and emission of H<sub>2</sub>S from wastewater include corrosion and reduction in the service life of wastewater infrastructure, odor nuisance in the community, and health impacts of wastewater operations and maintenance personnel (Neilsen, et al. WEFTEC 2006). *Section 522 of Water Quality Act, 1987* mandates the U.S. Environmental Protection Agency (EPA) to study and document corrosion level in wastewater systems in the United States of America (USA). The EPA's study "Hydrogen Sulfide Corrosion: Its Consequences, Detection and Control," conducted on 89 municipalities in September 1991 revealed that 80% of the municipalities reported accelerated corrosion and collapse of the wastewater infrastructure.

Health Impact: A study conducted on wastewater utility workers has shown reduced lung function due to chronic low level H<sub>2</sub>S exposure (Richardson, 1995; <http://www.ncbi.nlm.nih.gov/pubmed/7573079>). Inhalation of concentrations of 500-1,000 parts per million (ppm) can cause rapid unconsciousness and death through respiratory paralysis and asphyxiation. Other detrimental health effects can be observed at significantly lower H<sub>2</sub>S concentrations. H<sub>2</sub>S is strictly regulated by the Occupational Safety and Health Administration (OSHA) for all work environments where workers have a potential for exposure to the same. According to OSHA, the permissible exposure limit of 20 ppm is the ceiling (C) concentration and a peak exposure limit is 50 ppm for no more than 10 minutes if no other measurable exposure occurs. H<sub>2</sub>S samples collected at the headworks of various Louisiana WWTPs by the author have consistently recorded a 24-hour average concentration of 70 ppm, with peaks of 600 ppm on multiple occasions. Other wastewater infrastructures, such as lift station wetwells, manholes, gravity and force mains, and treatment units at WWTPs, have the potential for similar high levels of H<sub>2</sub>S. Such work environments pose significant occupational health risks for the operation and maintenance (O&M) staff.

Due to the potential for detrimental health impacts, the EPA through a Federal Register published in February 2010 has shown its intent to lift the Administrative Stay on reporting requirements for H<sub>2</sub>S from eligible facilities and including the reported values in its annual Toxic Release Inventory (TRI) report (<http://www.epa.gov/tri/lawsandregs/hydrogensulfide/indexf.html>)

Although, the new TRI requirement is not expected to immediately impact the reporting requirements for Wastewater Treatment Plants (WWTPs) for H<sub>2</sub>S emissions, WWTPs may see additional regulations in the near future.

Economic and Social Impact: Water Infrastructure Network (WIN) reported in the year 2000 that 50% of the \$23.5 billion spent nationally for replacement, repair, and addition to wastewater infrastructure all over the USA was due to hydrogen sulfide related corrosion. The emission of H<sub>2</sub>S from a wastewater infrastructure is also a common public nuisance due to the typical rotten egg smell associated with this gas. Consistent H<sub>2</sub>S odor in a neighborhood has the potential to impact the quality of life and negatively influence property prices in the area. Strict air quality regulations and greater public concerns have led to increased social focus on odor related issues (Kim et al. 2007).

Conventional odor control studies performed by municipalities to design their individual odor/corrosion control strategies largely depend on establishing a dilution to detection threshold (D/T) ratio and ascertaining the recognition threshold (R/T) for air samples collected from the study area. Often these samples for R/T and D/T are collected using a few grab samples (instantaneous samples using tedlar bags) over a few days and continuous sampling is rarely done. These conventional odor studies based on grab samples using R/T and D/T technique using a few days of data have a number of limitations and lead to inaccurate conclusions. However, thorough and proper H<sub>2</sub>S emission studies using continuous air monitoring are expensive and time consuming.

There is a demand to rapidly and economically identify and forecast H<sub>2</sub>S emissions from various wastewater infrastructures. To reduce detrimental health, social, and economic impacts, air quality management tools such as Emission Factors (EF) and predictive emission models for estimating H<sub>2</sub>S emissions will be very useful. Per the EPA: “*an air quality emission factor is the relationship between the amount of pollution produced and the amount of raw material processed, or amount (number) of product (units) produced, or amount of work done.*” Examples of emission factors include: mass of CO<sub>2</sub> emitted per distance driven by a vehicle (kg-CO<sub>2</sub>/km-driven); mass of SO<sub>2</sub> produced per unit amount of electricity produced (kg-SO<sub>2</sub>/KWH-electricity produced); mass of particulate matter emitted per ton of coal burnt (kg-PM/Ton-coal burnt). Determining Emission Factors (EF) is considered as an important tool in studying air quality pollution and control. Since 1972, the EPA has published, *AP-42 Compilation of Air Emission Factors (AP-42)*. AP-42 is a collection of EFs and process information for more than 200 air pollution source categories from a wide range of industry sectors (*Technology Transfer Network, Clearinghouse for Inventories and Emission Factors*; EPA).

In this study, the pollutant of concern is H<sub>2</sub>S from WWTP headworks and the parameters to describe the “unit of measure” for normalization are: i) flow of wastewater processed by the WWTP, ii) population served by a particular WWTP, and iii) service area associated with the WWTP. EF is an average value obtained from a long term observations study performed during normal operations of the polluting unit. AP-42 indicates that EF formulae, which include variable parameters such as temperature, wind velocity, pollutant unit dimensions, produce a

more realistic estimate. Therefore, in line with the EF guidelines established by AP-42, this dissertation will base its EF calculation methodology on variables such as: i) H<sub>2</sub>S emissions using continuous H<sub>2</sub>S concentrations within the headworks' influent chamber, ii) wastewater characteristics (temperature; pH; dissolved oxygen; biochemical oxygen demand; total sulfides and hydraulic retention time), iii) wastewater flow received at the WWTP, iv) service area, and v) population served.

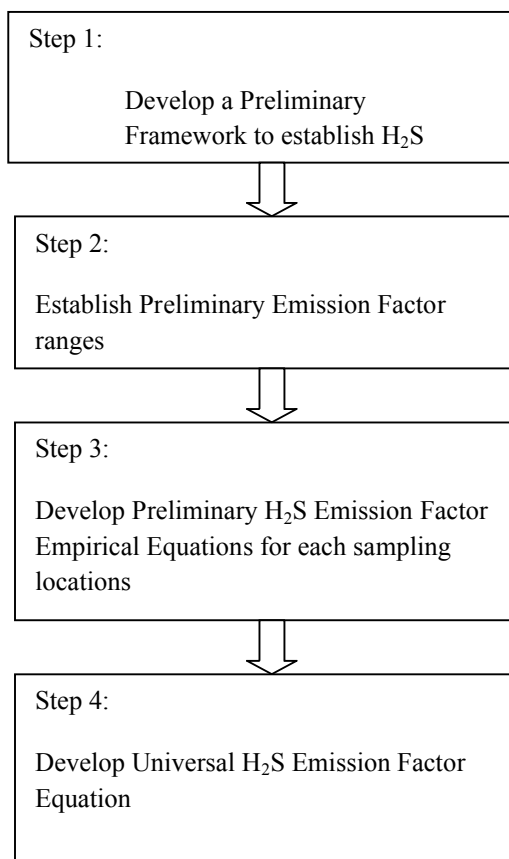
Considering the health and economic impacts of H<sub>2</sub>S emissions from wastewater treatment facilities and also due to the lack of any H<sub>2</sub>S emission factors or emission forecast models, the development of H<sub>2</sub>S emission factors and H<sub>2</sub>S emission model was considered as a very useful and important research which led to this dissertation research.

As the author and the principal investigator have access to the four Jefferson Parish WWTPs, these four WWTPs were considered for the research. As each site will have certain case/site specific parameters that will influence H<sub>2</sub>S emissions, it was thought that it will be useful to first determine an H<sub>2</sub>S emission model for each site. A following step is to compile all the data to develop a universal model which can be applied to other WWTPs anywhere in the world. Figure 1 illustrates the modeling approach used in this dissertation research.

This research is an attempt to perform an evaluation study to establish the feasibility of developing preliminary EF (based on WW flow, population served, and area served) ranges. Four Jefferson Parish WWTP headworks were chosen as the site for this evaluation study/pilot project as all flows pass through these units, and it also has one of the highest potentials to generate H<sub>2</sub>S. Based on the findings of this evaluation study, researchers could modify their methodology for any future research in this area.

It should be noted that this research focuses on the headworks of WWTPs rather than all units as the headworks has been identified as an important and significant source through a literature search as well as the author's preliminary air quality monitoring. Preliminary emission models (emission models) will be generated incorporating the wastewater data gathered and preliminary EFs calculated as part of this dissertation. Individual models for each of the four headworks locations are expected to generate the EFs for each individual site. While the author made an effort to develop a universal model combining the results obtained from all four WWTPs, any future researcher should refine this model and modeling approach to be able to obtain more reliable results. The Conclusions and Recommendations (Chapter 6) of this dissertation would serve as a useful template in this regard.

**Figure 1.1: Developing Universal H<sub>2</sub>S Emission Model**



Once H<sub>2</sub>S emission models and EF ranges are developed, these tools can be developed for: (i) generating an H<sub>2</sub>S emission inventory database for wastewater collection and other confined space treatment facilities, (ii) identify the most H<sub>2</sub>S emission intensive units in treatment/collection facilities, (iii) establish odor control strategies by directing resources to the most odor intensive locations, and (iv) perform dispersion modeling of H<sub>2</sub>S emissions and understand community health impacts.

Once developed, the EF model(s) and EFs can be used in understanding the H<sub>2</sub>S emissions as well as managing them:

- (a) Estimate/forecast H<sub>2</sub>S emission potential for variable conditions (flow; pH; temperature; population; area served).
- (b) Use the H<sub>2</sub>S emissions data to verify compliance with the OSHA requirements.
- (c) Use the H<sub>2</sub>S emission data to conduct atmospheric dispersion modeling to estimate the odor nuisance and health risks in the immediate community.
- (d) Use the H<sub>2</sub>S emission data to comply with the EPA requirements.
- (e) Build historical emission profiles using the wastewater parameters to defend against any court litigations in the future.
- (f) Evaluate the predicted H<sub>2</sub>S data to develop odor control strategies and cost optimization.

## 2.0 Scope and Objective

The scope of this dissertation research is to determine preliminary H<sub>2</sub>S emission factors for four WWTP headworks of Jefferson Parish followed by development of a preliminary H<sub>2</sub>S emission model(s) to predict H<sub>2</sub>S emissions from WWTP headworks under various scenarios.

### Need for Research

Literature review indicates that conventional odor studies have focused on sampling and analysis for performing odor emission studies. However, the following potential gaps in current studies have been identified:

- i) Literature review did not establish a robust hydrogen sulfide emission modeling study performed for wastewater industry.
- ii) Current studies are designed for sampling and analysis of a limited or particular type of sewer system infrastructure.
- iii) Prior studies mostly relied on grab sampling of air for H<sub>2</sub>S concentrations in and around wastewater treatment units. To record the hourly or seasonal variations, continuous air sampling is mandatory to gain a thorough understanding of concentration levels of pollutant(s) in the ambient air of the study unit. H<sub>2</sub>S monitoring studies conducted by the author has recorded a concentration inside the headworks influent chamber of 568 ppm as the maximum, 1 ppm as the minimum and an average of 85 ppm during the week of October 21-27, 2012, for a WWTP in Jefferson Parish, LA. The same location also recorded 102 ppm maximum, 0 ppm minimum, and 11 ppm as the average H<sub>2</sub>S concentration during the period of January 29 - February 7, 2013. Calculations based on grab air sample results therefore have the potential to under- or over-estimate emission of pollutant concentration from a source. Odor control systems designed and installed based on grab sampling of H<sub>2</sub>S have been observed to fail because of the lack of a good understanding of H<sub>2</sub>S emissions and their variations (Department of Public Works, City of Kenner).

There are numerous reasons to undertake an evaluation study, such as the one being proposed to assess H<sub>2</sub>S emissions from the headworks of WWTP:

- (1) Assist future researchers to develop a universal H<sub>2</sub>S emission model by refining preliminary empirical models developed as part of this research.
- (2) Rapidly identify hot spots related to H<sub>2</sub>S formation in a vast sewer network and proactively undertake odor control measures.

- (3) Identify and rank sewer infrastructure that has potential for health risk for operators and community at large.
- (4) Identify and rank sewer infrastructure for potentially accelerated deterioration and develop a sewer rehabilitation plan.
- (5) Perform H<sub>2</sub>S inventory analysis and prepare for future regulations that might impact the WWTPs reporting requirements.

## Specific Objectives

The specific objectives of this doctoral research are listed below:

1. Coordinate with municipalities and practicing engineers to understand their needs in terms of odor emission studies and identify any gaps in the conventional studies.
2. Develop a research framework/methodology to determine H<sub>2</sub>S emission factors (based on population, area served, and wastewater volume).
3. Determine preliminary H<sub>2</sub>S emission factors (EFs) and their ranges applicable for the East Bank, Bridge City, Marrero, and Harvey WWTPs (Jefferson Parish WWTPs) (based on population, area served, and wastewater volume).
4. Develop preliminary H<sub>2</sub>S emission models to estimate H<sub>2</sub>S emission rates at the headworks of four Jefferson Parish WWTPs;
5. Provide recommendation for developing preliminary universal H<sub>2</sub>S emission model(s) which can be used for other WWTPs anywhere in the world.

### 3.0 Literature Review

#### Odorous Compounds Present in Wastewater Influent

In general, the odorous compounds are characterized as small, hydrophobic and volatile molecules having one or two functional groups containing Oxygen (O), Sulfur (S), and Nitrogen (N). A list containing odorous compounds generally associated with sewers is shown in Table 3.1:

**Table 3.1: Odorous Compounds Associated with Municipal Wastewater**

<b>Odorous Compounds</b>	<b>Example Gases</b>
Inorganic Gases	Ammonia, Hydrogen Sulfide
Mercaptans	(Allyl, Amyl, Benzyl, Methyl, Ethyl) Mercaptan
Other Organic Sulfides	Dimethyl Sulfide, Thiocresol, Thiophenol
Diamines	Cadaverines (1, 5 pentanediamine)
Other Organic N	Indole, Pyridine, Skatole
Volatile Fatty Acids (VFA)	(Acetic, Propionic, Butyric) Acids
Amines	(Dibutyl, Di-isopropyl, Dimethyl, Triethyl) Amines

Source: Minimization of odors and corrosion in collection system: Water and Environment Research Foundation (WERF), 2005: <http://tools.werf.org/Files/Chapter%204.pdf>.

In the table above, hydrogen sulfide is known for its rotten egg smell, whereas mercaptans have an odor of decaying cabbage. Other organic sulfur containing compounds have garlic odors. The diamines are characterized by a putrid odor and the organic nitrogen containing compounds such as indole and skatole have a strong fecal odor. However, it is difficult to predict correctly the characteristic odor of these gas mixtures based on the available literature.

#### 3.1 Presence of Odorous Compounds in Wastewater

It has been noted from earlier literatures (Bach, 1931) that bad odors in wastewater are due to sulfur compounds and not nitrogenous compounds. Inorganic sulfur dominates over organic sulfur to a great extent in wastewater. Buswell (1931) as well reported that untreated sewage rarely contained more than 1.0 ppm of organic sulfur, whereas inorganic sulfur content was 90.0 ppm. Therefore, decomposition of sulfate pathway should be considered as most important in the production of hydrogen sulfide from sewage.



In another study, the concentration of volatile fatty acids (VFAs) during wastewater transportation was found varying during day and night in the range between 5 and 50 mg/m<sup>3</sup> (Hvitved-Jacobsen et al.,1995). Typically, 85% of the VFAs were acetate and 10% propionate. The remainders were formate, n-butyrate, and iso-butyrate. Sulfur and nitrogen containing odorous compounds in influent wastewater in sewage treatment facilities were also studied by Hwang et al. (1995) and summarized in Table 3.2. These odorous compounds are present in high concentration in the wastewater, i.e., in the water phase but not in the air phase in the sewer network.

**Table 3.2: Composition of Odorous Compounds in WWTP Influent**

Compounds	Average Concentration (microgram/liter)	Range of Concentration (microgram/liter)
Hydrogen Sulfide	23.9	15-38
Carbon Disulfide	0.8	0.2-1.7
Methyl Mercaptan	148	11-322
Dimethyl Sulfide	10.6	3- 27
Dimethyl Disulfide	52.9	30 - 79
Dimethyl amine	210	-
Trimethylamine	78	-
n-propylamine	33	-
Indole	570	-
Skatole	700	-

(-) Data Not Available

Source: Hwang et al (1995)

The emission of these compounds from the water to air phase depends on a number of other characteristics which will be discussed later in this chapter.

Although the emissions from a municipal wastewater system have various types of gases, odor is typically caused due to sulfur-bearing compounds. A sulfur bearing compound such as H<sub>2</sub>S is easy to measure and widely assumed as the most prevalent malodorous and corrosive compound often used as a marker for sewer odor (Design Manual Odor and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants US EPA; 1985). A select list of such compounds (which are typically found in a sewer atmosphere) along with their molecular weight and other details are listed in Table 3.3. It should be noted that the compounds with higher molecular weight are less prone to volatility and becoming airborne. These compounds are therefore less likely to cause an odor nuisance. H<sub>2</sub>S with one of the lowest molecular weights and an extremely low odor threshold is highly likely to volatilize, become airborne, and cause an odor nuisance.

**Table 3.3: Odorous Sulfur Compounds in Wastewater**

<b>Substance</b>	<b>Odor Threshold (ppm)</b>	<b>Molecular Weight</b>
Allyl Mercaptan	0.00005	74.15
Dimethyl Sulfide	0.0001	62.13
Ethyl Mercaptan	0.000019	62.1
<b>Hydrogen Sulfide</b>	<b>0.00047</b>	<b>34.1</b>
Methyl Mercaptan	0.0011	48.1
Thiocresol	0.000062	124.21
Thiophenol	0.000062	110.18

Source: Abridged from Design Manual Odor & Corrosion Control in Sanitary Sewer Systems and Treatment Plants

Other researchers working on the odor related problem in a wastewater treatment system have also observed that H<sub>2</sub>S may be considered as an indicator for odor level (Gostelow and Parsons, 2000). Hydrogen sulfide is, therefore, considered as relevant and representative parameter from an engineering point of view to deal with the odor problem in a sewer system.

### **3.2 General Chemistry of Hydrogen Sulfide**

Hydrogen sulfide (H<sub>2</sub>S, CAS # 7783-06-4) is an extremely hazardous, toxic compound. It is a colorless, flammable gas that can be identified in relatively low concentrations by a characteristic rotten egg odor. It is generated through bacterial breakdown of organic matter by anaerobic digestion. It is slightly heavier than air. The mixture of H<sub>2</sub>S and air is explosive. H<sub>2</sub>S is slightly soluble in water and forms a weak acid (pka=7). It forms metallic sulfide when it reacts with metal and thus has severe corrosive action. The vapor pressure of the gas is 1740 kpa at 20<sup>0</sup>C and the flash point is 207<sup>0</sup>C.

### **3.3 Sources of Sulfate/Sulfur Compounds in Wastewater**

The presence of sulfur compounds was detected in a municipal water supply by multiple researchers (Rudolf and Baumgartner, 1932) and the following four major sources were identified:

- Inorganic sulfur as sulfates, thiosulfates present in the community water supply.
- Inorganic combination of sulfur, such as, sulfate thiosulfates present in ground water, which finds its way to a sewer network through infiltration.
- Sulfur in inorganic combinations, proteins, etc., or as inorganic sulfates in human feces.
- Industrial wastes containing sulfur in both inorganic and organic combinations.

Out of these identified sources, sulfate ( $\text{SO}_4^{2-}$ ) from the water supply and through ground water infiltration, is considered as the most prominent source. The contribution of sulfur from human excreta is comparatively low. In some cases, sulfur from industrial wastes is also reported. Due to the greater hardness of water in the water supply, the sulfate content of sewage varies. There is a variation in the type of sulfur compounds in different domestic wastes, which may be in the form of calcium, magnesium, sodium, or ferrous sulfates. The inorganic sulfur may be present in the form of thiosulfate or sulfite.

### 3.4 Biochemical Mechanism for Formation of Hydrogen Sulfide

A sewer system can be looked at as a combination of four interrelated components which play an important role in the formation of malodorous compounds such as  $\text{H}_2\text{S}$  in particular. These are described briefly as:

**Sewer atmosphere:** This is the upper part of the flowing liquid which is either enclosed or confined in nature depending on the type of wastewater structure.

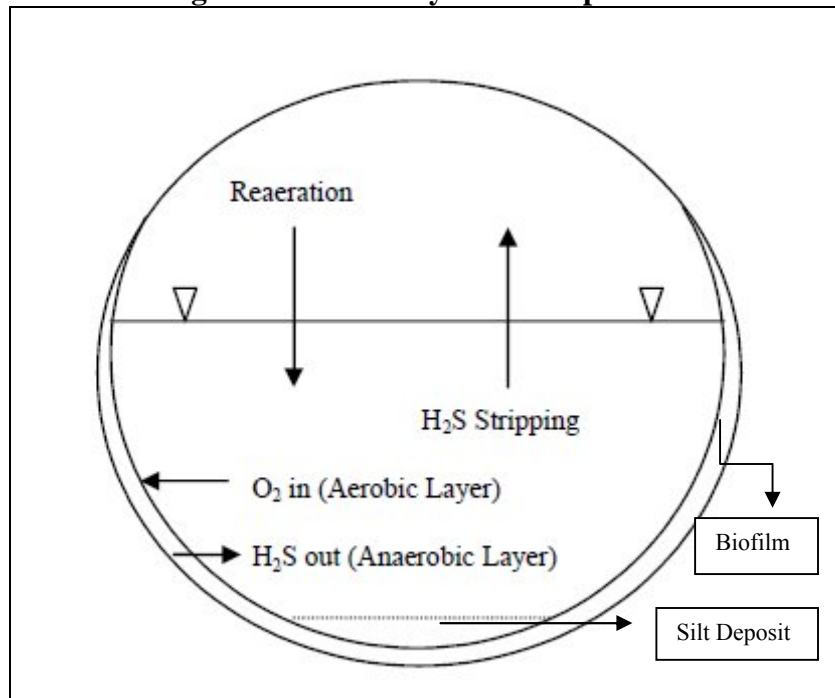
**Wastewater:** The liquid part of wastewater which transports the waste containing active biomasses.

**Biofilm:** The sewer biofilm or slime layer covers the inside of the wastewater infrastructure, such as treatment units or the conveyance system. It contributes significantly to  $\text{H}_2\text{S}$  production in sewers (Holder et al., 1985; Nielsen and Hvitved-Jacobsen, 1988; Pomeroy and Bowlus, 1946; Holder, 1986; El-Rayes, 1988). Generally, the biofilm attributes in two ways: i) by accumulating a high sulfur reducing bacteria (SRB) population in the slime layer, and ii) by creating an ideal environment for  $\text{H}_2\text{S}$  production. The bacterial population in biofilm is significantly greater than that in bulk liquid (Heukelekian, 1948). The biofilm prevents bacteria from washing away, protects against any environmental changes, and allows for significant growth of bacterial population to develop in the biofilm.

The environment inside the biofilm is ideal for  $\text{H}_2\text{S}$  production. A conceptual diagram of biofilm in a wastewater system is shown in Figure 3.1. It shows the aerobic layer on the liquid side and anaerobic layer on the treatment unit or conveyance system wall. However, the distribution of oxygen inside the biofilm is influenced by the availability of nutrients in the liquid and the reaction kinetics of the biofilm itself. Homogeneous reaction rate expressions were applied to determine biofilm kinetics by some researchers and used for describing substrate transfer in the biofilm and  $\text{H}_2\text{S}$  production in sewer (Neethling et al., 1989).

**Sediment:** It is an important component in the sewer system. It often occurs when flow velocity drops below a certain value.

**Figure 3.1: Sewer System Components**



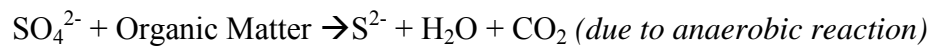
Source: Hvitved, 1998

Microbial transformation of organic matter occurs during transportation of wastewater (Nielsen et al., 1992). These processes take place in all components in the water phase, biofilm, and sediment of the sewer system under aerobic and anaerobic conditions (Hvitved-Jacobsen, 1998; Tanaka and Hvitved-Jacobsen, 1998). Thus, a sewer system shows a variety of environments for microorganisms to perform differently during their transformation processes, which again varies with various factors such as flow velocity of the wastewater, availability of dissolved oxygen, amount of substrates, deposition of sewer sediment, and growth of biofilm. In the presence of oxygen, the microbial transformation occurs in an aerobic condition, whereas in the absence of oxygen, a transformation takes place under an anaerobic situation, as discussed below.

## Sulfate Reduction

Sulfate reduction occurs due to the biological activity of sulfate reducing bacteria (SRB) of the genus *Desulfovibrio* and *Desulfobulbus* in an anaerobic condition (USEPA, 1985). This sulfate reduction process often takes place in wastewater sediment and biofilm which protect the bacterial colony from shear forces generated due to the flow of wastewater in a sewer system. The reaction kinetic for sulfide production mainly depends on the available sulfate concentration and the nature of organic substrates.

As per “Design Manual Odor and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants,” EPA 1985; the following chemical equations illustrate the formation of H<sub>2</sub>S:



Organic matter is oxidized by bacteria present in the sediment or slime layer and causes hydrogen removal. The hydrogen released is in turn accepted by various organic and inorganic substances. Table 3.4 below shows the various hydrogen acceptors and corresponding reduced products:

**Table: 3.4 Hydrogen Acceptor and Reduced Products in Sewer Infrastructure**

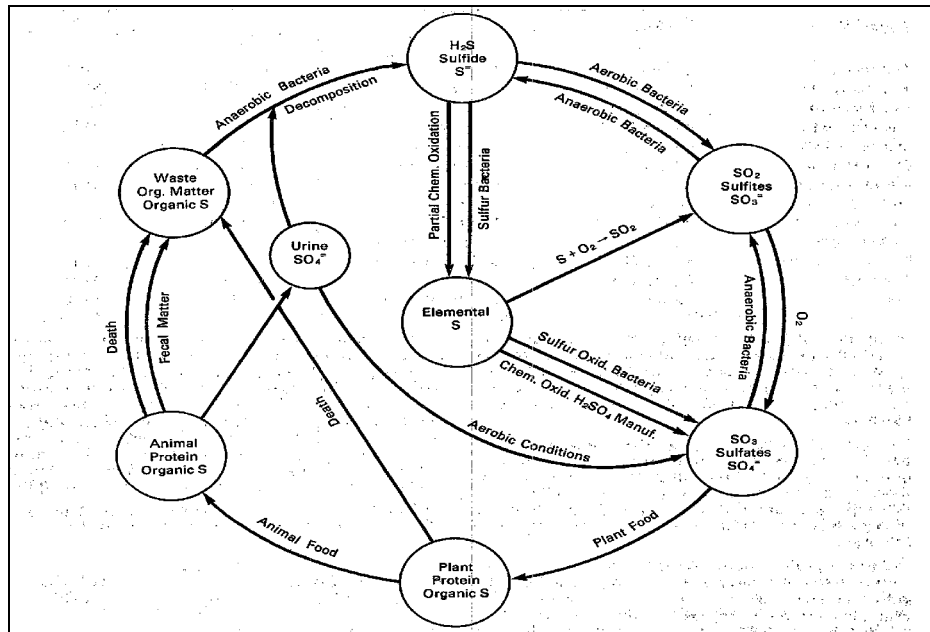
Category	Hydrogen Acceptor	Hydrogen Atom Added	Reduced Product
A	O <sub>2</sub>	4H <sup>+</sup>	2H <sub>2</sub> O
B	2NO <sub>3</sub> <sup>-</sup>	12H <sup>+</sup>	N <sub>2</sub> + 6H <sub>2</sub> O
C	SO <sub>4</sub> <sup>2-</sup>	10H <sup>+</sup>	H <sub>2</sub> S+4H <sub>2</sub> O
D	Oxidized Organics	x H <sup>+</sup>	Reduced Organics
E	CO <sub>2</sub>	8H <sup>+</sup>	CH <sub>4</sub> +2H <sub>2</sub> O

Source: Design Manual Odor and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants US EPA; 1985

In wastewater, simultaneous biochemical oxidation removes hydrogen from organic matter present in the wastewater in order to gain energy. Table 3.4 above lists typical hydrogen acceptors in order of preference for biochemical reaction. Categories A and B result in the formation of non-odorous products such as hydrogen and nitrogen. Reactions involved in Categories C and D typically lead to the formation of odorous products such as hydrogen sulfide and mercaptans.

As per Table 3.4 in the absence of dissolved oxygen and nitrates, sulfates are the preferred hydrogen acceptor by obligate and anaerobic bacteria. Figure 3.2 shows a sketch of the sulfur cycle.

**Figure 3.2: Sulfur Cycle**



Source: Design Manual Odor and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants US EPA; 1985

### 3.5 Factors Affecting H<sub>2</sub>S Formation in Wastewater

The rate of sulfide production in wastewater depends on different factors identified as follows:

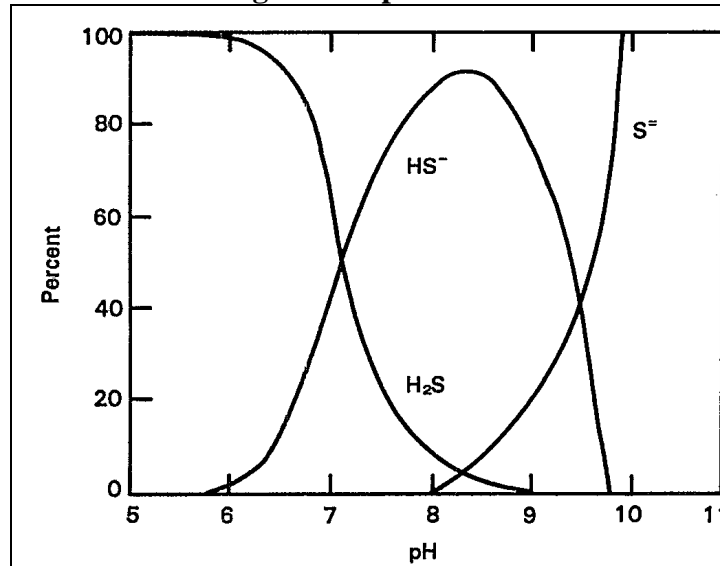
- **Concentration of organic matter and nutrients:**  
 These materials are considered as substrates which diffuse in the biofilm layer and are utilized by SRB. A high concentration of organic matter (e.g., BOD) will increase the bacterial growth and thus deplete DO and increase the sulfide production.
- **Level of dissolved oxygen (DO):**  
 The dissolved oxygen level in the wastewater is the determining parameter for breaking down of the carbonaceous matter occurring either in an aerobic or anaerobic situation. Aerobic bacteria generally dominate the outer layer of the biofilm at a DO concentration more than 1mg/l.

On the other hand, an increased DO will reduce the sulfide formation by limiting the food supply to the anaerobic bacteria. A low level of DO favors growth of anaerobic microorganisms and subsequent sulfide production.

- pH of the wastewater:

The pH is the controlling factor for dissociation of hydrogen sulfide in to dissolved hydrogen sulfide gas ( $H_2S$ ), hydrogen sulfide ion ( $HS^-$ ), and sulfide ion ( $S^{2-}$ ) in wastewater (EPA, 1992). This distribution of dissolved  $H_2S$ :  $HS^-$  is approximately 50:50 at pH 7, whereas at pH 6, the distribution changes to 90 percent dissolved  $H_2S$ : 10 percent  $HS^-$  in wastewater approximately (Figure 3.3). This dissolved hydrogen sulfide is released to the atmosphere from the solution and is influenced under turbulent conditions. As it is rare to achieve an equilibrium condition, therefore,  $H_2S$  concentration in a sewer atmosphere is difficult to predict on the basis of sulfide concentration in wastewater in a sewer. Yongsiri et al. (2004a) also reported the importance of wastewater pH in evaluating the potential hydrogen sulfide emission to the sewer atmosphere. In a field investigation, Nielsen et al. (2008) found that a decrease in pH increased the hydrogen sulfide gas emission in a sewer atmosphere.

**Figure 3.3: pH Curve**



Source: Design Manual Odor and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants US EPA; 1985

- Temperature:

The high temperature increases biological activities and high oxygen consumption, and increases sulfide production in a gravity sewer. In force main, sulfide production can take place at a low temperature if the anaerobic condition retains for a sufficient time. In general, each degree of temperature increase represents about a 7% increase of biological activity of SRB up to  $30^{\circ}C$ .

- Flow rate:

Low wastewater flow has an impact over turbulence and therefore reduces the re-aeration of the wastewater, and thus facilitates the growth of the biofilm (Hvitved-Jacobsen and Nielsen, 2000). The slow flowing wastewater sometimes increases the thickness of the diffusive layer on the biofilm and reduces the oxygen and nutrient supply, and limits the sulfide production.

- Surface area:

The flow influences the free water surface and as such determines the submerged pipe surface in which the biofilm layer may form.

- Hydraulic Retention time:

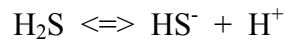
Retention time is an important factor particularly in force mains, submerged sewer in the presence of less oxygen. With the increase in time, more oxygen is consumed, redox potential decreases, stabilizes more organic carbon and thus the growth of SRB increases.

### **3.6 Distribution of Hydrogen Sulfide in Air-Water Interphase in a Sewer**

The extent of the odor problem from a wastewater network not only depends on the rate of sulfide production but also the rate of  $H_2S$  emission to the sewer atmosphere. Modeling on Sulfide formation process in a sewer network has been studied extensively by various workers (Thistlethwayte, 1972; Boon and Lister, 1975; Hvitved –Jacobsen et al. 1988; Nielsen et al. 1998). The odor does not arise as long as sulfide remains soluble in the water phase. Air-water transfer mechanism is, therefore, important to understand for  $H_2S$  emission in a sewer atmosphere (Yongsiri et al. 2005). However, the concept of mass transfer of hydrogen sulfide emission in a gravity sewer has been studied through the modeling approach as proposed by the EPA (1974).

In wastewater, the  $H_2S$  emission takes place from the free water surface. In this emission process, the main component involved is the molecular (aqueous)  $H_2S$  i.e.,  $H_2S_{(aq)}$ . Theoretically, it has been observed that during dissociation of  $H_2S$ , the bisulfide ion ( $HS^-$ ) coexists with  $H_2S_{(aq)}$  at some pH value of the wastewater and cannot pass through the air-water interface (Thistlethwayte, 1972; USEPA, 1974; Hvitved-Jacobsen, 2002). Therefore,  $H_2S$  dissociation occurs in wastewater as per following equation:





$$\text{Log} (\text{HS}^-)/(\text{H}_2\text{S}_{\text{aq}}) = \text{pH} - \text{pK}_a \quad (1)$$

Here, with reference to  $\text{pK}_a$  (negative logarithm of  $(\text{H}_2\text{S}_{\text{aq}})/\text{HS}^-$  equilibrium constant), acidic pH has an important role in leading the  $\text{H}_2\text{S}$  dissociation towards increasing the  $\text{H}_2\text{S}_{\text{(aq)}}$  fraction. On the other hand, the alkaline pH will reduce the  $\text{H}_2\text{S}_{\text{(aq)}}$  fraction.

The partitioning of  $\text{H}_2\text{S}$  between water and air phases at a given temperature and under equilibrium condition can be described as:

$$H_{\text{c,H}_2\text{S}} = H_{\text{H}_2\text{S}} / RT = C_{\text{A,H}_2\text{S}} / C_{\text{s,H}_2\text{S}} \quad (2)$$

Where  $H_{\text{c,H}_2\text{S}}$  = Henry's law constant for  $\text{H}_2\text{S}$  (non-dimensional);  $H_{\text{H}_2\text{S}}$  = Henry's law constant for  $\text{H}_2\text{S}$  ( $\text{atm mol}^{-1}\text{m}^3$ );  $R$  = universal gas constant;  $T$  = temperature (K);  $C_{\text{A,H}_2\text{S}}$  =  $\text{H}_2\text{S}$  concentration in Air phase ( $\text{gSm}^{-3}$ ) and  $C_{\text{s,H}_2\text{S}}$  =  $\text{H}_2\text{S}$  concentration in the water phase in equilibrium with the air phase ( $\text{g Sm}^{-3}$ ).

Therefore, odor and corrosion problems depend not only on the rate of sulfide formation in the wastewater under an anaerobic condition, but also on the rate of release of  $\text{H}_2\text{S}$  gas from the wastewater surface in the sewer to the sewer atmosphere.

Based on Henry's Law, the actual partial pressure of hydrogen sulfide in the sewer headspace is low relative to the saturation partial pressure. Therefore, a hydrogen sulfide gradient is created from the surface of the wastewater to the upper sewer atmosphere and ultimately acts as a driving force for emission of  $\text{H}_2\text{S}$  in the sewer atmosphere.  $\text{H}_2\text{S}$  is produced continuously due to the reduction of sulfate by sulfate reducing bacteria and is released to the atmosphere. This hydrogen sulfide gas causes malodor to the community and a corrosion problem in the sewer.

### **3.7 Hydrogen Sulfide Toxicity**

#### **3.7.1 Route of Exposure**

As previously discussed in Chapter 1, hydrogen sulfide is highly toxic and has the ability to impact the human body in various ways. Section 3.7 of this dissertation is an attempt to understand the various exposure routes, types of health impacts reported till date and various regulations for hydrogen sulfide exposure. This section will provide wastewater operators or personnel working in wastewater industry with critical information required to minimize or prevent occupational hydrogen sulfide exposure.

H<sub>2</sub>S exposure is possible through various routes such as inhalation, oral and dermal. In a wastewater treatment plant setup, operators face a high risk of H<sub>2</sub>S exposure. Multiple cases of death or other detrimental health impacts due to H<sub>2</sub>S exposure have been reported over the years with the Poison Control Center's National Data Collection. Most fatal cases of exposure were observed related to WWTP operators working in confined spaces (Adelson and Sunshine, 1966). Table 3.5 below shows the three major exposure routes and the associated health impacts. It is observed that inhalation of H<sub>2</sub>S is the major source of exposure and causes health impacts such as death, systemic failure (respiratory, cardiovascular, gastrointestinal, hematological, musculoskeletal, hepatic, renal, and ocular), and neurological effects. There is some limited evidence of reproductive impacts due to H<sub>2</sub>S exposure by inhalation.

Table 3.5 also indicates that the Agency for Toxic Substances and Disease Registry (ATSDR) currently does not have any study on their database which could conclusively establish health impacts due to oral or dermal exposure.

The ATSDR prepares its database based on information collected via case reports and occupational and community studies continuously performed all over the world.

**Table 3.5: Exposure Routes and Associated Health Impacts**

Exposure Routes	Health Impact						
	Death	Systemic Effect	Immunological Effect	Neurological Effect	Reproductive Effect	Development Effect	Cancer
<b>Inhalation</b>	<u>Yes</u>	<u>Yes</u>	None	<u>Yes</u>	Limited Data	None	None
<b>Oral</b>	None	None	None	None	None	None	None
<b>Dermal</b>	None	None	None	None	None	None	None

None - No data base found on ATSDR website

Source: Compiled from ATSDR

### 3.7.2 Reported Health Effects

Based on information listed in Table 3.5, above, detrimental health impacts due to H<sub>2</sub>S are primarily due to inhalation. Discussion will therefore be based on inhalation exposure routes and associated health risks such as death, systemic effects, and neurological effects.

Death: acute H<sub>2</sub>S exposure for concentration 500 ppm or more has led to loss of life (Beauchamp et al. 1984). WWTP operators should be particularly cautious of confined work spaces in a treatment plant and sludge plant as H<sub>2</sub>S concentration has a high probability to reach

500 ppm or more (Adelson and Sunshine, 1996; NIOSH 1985a). Acute exposure causes respiratory failure, coma, and cyanosis, which ultimately can lead to death of an individual. It must be noted that ambient air outside the perimeter of a wastewater infrastructure such as WWTP would rarely reach a concentration high enough to cause acute exposure leading to the death of an individual living near a wastewater facility.

The ATSDR has reported limited information on human fatality due to chronic H<sub>2</sub>S exposure. Studies were performed in the City of Rotorua, New Zealand, which is known for H<sub>2</sub>S emissions due to the natural geothermal activity. Bates et al. 1997 studied mortality rates for certain diseases in Rotorua and compared the same to the rest of New Zealand. This study concluded that chronic exposure of H<sub>2</sub>S could not be established as a valid cause for elevated mortality rates in the city as compared to the rest of the country.

#### **Systemic Effects:**

- Respiratory - acute exposure of >500 ppm H<sub>2</sub>S can cause rapid respiratory failure (Beauchamp et al. 1984). Respiratory distress has been noted in workers exposed to >40 ppm for <25 minutes (Spolyar 1951). A spirometric test comparing reduced lung function between sewer and water treatment plant workers was performed by Richardson, 1995. Significantly high spirometric values (FEV<sub>1</sub>/FVC) were observed among sewer workers as compared to water treatment plant workers. The study also found non-smoking sewer workers to be at a higher risk of obstructive lung diseases than their non-smoking water treatment plant counterparts.

- Cardiovascular - no specific cases were reported of cardiovascular irregularities related to wastewater operators. Acute H<sub>2</sub>S exposure leading to cardiovascular anomalies has been reported (Arnold et al. 1985). Electrocardiograms (EKGs) taken 2.5 hours after H<sub>2</sub>S exposure (<5 minutes) on workers showed cardiac arrhythmias (Krekel 1964). Extreme tachycardia, hypo, and hypertension were observed in workers subjected to unknown concentrations of H<sub>2</sub>S (Thomas 1969).
- Gastrointestinal - nausea and vomiting have been repeatedly reported on several occasions after inhalation of H<sub>2</sub>S (Allyn 1931; Audeau et al. 1985; Deng and Chang 1987; Krekel 1964). Acute health effects on a community have been studied. A two-day study which recorded 96.4 ppb (4 hour concentration) and 31 ppb (24 hour average) from a pulp industry resulted in a significant increase in reporting of nausea from the residents living near the plant (Haahtela et al. 1992).
- Musculoskeletal - exposure of 5 - 10 ppm of via H<sub>2</sub>S oral inhalation increased blood lactate concentrations. Studies found that men were sensitive to this effect at 5 ppm, whereas women showed sensitivity at 10 ppm (Bhambhani et al. 1996b, 1997).
- Endocrine - no studies could be found on the ATSDR website related to the endocrine effect due to H<sub>2</sub>S exposure on humans.
- Ocular - Keratoconjunctivitis, photophobia, and punctuate corneal erosion have been reported by individuals subjected to acute high H<sub>2</sub>S concentrations (Ahlborg 1951; Luck and Kaye 1989). Stinging of eyes has been regularly reported due to acute occupational H<sub>2</sub>S exposure (Audeau et al. 1985). Communities (mean annual exposure 4.3 ppb and 70 ppb peak) adjoining industrial units emitting H<sub>2</sub>S have reported 12 times more eye irritation than communities without such exposure (Jaakkola et al. 1990).
- Body weight - no studies could be found on the ATSDR website related to endocrine effect due to H<sub>2</sub>S exposure on humans

### **Neurological Effects**

As per the ASTDR, available information on neurotoxic effects due to acute H<sub>2</sub>S poisoning in humans is compiled from case reports. Exposure concentrations and duration, in a majority of the reported cases, are an estimate or unknown. However, neurological effects due to occupational exposure include fatigue, poor memory, dizziness (Beauchamp et al. 1984). Other cases have reported insomnia, vertigo, convulsions, headache, etc. (Arnold et al. 1985; Kerkel 1964).

Chronic exposure at the work place has been reported in workers working in the shale industry. Workers exposed to 20 ppm or more of H<sub>2</sub>S exposure developed neurological effects such as

fatigue, loss of appetite, poor memory, and dizziness. It was also observed that the frequency of the symptoms were directly proportional to the years of employment (Ahlborg 1951).

### **3.7.3 Exposure Regulations and Guidelines**

International, federal, and state government organizations regularly monitor exposure and toxicity cases (including H<sub>2</sub>S exposure) to update their regulations to better protect the public health. Regulators and public health professionals often review the Minimal Risk Levels (MRLs) for a toxic substance which are developed as part of the toxicological profile for a particular substance. MRL is an estimated human exposure level below which any appreciable noncancerous health risk in humans is unlikely. During toxicological profiling, MRL is typically established for acute (1 - 14 days), intermediate (15 - 365), and chronic (more than 365 days). The ATSDR has established MRLs for H<sub>2</sub>S for acute (0.07 ppm) and intermediate (0.02 ppm) duration. It is important to understand that Haber's Law states that the severity of toxic effect depends on total exposure which is a product of concentration (C) duration of exposure (t). For example, fatal H<sub>2</sub>S exposure of humans can take place at 150 ppm over exposure duration of 6 hours; The same adverse health impact can take place at 650 ppm for a little exposure duration of 6.5 minutes (Guidotti, 1994). Thus, the probability of an undesirable health impact is directly proportional to the concentration and duration of exposure. The MRL for H<sub>2</sub>S as discussed above and the Recommended Exposure Limits (REL) and Permissible Exposure Limit (PEL) as listed in Table 3.6 below are adjusted based on the duration of exposure. Therefore, WWTP operators need to be mindful of higher health risks associated as they are continuously exposed to elevated levels of H<sub>2</sub>S and other gases in their occupational environment.

So far, the ATSDR has not found sufficient evidence to establish an MRL for dermal exposure. It should, however, be noted that exposure above the MRL does not guarantee a detrimental health effect. Also, the MRL is intended to be a screening tool to assist regulators in deciding if REL or PEL need to be established for a given toxin. Therefore, the MRL values cannot be enforced by law nor be the basis for any clean-up action of a site.

Regulation standards established to protect occupational hazards and the community at large are primarily aimed at preventing keratoconjunctivitis (eye irritation) and respiratory tract irritation (Guidotti, 1994). Table 3.6 below lists various exposure limits from different national, state, and international organizations for H<sub>2</sub>S concentration in ambient air.

**Table 3.6: Hydrogen Sulfide Exposure Limits**

Agency		Duration	REL/PEL Concentration	Reference
International (Ambient)	World Health Organization (WHO) (REL <sup>1</sup> )	24 hour average	0.11 ppm	WHO 2006
National (Indoor)	National Institute for Occupational Safety & Health (NIOSH) (REL <sup>1</sup> )	10 minute ceiling TWA	10 ppm	NIOSH 2006
		Immediately Dangerous to Life & Health (IDLH) <sup>2</sup>	100 ppm	
	Occupational Safety & Health Administration (OSHA) (PEL <sup>4</sup> )	Acceptable ceiling concentration <sup>3</sup>	20 ppm	OSHA 2006
		Maximum <sup>5</sup> (10 minutes with no other exposure)	50 ppm	
Selected State (Ambient)	Arizona	1, 24 hours	0.045 ppm, 0.027 ppm	Arizona DEQ 2005
	California	1 hour	0.03 ppm	CalEPA 2005
	Delaware	1 hour	0.03 ppm	Delaware DNREC 2005
	Montana	1 hour	0.05 ppm	Montana DEQ 2005
	Nevada	1 hour	0.08 ppm	Nevada DEP 2005
	New York	1 hour	0.01 ppm	New York DEC 2005
	Wisconsin	1 hour	0.083 ppm	Wisconsin DNR 2004

Source: Abridged from Toxicology Profile for Hydrogen Sulfide; ATSDR 2006

1. Recommended Exposure Level (REL): NIOS time-weighted average (TWA) concentration for 10-hour work day, 40-hour week.
2. Immediately Dangerous to Life & Health (IDLH): Maximum environmental concentration of a contaminant which one could escape within 30 minutes without any escape impairing syndrome or irreparable health effects.
3. Acceptable Ceiling Concentration: A concentration of a substance that should not be exceeded, even instantaneously.
4. Permissible Exposure Limit (PEL): An OSHA allowable exposure level in workplace air averaged over an 8-hour shift of a 40-hour week.
5. Maximum- Acceptable maximum peak above ceiling concentration for an 8-hour shift for not more than 10 minutes when no other exposure occurs.

## **3.8 Jefferson Parish Wastewater Collection System**

### **3.8.1 Overview of the Collection System**

Jefferson Parish (JP) is located in southeastern part of Louisiana (LA). It is bounded by Lake Pontchartrain in the north, St. Charles and Lafourche Parishes in the west, Orleans and Plaquemines Parishes in the east, and the Gulf of Mexico in the south. The sewerage system is intersected by the Mississippi River into the East and West Bank collection system.

As per the U.S. Census Bureau, 2012, JP has a total area of 766 square kilometers and is home to 434,000 residents. In the early twentieth century, the Parish residents were initially serviced by individual septic tanks and these facilities used to discharge to the ground or one of the numerous surface water systems in the region. With the growth in population and subsequent establishment of various local, state, and federal regulations, the JP sewer system was modernized. In the 1960s -70s the JP sewer system operated 7 wastewater treatment plants on the East Bank and 14 WWTPs on the West Bank. Maintaining and operating close to 21 WWTP proved to be a significant challenge. By the late 1980s the number of WWTPs was consolidated to one on the East bank and five on the West bank. The current WWTPs and their respective average daily capacity million gallons per day (MGD) operated by JP are as follows (Table 3.7):

**Table 3.7: Designed Average Daily Flow**

<b>Treatment Plant</b>	<b>Average Daily Flow</b>
Bridge City	8 MGD
Marrero	12 MGD
Harvey	15 MGD
Rosethorne	0.2 MGD
Jonathan Davis	0.2 MGD
East Bank	15 MGD

Source: Jefferson Parish Department of Sewerage

It may be noted that the cities of Harahan and Kenner are located within Jefferson Parish, but they operate and maintain separate sewer collection and treatment systems.

Due to the unique topography of JP, sewage generated by various sources such as residence, schools, commercial property, and industry is collected by a service lateral from inside the property line and is in-turn connected to the Parish-maintained gravity line. The gravity lines often flow into a manhole which, in turn, are often connected to a larger diameter gravity line to carry the flow to a nearby wet well of a lift station. The lift station then pumps the flow received at periodic intervals through a force main to the next lift station or regional force main or, in some instances, directly to the headworks of a WWTP. The treatment plant receiving the flow processes the influent and eventually discharges the effluent into the Mississippi River or Barataria Bayou for Rosethorne and Jonathan Davis WWTPs. The sewer collection system in its present form comprises of the following infrastructure:

- Total number of Sewer Manholes 18,500
- Total number of Sewer Pump Stations 540
- Total length of Gravity Sewer Pipes 2,575 kilometers
- Total length of Force Mains 280 kilometers
- Total Number of WWTPs 6

*Source: Jefferson Parish Wastewater Collection Inflow and Infiltration Modeling and Assessment, August 2007, Hartman Engineering, Inc. and Digital Engineering*

### **3.8.2 East Bank Collection System**

The East bank collection system handles flow from all Jefferson Parish unincorporated areas and is bounded to the north by Lake Pontchartrain, on the south by the Mississippi River, on the west by the City of Kenner, and on the west by Orleans Parish (Figure 3.4).

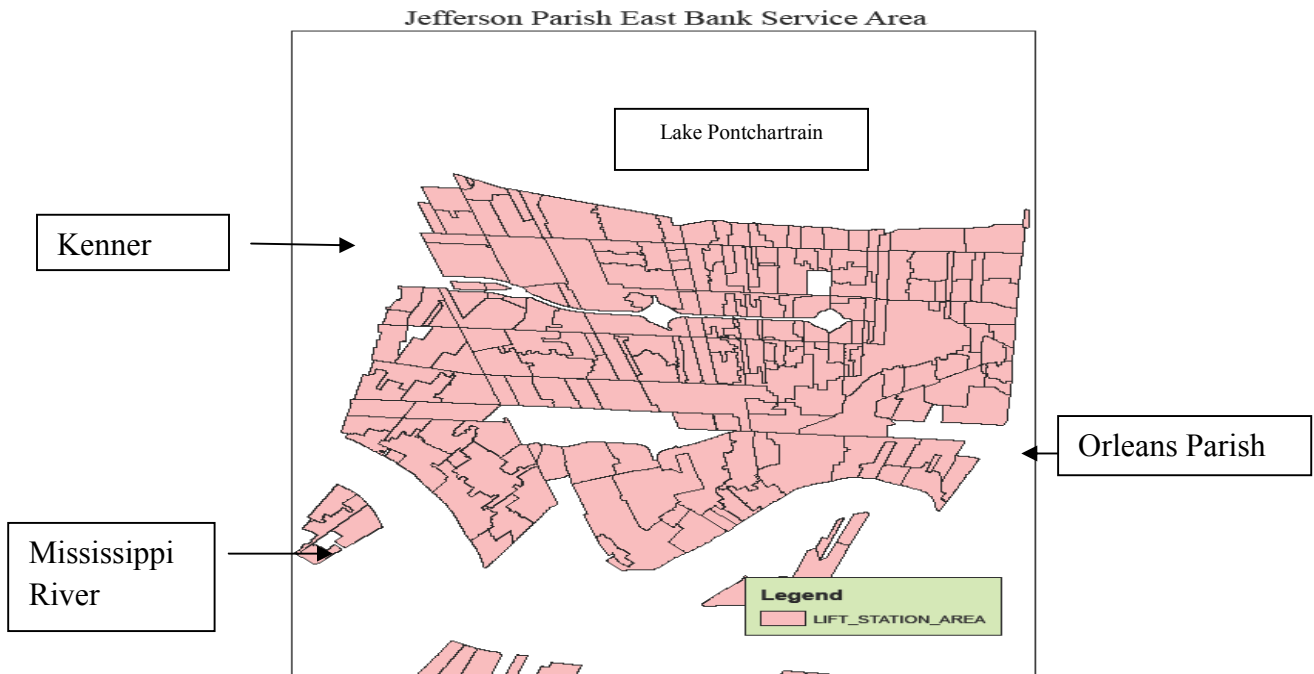
The system comprises of 810 kilometers of gravity sewer and 279 lift stations of various capacities. The East bank collection system has 10 major sewer lift stations which, in turn, receive flow from 55 secondary sewer lift stations. The secondary lift stations, in turn, accept



flow from 179 tertiary sewer lift stations. Table 3.8 below lists the East bank collection system primary sewer lift stations with the number of associated secondary and tertiary sewer lift stations.

The ten primary sewer lift stations feed the East bank wastewater treatment plant primarily via one of the three force mains. Eight of the ten primary sewer lift stations discharge into a common force main beginning at the G6-9 Helios sewer lift station as a 1.0-meter (42-inch) line. This force main progressively increases in size and enters the treatment plant as a 1.8-meter (72-inch) line. Sewers lift station E3-7 (Camp Plauche) pumps into the treatment plant with a 0.9-meter (36-inch) force main. An 8-inch force main brings in flow from the E4-3 Saints Camp sewer lift station. Figure 3.5, shows the various lift stations and associated force mains.

**Figure 3.4: East Bank Service Area**

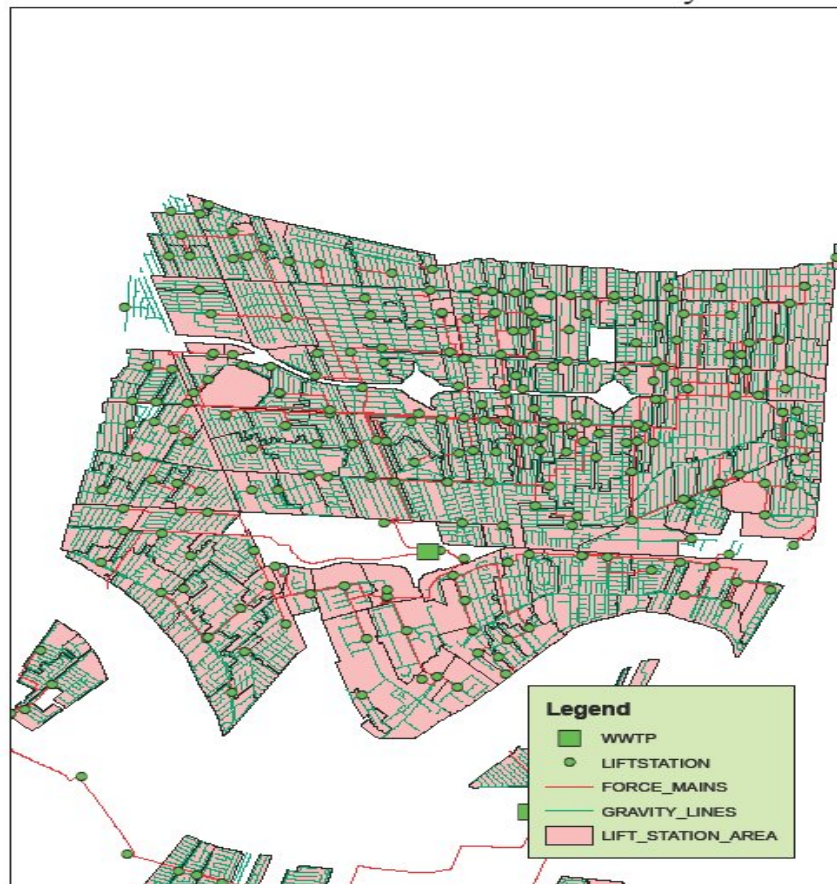


**Table 3.8: Primary and Associated Upstream Sewer Lift Stations**

<b>Primary Sewer Lift Station</b>	<b>Sub-basin Name</b>	<b>Number of Secondary Lift Stations</b>	<b>Number of Tertiary Lift Stations</b>
E6-7	Transcontinental & Vineland	3	54
E3-7	Camp Plauche	10	52
G6-9	Helios	11	48
F6-2	West Napoleon	6	35
E5-4	Transcontinental & West Metairie	2	15
F6-11	Houma & West Napoleon	2	12
G6-4	Galleria	3	9
F6-5	Cleary & West Napoleon	2	9
F6-1	Clearview & West Napoleon	2	2
E4-3	Saints Camp	1	1
<b>Total</b>		<b>55</b>	<b>237</b>

Source: Adapted from Jefferson Parish Department of Sewerage Inventory List

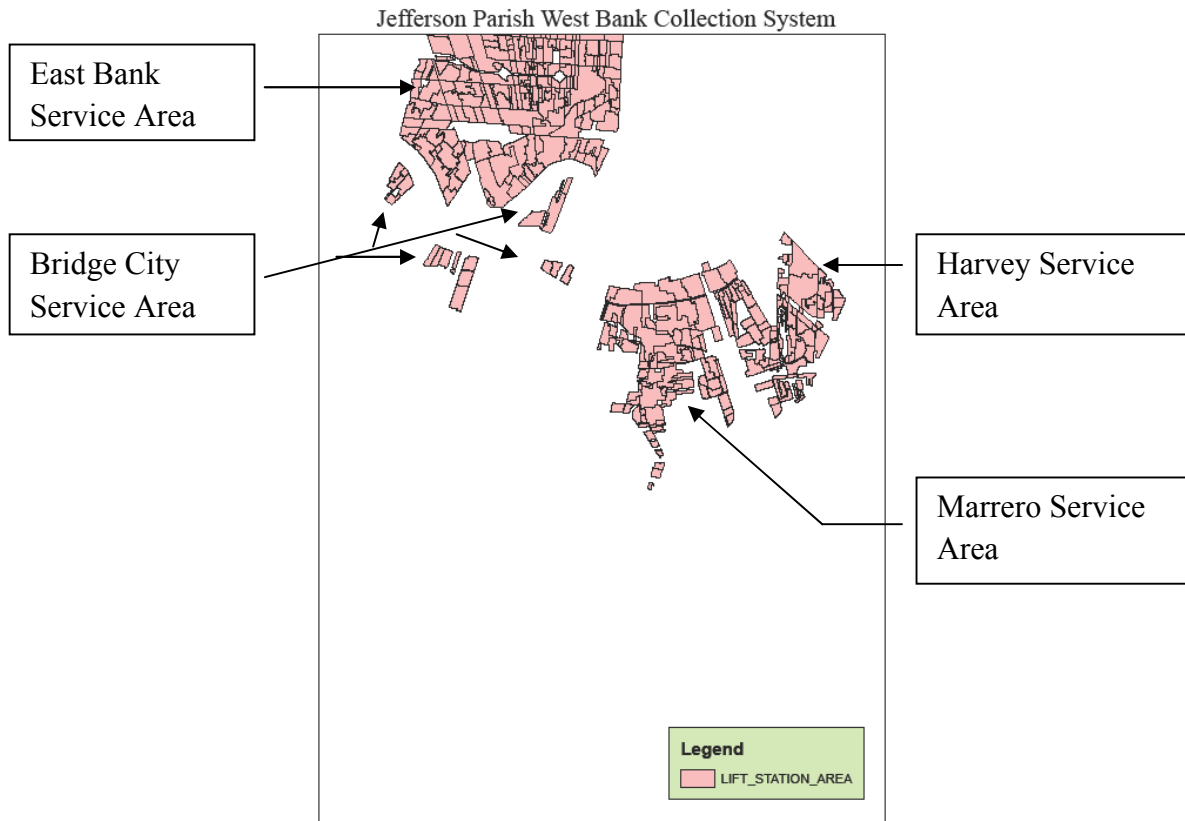
**Figure 3.5: East Bank Lift Stations and Force Mains**  
Jefferson Parish East Bank Collection System



### 3.8.3 West Bank Collection System

This system collects Jefferson Parish flow from the area bounded by the Mississippi River in the north, swamp land towards the south, Orleans Parish to its east, and St. Charles Parish to the west (Figure 3.6). The system comprises 1,126 kilometers (700 miles) of gravity sewer and 261 lift stations of various capacities. The West bank collection system is served by Bridge City WWTP, Marrero WWTP, Harvey WWTP, Rosethorne WWTP, and Jonathan Davis WWTP. Of these four WWTPs, Rosethorne and Jonathan Davis WWTPs are small 0.2 MGD package treatment plants. This report, therefore, focuses on the remaining three WWTPs located on the Jefferson Parish West bank.

**Figure 3.6: West Bank Service Area**

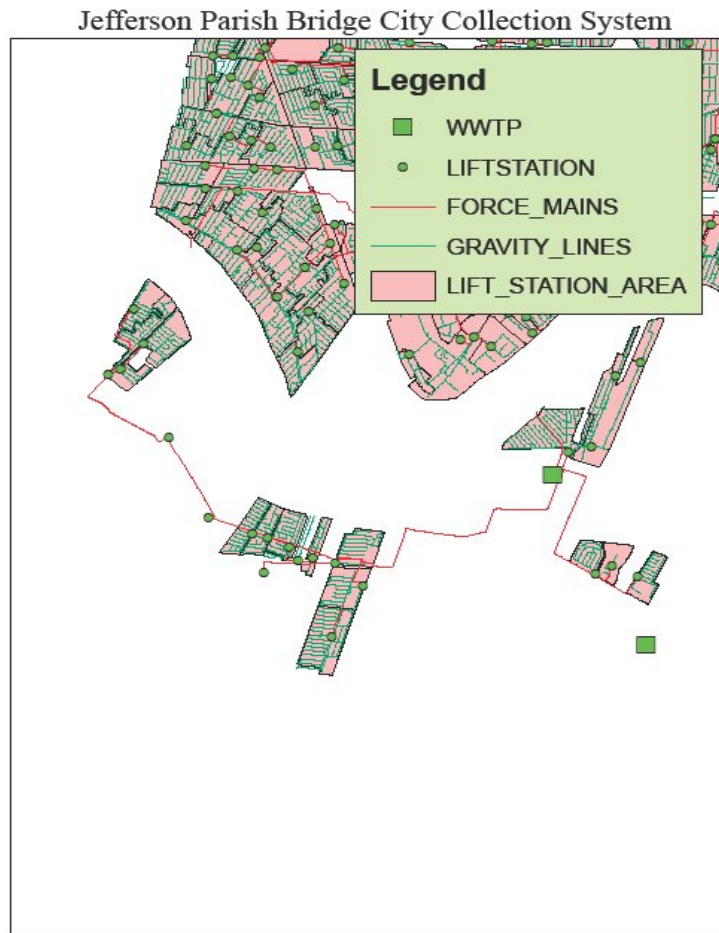


### **Bridge City WWTP**

This plant designed in 1987 and modified in 1991 has a capacity of 6 MGD average daily flow. The plant receives flows from all unincorporated areas west of the City of Westwego. In addition, the plant receives pre treated industrial waste from Avondale Shipyard, landfill leachate from Jefferson Parish landfills, other neighboring industries, and sludge hauled from the City of Gretna. Treated effluent is pumped to the Mississippi River using a 0.9-meter (36-inch) force main. The Bridge City collection system has four primary pump stations.

Figure 3.7 below shows the various lift stations and associated force mains for this service area. The plant receives flow from three influent force mains.

**Figure 3.7: Bridge City Lift Stations & Force Mains**



### **Marrero WWTP**

The Marrero WWTP built in 1965 is one of the oldest serving plants in Jefferson Parish. Marrero has a capacity of 12 MGD average daily flow and treats wastewater from the central portion of the West bank, except from the City of Westwego. The Marrero area, due to the service area size, is sub-divided into three sub-basins. Table 3.9 below lists the important details regarding the individual sub-basin. The Marrero WWTP receives flows from 101 lift stations spread all across the service area.

**Table 3.9: Marrero WWTP Service Area Breakdown**

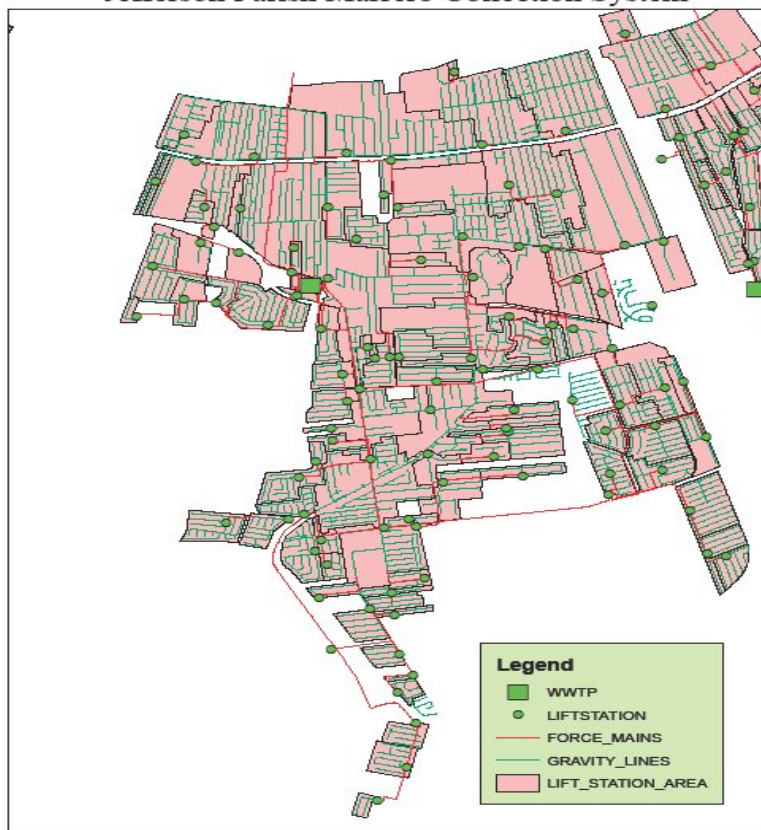
Sub-Basin Name	Type of Lift Station				Sub-basin Total
	Primary	Secondary	Tertiary	Quaternary	
Lafitte-Larose	1	4	20	9	34
Ames-Mayronne	1	11	17	11	40
Marrero Miscellaneous	1	8	10	8	27
Individual Total	3	23	47	28	<b>101</b>

Source: Adapted from Jefferson Parish Department of Sewerage Inventory List

Figure 3.8 below shows the various lift stations and associated force mains for this service area.

**Figure 3.8: Marrero Lift Stations and Force Mains**

Jefferson Parish Marrero Collection System



## Harvey WWTP

The Harvey WWTP built and commissioned in 1984 is designed to handle 15 MGD of average daily flow. It receives flow from the eastern portion of the West bank, except for the incorporated City of Gretna. The Harvey service area has been sub-divided into three sub-basins. Table 3.10 below provides important details of the sub-basin. The Harvey WWTP receives flow from 98 lift stations.

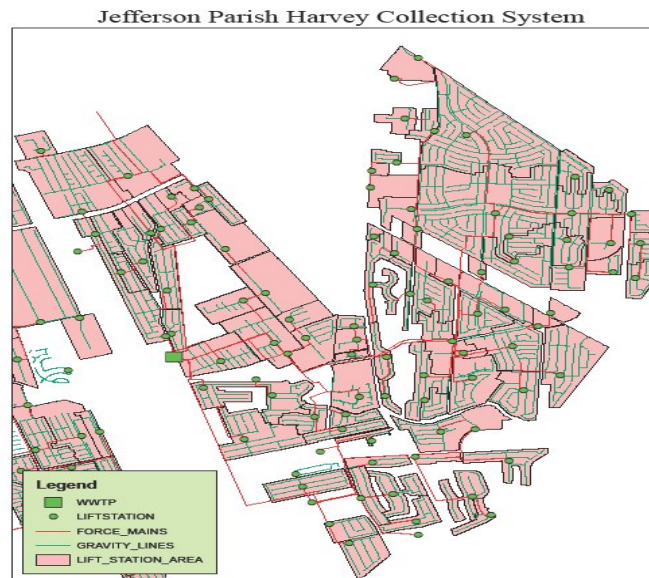
**Table 3.10: Harvey WWTP Service Area Breakdown**

Sub-Basin Name	Type of Lift Station				Sub-basin Total
	Primary	Secondary	Tertiary	Quaternary	
Lake Timberlane	1	9	6	2	18
Meadowbrook	1	7	15	15	38
Miscellaneous	8	15	11	6	40
Barataria	2	0	0	0	2
Individual Total	12	31	32	23	<b>98</b>

Source: Adapted from Jefferson Parish Department of Sewerage Inventory List

Figure 3.9 below shows the various lift stations and associated force mains for this service area.

**Figure 3.9: Harvey Lift Stations and Force Mains**



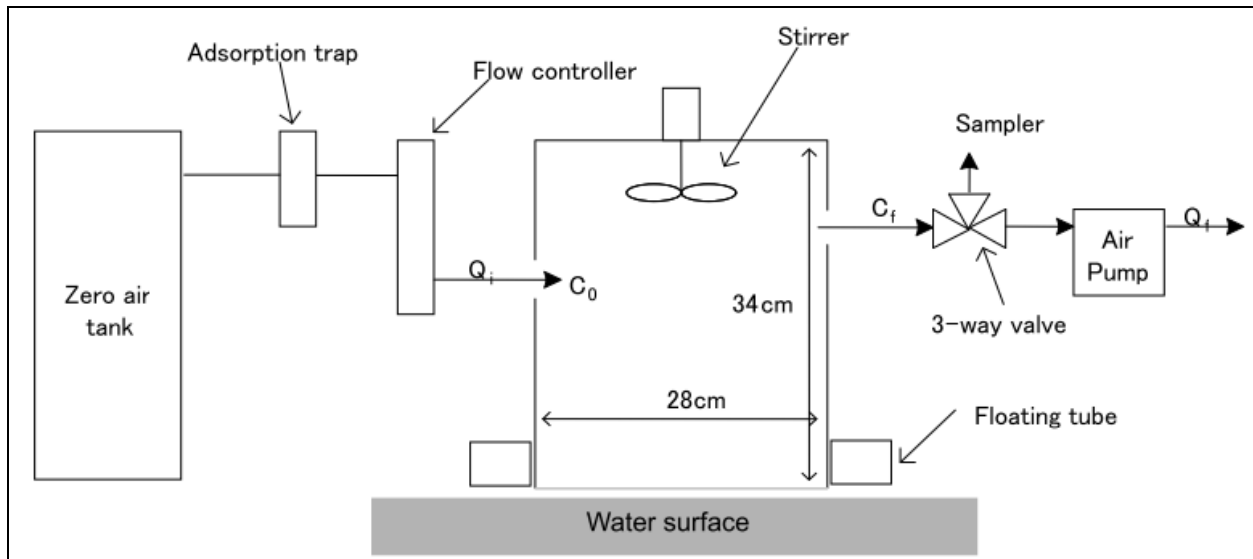
### 3.9 Conventional Hydrogen Sulfide Emission Study

In an effort to gain an understanding of current or contemporary H<sub>2</sub>S emission studies being performed at WWTPs and collection systems, the author reviewed journal articles and held discussions with engineering consultants and wastewater personnel. Due to space restrictions, three H<sub>2</sub>S emissions studied are selected from; North America (USA), Europe (Denmark), and Asia (South Korea). In the past, researchers have conducted emission studies for Reduced Sulfur Compounds (RSC) (including H<sub>2</sub>S) for various collection systems and treatment units. This section is an attempt to highlight the salient features of past research works and identify the potential for further research.

#### 3.9.1 Flux Chamber Study

Researchers at the Department of Earth and Environmental Sciences, Sejong University, South Korea measured emission factors of reduced sulfur compounds (RSCs: hydrogen sulfide, methyl mercaptan, dimethyl sulfide, dimethyl disulfide), ammonia, and trimethylamine from a medium sized WWTP in South Korea. Grab air samples were collected using a dynamic flux chamber unit (DFC) (Figure 3.10) for a period of three days for the following open air treatment units: i) primary settling tank, ii) aeration basin, and iii) final settling tank.

**Figure 3.10: Schematic of Air Sampling Using Dynamic Flux Chamber**



Source: Emission Characteristics and Factors of Selected Odorous Compounds at a Wastewater Treatment Plant, Sensor Journal, 2009



The air samples were collected in a tedlar bag from the sampler as shown in the schematic and transported to an outside laboratory for analyzing the RSC using gas chromatography (GC) with a pulsed flame photometric detector (PFPD). Emission fluxes for the odors RSC were established using the following mass balance equation:

$$J = \frac{V}{A} \left( L \frac{A_c}{V} + \frac{Q}{V} \right) C$$

where:

J = odor compound fluxes expressed as mass per area per time (ug/m<sup>2</sup>/minute)

V = volume of DFC (m<sup>3</sup>)

A = water surface area covered by DFC (m<sup>2</sup>)

L = the loss rate from the chamber wall per unit area as first order in concentration (m/minute)

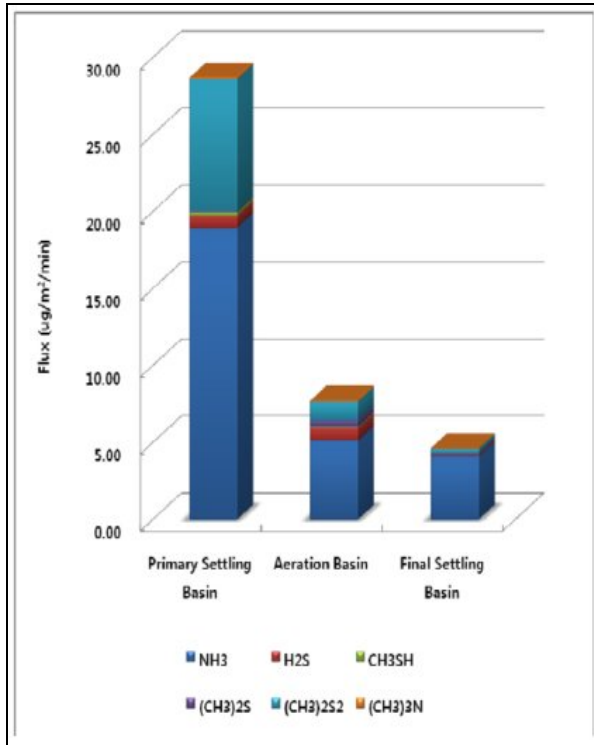
A<sub>c</sub> = surface area of the inner walls of DFC (m<sup>2</sup>)

Q = flow rate within the DFC (m<sup>3</sup>/minute)

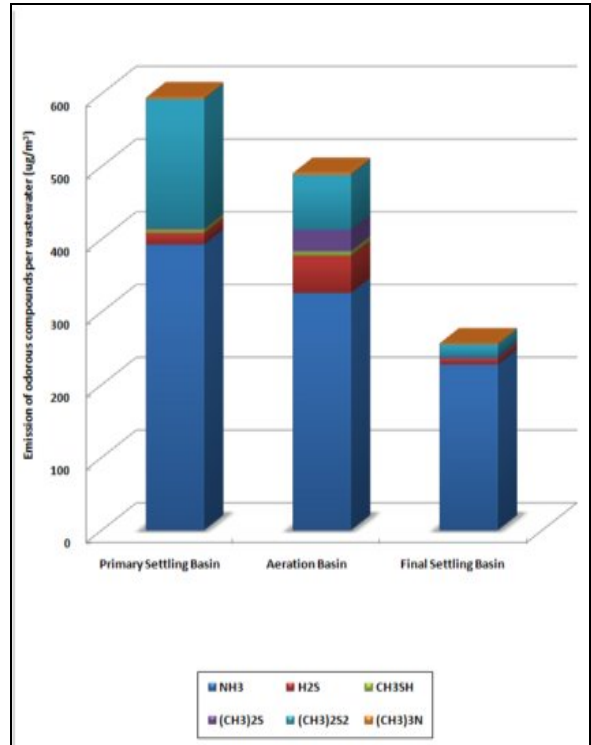
C = concentration of odor compounds in the DFC (ug/m<sup>3</sup>)

Researchers used the concentration obtained from the GC analysis and divided that with flow at the respective unit to arrive at the emission rates of various RSCs. Figures 3.11 and 3.12 illustrate the results from the DFC study performed at Sejon University.

**Figure 3.11: RSC Emission Flux for WWTP Units**



**Figure 3.12: RSC Emission per cubic meter of Wastewater**



Source: Emission Characteristics and Factors of Selected Odorous Compounds at a Wastewater Treatment Plant; Eui-Chan Jeon et. al

### 3.9.2 Establishing Emission Rates Using Dilution to Detection Threshold (D/T) Ratios

Municipalities hire consultants who frequently calculate D/T ratios in conjunction with the Recognition Threshold (R/T) ratio to ascertain the Odor Emission Rate (OER) and thereby rank or prioritize treatment units for odor level. D/T ratios study is primarily based on sensory testing of air samples collected from various treatment units.

The D/T study measures the strength of odor based on number of dilutions required to reduce the strength of odor to a level at which an average person is not expected to detect the same. The methodology involves sampling odorous air samples from various WWTP units for which the study must be conducted. Grab air samples are collected in tedlar bags and sent to a laboratory where an olfactometer is used to dilute the air samples at various ratios with fresh air. Along with the diluted odorous air, the equipment also delivers fresh air samples via a second tube to the panelist nose. Each individual member of the panel (Figure 3.13) is tasked to distinguish the odor dispensing tube from the fresh air tube.

**Figure 3.13: Panelists Performing Olfactory Test**



Source: St. Croix Sensory Inc.

Reports of choice made by various panelists are used to perform a statistical analysis to determine the level of dilution at which the odor is no longer detectable. This technique is called Forced Choice Triangular Olfactometry. Panelists are also asked to identify the dilution level at which they can first identify the odor as having any particular smell, such as rotten egg or rotten cabbage. This level of dilution is termed as the Recognition Threshold (R/T).

Based on historical data, the following thresholds have been established (Comprehensive Odor Control Study Harvey WWTP- Jefferson Parish, Jacobs Engineering, July 2010):

- D/T = 4 odors detected in the laboratory setting, but will go undetected to typical background odor in an urban setting.
- D/T = 7 odors may be detected in an urban setting, but may not be considered a nuisance in an urban setting.
- D/T = 10 odors are identified and may be considered a nuisance or offensive.

The OER for a treatment unit is calculated by multiplying the D/T ratio to the corresponding exhaust rate of the treatment unit being studied. Table 3.11 list the OER calculated and priority ranking in terms of odor emission potential for select Harvey WWTP treatment units. Table 3.11 data are reproduced from the Odor Control Study conducted by Jacobs Engineering for Jefferson Parish Harvey WWTP.

**Table 3.11: Odor Potential Rank from Various WWTP Units**

<b>Treatment Unit</b>	<b>D/T Ratio</b>	<b>OER (OU)</b>	<b>Odor Potential Rank</b>
Headworks	20,000	10	2
Aerated Grit Chamber	99000	49.5	1
Primary Clarifier Outlet Box	96000	0.7104	3
Secondary Clarifier Outlet Box	1000	0.00125	4

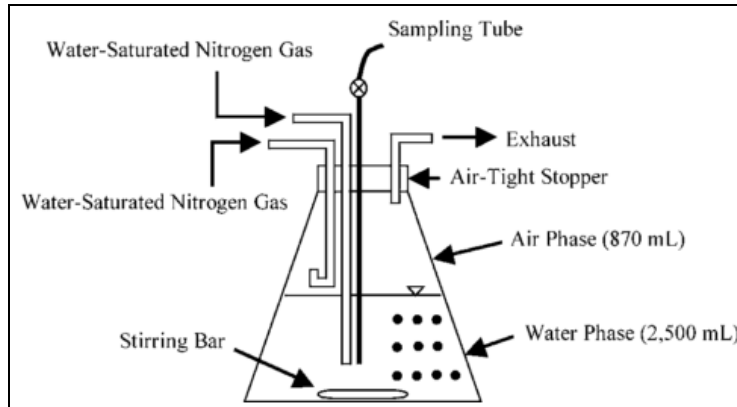
Source: Data Obtained from Jefferson Parish Dept. of Sewerage

### **3.9.3 Measuring Hydrogen Sulfide Emissions in Gravity Network**

Researchers at the Department of Environmental Engineering, University of Sohngaardsholmsvej, Denmark, performed multiple batch experiments on domestic wastewater collected from a municipal network handling exclusively domestic waste. Researchers collected wastewater samples from two different gravity lines. Wastewater samples collected to run the batch experiments were sampled between March - September of 2002 (10:00 am to 2:00 pm). Samples were collected only during a dry weather period.

Researchers conducted experiments in a closed plexiglass vessel (Figure 3.14) and established the mass-transfer coefficient of H<sub>2</sub>S (alpha factor) and the Henry's Law constant (beta factor). The hydraulic condition inside the plexiglass vessel was defined by the Froude number (Bates et al., 1966). The velocity (caused by the magnetic stirrer) inside the vessel was measured by a Laser.

**Figure 3.14: Experimental Setup Hydrogen Sulfide Emission**



Source: Influences of Wastewater Constituents on Hydrogen Sulfide Emission in Sewer Network; Chaturong Yongsiri et al.

A Doppler Anemometer was connected to a data-processing unit. The dots in Figure 3.14 show the velocity measuring points for the Laser Doppler Anemometer. The mean velocity ( $u$ ), which mimicked the velocity of wastewater inside a gravity sewer line, was computed for multiple stirring speeds. The highest Froude number applied for this study was 0.23. Based on results obtained from batch experiments, and emission sampling results from wastewater surface, the researchers generated the following equation:

$$R_{H_2S} = \alpha \{0.86f\} * \{0.86(1+0.2F^2)\} * (s*u)^{3/8} * \{C_w - (Bc_{A,H_2S}/fH_{c,H_2S,cw}) * 1.034^{(T-293)}\}$$

where:

$R_{H_2S}$ -  $H_2S$  Emission Rates ( $GSm^{-3}h^{-1}$ )

$C_A, H_2S$  -  $H_2S$  concentration in air phase  $Gsm^{-3}$

$C_w$  - dissolved sulfide concentration in water phase  $Gsm^{-3}$

$F$  - Froude number

$f$  -  $H_2S$  fraction relative to total sulfide

$H_{c,H_2S}$  - non-dimensional Henry's law constant for  $H_2S$

$s$  - sewer slope  $mm^{-1}$

$T$  - temperature K

$u$  - mean velocity  $ms^{-1}$

$\alpha$  - correction factor for overall mass-transfer coefficient in wastewater

$\beta$  - correction factor for saturation concentration in wastewater

## 4.0 Methodology

To achieve the established goals/objectives in Chapter 2, below agenda was developed for this research:

- Devising an air monitoring plan for continuously recording H<sub>2</sub>S emissions from the influent chamber of the headworks.
- Developing a plan to document variations in the H<sub>2</sub>S emissions over a relatively long period of time rather than estimating based on short term monitoring of few grab samples.
- Identifying wastewater parameters which have potential to influence H<sub>2</sub>S emissions and establishing a wastewater monitoring plan.
- Arranging the data into useable format for calculating H<sub>2</sub>S emission factors.
- Performing statistical analysis to develop a H<sub>2</sub>S model for individual WWTPs headworks and recommend roadmap for establishing a universal model.

In an effort to achieve the above agenda, this research was divided into various tasks as described below:

### Task 1: Identification of Variables Needed for the Research

Independent Variables for the Model: Flow rate; Population; Area Served; WW Temperature (or Ambient Temperature); DO; BOD; Total Sulfides, pH and Hydraulic Retention Time

Dependent Variable for the Model: Emission Rate of H<sub>2</sub>S

### Task 2: Identification and Selection of Monitoring Equipment

Continuous Monitor for H<sub>2</sub>S Concentration inside the Influent chamber

Air Flow Meter to Estimate the Volumetric Flow Rate from the influent chamber

Total Sulfides

Dissolved Oxygen

pH

Temperature

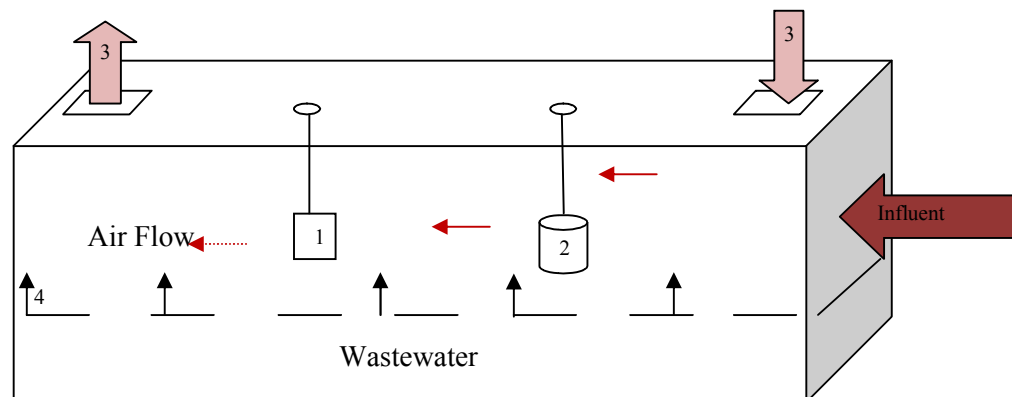
BOD

### Task 3: Procedure for Calculating H<sub>2</sub>S Emission Rate (ER)

$$\text{ER} = \text{Average H}_2\text{S Concentration} * \text{Cross Sectional Area} * \text{Average Velocity of the Gas Escaping from the Chamber}$$

Chamber sketch (Figure 4.1) below depicts wastewater flow (influent) entering an enclosed headworks influent chamber from the right. Air flow inside the chamber is maintained by some of the openings on the influent chamber tank (as represented by arrows marked “3”). Hydrogen Sulfide concentration emitted from wastewater surface is recorded by the OdorLogger (“2”). The air flow inside the headworks influent chamber is measured by the hot wire anemometer (“1”).

**Figure 4.1: Headworks Cross Sectional View**



Source: Sengupta, 2014

Legend: 1) Anemometer, 2) OdorLogger, 3) Air flow in/out of headworks chamber, 4) Air emissions from wastewater source.

### Task 4: Emission Factor Determination

EF1 = Based on Flow

EF2 =Based on Population

EF3 =Based on Area

#### 4.1 Emission Factor

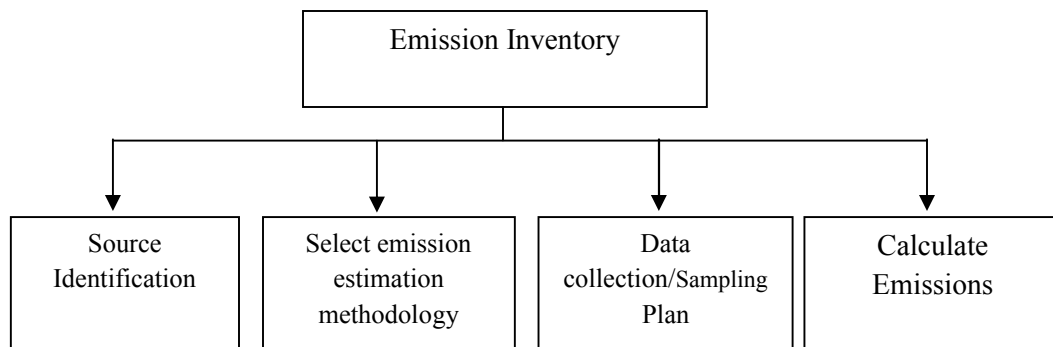
As per AP-42, EF is a representative value that combines quantity of pollutant released into the atmosphere with an activity associated to the emission of the pollutant. In this study, the pollutant of concern is H<sub>2</sub>S from WWTP headworks and the “activities” or parameters which impact emission of H<sub>2</sub>S are; i) flow of wastewater processed by the WWTP, ii) population served by a particular WWTP, and iii) service area associated with the WWTP. EF is an average value obtained from long term observations study performed during normal operations of the polluting unit. AP-42 indicates that EF formulae, which include variable parameters such as temperature, wind velocity, pollutant unit dimensions, etc., produce a more realistic estimate. Therefore, in line with the EF guidelines established by AP-42, this dissertation has based its EF calculation methodology on variables such as: i) wind velocity inside headworks influent chamber, ii) relevant dimension of headworks units, and iii) wastewater flow received at the WWTP.

This research provides preliminary EFs for WWTP headworks and attempts to understand the sensitivity of EF with respect to wastewater parameters which has the potential to impact H<sub>2</sub>S formation and emission. Based on the findings of this evaluation study, researchers could modify their methodology for any future research in this area.

#### 4.2 Framework for Calculating Preliminary Hydrogen Sulfide Emission Factor

This section formulates a methodology to calculate emission factors for H<sub>2</sub>S. The Ontario Ministry of Environment’s “Step by Step Guideline for Emission Calculation, Record Keeping and Reporting for Airborne Contaminant Discharge” published December 2007 (hereby referred to as Emission Guide) has been used as a guidance document to formulate methodology for this research. Figure 4.2 below shows the major steps involved to generate the Emission Inventory for a facility.

**Figure 4.2: Flow Chart Showing Guidelines for Calculating Air Emissions**



Source: Adapted from Step by Step Guideline for Emission Calculation, Record Keeping and Reporting for Airborne Contaminant Discharge



## Step 1 - Source Identification

Processes which typically lead to emission of airborne pollutant are: i) combustion, ii) manufacturing, iii) solvent evaporation, iv) storage, and v) fugitive discharge (Emission Guide, 2007). Based on treatment process knowledge, interaction with WWTP operators, past odor control studies performed, and multiple site visits, it was identified that fugitive emission of H<sub>2</sub>S from various treatment units (particularly WWTP headworks) at the WWTP was the primary source of H<sub>2</sub>S emission into the ambient atmosphere from the four facilities that were studied.

## Step 2 - Selection of Emission Calculation Techniques

Facilities responsible for pollutant emissions have various tools at their disposal to calculate emissions. Air emissions can be calculated by: i) Continuous Emission Monitoring System (CEMS), ii) Predictive Emission Monitoring (PEM), iii) Source Testing, iv) Mass Balance, v) Emissions Factor, vi) Emission Estimation Model, and vii) Engineering Calculation.

Table 4.1 below lists the emission sources and associates them to their preferred emission calculation techniques.

**Table 4.1 Emission Source and Preferred Emission Calculation Techniques**

<b>Emission Source</b>	<b>Emission Calculation Technique</b>
Combustion	CEMS
Manufacturing	Emissions Factor (EF), Source Testing
Solvent Evaporation	Mass Balance, Emission Factor (EF), Source Testing
Storage	Emission Estimation Model
Fugitive	CEMS, Emission Factor (EF)

Source: Adapted from Step by Step Guideline for Emission Calculation, Record Keeping and Reporting for Airborne Contaminant Discharge; Ontario Ministry of Environment

### Step 3 - Data Collection/Sampling Plan

Based on performing steps 1 and 2, it was established that the fugitive H<sub>2</sub>S emissions from the headworks influent chamber was expected to be calculated with reasonable accuracy by gathering continuous H<sub>2</sub>S concentration data from October 2012 to March 2013. This research was intended to serve as an evaluation or pilot study to understand the feasibility of calculating emission factors for various WWTP units. For this reason, the headworks, which has one of the highest H<sub>2</sub>S emission potential, was chosen to gather data for this evaluation phase study. Based on the findings of this evaluation study, EFs could be calculated for other H<sub>2</sub>S emission sources in a wastewater facility, thereby establishing an H<sub>2</sub>S emissions inventory. Resources available to gather data were judiciously used for performing this evaluation study.

1) Air Sampling - continuous monitoring of H<sub>2</sub>S concentration inside four influent chamber headworks was performed by the author for this study. The OdaLog Gas Logger (Type L2) (Gas Logger) used, continuously recorded H<sub>2</sub>S concentrations after every 5-minute interval. A single Gas Logger unit was used to monitor each of the four sampling headworks. Out of the four Gas Logger units, two units had a range of 0 - 1000 ppm and the remaining two had a range of 0 - 200 ppm. Two weeks of H<sub>2</sub>S sampling at each of the four locations indicated that the concentration ranges at the Bridge City and Marrero WWTP were in the range of 0 - 600 ppm and that of the East Bank and Harvey WWTP were typically in the range of 0 - 180 ppm. Based on the concentration ranges obtained during the 2-week period, equipment with suitable ranges were deployed at each locations. In order to record a homogenous H<sub>2</sub>S concentration, it was determined that the Gas Logger units would be installed ahead of any physical opening on the ceiling of the influent chamber. Therefore, the Gas Loggers were installed before the sluice gate openings. Care was taken to ensure that the Gas Loggers were not submerged in wastewater nor were they exposed to any ambient air. Depending on the site conditions the Gas Loggers were installed between 0.5 - 1.5 meters of the wastewater surface.

Per the manufacturer's recommendation, the units were typically recovered from the sampling locations for a period of 24 hours after a sampling session lasting for 14 days. During equipment recovery, H<sub>2</sub>S concentration data was downloaded in an Excel spreadsheet format and saved for further processing.

2) Air Velocity - was recorded inside the headworks influent chamber. Due to the extremely low air velocity (0.00 - 0.48 m/s), the author used a Hot Wire Anemometer (anemometer) for this project. The anemometer probe was inserted inside the headworks chamber perpendicular to the flow of wastewater. Per the manufacturer's recommendation, readings were measured after a lapse of 15 seconds. This is the time that the sensors of

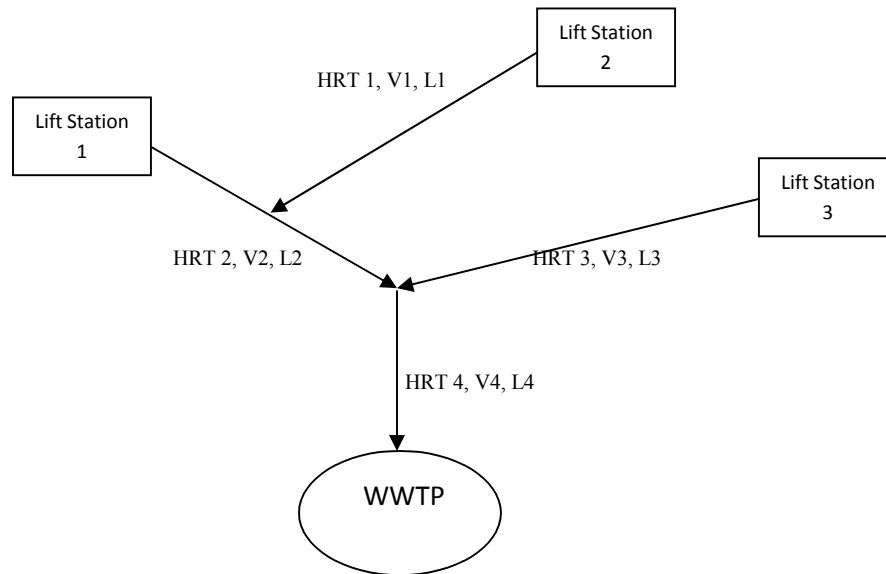
the anemometer take to get sufficiently hot upon startup. Air flow passing through the probe cools the hot wire of the anemometer probe. The higher the wind velocity, the greater is the cooling effect which, in turn, is converted and displayed as air velocity by the equipment. Air velocity was measured at multiple locations inside the headworks chamber to obtain an accurate velocity profile. The number of sampling points was controlled by individual site conditions. Air velocity was measured at each location twice a week for a period of six weeks.

3) Wastewater Flow Data - was obtained from the plant operators. Flow meters installed at the effluent pipes at each WWTP provided continuous flow information. Daily flow readings are reported by the WWTP as part of the National Pollutant Discharge and Elimination System (NPDES) permit requirement. Daily average flow data was used by the researchers for calculating the EF flow. Daily average flow readings were obtained from October 2012 to March 2013.

4) Wastewater Analysis - Wastewater samples were collected by the author from the headworks chambers at each location once a week for entire study period. Collected samples were sent to the Jefferson Parish East Bank laboratory for the following tests: i) BOD<sub>5</sub>, ii) pH, and iii) total sulfides. Dissolved oxygen (DO) was recorded by directly inserting a DO sampler probe into the wastewater flow received at the headworks influent chamber. Daily average wastewater flow data was obtained from the flow meters installed at each WWTP. All the data collected was tabulated for further processing. Sample collection was performed by the author. DO data obtained at each headworks registered 0 mg/liter. The DO level was observed to rise to 2 mg/liter during the event of force main discharge into the headworks. This is typically the case since aeration of influent happens upon force main discharge.

5) Hydraulic Retention Time (HRT) - Sewer CAD was used to model force main lengths and approximate wastewater velocities. This data was used to calculate partial hydraulic retention time (HRT). Since the majority of the force mains manifold multiple times before discharging to the treatment plant headworks, it was determined to calculate the partial hydraulic retention times. The partial HRT's calculated is the approximate time taken by wastewater to travel from its origin to the location of the manifold or point of discharge. This task was performed by the author with support from the Jefferson Parish Department of Sewerage. Figure 4.3 below shows an illustration for calculating HRT's. Due to unavailability of data such as force main lengths and manifold information at multiple locations in the entire Jefferson Parish network, this task remained incomplete. HRT data was therefore not used for any emission range calculation or was made part of the modeling input parameter.

**Figure 4.3: Schematic of Partial Hydraulic Retention Time (HRT)**



Legend: HRT 1-4 - Partial Hydraulic Retention Time, V 1-4- force main velocities, L 1-4- force main lengths

6) Population Information – The service area for each WWTP was first identified using Geographic Information Systems (GIS). Population for each service area was then obtained from the U.S. Census Bureau (2010). The population information was used to calculate the EF population.

7) Service Area Information – The service areas for each WWTP were calculated by the researchers with the help of existing GIS data base. The area information was used to calculate the EF area.

#### Step 4 - Calculating Emission Factors

The following are the formulae used to calculate EFs:

a) Emission Rates (ER) (mg/sec) =  $C \times \text{Sum} (A.V)$

- C= H<sub>2</sub>S Concentration inside the headworks influent chamber
- A= Cross sectional area inside the chamber through which the emission is expected to pass
- V= Air velocity inside the headworks influent chamber

b) Mass Emitted (kg/day) = (ER x 86,000) x 10<sup>6</sup>

c) EF-Flow (mg/cu. meter) = Mass Emitted/Flow

d) EF-Pop (mg/ head) = Mass Emitted/Population

e) EF-Area (gram/sq. kilometer) = Mass Emitted/Area

#### Step 5 - Perform Statistical Analysis

The SAS analytical model was used to perform the multivariate analysis (MVA) and develop empirical formulae for each location.

The input parameters included: i) weekly average EF-Flow, ii) weekly average EF-Population, iii) weekly average EF-Area, iv) weekly average temperature, and v) weekly wastewater parameters (BOD, pH, Total Sulfide). Dissolved oxygen was not used in the analysis as it was observed that the D.O. values were constantly in the vicinity of 0 mg/l. The D.O. level was found to increase only temporarily during force main discharge into the headworks. Similarly, partial HRT values were not used for modeling purposes as data set was incomplete. Also, it was beyond the scope of this research study to perform a full scale analysis of partial HRT for the entire Jefferson Parish sewer network.

### 4.3 Site Details

The EFs were developed based on H<sub>2</sub>S concentrations measured at the headworks influent chamber of four different WWTP in Louisiana. The Comprehensive Odor Control Report for Harvey WWTP by Jacobs Engineering, 2010, indicates that the headworks influent chamber has one of the highest H<sub>2</sub>S emissions potential among all the treatment plant units.

#### Bridge City WWTP Headworks

This site does not have a headworks building. The influent chamber is 6 meters (20 feet) wide and 1.5 meters (5 feet) deep. This location has four different force mains discharging wastewater directly into the headworks influent chamber. Table 4.2 below lists the various force main sizes and points of origin.

**Table 4.2: List of Influent Force Mains at Bridge City WWTP**

<b>Point of Origin Lift Station</b>	<b>Force Main Size</b>
Avondale LS	0.9 meter (36 inches)
Bridge City	0.5 meter (20 inches)
Bridge Circle	0.5 meter (20 inches)

Source: Jefferson Parish Dept. of Sewerage

This plant witnesses flow in the range of 2 - 8 MGD. Inside the influent chamber, researchers recorded an average flow depth of 0.9 meter (3 feet) during sampling. This location has two automatic and one manual bar screens along with a series of sluice gates to direct and divert flow per operational needs.

#### Marrero WWTP Headworks

The headworks building at this sampling site houses the influent chamber receiving the flow, two automatic bar screens, one manual bar screen, and a series of sluice gates for flow control. The length of the influent chamber is 9 meters (30 feet) wide by 1.5 meters (5 feet) deep. The Marrero WWTP has a unique collection system as all the force mains from various primary lift stations manifold and eventually discharge to the influent chamber as a single 0.9-meter (36-inch) force main.

This location typically witnesses flow between 4 - 12 MGD. Due to restrained site conditions, the average depth of the flow was recorded to be 0.9 meter (3 feet).

#### Harvey WWTP Headworks

The Harvey headworks unit comprises a building which houses the three automatic bar screens, a grit conveyor belt, and effluent sluice gates. Table 4.3 below lists the various force main sizes and points of origination.

**Table 4.3: List of Influent Force Mains at Harvey WWTP**

<b>Point of Origin Lift Station</b>	<b>Force Main Size</b>
Meadowbrook LS	0.9 meter (36 inches)
Lake Timberlane LS	0.6 meter (24 inches)
Gardere LS	0.5 meter (20 inches)
Manhattan- Broadway	0.6 meter (24 inches)

Source: Jefferson Parish Dept. of Sewerage

This treatment plant receives flow between 6 - 15 MGD. The average flow depth inside the influent chamber was recorded at 1.5 meters (5 feet) during sampling.

## East Bank WWTP Headworks

The East Bank was the final of the four sampling locations. This is also the only WWTP sampled which is located on the East bank of the Mississippi River. This site has a headworks building which houses the three automatic bar screens and sluice gates. The influent chamber, which is located outside the building, has two major force mains 1.8 meters (72 inches) and 1.06 meters (42 inches) discharging from multiple primary lift stations.

This treatment plant typically receives a flow of 8 -15 MGD during wet weather conditions.

## **4.4 Equipment Used**

### 4.4.1 Hydrogen Sulfide Odalog Logger

Hydrogen Sulfide was measured with the help of Odalog Logger L2 (Figure 4.4). This study used four such pieces of equipment with concentration ranges of 0 - 200 ppm and 0 – 1,000 ppm.

**Figure 4.4: H<sub>2</sub>S Odalog L2**



Source: [www.app-tek.com](http://www.app-tek.com)

This equipment can passively measure and record the H<sub>2</sub>S concentration inside any enclosed place. The manufacturer's technical specifications for this Odalogger are listed in Table 4.4 below.

**Table 4.4: Technical Specifications of Odalog L2**

<b>Specification</b>	
Instrument Temperature Range (C)	(-) 20 to (+) 50
Relative Humidity Range	15-90%
Dimension	Diameter 62 mm, Length 196 mm
Weight	420 grams
Power Supply	C-Size Battery
Battery Life	8 Months
Data Logging	42000 readings memory
Data Logging Interval	1 second to 1 hour

Source: [www.app-tek.com](http://www.app-tek.com)

#### 4.4.2 pH Meter

An Oakton benchtop microprocessor-based pH 700 was used to measure pH for the sample influent from various WWTP. The manufacturer’s technical specifications for this equipment are listed in Table 4.5 below.

**Table 4.5: Specifications for pH Meter**

<b>Product Type</b>	<b>pH Meter</b>
Meter style	Benchtop
Dimensions (" W)	6-7/8
Dimensions (" H)	2-3/4
Dimensions (" L)	6-1/8
Range (pH)	-2.00 to 16.00
Range (Temperature °C)	10 to 110
Accuracy (pH)	±0.01 pH
Accuracy (Temperature)	±0.5°C
Display	LCD
Calibration	Up to 6 points
Buffer recognition	USA, NIST
Datalogging (points)	100
CE Compliance	Yes

Source: [www.coleparmer.com](http://www.coleparmer.com)



#### 4.4.3 Dissolved Oxygen Meter

This research used the DOH-20D handheld dissolved oxygen monitor for in-situ monitoring of oxygen levels in the influent received inside the headworks chamber for each WWTP.

The manufacturer's technical specifications for this equipment are listed in Table 4.6 below.

**Table 4.6: Specifications for DO Meter**

<b>Parameter</b>	<b>DO</b>	<b>Temperature</b>
<b>Range</b>	0 to 19.99 mg/L	-10 to 45°C (14 to 113°F)
<b>Accuracy</b>	±1.5% FS	±0.3°C (0.5°F)
<b>Resolution</b>	0.01 mg/L	0.1°C (0.2°F)

Source: Omega

#### 4.4.4 Hot Wire Anemometer

The General Tools CIH 20DL (Figure 4.5) handheld hot wire anemometer (Figure 4.5) was used for this research to measure the low air velocity inside the headworks. The manufacturer's technical specifications for this equipment are listed in Table 4.7 below.

**Figure 4.5: Hot Wire Anemometer**



Source: Test Equipment Depot

**Table 4.7: Specifications for Anemometer**

<b>Air Flow Volume Measurement Range/Resolution</b>	0 to 2,542,700 CFM(0 to 72,000 CMM)/0.01 CFM (0.001 CMM)
<b>Air Speed Measurement Range/Accuracy</b>	2 to 7,874 ft./min (20 mm/sec to 40 m/sec)/±3%IR
<b>Thermometer Distance-to-spot (D:S) ratio</b>	8:1IR
<b>Thermometer Emissivity</b>	0.95 (fixed)IR
<b>Thermometer Measurement Range</b>	-25° to 999°F (-32° to 537°C)IR
<b>Thermometer Measurement Accuracy</b>	±5.4°F (±3°C)IR
<b>Thermometer Measurement Resolution</b>	0.1°max/ (F or C)IRT
<b>Response Time</b>	0.5 second
<b>Memory</b>	Nine readings + Max/Min/Avg+ Data Hold
<b>Extended length of telescoping hot wire probe</b>	70.8 in
<b>Dimensions</b>	7.24 x 2.75 x 1.57 in
<b>Weight</b>	11.3 oz

Source: Test Equipment Depot

## 5.0 Results and Discussion

As previously mentioned, all four WWTP headworks were subjected to continuous emission monitoring for H<sub>2</sub>S inside the influent chamber from October 2012 to March 2013. Critical wastewater parameters were collected on a weekly basis to compare their effects on emission factors at each location. This section provides the various emission factors and wastewater parameter ranges (minimum, maximum, and average) observed during the sampling period.

Tables 5.1 - 5.4 below have been divided into Emission Factor (EF) and Wastewater Parameter columns. The EF column has been further subdivided into EF-Flow, Population, and Area. The Wastewater Parameter column is subdivided into Flow, Temperature, BOD<sub>5</sub>, (BOD), pH, and total sulfide. All EFs are averaged weekly for their entire sampling period.

This chapter also compares the preliminary EFs calculated among different WWTP headworks and ranks the different headworks in terms of their H<sub>2</sub>S emission potential.

Finally, an attempt has been made to develop preliminary empirical formulae for each WWTP headwork location.

Refer to Appendix A.1 for all weekly average values discussed in this chapter.

### 5.1 Ranges of EFs and Corresponding Wastewater Parameters for WWTPs

As previously discussed in Chapter 3 (Section 3.5), sulfide production in the biofilm and sediments depends on various wastewater parameters. Based on the literature review performed, critical wastewater parameters which impact H<sub>2</sub>S formation were recorded on a daily or weekly basis. Section 5.1 discusses the variation of the EFs calculated and the attempts to explain the changes based on varying wastewater parameters.

#### Bridge City WWTP

Per Table 5.1, the EF-Flow decreased from a maximum of 755.31 mg/cu.m (week 3) to a minimum of 8.69 mg/cu.m (week 19), a reduction of approximately 99% during the entire study period. Similarly, the EF-Population decreased from 747.76 mg/head during the first week to 0 mg/head during the 19<sup>th</sup> week of sampling, a reduction of 100%. The EF-Area decreased from 532.06 g/sq. Km during the first week to 13.13 g/sq. Km during the 19<sup>th</sup> week of sampling, a reduction of 97.5%.

It should be noted that week 19, which shows the lowest EFs across all three EF indicators, was also the week which had the second highest flow (22,770.55 m<sup>3</sup>/day) as well as recorded some of the lowest temperature (17.31 Celsius) and BOD (60 mg/l) among the 21-week study period. Week 19 also had the highest pH (7.33>7.0) and the lowest dissolved sulfide levels (0 mg/l)

during the study. Similarly, weeks 3 and 1 recorded the highest EFs (see Table 5.1). Week 3 and week 1 recorded the lowest (7,030 m<sup>3</sup>/day) and third lowest (8,306.04 m<sup>3</sup>/day) flows. Weeks 3 and 1 had some of the highest (27.26 Celsius, 26.93 Celsius respectively) temperature recordings. Week 3 also recorded the highest BOD reading of 214 mg/l. Week 1 recorded the highest in terms of dissolved sulfides (2.1 mg/l), and fifth highest (6.54 <7.0) in pH reading during entire study period.

**Table 5.1: Recorded Ranges of Emission Factors and Wastewater Parameters for Bridge City WWTP**

Bridge City	Emission Factors			Wastewater Parameters				
	EF-Flow (mg/cu.m)	EF-Population (mg/head)	EF-Area (g/sq. Km)	Flow (m <sup>3</sup> /day)	Temperature (Centigrade)	BOD (mg/l)	pH	Total Sulfides (mg/l)
Minimum	8.69 (Week 19)	0 (Week 19)	13.13 (Week 19)	8,306 (Week 1)	16.79 (Week 12)	30 (Week 16)	6.37 (Week 13)	0 (Week 16-21)
Maximum	755.31 (Week 3)	747.76 (Week 1)	532.06 (Week 1)	23,961 (Week 14)	27.29 (Week 2)	214 (Week 3)	7.33 (Week 20)	2.1 (Week 1)
Average	255.41	246.29	207.28	12,458	20.12	93	6.89	0.41

#### Marrero WWTP

Per Table 5.2, the EF-Flow decreased from 910.88 mg/cu.m (week 2) to 12.89 mg/cu.m (week 19), a reduction of approximately 98.5% during the duration of this study. Similarly, the EF-Population decreased from 542.84 mg/head during the second week to 18.86 mg/head during the 19<sup>th</sup> week of sampling, a reduction of 96.5%. The EF-Area decreased from 875.02 g/sq. Km during the second week to 30.4 g/sq. Km (week 19) during the sampling period, a reduction of 96.5%.

It should be noted that week 19, which shows the lowest EFs across all three EF indicators, was also the week which had the highest flow (62,700 m<sup>3</sup>/day) as well as recorded the fifth lowest temperature (16.76 Celsius) during the study period. Week 19 also recorded a pH 7.21(>7.0) and the lowest dissolved sulfide levels (0 mg/l) during the study. Similarly, week 2 recorded the highest EFs (see Table 5.2). Week 2 also recorded the highest temperature (27.41 Celsius), high BOD (121 mg/l), low pH (6.81>7.0), and a high dissolved sulfide level of 1.65 mg/l during the entire study phase.

**Table 5.2: Recorded Ranges of Emission Factors and Wastewater Parameters for Marrero City WWTP**

Marrero	Emission Factors			Wastewater Parameters				
	EF-Flow (mg/cu.m)	EF-Population (mg/head)	EF-Area (g/sq. Km)	Flow (m <sup>3</sup> /day)	Temperature (Centigrade)	BOD (mg/l)	pH	Total Sulfides (mg/l)
Minimum	12.89 (Week 19)	18.86 (Week 19)	30.4 (Week 19)	16,213 (Week 10)	15.72 (Week 12)	34 (Week 13)	6.48 (Week 13)	0.00 (Week 19)
Maximum	910.88 (Week 2)	542.84 (Week 2)	875.02 (Week 2)	62,700 (Week 19)	27.41 (Week 2)	195 (Week 4)	7.45 (Week 17)	2.25 (Week 5, 10)
Average	269.48	164.38	264.97	28582	19.71	99	7.02	1.08

Harvey WWTP

Per Table 5.3, the EF-Flow decreased from 94.15 mg/cu.m (week 11) to 7.56 mg/cu.m (week 17), a reduction of approximately 92% for the sampling period. Similarly, the EF-Population decreased from 127.49 mg/head during the eighth week to 19.34 mg/head during the 14<sup>th</sup> week of sampling, a reduction of 85%. The EF-Area decreased from 152.51 g/sq. Km during the eighth week to 23.13 g/sq. Km during the 14<sup>th</sup> week of sampling, a reduction of 97.5%.

It should be noted that the 14<sup>th</sup> and 17<sup>th</sup> weeks, which show the lowest EFs across all three EF indicators, were also the weeks which recorded high wastewater flows in the WWTP. Week 17, in particular, witnessed the highest flow (57,265 cu. m/day) during the entire study phase, and week 14 with a flow of 40,057 cu. m/day was higher than the average flow of 36,631 cu. m/ day for the 21-week study period. In terms of temperature readings, week 14 (15.64 Celsius) had the second lowest temperature reading (3.5 degree Celsius less than the average for the study period). Week 17 (lowest EF-Flow), with a recorded temperature of 17.43 Celsius, was close to 2 degrees Celsius lower than the study phase average. Similarly, weeks 14 and 17 recorded BOD readings of 81 mg/l and 63 mg/l, which is significantly lower than the average BOD of 114 mg/l for the study period. Week 17 also recorded the third highest pH 7.20>7.0. Weeks 8 and 11 recorded the highest EFs. The flow for week 11 (22,249 cu.m/day) was the lowest recorded. The flow for week 8 at 32,040 cu. m/day was lower than the average flow recorded for the study period. Similarly, week 8 recorded a temperature of 21.94 Celsius, which was fourth highest recorded for the study period.

**Table 5.3: Recorded Ranges of Emission Factors and Wastewater Parameters for Harvey WWTP**

Harvey	Emission Factors			Wastewater Parameters				
	EF-Flow (mg/cu.m)	EF-Population (mg/head)	EF-Area (g/sq. Km)	Flow (m <sup>3</sup> /day)	Temperature (Centigrade)	BOD (mg/l)	pH	Total Sulfides (mg/l)
Minimum	7.56 (Week 17)	19.34 (Week 14)	23.13 (Week 14)	22,249 (Week 11)	14.96 (Week 12)	33 (Week 20)	6.52 (Week 1)	0 (Week 16-21)
Maximum	94.15 (Week 11)	127.49 (Week 8)	152.51 (Week 8)	57,265 (Week 17)	26.34 (Week 2)	230 (Week 10)	7.26 (Week 9)	2.15 (Week 5)
Average	43.74	63.15	75.54	36631	19.18	114.35	6.91	0.78

East Bank WWTP

Per Table 5.4, the EF-Flow decreased from 115.47 mg/cu.m (week 4) to 1.00 mg/cu.m (week 16), a reduction of approximately 99.1% from the study period. Similarly, the EF-Population decreased from 35.82 mg/head during the fourth week to 0.92 mg/head during the 16<sup>th</sup> week of sampling, a reduction of 96.5%. The EF-Area decreased from 78.56 g/sq. Km during the fourth week to 2.03 g/sq. Km during the 16<sup>th</sup> week of sampling, a reduction of 97.4%.

It should be noted that week 16, which shows the lowest EFs across all three EF indicators, was also the week which had the third highest flow (136,667 m<sup>3</sup>/day), as well as recorded some of the lowest temperature (17.02 Celsius) among the 21-week study period. Week 16 also had the lowest BOD (31 mg/l), a pH (7.43 >7.0) higher than the study period average of pH 6.97, and the lowest dissolved sulfide levels (0 mg/l). Similarly, week 4 recorded the highest EFs (see Table 5.4). Week 4 recorded the lowest flow (50,661 cu. m/day), fourth highest temperature (22.94 Celsius), and a pH (6.84 <7.0) lower than the average of pH 6.97 during the entire study phase.

**Table 5.4: Recorded Ranges of Emission Factors and Wastewater Parameters for East Bank WWTP**

East Bank	Emission Factors			Wastewater Parameters				
	EF-Flow (mg/cu.m)	EF-Population (mg/head)	EF-Area (g/sq. Km)	Flow (m <sup>3</sup> /day)	Temperature (Centigrade)	BOD (mg/l)	pH	Total Sulfides (mg/l)
Minimum	1 (Week 16)	0.92 (Week 16)	2.03 (Week 17)	50,661 (Week 4)	16.73 (Week 12)	31 (Week 16)	6.48 (Week 13)	0 (Week 14, 16-21)
Maximum	115.47 (Week 4)	35.82 (Week 4)	78.56 (Week 4)	188,613 (Week 19)	27.03 (Week 3)	289 (Week 6)	7.47 (Week 19)	2.25 (Week 5)
Average	45.23	17.77	38.97	89,874	19.79	102	6.98	0.98

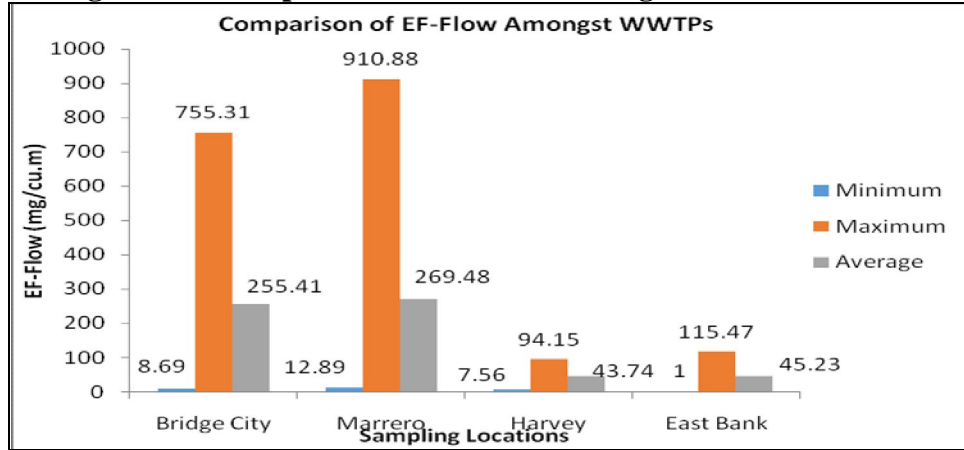
Majority of the EFs (maximum and minimum) listed in Tables 5.1 - 5.4 above could be explained due to the changes associated with the wastewater parameters. The EFs were found to be inversely proportional to flow and pH. Weeks which had some of the highest flow and pH during the entire observation period typically showed some of the lowest EFs. Correspondingly, the EFs were found to be directly proportional to BOD, temperature, and total sulfides. The weeks which had higher BOD, temperature, and total sulfide also typically had high EFs or higher than average values for the entire study period. This dissertation does recognize the fact that all average weekly EF data may not be explained based on the recorded wastewater data. It should be noted that wastewater parameters were recorded once a week. Multiple recordings of the wastewater parameters would improve the weekly average value which in turn would better correlate with the EFs which have been calculated based on continuous air emission data.

## 5.2 Comparison of EF Ranges Among Various WWTP Headworks

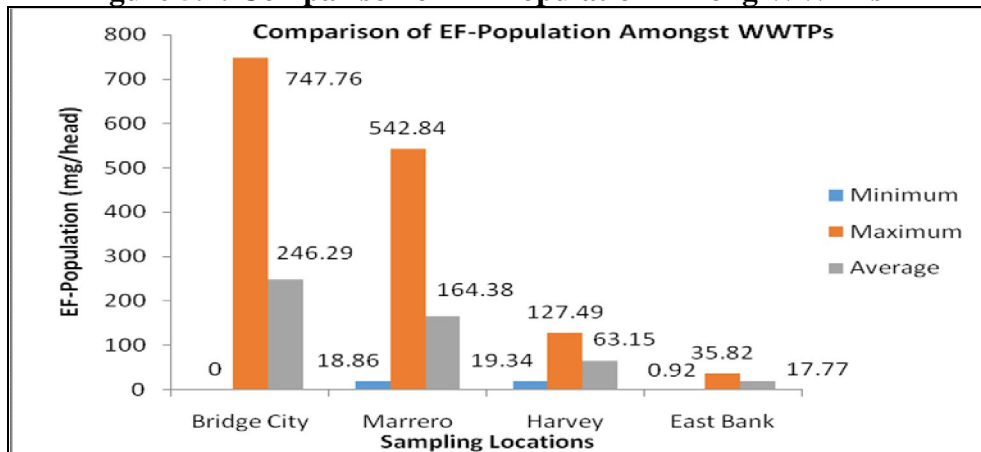
Figures 5.1 - 5.3 below show the comparison of EF-Flow, Population, and Temperature among all four WWTPs in terms of maximum, minimum, and average EF values. It was observed that the weekly average EF-Flows calculated for Marrero and Bridge City WWTPs are 5% apart. Whereas, the average EF-Flows for Harvey and East Bank WWTP are 4.3% apart. Similarly, the weekly average EF-Population for Marrero and Bridge City WWTP was calculated to be 32% apart. Similarly, the weekly average EF-Populations for Harvey and East Bank WWTP were calculated to be 72% apart.

Finally, the weekly average EF-Areas for Marrero and Bridge City WWTP were calculated to be 22% apart, whereas Harvey and East Bank WWTP's weekly average EF-Areas were 48% apart.

**Figure 5.1: Comparison of EF-Flow Among Various WWTPs**

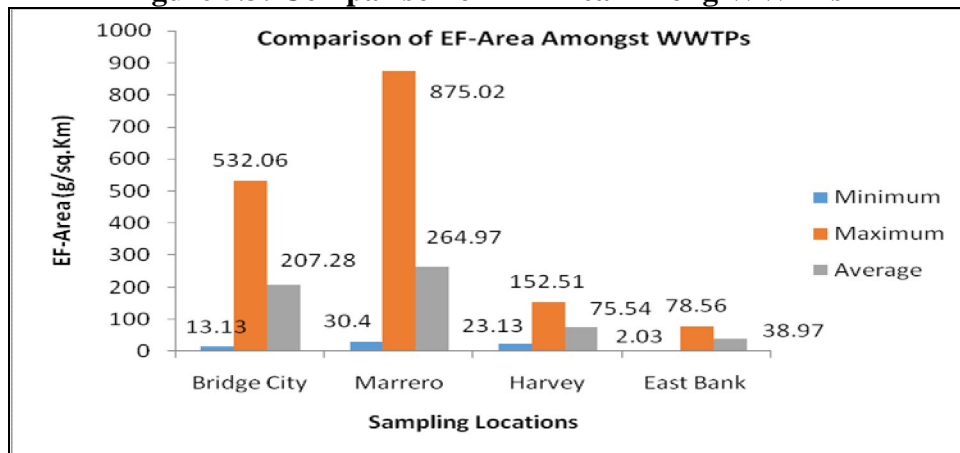


**Figure 5.2: Comparison of EF-Population Among WWTPs**





**Figure 5.3: Comparison of EF-Area Among WWTPs**



In an attempt to understand the differences in the EFs from various treatment plants, attention was directed to; i) quality of wastewater sampled/analyzed and ii) type of collection system. Based on the weekly wastewater data sampled and analyzed, it was observed that there were differences in the quality of wastewater influent at various wastewater facilities operated by Jefferson Parish. Differences were observed in wastewater parameters such as BOD, pH, total sulfides, flow and temperature amongst various treatment plant headworks. As previously discussed, all the above mentioned parameters have an ability to impact the formation and emission of hydrogen sulfide to various degrees. In addition to the differences observed in the wastewater quality, it was observed that the size and infrastructure assets (number of lift stations involved, number of manholes, size of gravity network etc) which forms part of a collection system discharging into one of the headworks influent chamber varies from one treatment plant to another. The author would also like to mention that condition of collection system assets also plays a vital role in determine the quality of wastewater reaching an influent headworks. For example if the gravity system associated with a particular treatment plant is old and suffers from sags it is possible that this system will experience higher inflow and infiltration which will impact the quality of wastewater received at the headworks thereby impacting hydrogen sulfide emissions.

### 5.3 Ranking of Various WWTP Headworks Emission Potential

Based on the average values calculated for the entire sampling period, Table 5.5 provides the preliminary ranking of WWTP (in terms of emission potential) based on individual EFs. The overall ranking was established by taking into account the individual EF rankings generated based on various EF calculations.

**Table 5.5: Comparison of Ranking of Sampling Locations**

Sampling Location	Individual EF Ranking			Overall Ranking
	EF-Flow	EF-Population	EF-Area	
Bridge City	2	1	2	2
Marrero	1	2	1	1
Harvey	4	3	3	3
East Bank	3	4	4	4

Table 5.6 below lists the individual and overall EF rankings across all the WWTPs and attempts to compare the EFs with the average wastewater parameters. The idea is to understand if a relation can be established between overall EFs and wastewater parameter rankings across all the WWTP locations. It can be seen that there are evidences to justify the overall EF ranking based on the corresponding wastewater rankings (value in parenthesis). Bridge City and Marrero WWTPs have some of the highest overall EF rankings and also some of the lowest flows. In addition, Bridge City has the lowest pH and highest temperature, whereas the Marrero WWTP recorded the highest total sulfide concentrations. The Harvey and East Bank WWTPs, which have some of the lowest EFs, also recorded some of the highest flows. It is, therefore, evident, that flow has the biggest impact on the EFs among all the wastewater parameters recorded.

**Table 5.6: EF Rankings and Corresponding Wastewater Parameters**

Sampling Location	Individual EF Ranking			Overall Ranking	Weekly Average Wastewater Parameters & Ranking				
	EF-Flow	EF-Population	EF-Area		Flow (m <sup>3</sup> /day)	Temperature (Centigrade)	BOD (mg/l)	pH	Total Sulfides (mg/l)
Bridge City	2	1	2	2	12,458 (4)	20.12 (1)	93 (4)	6.89 (4)	0.41 (4)
Marrero	1	2	1	1	28,582 (3)	19.71 (3)	99 (3)	7.02 (1)	1.08 (1)
Harvey	4	3	3	3	36,631 (2)	19.18 (4)	114.35 (1)	6.91 (3)	0.78 (3)
East Bank	3	4	4	4	89,874 (1)	19.79 (2)	102 (2)	6.98 (2)	0.98 (2)

### 5.4 Preliminary Empirical Models

As a first step, the Pearson’s Coefficient Matrix was generated to understand the correlation (range: -1 strongly inversely proportional to; +1 strongly directly proportional) and p-values (p<0.05; significant correlation).

The following Coefficient Matrix Tables provide an understanding regarding the correlation that exists between the dependent and independent variables and also the inter-correlation among various independent variables. While evaluating the matrix, independent variables (BOD, pH, total sulfide, Temperature and Flow) were chosen based on their ability to impact the outcome of the dependent variable (EF-Flow, Population and Area). Therefore, independent variables were selected for modeling purposes if they were significantly correlated to the dependent variable. In other words, if the value of the independent variable was closer to negative or positive one (1), it was determined to be significantly correlated to the dependent variable. Variables are not correlated if correlation is close to 0.

The next step is to understand the significance of the p-value in the matrix. If p<0.05, then we reject the null hypothesis (H<sub>0</sub>= not correlated) and accept the Alternate Hypothesis (H<sub>1</sub> = correlated). Therefore, in case a dependent variable shows p>0.05, it is assumed that for the raw data supplied no correlation (H<sub>0</sub>) was found between the dependent and independent variables. This leads us to drop that particular variable from being used in the final model.

The Parameter Estimate tables were next developed using only the independent variables selected based on results obtained from Pearson’s Coefficient Matrix. The software eventually generated the modeling equation and the associated R-Square value.

Emission Factor models (Flow, Population and Area Served) were generated by SAS model for each of the four headworks. Therefore, 12 different empirical models were generated at the end of this study (Table 5.7).

**Table 5.7: Tally of Models Generated**

<b>Location</b>	<b>Flow</b>	<b>Population</b>	<b>Area</b>	<b>Total Models</b>
<b>Bridge City</b>	1	1	1	3
<b>Marrero</b>	1	1	1	3
<b>Harvey</b>	1	1	1	3
<b>East Bank</b>	1	1	1	3
<b>Total Models</b>	4	4	4	<b>12</b>

### Bridge City

#### Emission Factor as a Function of Wastewater Flow (EF-Flow)

According to raw data, Flow (-0.69) was most indirectly proportional and Temperature (0.87) was most directly proportional to the independent parameter EF-Population. Table 5.8 below shows the Pearson's Coefficient Matrix for the Bridge City WWTP sampling location. The matrix shows that flow (0.0005), temperature (<0.0001), BOD (0.0015), and Total Sulfides (0.0022) all have p-values (marked in green) less than 0.05. However, according to the p-values (Row 2), Flow is highly inter-correlated with BOD (0.0058). Some degree of inter-correlation was found between Flow and Temperature and Flow and Total Sulfides (Row 2). However, the model was developed using flow and temperature as the raw data as these two independent variables were recorded more extensively (continuous averages) than the data available for Total Sulfide (weekly grab sample). Also, Flow and Temperature are more correlated to EF-Flow and have a higher impact (-0.69 and 0.87 respectively) on EF-Flow than any other variables. Therefore, modeling was performed using Flow and Temperature, as these variables are correlated to EF-Flow and are least inter-correlated.

**Table 5.8: EF-Flow Pearson's Coefficient Matrix**

Row	Variables	EF-Flow	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Flow	1	-0.69	0.87	0.64	0.07	0.62
			0.0005	<.0001	0.0015	0.7381	0.0022
2	Flow	-0.69	1	-0.53	-0.58	0.009	-0.50
		0.0005		0.0129	0.0058	0.9669	0.0209
3	Temperature	0.87	-0.53	1	0.50	-0.03	0.55
		<.0001	0.0129		0.0192	0.8901	0.0087
4	BOD	0.64	-0.58	0.50	1	0.17	0.28
		0.0015	0.0058	0.0192		0.4511	0.2055
5	pH	0.077	0.009	-0.03	0.17	1	-0.18
		0.7381	0.9669	0.8901	0.4511		0.4268
6	Total Sulfides	0.62	-0.50	0.55	0.28	-0.18	1
		0.0022	0.0209	0.0087	0.2055	0.4268	

From Table 5.9 it was established that flow and temperature were the most correlated to the independent variable (EF-Flow) and least inter-correlated. The Parameter Estimate table (Table 5.9) was next developed using only the independent variables selected based on results obtained from Pearson's Coefficient Matrix.

**Table 5.9: EF-Flow Parameter Estimates**

Variable	D F	Parameter Estimate	Standard Error	t Value	Pr >  t	Tolerance	Variance Inflation
Intercept	1	14.36	7.30984	1.97	0.0650	.	0
ln_flow	1	-1.98	0.49581	-4.01	0.0008	0.63207	1.58209
ln_temp	1	3.06	1.16879	2.63	0.0171	0.63207	1.58209

Mathematically the equation is as follows:

$$\ln(\text{EF-Flow}) = 14.36 - 1.98 * \ln(\text{Flow}) + 3.06 * \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.75. So, 75% of the raw data can be modeled based on the above equation.

Emission Factor as a function of Population Serviced (EF-Pop)

According to raw data, Flow (-0.68) was most indirectly proportional and Temperature (0.83) was most directly proportional to the independent parameter EF-Population. Table 5.10 indicates that Flow (0.0007), temperature (<0.0001), BOD (0.0049), and Total Sulfides (0.0029) show correlation with EF-Pop. Row 2, however, shows high inter-correlation (p<0.05) between Flow and BOD. Some degree of inter-correlation was found between Flow and Temperature and Flow and Total Sulfides (Row 2). However, the model was developed using flow and temperature as the raw data as these two independent variables were recorded more extensively (continuous averages) than the data available for Total Sulfide (weekly grab sample). Also, Flow and Temperature are more correlated to EF-Pop and have a higher impact (-0.68 and 0.83 respectively) on EF-Pop than any other variables. Therefore, modeling was performed using Flow and Temperature, as these variables are correlated to EF-Pop and are least inter-correlated.

**Table 5.10: EF-Population Pearson’s Coefficient Matrix**

Row	Variables	EF-Pop	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Pop	1	-0.68	0.83	0.58	0.09	0.61
			0.0007	<.0001	0.0049	0.6908	0.0029
2	Flow	-0.68	1	-0.53	-0.58	0.009	-0.50
		0.0007		0.0129	0.0058	0.9669	0.0209
3	Temperature	0.83	-0.53	1	0.50	-0.03	0.55
		<.0001	0.0129		0.0192	0.8901	0.0087
4	BOD	0.58	-0.58	0.50	1	0.17	0.28
		0.0049	0.0058	0.0192		0.4511	0.2055
5	pH	0.09	0.009	-0.03	0.17	1	-0.18
		0.6908	0.9669	0.8901	0.4511		0.4268
6	Total Sulfides	0.61	-0.50	0.55	0.28	-0.18	1
		0.0029	0.0209	0.0087	0.2055	0.4268	

The Parameter Estimate table (Table 5.11) was next developed using only the independent variables selected based on results obtained from Pearson’s Coefficient Matrix.

**Table 5.11: EF-Flow Parameter Estimate**

Variable	D F	Parameter Estimate	Standard Error	t Value	Pr >  t	Tolerance	Variance Inflation
Intercept	1	73.85	56.67179	1.30	0.2089	.	0
ln_flow	1	-12.60	3.84394	-3.28	0.0042	0.63207	1.58209
ln_temp	1	14.31	9.06137	1.58	0.1315	0.63207	1.58209

Mathematically the equation is as follows:

$$\ln(\text{EF-Pop}) = 73.85 - 12.6 * \ln(\text{Flow}) + 14.3 \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.63. So, 63% of the raw data can be modeled based on the above equation.

#### Emission Factor as a Function of Area Serviced (EF-Area)

According to Table 5.12 Flow (-0.66) was most indirectly correlated and Temperature (0.85) most directly correlated to EF-Area. p-values obtained as follows; Flow (0.001), Temperature (<0.0001), BOD (0.0061), and Total Sulfides (0.0023) show correlation with the EF-Area. Row 2 (Flow), however, shows greater inter-correlation between Flow and BOD. Some degree of inter-correlation was found between Flow and Temperature and Flow and Total Sulfides (Row 2). However, the model was developed using flow and temperature as the raw data as these two independent variables were recorded more extensively (continuous averages) than the data available for Total Sulfide (weekly grab sample). Also, Flow and Temperature are more correlated to EF-Area and have a higher impact (-0.66 and 0.85 respectively) on EF-Area than any other variables. Therefore, modeling was performed using Flow and Temperature, as these variables are correlated to EF-Area and are least inter-correlated.

**Figure 5.12: EF-Area Pearson's Coefficient Matrix**

Row	Variables	EF-Area	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Area	1	-0.66	0.85	0.57	0.03	0.62
			0.001	<.0001	0.0061	0.8703	0.0023
2	Flow	-0.66	1	-0.53	-0.58	0.009	-0.50
		0.001		0.0129	0.0058	0.9669	0.0209
3	Temperature	0.85	-0.53	1	0.50	-0.03	0.55
		<.0001	0.0129		0.0192	0.8901	0.0087
4	BOD	0.57	-0.58	0.50	1	0.17	0.28
		0.0061	0.0058	0.0192		0.4511	0.2055
5	pH	0.03	0.009	-0.03	0.17	1	-0.18
		0.8703	0.9669	0.8901	0.4511		0.4268
6	Total Sulfides	0.62	-0.50	0.55	0.28	-0.18	1
		0.0023	0.0209	0.0087	0.2055	0.4268	

The Parameter Estimate table (Table 5.13) was next developed using only the independent variables selected based on results obtained from Pearson's Coefficient Matrix.

**Figure 5.13: EF-Flow Parameter Estimate**

Variable	D F	Parameter Estimate	Standard Error	t Value	Pr >  t	Tolerance	Variance Inflation
Intercept	1	8.91	7.21523	1.24	0.2324	.	0
ln_flow	1	-1.31	0.48940	-2.69	0.0151	0.63207	1.58209
ln_temp	1	2.78	1.15366	2.41	0.0268	0.63207	1.58209

Mathematically the equation is as follows:

$$\ln(\text{EF-Area}) = 8.91 - 1.31 * \ln(\text{Flow}) + 2.78 * \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.64. So, 64% of the raw data can be modeled based on the above equation.

*Note: Above equations are valid for flow ranges 8,306 m<sup>3</sup>/day – 23,961 m<sup>3</sup>/day and Temperature ranges of 17°C to 27°C.*



Marrero

Emission Factor as a Function of Wastewater Flow (EF-Flow)

According to raw data, Flow (-0.57) was most indirectly proportional and Temperature (0.84) was most directly proportional to the independent parameter EF-Flow. Table 5.14, Row 1 (marked in green), indicates that Flow (0.0068), Temperature (<0.0001), and Total Sulfides (0.017) show correlation with EF-Flow ( $p < 0.05$ ). Row 2 (Flow), however, shows inter-correlation between the independent variables Flow and Total Sulfides. Therefore, modeling was performed using Flow and Temperature, as these variables are proportional to EF-Flow and are least inter-correlated.

**Table 5.14: Emission Factor as a Function of Wastewater Flow (EF-Flow)**

Row	Variables	EF-Flow	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Flow	1	-0.57	0.84	0.34	-0.20	0.51
			0.0068	<.0001	0.1208	0.3643	0.017
2	Flow	-0.57	1	-0.39	-0.47	-0.05	-0.70
		0.0068		0.0752	0.03	0.8221	0.0004
3	Temperature	0.84	-0.39	1	0.51	-0.12	0.44
		<.0001	0.0752		0.0179	0.5772	0.0412
4	BOD	0.34	-0.47	0.51	1	-0.02	0.44
		0.1208	0.03	0.0179		0.8989	0.0429
5	pH	-0.20	-0.05	-0.12	-0.02	1	0.29
		0.3643	0.8221	0.5772	0.8989		0.1872
6	Total Sulfides	0.51	-0.70	0.44	0.44	0.29	1
		0.017	0.0004	0.0412	0.0429	0.1872	

The Parameter Estimate table (Table 5.15) was next developed using only the independent variables selected based on results obtained from Pearson’s Coefficient Matrix.

**Table 5.15: EF-Flow Parameter Estimate**

Variable	DF	Parameter	Standard	t Value	Pr >  t	Tolerance	Variance
Intercept	1	16.45	4.33084	3.8	0.0013	.	0
ln_flow	1	-2.0	0.29846	-6.71	<.0001	0.83499	1.19762
ln_temp	1	3.03	0.70333	4.32	0.0004	0.83499	1.19762

Mathematically the equation is as follows:

$$\ln(\text{EF-Flow}) = 16.45 - 2.00 * \ln(\text{flow}) + 3.03 * \ln(\text{temperature})$$

The R-Square Value for the above model is 0.85. So, 85% of the raw data can be modeled based on the above equation.

#### Emission Factor as a Function of Wastewater Population (EF-Pop)

According to raw data, Flow (-0.5) was most indirectly proportional and Temperature (0.89) was most directly proportional to the independent parameter EF-Pop. Table 5.16, Row 1 (marked in green), indicates that Flow (0.0195), Temperature (<0.0001), and Total Sulfides (0.03) show correlation with EF-Flow ( $p < 0.05$ ). Row 2 (Flow), however, shows an inter-correlation between the independent variables Flow and Total Sulfides. Therefore, modeling was performed using Flow and Temperature, as these variables are correlated to EF-Flow and are least inter-correlated.

**Table 5.16: Emission Factor as a Function of Wastewater Population (EF-Population)**

Row	Variables	EF-Pop	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Pop	1	-0.5	0.89	0.38	-0.26	0.46
			0.0195	<.0001	0.0835	0.2381	0.0328
2	Flow	-0.5	1	-0.39	-0.47	-0.05	-0.7
		0.0195		0.0752	0.03	0.8221	0.0004
3	Temperature	0.89	-0.39	1	0.51	-0.12	0.44
		<.0001	0.0752		0.0179	0.5772	0.0412
4	BOD	0.38	-0.47	0.51	1	-0.02	0.44
		0.0835	0.03	0.0179		0.8989	0.0429
5	pH	-0.26	-0.05	-0.12	-0.02	1	0.29
		0.2381	0.8221	0.5772	0.8989		0.1872
6	Total Sulfides	0.46	-0.7	0.44	0.44	0.29	1
		0.0328	0.0004	0.0412	0.0429	0.1872	

The Parameter Estimate table (Table 5.17) was next developed using only the independent variables selected based on results obtained from Pearson's Coefficient Matrix.

**Table 5.17: EF-Population Parameter Estimate**

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr >  t	Tolerance	Variance Inflation
Intercept	1	7.44	3.77217	1.97	0.0638	.	0
ln_flow	1	-1.19	0.25996	-4.58	0.0002	0.83499	1.19762
ln_temp	1	3.16	0.6126	5.17	<.0001	0.83499	1.19762

Mathematically the equation is as follows:

$$\ln(\text{EF-Pop}) = 7.44 - 1.19 * \ln(\text{Flow}) + 3.16 * \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.81. So, 81% of the raw data can be modeled based on the above equation.

#### Emission Factor as a Function of Wastewater Area (EF-Area)

According to raw data, Flow (-0.5) was most indirectly proportional and Temperature (0.89) was most directly proportional to the independent parameter EF-Area. Table 5.18, Row 1 (marked in green), indicates that Flow (0.0195), Temperature (<0.0001), and Total Sulfides (0.03) show correlation with EF-Flow ( $p < 0.05$ ). Row 2 (Flow), however, shows an inter-correlation between the independent variables Flow and Total Sulfides. Therefore, modeling was performed using Flow and Temperature, as these variables are correlated to EF-Flow and are least inter-correlated.

**Table 5.18: Emission Factor as a Function of Wastewater Area (EF-Area)**

Row	Variables	EF-Area	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Area	1	-0.5	0.89	0.38	-0.26	0.46
			0.0195	<.0001	0.0835	0.2381	0.0328
2	Flow	-0.5	1	-0.39	-0.47	-0.05	-0.7
		0.0195		0.0752	0.03	0.8221	0.0004
3	Temperature	0.89	-0.39	1	0.51	-0.12	0.44
		<.0001	0.0752		0.0179	0.5772	0.0412
4	BOD	0.38	-0.47	0.51	1	-0.02	0.44
		0.0835	0.03	0.0179		0.8989	0.0429
5	pH	-0.26	-0.05	-0.12	-0.02	1	0.29
		0.2381	0.8221	0.5772	0.8989		0.1872
6	Total Sulfides	0.46	-0.7	0.44	0.44	0.29	1
		0.0328	0.0004	0.0412	0.0429	0.1872	

The Parameter Estimate table (Table 5.19) was next developed using only the independent variables selected based on results obtained from Pearson’s Coefficient Matrix.

**Table 5.19: EF-Area Parameter Estimate**

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr >  t	Tolerance	Variance Inflation
Intercept	1	7.92	3.77221	2.1	0.0499	.	0
ln_flow	1	-1.19	0.25996	-4.58	0.0002	0.83499	1.19762
ln_temp	1	3.16	0.61261	5.17	<.0001	0.83499	1.19762

Mathematically the equation is as follows:

$$\ln(\text{EF-Area}) = 7.92 - 1.19 * \ln(\text{Flow}) + 3.16 * \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.81. So, 81% of the raw data can be modeled based of the above equation.

*Note: Above equations are valid for flow ranges 16,213 m<sup>3</sup>/day – 62,700 m<sup>3</sup>/day and Temperature ranges of 16°C to 27°C.*

### Harvey

#### Emission Factor as a Function of Wastewater Flow (EF-Flow)

According to raw data, Flow (-0.82) was most indirectly proportional and Temperature (0.65) was most directly proportional to the independent parameter EF-Area. Table 5.20 Row 1 (marked in green), indicates that Flow (<0.0001), Temperature (0.0013), and Total Sulfides (0.0052) show correlation with EF-Flow (p<0.05). Row 2 (Flow), however, shows a higher inter-correlation between the independent variables Flow and Total Sulfides. Therefore, modeling was performed using Flow and Temperature, as these variables are correlated to EF-Flow and are least inter-correlated.

**Table 5.20: Emission Factor as a Function of Wastewater Flow (EF-Flow)**

Row	Variables	EF-Flow	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Flow	1	-0.82842	0.65413	0.15259	-0.2097	0.58697
			<.0001	0.0013	0.509	0.3616	0.0052
2	Flow	-0.8284	1	-0.52682	-0.3372	0.24577	-0.70777
		<.0001		0.0141	0.135	0.2829	0.0003
3	Temperature	0.65413	-0.52682	1	0.38236	-0.4447	0.24262
		0.0013	0.0141		0.0872	0.0434	0.2893
4	BOD	0.15259	-0.33719	0.38236	1	-0.1566	0.26359
		0.509	0.135	0.0872		0.4978	0.2483
5	pH	-0.2097	0.24577	-0.44473	-0.1566	1	0.15788
		0.3616	0.2829	0.0434	0.4978		0.4943
6	Total Sulfides	0.58697	-0.70777	0.24262	0.26359	0.15788	1
		0.0052	0.0003	0.2893	0.2483	0.4943	

The Parameter Estimate table (Table 5.21) was next developed using only the independent variables selected based on results obtained from Pearson’s Coefficient Matrix.

**Table 5.21: EF-Flow Parameter Estimate**

Variable	DF	Parameter	Standard	t Value	Pr >  t	Tolerance	Variance
Intercept	1	25.13	4.50983	5.57	<.0001	.	0
ln_flow	1	-2.31	0.32963	-7.03	<.0001	0.71494	1.39872
ln_temp	1	0.89	0.54164	1.65	0.1168	0.71494	1.39872

Mathematically, the equation is as follows:

$$\ln(\text{EF-Flow}) = 25.13 - 2.31 * \ln(\text{Flow}) + 0.89 * \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.83. So, 83% of the raw data can be modeled based on the above equation.

### Emission Factor as a Function of Wastewater Population (EF-Pop)

According to raw data, Flow (-0.69) was most indirectly proportional and Temperature (0.65) was most directly proportional to the independent parameter EF-Pop. Table 5.22, Row 1 (marked in green), indicates that Flow (0.004), Temperature (0.0014), and Total Sulfides (0.0171) show correlation with EF-Flow ( $p < 0.05$ ). Row 2 (Flow), however, shows a higher inter-correlation between the independent variables Flow and Total Sulfides. Therefore, modeling was performed using Flow and Temperature, as these variables are correlated to EF-Flow and are least inter-correlated.

**Table 5.22: Emission Factor as a Function of Wastewater Population (EF-Pop)**

Row	Variables	EF-Pop	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Pop	1	-0.69	0.65	0.17	-0.23	0.51
			0.0004	0.0014	0.4515	0.3089	0.0171
2	Flow	-0.69	1	-0.52	-0.33	0.24	-0.7
		0.0004		0.0141	0.135	0.2829	0.0003
3	Temperature	0.65	-0.52	1	0.38	-0.44	0.24
		0.0014	0.0141		0.0872	0.0434	0.2893
4	BOD	0.17	-0.33	0.38	1	-0.15	0.26
		0.4515	0.135	0.0872		0.4978	0.2483
5	pH	-0.23	0.24	-0.44	-0.15	1	0.15
		0.3089	0.2829	0.0434	0.4978		0.4943
6	Total Sulfides	0.51	-0.7	0.24	0.26	0.15	1
		0.0171	0.0003	0.2893	0.2483	0.4943	

The Parameter Estimate table (Table 5.23) was next developed using only the independent variables selected based on results obtained from Pearson's Coefficient Matrix.

**Table 5.23: EF-Population Parameter Estimate**

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr >  t	Tolerance	Variance Inflation
Intercept	1	14.0	4.81548	2.91	0.0094	.	0
ln_flow	1	-1.26	0.35197	-3.59	0.0021	0.71494	1.39872
ln_temp	1	1.08	0.57835	1.87	0.0777	0.71494	1.39872

Mathematically, the equation is as follows:

$$\ln(\text{EF-Pop}) = 14.0 - 1.26 * \ln(\text{Flow}) + 1.08 * \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.64. So, 64% of the raw data can be modeled based on the above equation.

Emission Factor as a Function of Wastewater Area (EF-Area)

According to raw data, Flow (-0.69) was most indirectly proportional and Temperature (0.65) was most directly proportional to the independent parameter EF-Area. Table 5.24, Row 1 (marked in green), indicates that Flow (0.0004), Temperature (0.0014), and Total Sulfides (0.0171) show correlation with EF-Flow ( $p < 0.05$ ). Row 2 (Flow), however, shows a higher inter-correlation between the independent variables Flow and Total Sulfides. Therefore, modeling was performed using Flow and Temperature, as these variables are correlated to EF-Flow and are least inter-correlated.

**Table 5.24: Emission Factor as a Function of Wastewater Area (EF-Area)**

Row	Variables	EF-Area	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Area	1	-0.69	0.65	0.17	-0.23	0.51
			0.0004	0.0014	0.4515	0.3088	0.0171
2	Flow	-0.69	1	-0.52	-0.33	0.24	-0.70
		0.0004		0.0141	0.135	0.2829	0.0003
3	Temperature	0.65	-0.52	1	0.38	-0.44	0.24
		0.0014	0.0141		0.0872	0.0434	0.2893
4	BOD	0.17	-0.33	0.38	1	-0.15	0.26
		0.4515	0.135	0.0872		0.4978	0.2483
5	pH	-0.23	0.24	-0.44	-0.15	1	0.15
		0.3088	0.2829	0.0434	0.4978		0.4943
6	Total Sulfides	0.51	-0.7	0.24	0.26	0.15	1
		0.0171	0.0003	0.2893	0.2483	0.4943	

The Parameter Estimate table (Table 5.25) was next developed using only the independent variables selected based on results obtained from Pearson’s Coefficient Matrix.

**Table 5.25: EF-Area Parameter Estimate**

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr >  t	Tolerance	Variance Inflation
Intercept	1	14.18	4.81586	2.95	0.0086	.	0
ln_flow	1	-1.26	0.352	-3.59	0.0021	0.71494	1.39872
ln_temp	1	1.08	0.5784	1.87	0.0778	0.71494	1.39872

Mathematically, the equation is as follows:

$$\ln(\text{EF-Area}) = 14.18 - 1.26 * \ln(\text{Flow}) + 1.08 * \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.64. So, 64% of the raw data can be modeled based of the above equation.

*Note: Above equations are valid for flow ranges 22,249 m<sup>3</sup>/day – 57,265 m<sup>3</sup>/day and Temperature ranges of 15°C to 26°C.*

### East Bank

#### Emission Factor as a Function of Wastewater Flow (EF-Flow)

According to raw data, Flow (-0.74) was most indirectly proportional and Temperature (0.78) was most directly proportional to the independent parameter EF-Flow. Table 5.26, Row 1 (marked in green), indicates that Flow (0.0001), Temperature (<0.0001), BOD (0.0058), and Total Sulfides (0.0102) show correlation with EF-Flow (p<0.05). Row 2 (Flow), however, shows a higher inter-correlation between the independent variables Flow and BOD. Some degree of correlation was found between Flow and Temperature and Flow and Total Sulfides (Row 2). However, the model was developed using flow and temperature as the raw data for these two independent variables were recorded more extensively (continuous averages) than the data available for Total Sulfide (weekly grab sample). Also, Flow and Temperature are more correlated to EF-Flow and have a higher impact (-0.74 and 0.78 respectively) on EF-Flow than any other variables.



**Table 5.26: Emission Factor as a Function of Wastewater Flow (EF-Flow)**

Row	Variables	EF-Flow	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Flow	1	-0.74	0.78	0.58	-0.42	0.54
			0.0001	<.0001	0.0058	0.0531	0.0102
2	Flow	-0.74	1	-0.51	-0.57	0.37	-0.45
		0.0001		0.0162	0.0069	0.0936	0.0378
3	Temperature	0.78	-0.51	1	0.41	-0.46	0.25
		<.0001	0.0162		0.0608	0.035	0.2587
4	BOD	0.58	-0.57	0.41	1	-0.30	0.44
		0.0058	0.0069	0.0608		0.1843	0.0439
5	pH	-0.42	0.37	-0.46	-0.30	1	-0.07
		0.0531	0.0936	0.035	0.1843		0.759
6	Total Sulfide	0.54	-0.45	0.25	0.44	-0.07	1
		0.0102	0.0378	0.2587	0.0439	0.759	

The Parameter Estimate table (Table 5.27) was next developed using only the independent variables selected based on results obtained from Pearson’s Coefficient Matrix.

**Table 5.27: EF-Flow Parameter Estimate**

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr >  t	Tolerance	Variance Inflation
Intercept	1	24.95	8.35965	2.98	0.0079	.	0
ln_flow	1	-2.48	0.50888	-4.87	0.0001	0.65145	1.53504
ln_temp	1	2.17	1.18902	1.83	0.0842	0.65145	1.53504

Mathematically, the equation is as follows:

$$\ln(\text{EF-Flow}) = 24.95 - 2.48 * \ln(\text{Flow}) + 2.17 * \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.76. So, 76% of the raw data can be modeled based of the above equation.

Emission Factor as a Function of Wastewater Population (EF-Pop)

According to raw data, Flow (-0.7) was most indirectly proportional and Temperature (0.81) was most directly proportional to the independent parameter EF-Pop. Table 5.28, Row 1 (marked in green), indicates that Flow (0.0004), Temperature (<0.0001), BOD (0.0154), and Total Sulfides (0.0039) show a correlation with EF-Flow (p<0.05). Row 2 (Flow), however, shows a higher inter-correlation between the independent variables Flow and BOD. Some degree of correlation

was found between Flow and Temperature and Flow and Total Sulfides (Row 2). However, the model was developed using flow and temperature as the raw data for these two independent variables were recorded more extensively (continuous averages) than the data available for Total Sulfide (weekly grab sample). Also, Flow and Temperature are more correlated to EF-Flow and have a higher impact (-0.7 and 0.81 respectively) on EF-Pop than any other variables.

**Table 5.28: Emission Factor as a Function of Wastewater Population (EF-Pop)**

Row	Variables	EF-Pop	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Pop	1	-0.70089	0.81307	0.521	-0.40011	0.60158
			0.0004	<.0001	0.0154	0.0723	0.0039
2	Flow	-0.70089	1	-0.51784	-0.5705	0.37539	-0.4558
		0.0004		0.0162	0.0069	0.0936	0.0378
3	Temperature	0.81307	-0.51784	1	0.41584	-0.46202	0.25804
		<.0001	0.0162		0.0608	0.035	0.2587
4	BOD	0.521	-0.57051	0.41584	1	-0.30141	0.4437
		0.0154	0.0069	0.0608		0.1843	0.0439
5	pH	-0.40011	0.37539	-0.46202	-0.3014	1	-0.07122
		0.0723	0.0936	0.035	0.1843		0.759
6	Total Sulfide	0.60158	-0.4558	0.25804	0.4437	-0.07122	1
		0.0039	0.0378	0.2587	0.0439	0.759	

The Parameter Estimate table (Table 5.29) was next developed using only the independent variables selected based on results obtained from Pearson’s Coefficient Matrix.

**Table 5.29: EF-Population Parameter Estimate**

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr >  t	Tolerance	Variance Inflation
Intercept	1	14.56	7.40363	1.97	0.0647	.	0
ln_flow	1	-1.61	0.45069	-3.59	0.0021	0.65145	1.53504
ln_temp	1	2.11	1.05304	2.01	0.0598	0.65145	1.53504

Mathematically, the equation is as follows:

$$\ln(\text{EF-Pop}) = 14.56 - 1.61 * \ln(\text{Flow}) + 2.11 * \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.68. So, 68% of the raw data can be modeled based on the above equation.

#### Emission Factor as a Function of Wastewater Area (EF-Area)

According to raw data, Flow (-0.7) was most indirectly proportional and Temperature (0.81) was most directly proportional to the independent parameter EF-Area. Table 5.30, Row 1 (marked in green), indicates that Flow (0.0004), Temperature (<0.0001), BOD (0.0154), and Total Sulfides (0.0039) show a correlation with EF-Flow (p<0.05). Row 2 (Flow), however, shows a higher inter-correlation between the independent variables Flow and BOD. Some degree of correlation was found between Flow and Temperature and Flow and Total Sulfides (Row 2). However, the model was developed using flow and temperature as the raw data for these two independent variables were recorded more extensively (continuous averages) than the data available for Total Sulfide (weekly grab sample). Also, Flow and Temperature are more correlated to EF-Flow and have a higher impact (-0.7 and 0.81 respectively) on EF-Area than any other variables. Therefore, modeling was performed using Flow and Temperature, as these variables are correlated to EF-Flow and are least inter-correlated.

**Table 5.30: Emission Factor as a Function of Wastewater Area (EF-Area)**

Row	Variables	EF-Area	Flow	Temperature	BOD	pH	Total Sulfides
1	EF-Area	1	-0.7	0.81	0.52	-0.4	0.6
			0.0004	<0.0001	0.0154	0.0723	0.0039
2	Flow	-0.7	1	-0.51	-0.57	0.37	-0.45
		0.0004		0.0162	0.0069	0.0936	0.0378
3	Temperature	0.81	-0.51	1	0.41	-0.46	0.25
		<.0001	0.0162		0.0608	0.035	0.2587
4	BOD	0.52	-0.57	0.41	1	-0.3	0.44
		0.0154	0.0069	0.0608		0.1843	0.0439
5	pH	-0.4	0.37	-0.46	-0.3	1	-0.07
		0.0723	0.0936	0.035	0.1843		0.759
6	Total Sulfide	0.6	-0.45	0.25	0.44	-0.07	1
		0.0039	0.0378	0.2587	0.0439	0.759	

The Parameter Estimate table (Table 5.31) was next developed using only the independent variables selected based on results obtained from Pearson’s Coefficient Matrix.

**Table 5.31: EF-Area Parameter Estimate**

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr >  t	Tolerance	Variance Inflation
Intercept	1	15.35	7.40363	2.07	0.0527	.	0
ln_flow	1	-1.61	0.45069	-3.59	0.0021	0.65145	1.53504
ln_temp	1	2.11	1.05304	2.01	0.0598	0.65145	1.53504

Mathematically, the equation is as follows:

$$\ln(\text{EF-Area}) = 15.35 - 1.61 * \ln(\text{Flow}) + 2.11 * \ln(\text{Temperature})$$

The R-Square Value for the above model is 0.68. So, 68% of the raw data can be modeled based of the above equation.

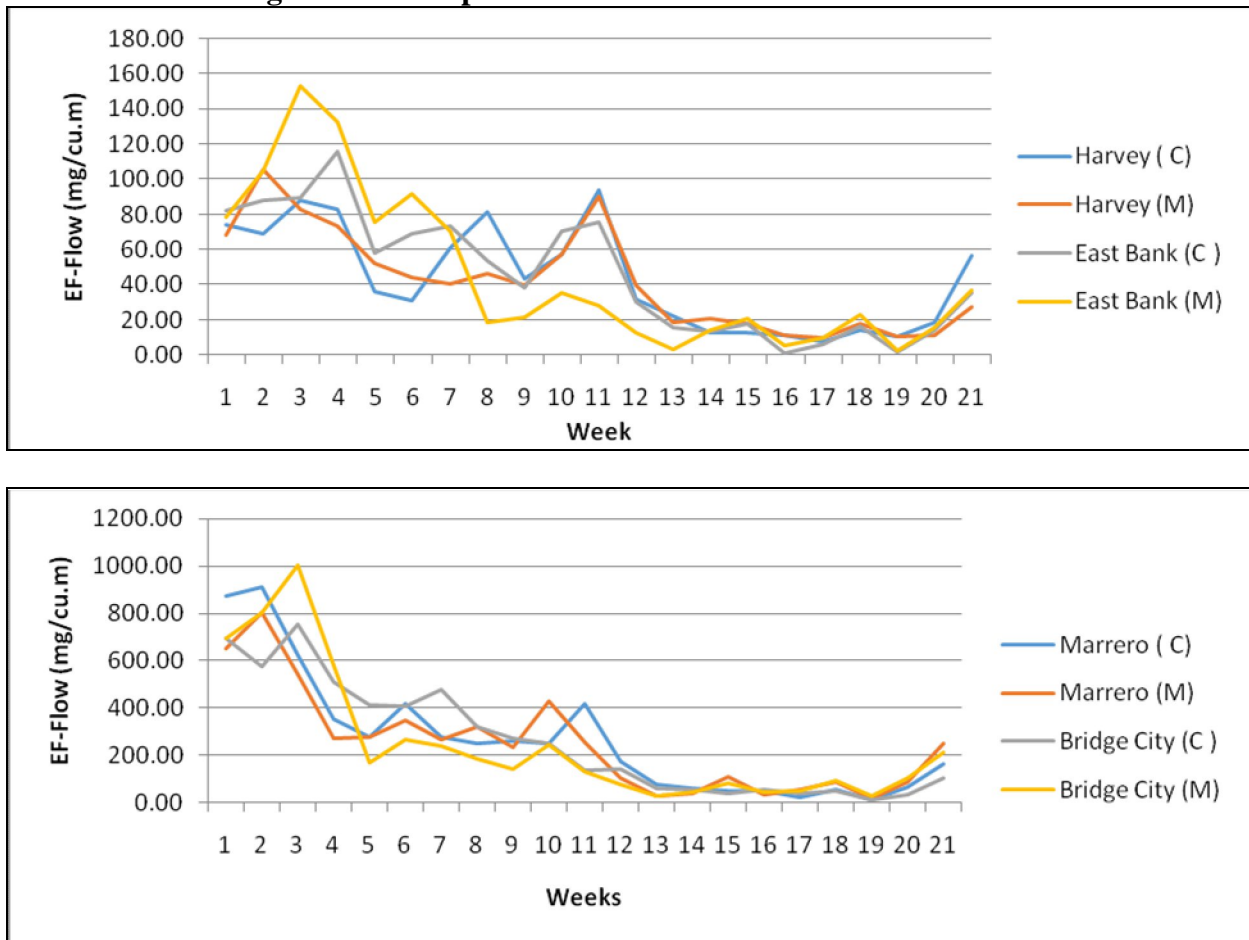
*Note: Above equations are valid for flow ranges 50,661 m<sup>3</sup>/day – 188,613 m<sup>3</sup>/day and Temperature ranges of 17°C to 27°C.*

In all the above models it is observed that EFs are a function of flow and temperature. According to the Pearson’s coefficient matrix, it can be observed that flow is strongly inversely and temperature is directly proportional to EF-Flow, Population, and Area. Among all the independent variables Flow and Temperature were least correlated to each other. Therefore, Flow and Temperature are the best suited independent variables among all the data collected for modeling EFs.

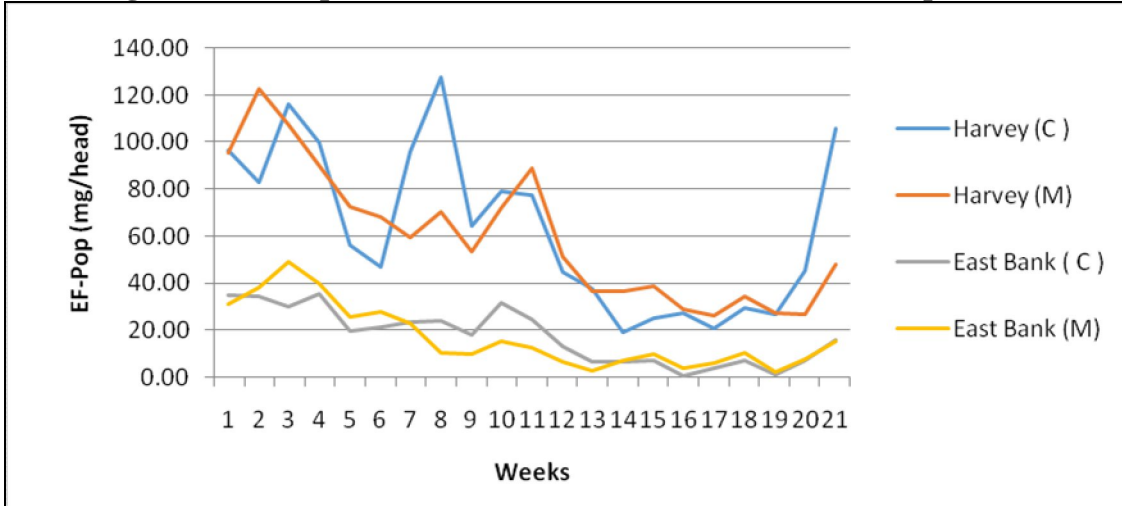
### 5.5 Comparison of Actual and Modeled Emission Factors

The Emission Factors were generated using the preliminary empirical models developed for EF-Flow, Population, and Area. The EFs generated by the models were compared against the observed EFs. Figure 5.4 - 5.8 show that the values generated by EF models (M) were extremely close to the calculated EF values (C). Appendix A.3 includes individual comparative graphs for each location for temperature parameter.

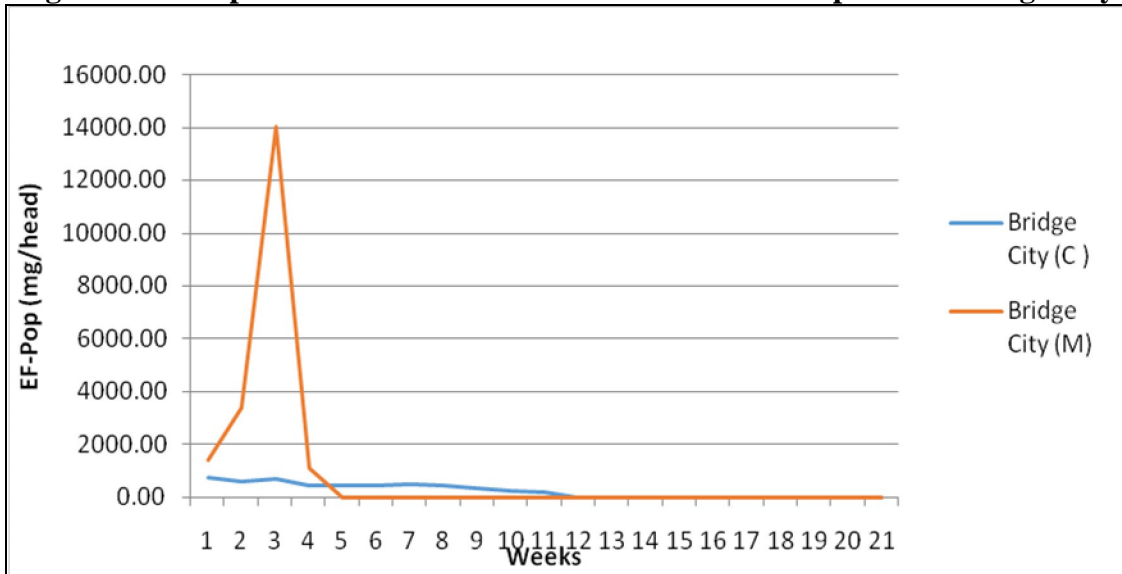
**Figure 5.4: Comparison between Actual and Modeled EF-Flow**



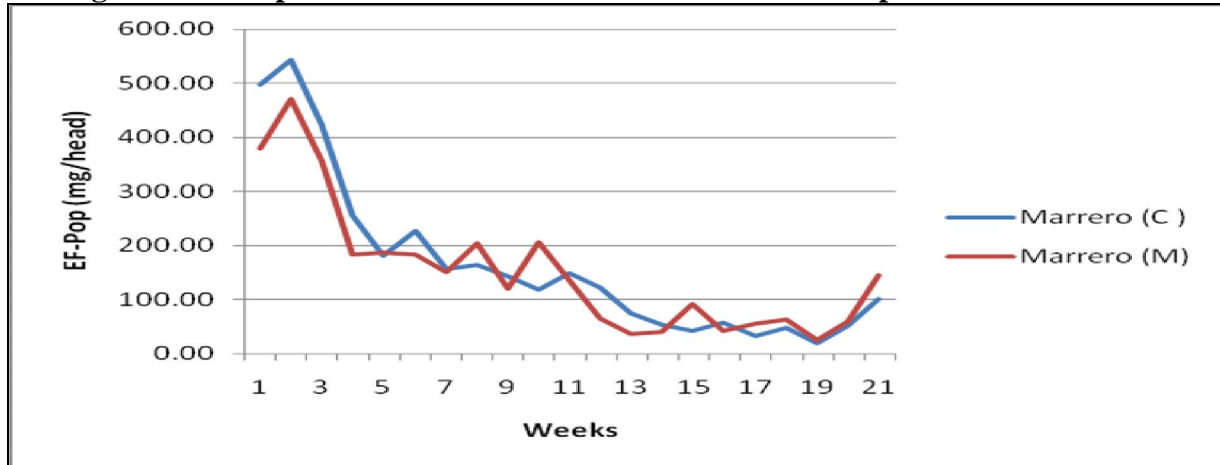
**Figure 5.5: Comparison between Actual and Modeled EF-Population**



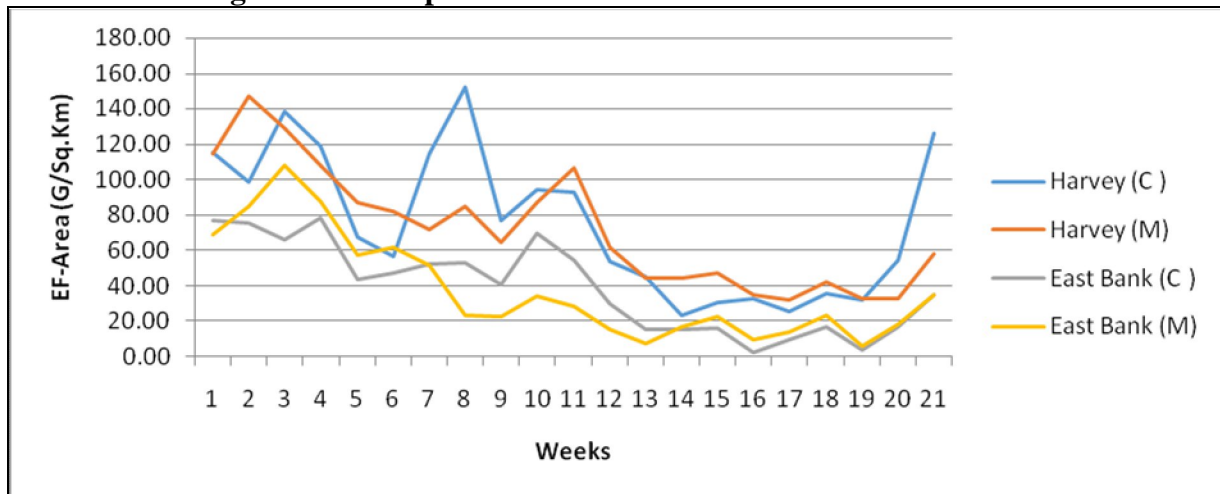
**Figure 5.6 Comparison between Actual and Modeled EF-Population-Bridge City**



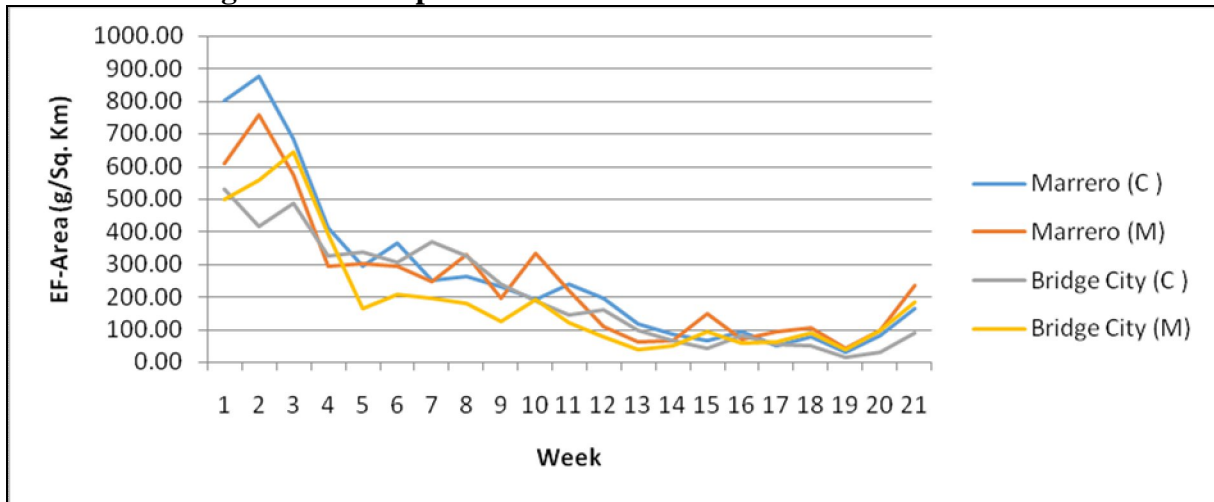
**Figure 5.7 Comparison between Actual and Modeled EF-Population-Marrero**



**Figure 5.8: Comparison between Actual and Modeled EF-Area**



**Figure 5.9: Comparison between Actual and Modeled EF-Area**





## 5.6 Comparison of Literature Review and Dissertation Results Obtained

EF-Flow data which was generated as part of this study was compared to data generated as part of the DFC study (Chapter 3; Section 3.9.1). It is observed that the EFs obtained in this research are higher than those from the DFC study. The following are some of the probable reasons for this difference:

- This dissertation research was performed on covered air treatment units (headworks) unlike the DFC study which were all performed on open air treatment units (primary and secondary settling tank, aeration units). Enclosed units have a higher potential for H<sub>2</sub>S build-up, which consequently translates to a higher concentration and EFs;
- In the DFC study, data was collected for a couple of hours for a period of three days. Lack of continuous air emissions data can lead to a skewed data set resulting in under or over reporting of EFs;
- The DFC study was only collected for one day during the summer time. Therefore, it is a possibility that the researchers may have missed out on recording high emission data (typically during high temperature seasons) which may lead to under estimation of EFs;
- The DFC study also does not discuss the flow conditions associated during the study period. According to this dissertation, Flow is a primary variable which has the most impact on H<sub>2</sub>S emissions. Rain events during or prior to the day's data were collected for the DFC study and could have lowered the emissions rates for the test units;
- The units studied as part of the DFC study and this dissertation are not of the same type. As per Table 3.11, the headworks units have a higher emission potential than other downstream treatment units, such as settling tanks or aeration chambers.

According to the above items, it is not feasible to compare the EF results obtained as part of this dissertation and the DFC study.

This dissertation also attempts to compare the conventional studies as discussed in the literature review with the results obtained from this dissertation. Table 5.32 below is a comparative chart of various air emission studies.

**Table 5.32: Comparison of Various Emission Control Studies**

<b>Item</b>	<b>DFC Study</b>	<b>D/T or R/T</b>	<b>Gravity Emission Study</b>	<b>EF Study (Dissertation)</b>
Emission Model	No	No	No	Yes
Air Monitoring	Grab	Grab	Grab	Continuous
Duration of study	3 days	2 weeks	24 weeks (4 hours/day)	21 weeks (24x7 except for data d/l periods)
Parameters Tested in Treatment Unit	Flow, Air emissions	Air emissions	Air emissions, Dissolved sulfide, Temperature	BOD, pH, Total Sulfide, Temperature, Dissolved Oxygen, Flow, Air emissions
Test Location	Primary & secondary settling tank, aeration chamber (open air)	Headworks, aerated grit chamber, secondary clarifier outlet box, dewatering building (confined space)	Gravity sewer (laboratory model; confined space)	Headworks (confined space)
Applicability	Open treatment units	Confined space collection or treatment units	Collection unit (gravity system)	Confined space treatment and collection units. Potentially be modified to test open treatment units
Ability for In-house Municipal Personnel to Perform study	No ( <i>data handling, testing and interpretation needs special training</i> )	No ( <i>data handling, testing and interpretation needs special training</i> )	No ( <i>data handling, testing and interpretation needs special training</i> )	Yes ( <i>no special training required, input data required-flow &amp; temperature are easily available to in-house maintenance staff</i> )
Resource Intensive	Yes ( <i>involves outside laboratory testing</i> )	Yes ( <i>involves outside laboratory testing</i> )	Yes ( <i>involves outside laboratory testing</i> )	No ( <i>in-house municipal laboratories can perform this test</i> )

Based on the literature review, it was observed that the conventional air emission studies are resource intensive, time consuming, and require an outside agency to perform testing, data collection, and interpretation. Present studies also don't establish any emissions model which can be used by in-house municipal staff for predicting hydrogen sulfide emissions in their respective sewer system. Discussions with Jefferson Parish municipalities revealed that an in-house air emission testing capability would serve as a great tool to identify potential locations for health risk, odor, and corrosion hot spots, particularly due to Hydrogen Sulfide emissions. This study serves as a demonstration tool for using EFs to ascertain H<sub>2</sub>S ranges and develops preliminary empirical models to predict H<sub>2</sub>S emissions. Based on the findings of this study, future experiments can be designed to expand this air emission tool for other closed treatment units and collection system. Also, similar studies can be designed to ascertain concentrations of multiple gases associated with sewer. Modifying the testing methodology, future researchers could potentially develop models which can be used to predict emissions from open air treatment sources.

## 6.0 Conclusion

The scope of this dissertation was to understand the feasibility of establishing emission factors and develop preliminary empirical formulae for H<sub>2</sub>S emissions from Bridge City, Harvey, Marrero, and East Bank WWTP headworks. The three point objective of: i) developing a framework, ii) establishing EF ranges (flow, population, and area), and iii) developing preliminary empirical formulae has been discussed in Chapters 4 and 5 of this study.

Hydrogen Sulfide emissions and temperatures from the headworks were continuously monitored at each location by OdaLog units. Wastewater parameters such as BOD, total sulfides, pH, and dissolved oxygen were measured once a week. Continuous flow data was obtained from the flow meters installed at each location.

The following are the salient features of this study:

- 1) Preliminary EF ranges were established as a function of flow, population, and area served by the treatment facility at four Jefferson Parish WWTPs.
- 2) The EFs calculated were compared with BOD, pH, total sulfides, flow, and ambient temperature inside the headworks chamber to test sensitivity of EFs to these independent variables.
- 3) The EFs from various WWTP headworks were compared and ranks assigned with 1 being highest emission potential and 4 being the least emission potential. The overall ranking based on the EF calculated for flow, population, and area across all sampling locations are: 1. Marrero, 2. Bridge City, 3. Harvey, and 4. East Bank.
- 4) Observed wastewater parameters can be used as an indicator to predict the maximum, minimum, and average H<sub>2</sub>S emissions from various sampling locations.
- 5) Various iterations were performed to develop statistical models to predict EF-Flow, Population, and Area.
- 6) Preliminary EF-Flow models developed for each location and their subsequent R<sup>2</sup> values are as follows:

$$\ln (EF-Flow) = 14.36 - 1.98 * \ln (F) + 3.06 * \ln (T) (R^2 = 0.75) (Bridge\ City)$$

$$\ln (EF-Flow) = 16.45 - 2.00 * \ln (F) + 3.03 * \ln (T) (R^2 = 0.85) (Marrero)$$

$$\ln (EF-Flow) = 25.13 - 2.31 * \ln (F) + 0.89 * \ln (T) (R^2 = 0.83) (Harvey)$$

$$\ln (EF-Flow) = 24.95 - 2.48 * \ln (F) + 2.17 * \ln (T) (R^2 = 0.76) (East\ Bank)$$

Where: F-Flow and T-Temperature

7) Preliminary EF-Population models developed for each location and their subsequent R<sup>2</sup> values are as follows:

$$\ln (EF-P) = 7.44 - 1.19 * \ln (F) + 3.16 * \ln (T) (R^2 = 0.81) (Marrero)$$

$$\ln (EF-P) = 14.00 - 1.26 * \ln (F) + 1.08 * \ln (T) (R^2 = 0.64) (Harvey)$$

$$\ln (EF-P) = 14.56 - 1.61 * \ln (F) + 2.11 * \ln (T) (R^2 = 0.68) (East Bank)$$

Where: EF-P: Emission Factor Population, F-Flow, and T-Temperature

8) Preliminary EF-Area models developed for each location and their subsequent R<sup>2</sup> values are as follows:

$$\ln (EF-Area) = 8.91 - 1.31 * \ln (F) + 2.78 * \ln (T) (R^2 = 0.64) (Bridge City)$$

$$\ln (EF-Area) = 7.92 - 1.19 * \ln (F) + 3.16 * \ln (T) (R^2 = 0.81) (Marrero)$$

$$\ln (EF-Area) = 14.18 - 1.26 * \ln (F) + 1.085 * \ln (T) (R^2 = 0.64) (Harvey)$$

$$\ln (EF-Area) = 15.35 - 1.61 * \ln (F) + 2.11 * \ln (T) (R^2 = 0.68) (East Bank)$$

Where: F-Flow and T-Temperature

9) Using the above models, Jefferson Parish personnel can predict the H<sub>2</sub>S emissions for the sampling location for the observed flow and temperature ranges, as discussed in Chapter 5.

10) Models generated in this study are the first step toward developing an H<sub>2</sub>S emission inventory for a WWTP. The methodology used for this study can prove to be a potential first step towards establishing similar models for other common WWTP emissions, such as methane, which is also a greenhouse gas.

11) The models have the potential to be used by municipalities to assess health risks for their sewer personnel and community at large. With further data collection efforts, the models can be modified to assist municipalities to identify potential locations for accelerated infrastructure corrosion. Emission inventory and identification of emission hot spots can assist the municipalities to dedicate their limited budgets to optimize their hydrogen sulfide control plan.

## **7.0 Recommendations**

The following recommendations can be presented based on the results obtained from this study:

1. During the course of this study, the feasibility of using the EF concept has been largely established across WWTPs of various capacities. It should be a good next step to focus research attention on one of the WWTPs and deploy additional air monitoring units across the headworks chamber to obtain a homogenous emission profile.
2. Future researchers should collect multiple weekly wastewater samples to obtain a more comprehensive data on ranges of BOD, pH, total sulfides, and dissolved oxygen.
3. Researchers could attempt to collect emission data by mimicking a headworks condition in a laboratory. In a controlled environment, researchers will be able to alter individual wastewater parameters and observe their effects on air emissions and subsequent EF-Flow. Models generated in laboratory conditions could be tested to predict emissions for a treatment location.
4. After reviewing the results obtained from performing tasks 1, 2, and 3, further data collection should be performed across different treatment units and eventually across different treatment locations to establish a robust universal prediction model.

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## **APPENDIXES**

## Appendix A.1 Weekly Averages

Bridge City	Emission Factors			Wastewater Parameters				
	EF-Flow (mg/cu.m)	EF-Population (mg/head)	EF-Area (g/sq.Km)	Avg. Daily Flow (m <sup>3</sup> /day)	Temperature (Centigrade)	BOD (mg/l)	pH	T.Sulfides (mg/l)
Week 1	696.94	747.76	532.06	8306.04	26.93	74	6.54	2.1
Week 2	574.85	587.82	418.26	7875.88	27.29	143	6.71	1.5
Week 3	755.31	688.71	490.05	7030.00	27.26	214	7.19	0
Week 4	507.91	460.98	328.01	7033.80	22.82	84	7.02	1.25
Week 5	411.81	472.94	336.52	12118.20	21.58	154	7.11	0
Week 6	408.91	430.76	306.51	8320.48	19.64	191	6.83	1.75
Week 7	474.71	520.23	370.16	8888.96	19.87	118	7.12	0.55
Week 8	321.30	458.31	326.11	12010.53	22.20	33	6.8	0.15
Week 9	272.78	337.60	240.22	9908.50	17.88	52	6.89	0.25
Week 10	246.67	262.53	186.80	8366.08	19.14	160	7.02	0.3
Week 11	132.52	204.43	145.46	10204.27	17.75	65	6.91	0.25
Week 12	140.77	0.000224	159.44	12403.20	16.79	65	6.90	0.45
Week 13	57.86	0.000135	96.07	23961.53	17.95	55	6.37	0.00
Week 14	51.76	0.000089	63.16	17315.22	16.81	34	6.42	0.00
Week 15	37.88	0.000059	41.82	15488.80	19.69	34	6.92	0.45
Week 16	49.50	0.000111	80.37	19820.26	18.87	30	7.27	0.00
Week 17	33.89	0.000072	50.95	17062.00	17.72	62	7.08	0.00
Week 18	43.85	0.000071	46.53	11660.03	17.10	60	7.13	0.00
Week 19	8.69	0.000030	13.13	22770.55	17.31	60	7.33	0.00
Week 20	23.39	0.000030	24.50	11104.14	17.30	74	6.51	0.00

<b>Harvey</b>	<b>Emission Factors</b>			<b>Wastewater Parameters</b>				
	<b>EF-Flow (mg/cu.m)</b>	<b>EF- Population (mg/head)</b>	<b>EF- Area (g/sq. Km)</b>	<b>Flow (m<sup>3</sup>/day)</b>	<b>Temperature (Centigrade)</b>	<b>BOD (mg/l)</b>	<b>pH</b>	<b>T.Sulfides (mg/l)</b>
Week								
Week 1	74.04	96.30	115.20	28880.00	25.77	100	6.52	0
Week 2	69.52	82.73	98.96	24168.00	26.34	113	6.71	1.75
Week 3	88.33	116.06	138.83	26752.00	26.20	105.9	6.82	0.85
Week 4	82.83	99.55	119.09	26340.08	21.85	104	6.84	1.5
Week 5	36.24	56.49	67.57	29830.00	20.72	220	7.05	2.15
Week 6	31.39	47.11	56.35	32535.60	21.61	193	6.72	0
Week 7	61.31	95.92	114.74	32094.80	18.85	92	6.92	1.85
Week 8	81.46	127.49	152.51	32040.33	21.94	110	7.06	1.95
Week 9	43.80	64.28	76.90	30324.00	15.91	59	7.26	1.1
Week 10	57.19	79.02	94.53	27740.00	18.94	230	6.75	1.55
Week 11	94.15	77.69	92.93	22249.00	17.79	84	7.1	1.65
Week 12	31.56	44.94	53.76	29602.76	14.96	38	7.04	1.85
Week 13	22.20	37.64	45.03	43256.03	17.00	38	6.53	0.00
Week 14	12.87	19.34	23.13	40057.18	15.64	81	6.84	0.00
Week 15	12.54	25.50	30.51	45887.85	19.24	161	6.77	0.55
Week 16	11.33	27.39	32.76	53536.30	17.58	81	7.19	0.00
Week 17	7.56	21.09	25.22	57265.05	17.43	63	7.20	0.00
Week 18	14.42	28.85	34.82	43225.00	16.12	122	7.14	0.00
Week 19	10.33	26.86	32.13	53953.35	16.76	71	7.24	0.00
Week 20	18.62	45.45	54.37	51295.66	15.75	33	6.67	0.00
Week 21	56.84	105.56	126.27	38224.58	18.86	123	6.84	0.00

<b>Marrero</b>	<b>Emission Factors</b>			<b>Wastewater Parameters</b>				
<b>Week</b>	<b>EF-Flow (mg/cu.m)</b>	<b>EF- Population (mg/head)</b>	<b>EF- Area (g/sq. Km)</b>	<b>Flow (m<sup>3</sup>/day)</b>	<b>Temperature (Centigrade)</b>	<b>BOD (mg/l)</b>	<b>pH</b>	<b>T. Sulfides (mg/l)</b>
Week 1	870.72	497.69	802.23	19843.60	25.60	105	6.78	0.85
Week 2	910.98	542.84	875.02	19805.60	27.41	121	6.81	1.65
Week 3	625.67	422.65	681.28	22768.33	26.45	135	7.05	1.85
Week 4	352.58	255.41	411.69	24028.67	21.85	195	6.68	1.9
Week 5	276.58	181.51	292.57	24022.33	22.02	105	7.17	2.25
Week 6	419.90	225.78	363.94	18303.33	19.73	108	7.03	1.5
Week 7	280.64	155.12	250.04	20266.67	19.32	72	7.11	1.95
Week 8	252.77	162.82	262.46	22852.78	22.25	111	7.14	2.1
Week 9	261.23	143.02	230.54	18129.17	17.25	102	7.2	1.95
Week 10	250.87	118.61	191.18	16213.33	19.56	153	7.42	2.25
Week 11	416.99	148.54	239.43	18525.00	18.04	72	7.11	2
Week 12	176.83	122.38	197.27	23636.00	15.72	68	7.12	1.65
Week 13	78.17	73.53	118.52	49653.33	17.25	34	6.48	0.00
Week 14	59.09	53.68	86.52	39105.45	16.27	55	6.86	0.00
Week 15	48.44	40.77	65.72	32680.00	19.79	142	7.04	0.75
Week 16	53.39	56.91	91.73	50096.67	18.21	69	7.05	0.00
Week 17	25.08	31.62	50.96	42465.00	18.63	59	7.45	0.00
Week 18	57.49	47.31	76.27	28011.43	16.64	77	7.05	0.10
Week 19	12.89	18.86	30.40	62700.00	16.76	88	7.21	0.00
Week 20	67.77	54.07	87.16	26600.00	15.94	106	6.73	0.00
Week 21	163.92	101.39	163.43	20520.00	19.18	127	6.86	0.00

East Bank	Emission Factors			Wastewater Parameters				
	EF-Flow (mg/cu.m)	EF-Population (mg/head)	EF-Area (g/sq. Km)	Flow (m <sup>3</sup> /day)	Temperature (Centigrade)	BOD (mg/l)	pH	T.Sulfides (mg/l)
Week								
Week 1	81.98	35.04	76.85	70459.6	26.25	120	6.85	1.25
Week 2	87.51	34.47	75.61	64083.2	26.98	96	6.66	1.9
Week 3	89.36	30.21	66.26	55191.2	27.03	186	6.71	0.25
Week 4	115.47	35.82	78.56	50661.6	22.94	110.6	6.84	0.85
Week 5	57.98	20.00	43.86	58472.5	20.87	147	6.79	2.25
Week 6	69.00	21.43	47.01	50737.6	19.39	289	6.82	2.1
Week 7	72.93	23.89	52.40	55799.2	19.15	110.6	6.78	1.45
Week 8	53.84	24.19	53.06	106564.7	21.60	87	7.07	2.05
Week 9	38.05	18.61	40.80	82213	17.33	95	7.15	2.15
Week 10	70.41	31.99	70.15	75574.4	19.83	164	7.27	1.75
Week 11	48.34	24.81	54.41	79971	18.89	91	6.96	1.85
Week 12	23.40	13.60	29.82	99256	16.73	60	7.22	2.10
Week 13	8.15	6.82	14.95	169297.6	17.24	53	6.48	0.00
Week 14	13.07	7.02	15.40	98919.43	17.55	64	6.65	0.00
Week 15	17.98	7.21	15.81	87067.5	18.29	124	6.92	0.50
Week 16	1.00	0.92	2.03	136667	17.02	31	7.43	0.00
Week 17	6.09	4.17	9.14	113658	17.64	55	7.41	0.00
Week 18	16.38	7.65	17.10	78502.57	17.00	71	7.32	0.00
Week 19	1.73	1.68	3.68	188613	17.10	77	7.47	0.10
Week 20	14.00	7.46	16.37	90516	16.90	32	7.05	0.00
Week 21	35.61	16.02	35.14	75148.8	19.94	103	6.65	0.00

## Appendix A.2 SAS MODEL Input Data

### Bridge City SAS Input Data

#### SAS Code

```
data bcity;
input ef_flow ef_popln ef_area flow temp bod bodl ph sulfide sulfidel;
datalines;
696.94747.76532.068306.0426.9374614.646966.542.117.442684
574.85587.82418.267875.8827.291431126.250846.711.511.81382
755.31688.71490.057030.0027.262141504.427.1900
507.91460.98328.017033.8022.8284590.83927.021.258.79225
411.81472.94336.5212118.2021.581541866.20287.1100
408.91430.76306.518320.4819.641911589.211686.831.7514.56084
474.71520.23370.168888.9619.871181048.897287.120.554.888928
321.30458.31326.1112010.5322.2033396.34766.80.151.80158
272.78337.60240.229908.5017.8852515.2426.890.252.477125
246.67262.53186.808366.0819.141601338.57287.020.32.509824
132.52204.43145.4610204.2717.7565663.27733336.910.252.551066667
140.770.000224159.4412403.2016.7965806.2086.900.455.58144
57.860.00013596.0723961.5317.95551317.8843336.370.000
51.760.00008963.1617315.2216.8134588.71741826.420.000
37.880.00005941.8215488.8019.6934526.61926.920.456.96996
50.670.00011178.8519820.2618.8730594.60771437.270.000
33.890.00007250.9517062.0017.72621057.8447.080.000
47.130.00007150.3611660.0317.1060699.60171437.130.000
8.690.00001813.1322770.5517.31601366.2337.330.000
30.000.00004229.9711104.1417.3074821.70657146.510.000
101.340.00012588.979982.6020.551031028.20786.420.000
;
run;
proc univariate normal;
var /*ef_popln*/ ef_flow;
histogram;
run;
data bcity;
set bcity;
ln_efflow= log(ef_flow);
ln_efpopln= log(ef_popln);
ln_bod=log(bod);
ln_temp= log(temp);
ln_flow=log (flow);
ln_efarea=log(ef_area);
efflow2=sqrt(ef_flow);
ph2= sqrt(ph);
ln_ph=log(ph);
run;
proc univariate normal;
var ln_efflow;
histogram;
qqplot/normal(mu=est sigma=est color=red);
run;
```



```

proc corr;
var ef_flow flow temp bod bod1 ph sulfide sulfidel;
run;
proc reg;
model ln_efflow= ln_flow ln_temp ln_bod ph sulfide/ selection= stepwise
sle=0.2 vif tol cp;
run;
proc reg;
model ln_efpopln= ln_flow ln_temp ln_bod1 ph sulfidel/ selection= stepwise
sle=0.2 vif tol cp;
run;
proc reg;
model ln_efarea= ln_flow ln_temp ln_bod1 ph sulfidel/ selection= stepwise
sle=0.2 vif tol cp;
run;

```

## Harvey SAS Input Data

SAS code

```

data harvey;
input ef_flow ef_popln ef_area flow temp bod bod1 ph sulfide sulfidel;
datalines;
74.0496.30115.2028880.0025.7710028886.5200
69.5282.7398.9624168.0026.341132730.9846.711.7542.294
88.33116.06138.8326752.0026.20105.92833.03686.820.8522.7392
82.8399.55119.0926340.0821.85105.92789.4144726.841.539.51012
36.2456.4967.5729830.0020.722206562.67.052.1564.1345
31.3947.1156.3532535.6021.611936279.37086.7200
61.3195.92114.7432094.8018.85922952.72166.921.8559.37538
81.46127.49152.5132040.3321.941103524.4366677.061.9562.47865
43.8064.2876.9030324.0015.91591789.1167.261.133.3564
57.1979.0294.5327740.0018.942306380.26.751.5542.997
94.1577.6992.9322249.0017.79841868.9167.11.6536.71085
31.5644.9453.7629602.7614.96381124.904887.041.8554.765106
22.2037.6445.0343256.0317.00381643.7292676.530.000
12.8719.3423.1340057.1815.64813244.6317276.840.000
12.5425.5030.5145887.8519.241617387.943856.770.5525.2383175
11.3327.3932.7653536.3017.58814336.44037.190.000
7.5621.0925.2257265.0517.43633607.698157.200.000
14.4229.5535.3543225.0016.121225273.457.140.000
10.3326.8632.1353953.3516.76713830.687857.240.000
18.6245.6654.6251295.6615.75331692.7566866.670.000
56.84105.56126.2738224.5818.861234701.623346.840.000
;
run;
proc univariate normal;
var /*ef_popln*/ ef_flow;
histogram;
run;
data harvey;
set harvey;
ln_efflow= log(ef_flow);
ln_efpopln= log(ef_popln);

```

```

ln_bod1=log(bod1);
ln_temp= log(temp);
ln_flow=log (flow);
ln_efarea=log(ef_area);
efflow2=sqrt(ef_flow);
ph2= sqrt(ph);
ln_ph=log(ph);
run;
proc univariate normal;
var efflow2;
histogram;
qqplot/normal(mu=est sigma=est color=red);
run;
proc corr;
var ef_flow flow temp bod bod1 ph sulfide sulfidel;
run;
proc reg;
model ln_efflow= ln_flow ln_temp ln_bod1 ph sulfidel/ selection= stepwise
sle=0.2 vif tol cp;
run;
proc reg;
model ln_efflow= flow temp bod ph sulfide/ selection= stepwise sle=0.2 vif
tol cp;
run;
proc reg;
model ln_efpopln= ln_flow ln_temp ln_bod1 ph sulfidel/ selection= stepwise
sle=0.2 vif tol cp;
run;
proc reg;
model ln_efarea= ln_flow ln_temp ln_bod1 ph sulfidel/ selection= stepwise
sle=0.2 vif tol cp;
run;

```

## Marrero SAS Input Data

### SAS Code

```

data marrero;
input ef_flow ef_popln ef_area flow temp bod bod1 ph sulfide sulfidel;
datalines;
870.72497.69802.2319843.6025.601052083.5786.780.8516.86706
910.98542.84875.0219805.6027.411212396.47766.811.6532.67924
625.67422.65681.2822768.3326.451353073.7257.051.8542.12141667
352.58255.41411.6924028.6721.851954685.596.681.945.65446667
276.58181.51292.5724022.3322.021052522.3457.172.2554.05025
419.90225.78363.9418303.3319.731081976.767.031.527.455
280.64155.12250.0420266.6719.32721459.27.111.9539.52
252.77162.82262.4622852.7822.251112536.6583337.142.147.99083333
261.23143.02230.5418129.1717.251021849.1757.21.9535.351875
250.87118.61191.1816213.3319.561532480.647.422.2536.48
416.99148.54239.4318525.0018.04721333.87.11237.05
176.83122.38197.2723636.0015.72681607.2487.121.6538.9994
78.1773.53118.5249653.3317.25341688.2133336.480.000
59.0953.6886.5239105.4516.27552150.86.860.000
48.4440.7765.7232680.0019.791424640.567.040.7524.51

```

```

53.3956.9191.7350096.6718.21693456.677.050.000
25.0831.6250.9642465.0018.63592505.4357.450.000
57.4948.3477.9228011.4316.64772156.887.050.102.801142857
12.8918.8630.4062700.0016.76885517.67.210.000
64.9350.5881.5426600.0015.941062819.66.730.000
163.92101.39163.4320520.0019.181272606.046.860.000

```

```

;
run;
proc univariate normal;
var /*ef_popln*/ ef_flow;
histogram;
run;
data marrero;
set marrero;
ln_efflow= log(ef_flow);
ln_efpopln= log(ef_popln);
ln_bod=log(bod);
ln_temp= log(temp);
ln_flow=log (flow);
ln_efarea=log(ef_area);
efflow2=sqrt(ef_flow);
ph2= sqrt(ph);
ln_ph=log(ph);
run;
proc univariate normal;
var ln_efflow;
histogram;
qqplot/normal(mu=est sigma=est color=red);
run;
proc corr;
var ef_flow flow temp bod bod1 ph sulfide sulfidel;
run;
proc reg;
model ln_efflow= ln_flow ln_temp / selection= forward sle=0.2 vif tol cp;
run;
proc corr;
var ef_popln flow temp bod bod1 ph sulfide sulfidel;
run;
proc reg;
model ln_efpopln= ln_flow ln_temp / selection= stepwise sle=0.2 vif tol cp;
run;
proc corr;
var ef_area flow temp bod bod1 ph sulfide sulfidel;
run;
proc reg;
model ln_efarea= ln_flow ln_temp / selection= stepwise sle=0.2 vif tol cp;
run;

```

## SAS East Bank Input Data

SAS Code

```
data eastbank;
input ef_flow ef_popln ef_area flow temp bod bod1 ph sulfide sulfidel;
datalines;
81.9796655835.0397449376.8463051170459.626.253333331208455.1526.851.2588.0745
87.5108546134.4746398375.606962864083.226.97555556966151.98726.661.9121.75808
89.3556297630.2125941666.2597925255191.227.0277777818610265.56326.710.25
13.7978
115.467096635.8198206178.5571033550661.622.93888889110.65603.172966.840.85
43.06236
57.9831322920.0001071843.8626006558472.520.865277781478595.45756.792.25
131.563125
68.9961949621.4338595347.0069891450737.619.3928914663.16646.822.1106.54896
72.9325842923.8926433252.3993928255799.219.15111111110.66171.391526.781.45
80.90884
53.843011924.1934176353.05902644106564.666721.60092593879271.1267.072.05
218.4575667
38.0541169218.6052202240.803448578221317.33194444957810.2357.152.15176.75795
70.4127028431.987254870.1518332275574.419.8322222216412394.20167.271.75
132.2552
75.6856337324.8078829254.406621517997118.89111111917277.3616.961.85147.94635
23.4058602713.5992794329.824828319925616.73333333605955.367.222.10208.4376
8.153765766.81823974614.95320622169297.617.24111111538972.77286.480.000
13.069143737.02246048815.4010864698919.4285717.54761905646330.8434296.650.000
17.975270097.20751181215.8069259187067.518.2916666712410796.376.920.50
43.53375
1.0049787650.9233586562.02503474713666717.01587302314236.6777.430.000
6.0891066844.1683996899.14179355411365817.63888889556251.197.410.000
16.377068677.65339107916.7847918878502.5714317715573.6825717.320.000
1.7347845521.6773241773.67857031418861317.097222227714523.2017.470.1018.8613
14.146072537.57286955416.608198659051616.8968254322896.5127.050.000
35.6076989216.0225976935.1394518775148.819.944444441037740.32646.650.000

;
run;
proc univariate normal;
var /*ef_popln*/ ef_flow;
histogram;
run;
data eastbank;
set eastbank;
ln_efflow= log(ef_flow);
ln_efpopln= log(ef_popln);
ln_bod1=log(bod1);
ln_temp= log(temp);
ln_flow=log (flow);
ln_efarea=log(ef_area);
efflow2=sqrt(ef_flow);
ph2= sqrt(ph);
ln_ph=log(ph);
run;
proc univariate normal;
```

```

var ln_efflow;
histogram;
qqplot/normal(mu=est sigma=est color=red);
run;
proc corr;
var ef_popln flow temp bod bod1 ph sulfide sulfidel;
run;
proc reg;
model ln_efflow= ln_flow ln_temp ln_bod1 / selection= stepwise sle=0.2 vif
tol cp;
run;
proc reg;
model ln_efflow= flow temp bod ph sulfide/ selection= stepwise sle=0.2 vif
tol cp;
run;
proc reg;
model ln_efpopln= ln_flow ln_temp / selection= stepwise sle=0.2 vif tol cp;
run;
proc reg;
model ln_efarea= ln_flow ln_temp ln_bod1 ph sulfidel/ selection= stepwise
sle=0.2 vif tol cp;
run;

```

## VITA

The author was born in the port city of Calcutta, India in 1980. Mr. Amitdyuti Sengupta completed his Bachelors in Civil Engineering from Nagpur University, Nagpur India in 2004 with a First Division. He finished his Masters in Environmental Engineering from the University of New Orleans in May 2007 and this Doctoral Program in May 2014.

The author has been a Deans scholar during his tenure as a masters candidate at the University of New Orleans and Crescent City Scholar from 2008-2010. Mr. Sengupta also won the 2006 Gus vonBodungen Air and Waste Management Association (AWMA) annual scholarship from the state of Louisiana. He is also the recipient of a scholarship offered by Hessen Ministry of Art and Science Germany for studying at The University of Kassel in January of 2007.

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