11-15-2019

Development of a System for Assessing and Minimizing Health Risk during Wastewater Conveyance and Treatment Processes

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Recommended Citation

Pitiriciu, Mariana, "Development of a System for Assessing and Minimizing Health Risk during Wastewater Conveyance and Treatment Processes" (2019). *FIU Electronic Theses and Dissertations*. 4290.
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FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

DEVELOPMENT OF A SYSTEM FOR ASSESSING AND MINIMIZING HEALTH RISK DURING WASTEWATER CONVEYANCE AND TREATMENT PROCESSES

A dissertation submitted in partial fulfillment of the
requirements for the degree of
DOCTOR OF PHILOSOPHY
in
CIVIL ENGINEERING
by
Mariana Pitiriciu

2019

To: Dean John L. Volakis
College of Engineering and Computing

This dissertation, written by Mariana Pitiriciu, and entitled Development of a System for Assessing and Minimizing Health Risk During Wastewater Conveyance and Treatment Processes, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

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Date of Defense: November 15, 2019

The dissertation of Mariana Pitiriciu is approved.

Dean John L. Volakis
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Vice President for Research and Economic Development
and Dean of the University Graduate School

Florida International University, 2019

DEDICATION

I dedicate this dissertation to my beloved late father, my mom, my husband, my brother, and my mentor, Mr. Daniel Rosemond.

ACKNOWLEDGMENTS

I want to express my sincerest appreciation to all those who supported me and made the completion of this dissertation possible. I am grateful to my major advisor Berrin Tansel and to the members of my dissertation committee, Dr. Hassan Zahedi, Dr. Walter Tang, Dr. Shonali Laha, and Dr. Wallied Orabi; their orientations and support were very valuable for me.

I wish to express my most sincere gratitude to my advisor Dr. Berrin Tansel, who accepted me as her student for the Ph.D. program; I was blessed to have her support, technical advice, and guidance in the completion of this dissertation.

I want to thank the Department of Civil and Environmental Engineering (CEE) and the University Graduate School for the assistance and kindness from the Dean's Office, chair, directors, professors, colleagues, and administrative staff.

Also, special thanks to Dr. Danny Crew (City Manager at the City of Miami Gardens); Mr. Tom Ruiz (Director of Public Works at the Miami Gardens); Mr. Daniel Rosemond (City Manager at the City of Hallandale Beach); Mr. Steven Parkinson, P.E. (Assistant City Manager at the City of Hallandale Beach); Mr. James Sylvain, P.E. (Director of Public Works Director at the City of Hallandale Beach); and Mr. Amer Awwad, P.E. (Senior Mechanical Engineer at the Applied Research Center at Florida International University) for their technical advice, continuing support, and motivation in completing this dissertation.

Finally, I would like to thank my family from Romania (my mom, my late father, and my brother and his family) for their encouragement and emotional support; my husband for his continuing support and encouragement; my friends, Dr. Claudia Cardonas, Dr. Zuhal Ozturk, and Mr. Carlos Hernandez; and my lovely two dogs for keeping me company during many long nights and weekends. This work would not have been possible without them in my life.

ABSTRACT OF THE DISSERTATION

DEVELOPMENT OF A SYSTEM FOR ASSESSING AND MINIMIZING HEALTH RISK DURING WASTEWATER CONVEYANCE AND TREATMENT PROCESSES

by

Mariana Pitiriciu

Florida International University, 2019

Miami, Florida

Professor Berrin Tansel, Major Professor

Many studies on volatile organic compound (VOC) emissions have focused on treatment plants sewage at various locations throughout the world, but they seldom report VOC emissions derived from sewer networks and sewer transportation systems, as compared to wastewater treatment plants. This study focuses on understanding the occurrence of VOCs produced from sewer networks in municipalities or counties throughout the State of Florida (United States) and identifying potential health risks to sewer workers. Common VOCs were identified in wastewater treatment plant influents using available analytical reports. Gas-phase samples from sewer manholes in the City of Hallandale Beach were collected and analyzed following the U.S. Environmental Protection Agency (USEPA) Method TO-15. The potential adverse health effects of the VOCs, according to their non-carcinogenic and carcinogenic classifications by the USEPA IRIS, were evaluated using risk assessment. Considering the toxicity classification and high concentrations of the identified VOCs, the risk was evaluated for tetrachloroethene, chloroform, 1,4-dichlorobenzene, methylene chloride, and toluene.

The hazard quotient (HQ) gave values less than unity for tetrachloroethene, chloroform, 1,4-dichlorobenzene, toluene, and methylene chloride concentrations from liquid-phase samples from Hallandale and Orlando. This result implies that the non-carcinogenic effects have no health concerns for the sewer workers. On the contrary, the HQ gave values of more than unity value for tetrachloroethylene and chloroform for concentrations measured in the gas-phase samples from Hallandale, which suggested a high probability of health concerns for sewer workers. The calculated HQ for tetrachloroethylene and chloroform for concentrations measured in the gas-phase samples in Hallandale ranged from 0.007 to 13.76 and 0.34 to 2.67, respectively. Based on Monte Carlo simulations, the 95th percentile of the total non-carcinogenic risk for the five VOCs was 31.13, which could pose a threat to human health because it surpasses the acceptable upper confidence limit (1.0).

Carcinogenic risks for tetrachloroethene and chloroform for gas-phase concentrations from Hallandale ranged from 7.12 x 10^{-8} to 1.43 x 10^{-4} and 7.88 x 10^{-5} to 3.74 x 10^{-4}, respectively, which exceeded the acceptable USEPA level of 1.0 x 10^{-6}. Carcinogenic risks for chloroform for concentrations identified in the liquid-phase from Hallandale and Orlando ranged from 7.88 x 10^{-7} to 5.7 x 10^{-6} and 9.98 x 10^{-7} to 7.51 x 10^{-6}, respectively, which also exceeded the acceptable level. Monte Carlo simulations were used to estimate the carcinogenic risks and to give a better understanding of the variability of exposure in the sewer systems and possible health effects on sewer workers. The 95th percentile of the carcinogenic risks for tetrachloroethene and chloroform from gas-phase concentrations in Hallandale was 1.32 x 10^{-4} and 4.72 x 10^{-4}, which exceeds the acceptable upper level of 1.0 x 10^{-6}.

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ABBREVIATIONS AND ACRONYMS

AT	Average time
ATSDR	Agency for Toxic Substances and Disease Registry
CA	Gas-phase concentration of pollutant
C_l	Liquid-phase concentration of pollutant
BW	Body weight
C.F.R.	Code of Federal Regulations
DF	Dilution Factor
EC	Lifetime exposure concentrations
ED	Exposure duration
EF	Exposure frequency
ET	Daily exposure time
EW	Exposure weeks
GS/MS	Gas chromatography-mass spectrometry
HQ	Hazard quotient
IARC	International Agency for Research in Cancer
IR	Inhalation rate
IRIS	Integrated Risk Information System
IUR	Inhalation unit risk
LAAD	Lifetime average daily dose
LT	Lifetime
MDL	Method detection limit
PQL	Practical quantitation limit

RfC	Reference concentration
SF	Slope factor
TCE	Trichloroethylene
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compounds
VSC	Volatile sulfur compounds
WHO	World Health Organization
WOE	Weight of evidence
WWTP	Wastewater treatment plant

SYMBOLS

atm · m^3	Cubic meter-atmosphere
°C	Degrees Celsius
g/h	Gram per hour
K	Kelvin temperature scale
kg/yr	Kilogram per year
mol · K	Mol Kelvin
m^3/hr	Cubic meter per hour
ppm	Parts per million
T	Temperature
µg/m^3	Microgram per cubic meter
µg/l	Milligram per liter

1. INTRODUCTION

1.1 Motivation

Many studies on volatile organic compound (VOC) emissions have focused on treatment plant sewage at various locations throughout the world. In studies, researchers seldom report VOC emissions derived from sewer networks and sewer transportation systems, as compared to wastewater treatment plants (WWTPs; Atasoy et al., 2004; Ras et al., 2008). This lack of reporting is mainly because of insufficient sampling and the analytical limitations for the analysis of VOCs that are present at a trace level and over a range of concentrations (Wang et al., 2012).

Various sources discharge VOCs into municipal wastewater collection systems, including residential households, industries, commercial establishments, and public institutions. VOCs present in groundwater, and soil vapors can also infiltrate into sewer systems through cracks or other openings in the sewer networks. VOCs from groundwater remediation systems, effluents, and other sources (including those from illegal discharges) can also be discharged directly into sewer systems. These discharges cause concerns related to the transfer of VOCs from the aqueous to the gaseous phase. The primary concerns are (a) worker exposure to toxic chemicals during wastewater collection and treatment; (b) emissions of toxic contaminants released to the environment once they reach the vapor state, rendering them much more mobile; (c) accumulation of explosive gases in confined environments in sewer collection and treatment systems; (d) increasing amounts of reactive hydrocarbons in the atmosphere, which can contribute to the formation of photochemical oxidants; and (e) emissions of reactive organic gases that contribute to tropospheric ozone formation (Huang et al., 2012; Quigley and Corsi, 1995). During the sewage transportation process, biological reactions under microaerobic and anaerobic conditions may cause the formation of a wide variety of VOCs, subsequently releasing them into the atmosphere (Vincent, 2001). Furthermore, these hazardous air pollutants result from physical or biological reactions in sewers, and their accumulation may harm the health of sewer workers (Hass and Hermann, 1996, 1998; Lee et al., 2002; Paxeus et al., 1992).

Many VOCs are known, probable, or possible human carcinogens, raising concerns for people exposed to these chemical hazards (U. S. Environmental Protection Agency [USEPA], 2005). Examples of toxic VOCs identified in previous studies from sewer networks include dichloromethane, styrene, toluene, and different types of benzene-like compounds, such as chlorobenzene, methylbenzene, and ethylbenzene (Corsi et al., 1995; Niu et al., 2014; Wang et al., 2012; Yeh et al., 2011). Some of these pollutants are carcinogenic, and the safety of sewer workers is essential from a health risk perspective (Yeh et al., 2011). The workers who perform routine work in the sewer network systems, as well as those who work at wastewater treatment facilities, are exposed to hazardous chemicals that may have possible health effects (Paxeus et al., 1992; Yeh et al., 2011).

1.2 Wastewater

There is no single concise definition of wastewater. However, most of the definitions describe wastewater as the flow of used water from the community. According to Lin (2001), “wastewater, also known as sewage, originates from household wastes, human and animal waste, industrial wastewaters, storm run-off, and groundwater infiltration." Municipal wastewater is the general term given to the liquid wastes collected in sanitary sewers and conveyed to municipal sewage treatment plants.

The wastewater can be classified into two categories. The first category is domestic wastewater, which refers to sanitary wastewater discharged from residences, commercial buildings, mobile homes, schools, hotels, offices, factories, and other business enterprises. The second category is industrial wastewater, which refers to wastewater discharged into the city sewer system by small manufacturing facilities within municipal limits only after pretreatment.

1.3 Chemical Constituents of Wastewater

Wastewater, or sewage, is a complex mixture of water and solids generated by industrial, commercial, and domestic activities, in addition to surface water, groundwater infiltration, and stormwater. The total solids in the wastewater, which comprise the dissolved and suspended solids, contain organic and inorganic material. Organic matter may include carbohydrates, oil, fats, grease, proteins, pesticides, and other agricultural chemicals, VOCs, and other toxic chemicals. The inorganic matter may include plant nutrients (such as nitrogen, phosphorus, and potassium), heavy metals (e.g., cadmium, chromium, copper, mercury, nickel, lead, and zinc), chlorides, sulfur, alkalinity, pH, and other inorganic pollutants. Gases, such as methane, carbon dioxide, oxygen, and hydrogen sulfide, can also be present in wastewater. Also, the wastewater may contain pathogenic microorganisms (viruses, bacteria, protozoa, and helminths) and micro-pollutants (e.g., medicines, cosmetics, and cleaning agents).

1.4 Definition and Classification of VOCs

The USEPA defines VOCs as “any carbon compounds excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates and ammonium carbonate, which participate in atmospheric photochemical reactions. This includes any such compound other than the following which has been determined to have negligible photochemical reactivity: methane, ethane, acetone, methyl acetate, completely methylated siloxanes and other halogenated hydrocarbons and perfluorocarbon compounds” (Spengler et al., 2001).

The World Health Organization (WHO, 1989) classifies organic compounds according to their boiling points because the temperature determines their volatility. There are four categories of organic pollutants, as shown in Table 1. VOCs are grouped in Category 2, and they have two different boiling point ranges. The lower range is between 50 to 100 °C, while the upper limit range between 240 to 260 °C.

Table 1
Classification of Organic Pollutants

Category	Classification	Abbreviation	Boiling-point range (°C)
1	Very volatile organic compounds	VVOC	Less than 0 to 50-100
2	Volatile organic compounds	VOC	50-100 to 240-260
3	Semi-volatile organic compounds	SVOC	240-260 to 380-400
4	Organic compounds associated with particulate matter	POM	More than 380

Note. Adopted from *Human Health Risk Assessment of Trace Chemicals in the Residential Environment Using Probabilistic Techniques*, N. Hamidin, 2009.

1.5 Classification of Sewer Systems

Wastewater and stormwater can be removed using three types of sewer systems: (a) sanitary sewer systems, in which the wastewater flow consists of domestic wastewater, industrial wastewater, and infiltration or inflow; (b) storm sewer systems, in which runoff results from rainfall and snowmelt; and (c) combined sewer systems, in which wastewater flows are a combination of domestic wastewater, industrial wastewater, infiltration or inflow, and stormwater.

Field workers may develop chronic diseases due to chronic exposure to hazardous substances and conditions during wastewater collection and treatment. The release of the VOCs from the wastewater collection system at the sewer line support systems (such as drop manholes, junction boxes, and pump stations) results in potential health risks for field maintenance personnel. Similar health concerns exist because of the chronic exposure of plant personnel to VOCs released during different processes, such as bar screens, grit chambers, equalization basins, primary and secondary sedimentation tanks, biological treatment processes, and emission from digesters.

1.6 Sewer Systems

Sewers are underground pipes that either convey wastewater and stormwater to a treatment plant or convey stormwater to the point of disposal. In the early part of the last century, the United States started the development of the sewer system and the expansion of most of the wastewater collection mains (Tafuri and Selvakumar, 2001). The sewage system is one of the most capital-intensive and critical infrastructure systems globally and particularly in the United States (Wirahadikusumah et al., 1988). Due to rapid growth in the economies of the United States and Canada, the installation of the majority of North America's underground infrastructure utilities took place in the 1950s and 1960s (Hashemi et al., 2011). Because these underground facilities have exceeded their design lives and have significantly deteriorated, failure of these aging systems has become everyday news. It is the ultimate responsibility of municipalities, towns, and counties to maintain and renew these aging and deteriorating underground infrastructures to a level of service satisfactory enough to ensure the public's health and to safeguard the environment from pollution. Furthermore, the sewer workers provide an essential service that contributes to the protection of the public's health by maintaining the sewage infrastructure, which disposes the wastewater and hazardous agents produced by an urbanized society (Al Zabadi et al., 2011).

Due to their underground placement and low visibility, sewer systems are difficult to monitor, maintain, and rehabilitate. Sewer infrastructure involves immense investments, and limited budgets usually hinder this infrastructure (Wirahadikusumah et al., 1998). Thus, regular inspections, testing, and assessment activities are necessary for the implementation of the most efficient maintenance activities to prevent failures, environmental pollutions, and wastewater treatment overflow (Wirahadikusumah et al., 1998).

1.7 Separate and Combined Sewers

According to their discharge types, community sewer systems are either separate or combined sewer systems. Separate sewers consist of sanitary sewers and stormwater sewer networks separately. On the contrary, combined sewers are designed for the collection and conveyance of both sanitary sewage and stormwater runoff in one pipe. Whereas the combined sewer systems are common in the old U.S. and European urban communities, in the United States, there has been an inclination to replace combined sewer systems with separate sewer systems (Lin, 2001).

1.8 Collector Sewers

Collector sewers (trunks or mains) are pipes that collect wastewater from individual sources and carry it to interceptors. Interceptors are major lines receiving wastewater from collector sewers and transporting to a treatment plant.

1.9 Lift Stations

A lift station (or sewage pump station) is a service through which wastewater is moved or transferred from a lower to a higher elevation, especially in places where the elevation is not adequate for gravity or where the excavation work might result in exorbitant costs. The key elements of a lift station are a wastewater receiving tube or a well, which includes a grinder or a screen (to eliminate rough and bristly material); piping; valves; pump motors; a power supply; and an alarm system. When installing a lift station, workers also install odor and ventilation systems.

1.10 Sewer Manholes and Accessories

Utility companies install sewer manholes along sewer lines, and their primary purpose is to serve as an access point for inspection, cleaning, maintenance, and system upgrades. Also, the manholes are installed at sewer line intersections and changes in elevation, direction, size, diameter, and slope. Workers also use manholes as access points for prompt inspection and cleaning of the sewer pipes.

1.11 Wastewater Treatment Plants

WWTPs are facilities designed to remove contaminants from municipal wastewater. These WWTPs include physical, chemical, and biological processes that are used to remove contaminants and produce treated wastewater (or treated effluent) that is safe enough for release into the environment. For traditional WWTPs, the preliminary treatment of the wastewater is a mechanical process of removing large objects, rags, and wood; this process prevents damage to pumps and other equipment. After preliminary treatment, there are four levels of wastewater treatment: primary, secondary, tertiary, and quaternary. Primary treatment is a mechanical process that removes most of the settleable solids and oils. Secondary treatment involves biological treatment and is mandatory in the United States for all publicly owned WWTPs. Tertiary and quaternary treatments, known as advanced wastewater treatments, target specific pollutants or wastewater characteristics that are unallowable in the discharge.

1.12. Sources of VOCs in Wastewater

The occurrence of VOCs in wastewater can be characterized based on the sources contributing to their appearance, as follows:

- water supply,
- industries,
- commercial institutions,
- household and consumer products,
- surface runoff, and
- chemical and biogenic reactions occurring water and wastewater treatment.

1.12.1 Water Supply

As of result of its formation during the chlorination of drinking water, wastewater and swimming pools, chloroform may be released into the atmosphere. It can also be released from other sources such as hazardous waste sites, sanitary landfills, and pulp and paper mills. Carbon tetrachloride and methylene chloride can also be produced during these processes. Bromoform can be created as well, when brominating is used to disinfect water supplies and wastewater effluents.

1.12.2 Industries

According to Lucas (1989), the USEPA estimated VOC losses from 1,671 WWTPs, which accounted for approximately 81% of the total wastewater flows. This report also concluded that 97% of the wastewater flows were collected from indirect discharges from industries. Seven potential hazardous pollutants accounted for 98% of the VOCs discharged by 11 industrial categories. These VOCs were carbon tetrachloride, trichloroethylene (TCE), tetrachloroethene, methylene chloride, ethylene dichloride, chloroform, and acrylonitrile. Benzene, carbon tetrachloride, TCE, and methylene chloride are the chemicals contributed most by industries (American Society of Civil Engineering [ASCE], 1995).

Benzene is usually in the industrial wastewater produced by oil production and petroleum refinery. Benzene is also used by many industries that provide consumer products, such as detergents, deodorants, shampoo, paintbrush cleaners, tar remover, solvents, thinners, oven cleaners, and many others. They can enter the sewer systems from the wastewater discharged by these industries. Carbon tetrachloride, methylene chloride, and TCE are utilized in industries that produce solvent. They can reach the sewer system through wastewater discharged by degreasing, dewaxing, and many types of industrial cleaning operations. Methylene chloride is used as a solvent and as a paint-stripping agent; it is also used in industries manufacturing oven cleaners, leather coating, degreaser, and tart removers. Tetrachloroethene is used to manufacture a variety of household products, such as detergents, perfumes, degreasers, and paintbrush cleaners. Chloroform is produced during the disinfection processes of drinking water and wastewater. In the United States, most of the chloroform produced is used to make HCFC-22 for export and miscellaneous uses. In the past, there were other uses of chloroform, such as fumigant in fire extinguishers; as an aesthetic; as an extracting solvent for fats, oil, and greases; and as a dry-cleaning spot remover. According to the Agency for Toxic Substances and Disease Registry (ATSDR, 1997), chloroform is no longer used in these products.

1.12.3 Commercial Institutions

Many products containing VOCs, such as cleaning fluids and solvents, are used by hospitals, schools, jails, and commercial laundries, and their wastewater is discharged into the sewer systems.

1.12.4 Surface Runoff

It was reported by Noll and De Paul (1987) that runoff from combined sewers contains a higher concentration of VOCs compared to the area having separate sewers. These researchers studied wastewater inflows of combined sewers for treatment facilities in the metropolitan area of Chicago, and they reported elevated concentrations of benzene, toluene, xylenes, cyclohexenes, and alkanes. It was concluded that it is possible that gasoline spills on streets and parking lots contribute to the surface runoff and eventually find their way into the treatment facilities.

1.12.5 Chemical and Biogenic Reactions Occurring Wastewater Treatment

Chloroform, methylene chloride, and carbon tetrachloride are chlorination byproducts. They can be produced during the disinfection of drinking water and wastewater effluents. Bishop et al. (1990) investigated the chlorination of partially nitrified and nitrified secondary effluent. These researchers concluded that higher values of trihalomethanes (µg/l) were formed with nitrified wastewater compared to the partially nitrified wastewater. Caballero and Griffith (1989) argued that concentrations of benzene, BTX, and ethylbenzene in digester gas had elevated values because of their removal in sludge streams, followed by desorption and formation, during the anaerobic digestion process.

1.13. VOC Emissions from Sewers

Numerous factors govern the transfer of VOCs to the ambient air along with the sewer collection systems. Some of these factors are kinetic energy due to turbulence, mixing associates with turbulence in the flowing wastewater stream, the magnitude of ventilation and patterns associated with the sewer headspace, and the physical-chemical proprieties of VOCs.

During a study of the hazardous air pollutant emissions from a municipal sewer in 1997, Corsi concluded that a significant fraction of VOC discharges to sewers seem to be emitted from collection systems before reaching the treatment facility. He also argued that the estimates of VOCs dischargers to be based on mass loading at treatment plants are most likely significantly underestimated. Furthermore, the potential for municipal sewer collection systems to serve as significant area sources of pollutant emissions is highlighted by the fact that sewers are generally distributed throughout urban areas, conveying wastewaters from commercial institutions, industries, and residential areas.

2. OBJECTIVES AND APPROACH

2.1 Research Objective

The focus of this study was to gain a comprehensive understanding of the occurrence of volatile organic chemicals discharged from Hallandale Beach's sewers networks and other municipalities or counties throughout the State of Florida; this research was undertaken in order to identify potential health risks to the sewer workers. Also, because of this study, a decision-making tool was developed, based on field data and risk estimation methods, for reducing the health risks of sewer workers due to exposure to VOC emissions during field activities (i.e., routine maintenance, inspection, and sampling). The compilation of literature and field data, in addition to the quantitative health risk assessment, will provide an objective analysis and determine the necessary levels of protection for sewer workers during field activities. The ability to quantify expected risks and their probabilities under uncertainty provides an objective approach for risk estimation analyses. The findings from this study will provide a basis for wastewater utility managers and regulators to bring awareness to and develop appropriate health and safety training and protective equipment and to implement policies for the protection of field personnel and maintenance crews.

The first goal of this study was to identify the most common VOCs emitted from sewer systems and their respective concentrations through the following data compilation activities: (a) gathering available data from municipalities and counties in the State of Florida, (b) reviewing existing data from the literature to characterize the VOCs at various points in the sewer systems for the collection and treatment of sewage, and (c) sampling of sewer manholes located in the City of Hallandale Beach. Furthermore, the data from different sources and field sampling events were compared and analyzed, with a focus on the occurrence of the most common VOCs emitted from sewer conveyance systems and wastewater treatment processes.

The second goal of this study was to estimate the risk assessment, clustering contaminants as carcinogenic or non-carcinogenic, and to understand the potential health effects of the sewer workers due to VOC exposure. The specific objectives were to (a) determine the number of individuals likely to acquire cancers due to VOC exposure from inhalation intake; (b) in the case of non-carcinogenic effects, determine the hazardousness of an individual VOC by inhalation; and (c) apply the Monte Carlo probabilistic technique when screening calculations using conservative point estimates are above the levels of concern.

2.2 Health Risks and Assessment of VOC

Human exposure to VOCs in the working environment has resulted in several harmful health effects, either cancer-causing or non-cancer-causing (Hagerman et al., 1997). They play a vital role in the creation of tropospheric ozone and other particulates, thereby causing photochemical smog (Zheng et al., 2010; Zheng et al., 2013). They also lead to various symptoms, such as irritations of the nose, throat, and eyes, and can cause headaches, nausea, dizziness, allergic skin reactions, and damage to internal organs such as the liver and kidneys. Moreover, some VOCs may not be immediate hazards but can lead to chronic health risks. When exposed to benzene, people develop aplastic anemia, and higher doses lead to leukemia (Collins, 2003), toxicity to the genes, and brain developmental effects (Chen, 2000). Furthermore, researchers linked xylene to neurological problems (Savolainen et al., 1979). Long-term exposure causes headaches, fatigue, reductions in focus, and short-term memory loss (Shuai et al., 2018). Researchers have linked styrene and toluene to hearing loss (Estill et al., 2017), neurological problems (Chouanière et al., 2002), and color blindness (Gong et al., 2002). Long exposure to chloroform causes hepatitis, jaundice, irritation, and depression (Shuai et al., 2018). Inhalation of benzene, ethylbenzene, and naphthalene has caused cancer.

Researchers developed assessments of health risks to improve standards and reduce the harmful effects on human life. The assessment created by the U.S. National Research Council (NRC) has garnered international acceptance, and researchers have utilized it as a tool for assessing the risks. As shown in Figure 1, it comprises four steps. Researchers first identify whether exposure to a particular compound can cause problems for human health. Then, researchers analyze the quantity of the compounds, frequency, and time of exposure. They assess the response to the dosage. Subsequently, they characterize the risks for the compound.

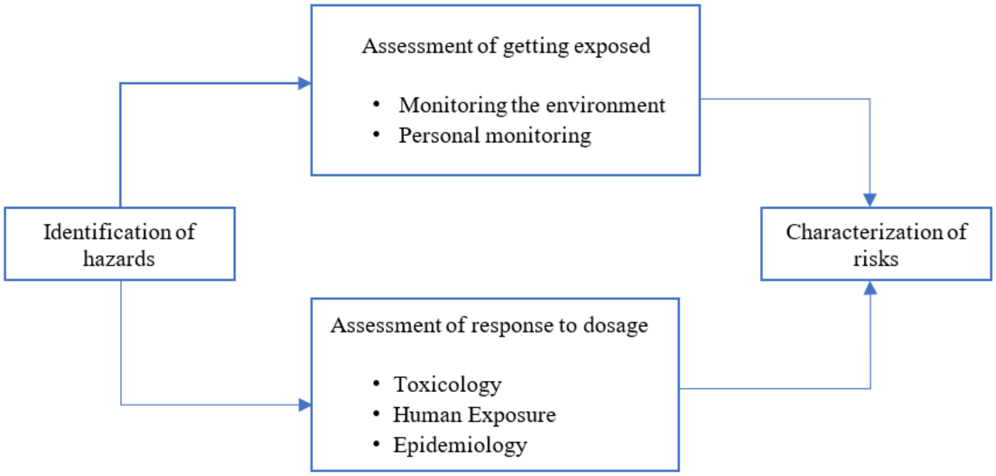


Figure 1. Health risk assessment.

2.3 Literature Review

A significant number of studies performed during the 1980s reported the occurrence and concentrations of VOCs in publicly owned treatment works (POTW). Researchers expect the current toxicant loadings at treatment plants to be lower because of the implementation of strict pretreatment requirements, better housekeeping at industrial sites, and proper disposal of household and consumer products; these have probably diminished toxicant concentrations. Some of these studies include USEPA (1982a), USEPA (1982b), RTI (1998), Ontario-Canada (1988), and East Bay Municipal Utility District (1989). In 1993, the Association of Metropolitan Sewage Agencies conducted a comprehensive survey with volunteer participants from its major member agencies when it was negotiating with the USEPA for the development of the Maximum Achievable Control Technology (MACT) rule for POTWs (published in 1999).

2.3.1 Concentration of VOC Emissions

Corsi and Quigley (1996) argued that industry-specific National Emission Standards for hazardous pollutants were to be developed based on estimates of VOC emissions derived from extrapolation measurements or empirical models. For this reason, these researchers analyzed VOC emissions from a pilot-scale drop structure constructed at the WWTP in Burlington, Ontario, Canada. They concluded that the reduction of VOC emissions from sewer drop structure or junction boxes could be achieved when it is possible to modify existing structures to allow for partially or fully submerged pipes. Also, the liquid flow rate had a substantial influence on VOC stripping efficiencies at drop structures. These VOC stripping efficiencies were reported to strongly be a function of Henry's law coefficient.

Due to the increasing amount of regulations on dangerous air pollutants, there have been studies addressing the control of VOC emissions from industrial treatment plants. However, there has been very little investigation of the emissions from sewer collection systems.

Quigley and Corsi (1995) evaluated VOC emissions from a large sewer interceptor from southern Ontario. Benzene, toluene, ethylbenzene, xylenes, and tetrachloroethene were the compounds targeted in this study. These researchers analyzed these compounds during three daytime monitoring events and one 24-hour event. Individual concentrations of toluene, ethylbenzene, xylenes, and tetrachloroethene identified in the sewer headspace ranged from 0 to 46 ppm. Levels of benzene were not detected. During the 24-hour sampling event, these researchers estimated the average emissions of total nonmethane hydrocarbons at 265 g/h (2,300 kg/yr) from a single manhole cover and a peak of 630 g/h (5,500 kg/yr), respectively. Across the four manhole covers, the highest headspace outgassing rates were estimated at 2,300 m^3/h, which by far exceeded the rates previously estimated and published in the technical literature at that time. These researchers also concluded that 29%–44% of the removal of individual VOCs from wastewater was due to a series of two drop structures, which were the primary source of VOC stripping. Furthermore, these researchers argued that large fractions of VOCs exit the sewers and enter the atmosphere before reaching the WWTP.

Roghani et al. (2018) used different techniques to collect and analyze gas samples from an aging sewer pipe system in the southern San Francisco Bay area over the years of 2014–2017. The results indicated that concentrations of TCE were ranging from non-detected to 1,600 µg/m^3. TCE concentrations were detected along sewer lines adjacent to and extending hundreds of feet away from well-defined groundwater contamination plumes, where TCE was a primary contaminant.

Ramírez et al. (2011) proposed an analytical method based on thermal desorption-gas chromatography-mass spectrometry (GC/MS) to determine the presence of 99 VOCs in gas-phase samples simultaneously. This method was applied to the analysis of gas-phase samples taken in the WWTP in Tarragona, Spain, which is an industrial center. This WWTP receives the wastewater from an area of approximately 1,100 ha, a refinery, and several chemical and petrochemical plants. In the samples collected from the tank after the primary sedimentation, Ramírez and colleagues found very high concentrations of VOCs, with a maximum value of 1,843 µg/m^3. Other high concentrations reported were styrene (408–574 µg/m^3), chloroform (2.22–155 µg/m^3), ethylbenzene (20.5–96.9 µg/m^3), and m- and p-xylene (35.3–136 µg/m^3). These researchers argued that the most abundant VOCs identified in the samples should be included in the USEPA List of Hazardous Air Pollutants (1994). Furthermore, according to WHO Air Quality Guidelines (2002), acrylonitrile and styrene, which have the highest concentrations levels, are considered hazardous organic pollutants with carcinogenic effects in animals and humans.

2.3.2 Health Risk Assessment

Niu et al. (2014) performed a health risk assessment to study the compounds coming from wastewater pumping stations in Tianjin, China. Thirty-two samples from wastewater were analyzed, and only 15 kinds of chemical hazards were detected. Dichloromethane, hydrogen sulfide, carbon disulfide, and chlorobenzene were the predominant contaminants and had the highest concentrations, ranging from 7.40 to 89.95

µg/m^3, 0 to 87.50 µg/m^3, 0.98 to 17.08 µg/m^3, and 0 to 14.69 µg/m^3, respectively. These researchers used a probabilistic technique for evaluating the potential health risks of four predominant compounds. They estimated the 95th percentile of the non-carcinogenic risk at approximately 1.73, which is higher than the upper confidence limit (1.0), which can cause a threat to human health. Also, it was concluded that the 95th percentile of the carcinogenic risk was much lower than the maximum acceptable level (1 x 10^{-6}), and there were no concerns to human health.

Sivret et al. (2016) measured volatile sulfur compounds (VSCs) and VOC emissions from 21 locations in four cities in Australia for nearly four years to identify their contributions to sewer odors. Generally, most of the measured VOC concentrations were less than 250 µg/m^3. Some VOCs registered high concentrations (trimethyl benzene, toluene, m- and p-xylenes, 1,4-dichlorobenzene, and trichloromethane). Sivret et al. (2016) argued that VOC emissions from sewer headspace air are unlikely to contribute to sewer odors because most of the VOCs had the 95th percentile concentrations below their respective odor threshold values (OTVs). These researchers also concluded that the highest VSCs in the sewer headspace air were hydrogen sulfide (median concentration of 168,700 µg/m^3 in samples from Perth), followed by methyl mercaptan (1,880 and 976 µg/m^3 in samples from Sydney and Melbourne, respectively), and then a range of sulfides. Furthermore, they concluded that VSCs are likely to contribute to sewer odors.

Wang et al. (2012) developed an analytical technique for characterizing VOCs emitted from the sewer system in Sydney, Australia. Samples were collected using sorbent tubes supported by a Thermal Desorber connected with GC/MS. These researchers validated this method by collecting samples from two sewer sites and further analyzing them. The average concentrations of target VOCs from the two locations reported were 202.00 and 654.25 µg/m^3 for chloroform, 5.52 and 8.85 µg/m^3 for benzene, 111.33 and 61.15 µg/m^3 for toluene, and 151.37 and 254.31 µg/m^3 for total xylenes.

According to Yeh et al. (2011), Taiwan is highly developed, but it lacks effective sewer management. All residential, industrial, and commercial wastewater flow into a common sewer, leading to a complicated situation. Yeh et al. (2011) analyzed the compounds and concentrations of hazardous pollutants from eight locations throughout the sewer networks from Kaohsiung, Taiwan. These researchers concluded that benzene and trichloromethane maximum concentrations were 148.4 and 327.3 ppm, respectively. Cancer risks, due to benzene and trichloromethane, for sewer workers without personal protection, approached levels of 2.77–3.98 x 10^{-3} and 29.74–42.70 x 10^{-3}, respectively. When ventilating for around 15 minutes, Yeh et al. (2011) reported that the cancer risks for benzene and trichloromethane reduced significantly, to 3.0–4.0 x 10^{-7} and 2.9–4.1 x 10^{-6}, respectively. Hence, the authors concluded that there should be a strict rule about ventilating sewage for some time before the worker enters it.

Fisher et al. (2018) analyzed emissions of VSCs and VOCs from sludge samples collected from the biosolids processing trains of five WWTPs in Sydney, Australia. These researchers concluded that the VSCs were the predominated odorants emitted throughout the wastewater treatment process. Hydrogen sulfide, methyl mercaptan, and dimethyl sulfide were reported as the dominant sulfur compounds. These researchers also identified VOC emissions, and the ratio of total VSCs to VOCs varied between the five sites monitored. The highest VOC emissions were identified from dewatered sludge from two sites with lower VSC emissions. Toluene and trimethyl benzene were the highest concentrations of VOCs emitted. Fisher et al. (2018) concluded that the variations of VOC emissions of industrial origin are likely dependent on the industrial flows to the WWTPs and the treatment stage that influences their formation and emission.

The overwhelming release of VOCs from WWTPs has lots of health risks for the public. Yang et al. (2014) prepared a miniature bioreactor to analyze the distribution of three aromatic (benzene, toluene, and xylenes) and four chlorinated (chloroform, carbon tetrachloride, TCE, and tetrachloroethylene) VOCs. The VOC distribution was analyzed amongst sludge phases, water, and air in wastewater treatment processes. They also investigated the distribution of VOCs in a large WWTP in northern China for changes in temperature and treatment and conducted an assessment of cancer risk. The wastewater received by this WWTP is approximately 95% of domestic sewage and the remaining is from local industries. They used a Gaussian plume model to simulate the atmospheric conditions. According to Yang et al. (2014), benzene easily released into the environment, whereas most of the chlorinated hydrocarbons stayed in the water phase during the treatment. Hence, they concluded that aromatic compounds travel longer distances than the chlorinated compounds. Even those living four kilometers away from a WWTP receive exposure to carcinogenic compounds. Instead of completely controlling the release of VOCs from the plants, it is necessary to identify the atmospheric emissions and health concerns of the VOC species in order to reduce the health impacts by VOCs released from this particular source.

2.3.3 Health of Sewage Workers

Al Zabadi et al. (2011) studied the exposure of hazardous chemicals of sewer workers and office workers in the city of Paris. These researchers measured the concentrations of 13 polycyclic aromatic hydrocarbons and 12 VOCs. Also, the DNA and chromosomal damages were analyzed from urinary extracts from both groups of workers they investigated, and it was concluded that sewer workers had significant DNA and chromosomal damages compared to office workers. Concentrations of benzene (mean ± standard error) reported by these researchers were $19.1 \pm 2.9\ \mu g/m^3$ for sewer workers and $4.1 \pm 0.53\ \mu g/m^3$ for office workers. Al Zabadi et al. concluded that the benzene-associated lifetime excess cancer risk for sewer workers in the city of Paris was significant. The cancer risk ranged from 4.2×10^{-5} to 14.9×10^{-5}, which is over the acceptable cancer risk range, according to American regulatory agencies.

Yang et al. (2012) investigated the link between the emission rates of VOCs from a municipal WWTP from Harbin City in China and the associated health risks of the workers. Concentrations of VOCs in the gas phase and water phase were analyzed from wastewater samples collected from different treatment processes of this WWTP. The VOCs studied by these researchers were toluene, benzene, xylenes, chloroform, carbon tetrachloride, and TCE. Yang et al. concluded that benzene was a VOC with relatively high emission rates and significant health risks. Given the treatment technologies considered, the highest cancer and non-cancer risks to the workers were estimated at the sedimentation process, and lower VOC emissions and health risks were estimated in anaerobic treatment. These results have provided insights into the health risks that will take place in the future for the workers.

Greff-Mirguet et al. (2014) used bioaerosol sampling to assess the exposure of air-transmitted endotoxins during sewer work. These researchers obtained and quantified different samples in underground sewers by utilizing 37-mm cassettes that contained different filters. The concentrations of these VOCs in the workplaces were higher than the other places. Hence, sewage workers are prone to constant exposure.

A summary of previous studies related to this aforementioned research is presented in Table 2.

Table 2
Summary of Previous Related Studies

No	Publication title	Authors / Year published
1	VOC emissions from sewer junction boxes and drop structures: Estimation methods and experimental results.	Corsi and Quigley (1996)
2	Aromatic VOC emissions from a municipal sewer interceptor.	Corsi et al. (1995)
3	Occurrence of chlorinated VOCs in a sanitary sewer system: Implications for assessing vapor intrusion alternative pathways.	Roghani et al. (2018)
4	Determination of VOC in industrial wastewater plant air emissions by multi-sorbent adsorption and thermal desorption-gas chromatography-mass spectrometry.	Ramírez et al. (2011)
5	Health risk assessment of odors emitted from urban wastewater pump stations in Tianjin, China.	Niu et al. (2014)
6	Prioritisation of odorants emitted from sewers using odour activity values.	Sivret et al. (2016)

(continued)

No	Publication title	Authors / Year published
7	Characterising VOV from sewer emissions by thermal desorption coupled with gas-chromatography-mass spectrometry.	Wang et al. (2012)
8	Estimating cancer risk increment from air pollutant exposure for sewer workers working in an industrial city.	Yeh et al. (2011)
9	Distribution and sensorial relevance of VOCs emitted throughout wastewater biosolids processing.	Fisher et al. (2017)
10	Underestimated public health risks caused by overestimated VOC removal in wastewater treatment processes.	Yang et al. (2014)
11	Integrated exposure assessment of sewage workers to genotoxicants: A urinary biomarker approach and oxidative stress evaluation.	Al Zabadi et al. (2011)
12	Comparative assessments of VOC emission rates and associated health risks from wastewater treatment processes.	Yang et al. (2012)
13	Exposure to airborne endotoxins among sewer workers: An exploratory study.	Greff-Migruet et al. (2014)

3. MATERIALS AND METHODS

In order to achieve the objectives of this research study, the following steps were established:

- Select study sites in which governmental entities own and operate WWTP facilities.
- Collect relevant data from these sites, including VOC species and their respective concentrations, from wastewater influents, in particular, before reaching the treatment facilities.
- Identify common VOCs from these sites. Compute gas-phase concentrations from liquid-phase samples.
- Collect gas-phase samples from sewer manholes located in the City of Hallandale Beach and compare results with data obtained from the liquid wastewater samples.
- Identify similar data from previous studies and identify common VOCs and their respective concentrations. Compare results with information obtained from the study sites from Florida and Hallandale Beach.
- Calculate the risk characterization for carcinogenic and non-carcinogenic compounds identified in the sewer systems.
- Estimate the uncertainty of health risk using the Monte Carlo technique and perform a sensitivity analysis.
- Recommend basic steps for sewer system owners to bring awareness and promote the safety of the sewer workers.

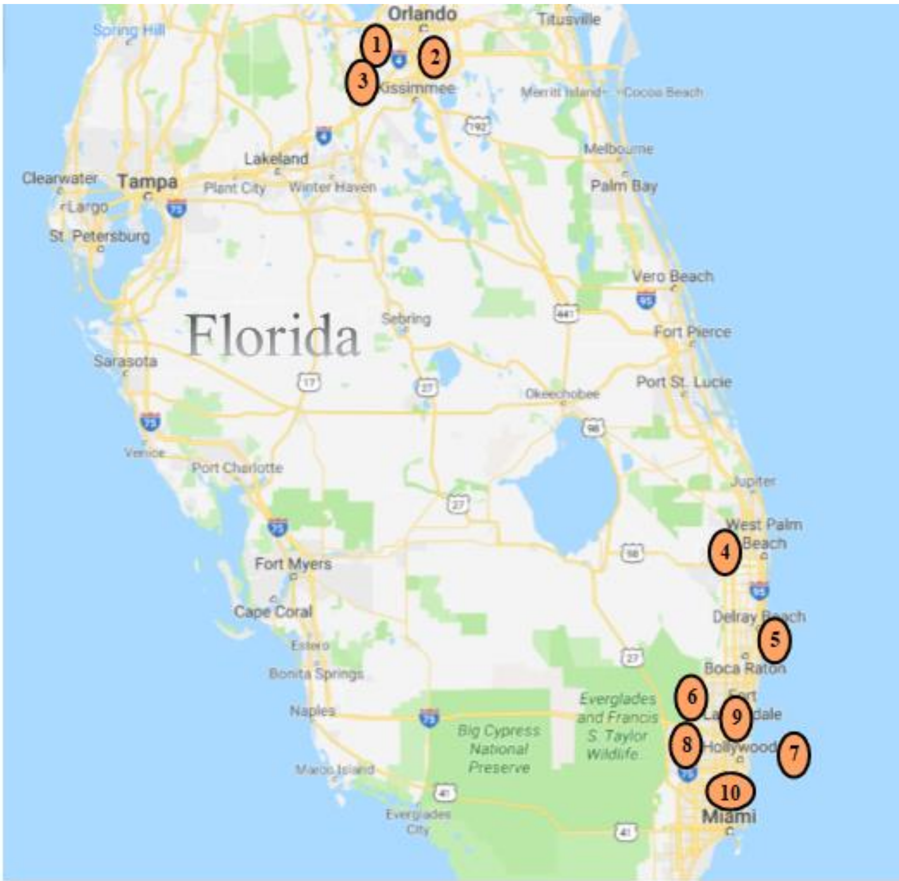
3.1 VOCs From Study Sites in the State of Florida

The City of Hallandale Beach was the primary focus study area for this research because of my familiarity with the region serving as the City Engineer and experience working daily on capital projects and managing the operations and maintenance of water and wastewater facilities. Over two years, 2017 and 2018, I contacted cities from Miami-Dade, Broward, West Palm Beach, and Sarasota counties and had multiple phone conversations and meetings with utility managers, city engineers, and public works directors to understand the type of wastewater facilities they own and operate. The research topic was shared with these individuals to identify data, including VOC concentrations from wastewater influents or any other data that might include VOC concentrations from any wastewater collection systems or treatment plants. Because of the sensitivity of this research topic, during conversations with these individuals, I was advised that the best way to obtain public records from municipalities and counties was to make an official request from each organization. It is important to note that in the United States, statutory rights are in place to inspect or obtain copies of a vast number of public records.

Furthermore, Florida's public records use the state's Public Records Act, which states that "all state, county, and municipal records are open for personal inspection and copying by any person" (Florida Statutes, Chapter 119, Section 1). The requests for public records can be made online through the organization's website or via email or phone, usually through the municipal or county clerk. Each agency charges fees based on the volume of the public records requested, the use of the agency's information technology resources, or the clerical or supervisory personnel assigned to make copies or safeguard documents.

In this study, several municipalities and counties from the State of Florida, United States that own and operate wastewater treatment facilities were contacted, and requests for copies of public records were made in efforts to identify existing data (including species and concentrations of VOCs in the wastewater). The study sites were selected within Florida, mostly because of the similarity of the geographical conditions and availability of data. Because of its unique weather conditions (which are subtropical), it was determined that the results and recommendations might be valuable for entities other than Hallandale Beach, which is a relatively small area of approximately four square miles. Also, it was important for this type of research that the sewer workers were performing similar field activities year-round because of the similarity of the weather. A period of five years was considered to be sufficient for collecting the data from the selected study sites. There was no particular number of sites favored for this study, but the intent was to obtain as much data as possible.

Wastewater analytical reports were obtained from 2014 to 2018 from different locations (as presented in Figure 2): the City of Orlando, the City of West Palm Beach, the City of Boca Raton, the City of Sunrise, the City of Hollywood, and the Miami-Dade Water and Sewer Department. All reports included VOC concentrations from the wastewater influents of their respective WWTP. These organizations informed me that they do not collect gas-phase samples from the wastewater collection and treatment facilities. The City of North Miami, the City of Fort Lauderdale, the City of Plantation, and the City of Sarasota informed me that they do not have information on VOCs in wastewater influents. Summaries of the VOC concentrations in liquid wastewater influents in mg/l are summarized in Appendix E.



1, 2 and 3 - Orlando, Conserv I Conserv II and Iron Bridge
4 - West Palm Beach, East Central Regional Water Reclamation Facility
5 - City of Boca Raton, Wastewater Treatment Plant
6 - Sunrise, Sawgrass Wastewater Treatment Plant
7, 8 and 9 - Hollywood, Southern Regional Wastewater Treatment Plant
(Hallandale Beach, Pembroke Park and Unincorporated Broward County)
10 - Miami-Dade, South District Wastewater Treatment Plant

Figure 2. Study sites: Wastewater treatment plant locations.

3.1.1 Study Site 1: City of Orlando Conserv I

The City of Orlando owns and operates three WWTPs, and they are Water Conserv I, Water Conserv II, and Iron Bridge. These facilities had a combined capacity of 72.5 million gallons per day in 2007, as reported on the City of Orlando's website. Copies of the laboratory analysis results from 2014 to 2018 were obtained via request of public records from the City of Orlando (City of Orlando, request of public records, January 15, 2019).

Water Conserv I (WCI) is a regional WWTP operated and owned by the City of Orlando, with a total permitted capacity of 7.5 million gallons per day. The wastewater treated by WCI is designed to service about 400,000 people in the City of Orlando. Environmental testing agencies collect sewer liquid influent samples from the WCI facility annually from four locations. Environmental Conservation Laboratories and Test America Laboratories, Inc. prepared the laboratory analytical reports for the liquid sewer influents of the CWI facility. The species and ranges of concentrations for VOCs identified in the influent of CWI from 2014 to 2018 were chloroform (1.3–5.8 µg/l), 1,4-dichlorobenzene (0.11[I]–6.2 µg/l), acetone (27–130 µg/l), toluene (8–29 µg/l), methylene chloride (2.6–24 µg/l), trichlorobenzene (11 µg/l), ethylbenzene (0.27[I]–1.7) µg/l), benzene (0.25(I)–1.7) µg/l), and xylenes (0.58–0.86 µg/l). The values reported as "I" were greater than the method detection limit (MDL) but less than the practical quantitation limit (PQL).

3.1.2 Study Site 2: City of Orlando Conserv II

Water Conserv II (WCII) is a WWTP that provides service to a majority of the southwest section of Orlando and has a design capacity of 25 million gallons per day, servicing about 250,000 people. Environmental testing agencies collect sewer liquid influent samples from WCII facilities from four locations. Environmental Conservation Laboratories and Test America Laboratories, Inc. prepared the laboratory analytical reports for sewer liquid influent of the CWII facility. The species and ranges of concentrations for VOCs identified in the influent of CWII from 2014 to 2018 were chloroform (3.8–8.9 µg/l), 1,4-dichlorobenzene (2.2–5 µg/l), toluene (95–240 µg/l), methylene chloride (2.6–24 µg/l), trichlorobenzene (1.8–62 µg/l), ethylbenzene (0.48–3.2 µg/l), and tetrachloroethylene (0.51–0.64 µg/l).

3.1.3 Study Site 3: City of Orlando Iron Bridge

The City of Orlando operates and primarily owns the Iron Bridge, a regional WWTP. It has a total permitted capacity of 72.5 million gallons per day. The majority of the wastewater flows treated by Iron Bridge are from the City of Orlando. Also, other sources contribute flows, including parts of Winter Park, Maitland, Casselberry, and unincorporated portions of Orange and Seminole Counties. Environmental testing agencies collect sewer liquid influent samples from the Iron Bridge facility annually from four locations. Environmental Conservation Laboratories and Test America Laboratories, Inc. prepared the laboratory analytical reports on the liquid sewer influent of the Iron Bridge facility. The species and ranges of VOC concentrations identified in the influents of Iron Bridge from 2014 to 2018 were chloroform (2.7–6.8 µg/l), 1,4-dichlorobenzene (0.97–1.9 µg/l), acetone (220–420 µg/l), toluene (1.8–9.8), methylene chloride (2.2–5.8 µg/l), ethylbenzene (0.37[I]–1.5) µg/l), and tetrachloroethylene (1.8–2.4 µg/l).

3.1.4 Study Site 4: City of West Palm Beach

The East Central Regional Water Reclamation Facility is a WWTP located in the City of Palm Beach, permitted to process 70 million gallons of wastewater per day and serving the City of Lake Worth, the City of West Palm Beach, the Town of Palm Beach, the City of Riviera Beach, and Palm Beach County. The ranges of VOC concentrations from the East Central Regional Reclamation Facility’s wastewater influents from 2014 to

2018 as reported by the City of West Palm Beach were chloroform (4.2–6.7 µg/l) and toluene (8–17.1 µg/l). Copies of the wastewater influent laboratory analysis results were obtained via request of public records from the City of West Palm Beach (City of West Palm Beach, request of public records, January 30, 2019).

3.1.5 Study Site 5: City of Boca Raton

The WWTP owned and operated by the City of Boca Raton has a capacity of 17.5 million gallons per day. According to analytical results provided by Advanced Environmental Laboratories, Inc., from 2014 to 2018, the species and the ranges of VOC concentrations identified in the City of Boca Raton's wastewater influents were chloroform (7.4 µg/l), ethylbenzene (1 µg/l), tetrachloroethylene (1.1 µg/l), dibromochloromethane (1.6–76.5 µg/l), toluene (90.93 µg/l), methylene chloride (59 µg/l), methyl tert-butyl ether (7.3 µg/l), toluene (4.2–4.3 µg/l), trichloroethane (1.9 µg/l), vinyl chloride (0.84 µg/l), and total xylenes (5.1 µg/l). Copies of the laboratory analysis results were obtained via request of public records from the City of Boca Raton (City of Boca Raton, request of public records, January 20, 2019).

3.1.6 Study Site 6: City of Sunrise

Sawgrass WWTP is part of Sunrise's utility system and is one of its three wastewater treatment facilities, serving more than 215,000 residential and commercial customers and encompassing Sunrise, Southwest Ranches, Weston, and portions of Davie. The analytical reports provided by Pace Analytical Services, Inc. from 2014 to 2018 reported species and ranges of VOC concentrations identified in the influent of the City of Sunrise's Sawgrass WWTP. The VOCs reported were chloroform (1.9–53.7 µg/l), bromodichloromethane (2–37.5 µg/l), bromoform (7–42.4 µg/l), dibromochloromethane (3.5–76.5 µg/l), and toluene (0.93 µg/l). Copies of the laboratory analysis results were obtained via request of public records from the City of Sunrise (City of Sunrise, request of public records, January 20, 2019).

3.1.7 Study Site 7: City of Hallandale Beach

The City of Hollywood owns and operates the Southern Regional WWTP (SRWWTP), and SRWWTP is currently rated and permitted for 48.75 million gallons per day on an annual average basis (Hazen & Sawyer, 2007, City of Hollywood, Florida, Wastewater Master Plan). Six large users, including unincorporated Broward County and the neighboring municipalities of Dania Beach, Hallandale Beach, Miramar, Pembroke Park, and Pembroke Pines, also transport their wastewater flows to the Hollywood wastewater collection system for treatment and disposal. The Town of Davie and the City of Cooper City both transport secondary-treated effluent from their respective treatment facilities directly to the SRWWTP effluent pump station for disposal. A network of piping, force mains, and a pump station collect and transport the wastewater flows from customers within the City of Hollywood limits to the plant for treatment and disposal by a network of piping, force mains, and a pump station. Each large user operates their wastewater collection and transmission facilities, which connect into the Hollywood system, and they must submit an annual laboratory analysis, conducted by a state-certified laboratory, of composite samples of the combined industrial and domestic waters leaving their facilities at each point of connection. Copies of the laboratory analytical reports of the wastewater influents were obtained from the City of Hollywood from 2014 to 2018 via request of public records (City of Hollywood, request of public records, January 19, 2019).

Wastewater lift stations pump the wastewater from the City of Hallandale to the City of Hollywood's sanitary sewer systems through four separate metered connections. Pace Analytical Service, LLC takes annual wastewater liquid-phase samples. The species and ranges of VOC concentration reported on the analytical reports by Pace Analytical Services from 2014 to 2018 were chloroform (0.58–5.4 µg/l), 1,2-dichlorobenzene (1.4 µg/l), 1,4-dichlorobenzene (0.56–5.6 µg/l), toluene (0.54–7.8 µg/l), and total xylenes (8.1 µg/l).

3.1.8 Study Site 8: Town of Pembroke Park

Wastewater lift stations pump the wastewater from the Town of Pembroke Park to the City of Hollywood's sanitary sewer systems through one metered connection. The species and ranges of VOC concentrations from 2014 to 2018 reported by Pace Analytical Services, LLC were chloroform (1.8–11.7 µg/l), 1,4-dichlorobenzene (2.6–6.3 µg/l), toluene (2.1–3.71 µg/l), bromodichloromethane (0.88–3.2 µg/l), and chlorobenzene (13.9 µg/l).

3.1.9 Study Site 9: Unincorporated Broward County

Wastewater lift stations pump the wastewater from the unincorporated Broward County to the City of Hollywood's sanitary sewer systems through two separate metered connections. The species and ranges of VOC concentrations reported in the annual reports by Broward County were chloroform (0.74–3.89 µg/l), dichloromethane (0.65–1.78 µg/l), dibromochloromethane (0.54 µg/l), 1,4-dichlorobenzene (0.75–1.73 µg/l), ethylbenzene (4.67–9.86 µg/l), toluene (0.88–2.9 µg/l), and total xylenes (0.91–84 µg/l).

3.1.10 Study Site 10: Miami-Dade

Miami-Dade County Water and Sewer Department owns and operates three WWTPs, and they are South District Wastewater Treatment Plant, Central District Wastewater Treatment Plant, and North District Wastewater Treatment Plant. For this study, records were obtained only from the South District Wastewater Treatment Plant, which has a total permitted capacity of 285 million gallons per day, as of 2013. Pace Analytical Services, LLC provides an annual sampling from wastewater influents. The species and ranges of concentration of VOCs reported on the analytical reports by Pace Analytical Services, LLC from 2014 to 2018 were chloroform (1.3–2.4 µg/l), 1,4-dichlorobenzene (2.1–3.6 µg/l), toluene (3.8–8.6 µg/l), and xylenes (0.61 µg/l; Miami-Dade, Environmental Resources Management, request of public records, January 19, 2019).

3.2 Data Analysis From Study Sites in the State of Florida

All VOC concentrations obtained from the study sites described in the previous subchapter were obtained from samples of the wastewater in the aqueous phase. According to LaGrega et al. (1994), when a volatile chemical is dissolved in water, part of the chemical in the gaseous phase exists in the air immediately above the surface water. Furthermore, to describe the solubility of a gas in a liquid, Henry's law is used, which states the following:

"Under equilibrium conditions, the partial pressure of a gas (volatile chemical) above the liquid is proportional to the concentration of a chemical in the liquid."

Henry's law is described by the following equation:

$$P_g = H \; x \; C_l \qquad \text{Equation 1}$$

where P_g is the partial pressure of the gas (atm), H is Henry's constant, and C_l is the concentration of a chemical in the liquid.

Henry's constant can also be defined, from the definition of partial pressure, as the ratio of the concentration in the gas to the concentration in the liquid, as expressed by the following equation:

$$H = \; C_g \, / \, C_l \qquad \text{Equation 2}$$

where C_g is the concentration of a chemical in the gas phase (air) and C_l is the concentration of a chemical in the liquid phase (aqueous).

All VOC concentrations were obtained from samples of wastewater in the liquid phase, and an equilibrium partitioning was assumed. The concentration, C_g, of the VOC in the gas phase at equilibrium is given by the following equation:

$$C_g = \; C_l \; x \; H_c \qquad \text{Equation 3}$$

where H_c is the dimensionless Henry's law constant and C_l is the sewer liquid VOC concentration. Because Henry's law constant varies with temperature, the C_g values were computed using H_c at the temperature during the collection of liquid sewer samples.

The analytical reports from the City of Orlando and Miami-Dade did not record the temperature during sample collection. Since the environmental testing agencies collected the annual samples from the City of Orlando in October, which has an average temperature of 24 °C (https://www.holiday-weather.com/orlando/averages/), and the annual samples from Miami-Dade were collected in February, which has an average temperature of 20 °C (https://www.holiday-weather.com/miami/averages/february/), the C_g values were computed using H_c at 24 °C and 20 °C, respectively.

The following equation gives values of the dimensionless Henry's law constant, H_c:

$$H_c = H/R\,T \qquad \text{Equation 4}$$

where H is Henry's constant (atm · m^3)/(mol), R is the universal gas constant equal to 8.25 x 10^{-5} (atm · m^3)/(mol · K), and T is the temperature (K).

The chemical composition of the water and the temperature significantly affect Henry's constant (LaGrega et al., 1994). For example, Kavanauh and Trussell (1980) reported that, for volatile hydrocarbons, Henry's constant increases threefold with a 10 °C increase in temperature. The regression equations for selected VOCs were adopted from LaGrega et al. (1994; see Appendix A). The tabulated values define Henry's constant as a function of temperature:

$$H = e^{\left(A - \frac{B}{T}\right)} \qquad \text{Equation 5}$$

where H is Henry's constant [(atm · m^3)/(mol)], T is the temperature (K), and A and B are the regression coefficients based on the adopted source data. As listed in Appendix A, the coefficients A and B were adopted from two different sources of data. The source Z indicates that the coefficients A and B were adapted from Howe et al. (1987), and the source AA indicates that the coefficients were adopted from Gossett (1987).

After the C_g values were computed, the mean values and standard deviations for the gas-phase concentrations for the predominant VOCs were calculated (presented in Tables 6–12).

3.3 VOCs From Past Studies

Researchers rarely report VOC emissions resulting from sewer collection systems, compared to those from WWTPs (Atasoy et al., 2004; Ras et al., 2008). Six comparable VOC studies from sewer networks in the peer-reviewed literature were identified during this research: Huang et al. (2012), Wang et al. (2012), Niu et al. (2014), and Sivret et al. (2016).

3.3.1 Municipal Sewer Systems, Southern Taiwan

Huang et al. (2012) identified 71 VOCs at 15 monitoring sites from two municipal sewer systems in Kaohsiung in southern Taiwan, which is a heavily industrialized area. They collected the air samples in compliance with the USEPA Method TO-15, and they analyzed these samples using a gas chromatograph and a mass spectrometer. The researchers reported the overall mean concentrations of 71 VOC species obtained from two areas, including winter (dry) and summer (wet) periods. In one area, the most abundant species were vinyl chloride (208.35 $\mu g/m^3$), trichloroethane (107.85 $\mu g/m^3$), toluene (94.23 $\mu g/m^3$), and tetrachloroethane (90.46 $\mu g/m^3$). In the second area, the most abundant species were m-/p-xylene (200.5 $\mu g/m^3$) and toluene (147.53 $\mu g/m^3$), followed by ethylbenzene (53.19 $\mu g/m^3$).

3.3.2 Sewer Networks in Sydney, Australia: Five Sites

Wang et al. (2012) analyzed gas-phase samples collected from five selected sewer network sites operated by Sydney Water Corporation between January and May 2011. They collected samples using Tenax sorbent tubes, and they performed the analysis using GC/MS. The results from this study showed up to 100 different VOC compounds present in the emissions from the sewer networks in Sydney. The average concentrations for the key VOC compounds measured at the five sewer networks by these researchers were ethylbenzene (7.49, 31.5, 36.8, 4.63, and 32 µg/m^3), toluene (24.7, 40.4, 49.6, 23.8, and 42.6 µg/m^3), and tetrachloroethylene (2,592; 449; 1,516; 1,039; and 5,193 µg/m^3).

3.3.3 Sewer Networks in Sydney, Australia: Two Sites

Wang et al. (2012) developed an analytical method to optimize the determination of VOCs in the sewer gas emissions by collecting samples using sorbent tubes, followed by thermal desorption coupled with GC/MS (TD-GS/MS). These researchers reported the average concentrations of target VOCs measured in two sewer sites for chloroform (202 and 654.25 µg/m^3), benzene (5.52 and 8.85 µg/m^3), and toluene (111.33 and 61.15 µg/m^3).

3.3.4 Urban Wastewater Pump Stations, Tianjin, China

Niu et al. (2014) collected and analyzed air samples from wastewater pump stations in a residential area in Tianjin (in North China) using GC/MS. These researchers reported 15 kinds of VOC concentrations, including dichloromethane (not detected [ND]–14.69 µg/m^3), chlorobenzene (7.40–89.95 µg/m^3), benzene (1.46–11.8 µg/m^3), toluene (0.15–12.14 µg/m^3), and ethylbenzene (0.58–8.21 µg/m^3).

3.3.5 Sewer Headspace, Australia

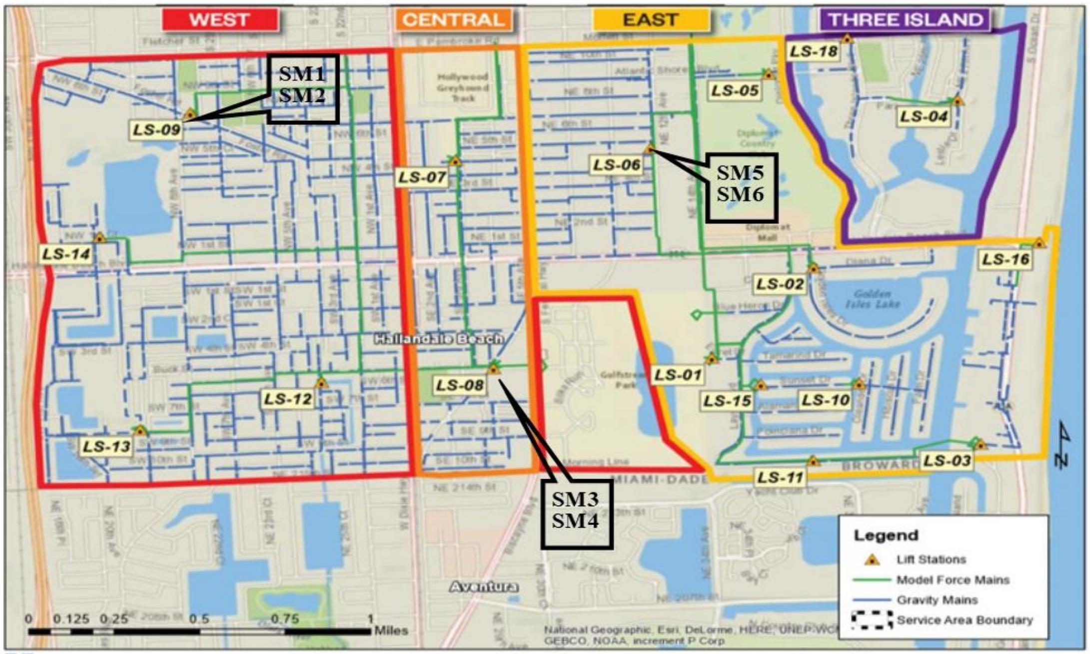
Sivret et al. (2016) measured VOC emissions from 21 monitoring sites in three cities (Sydney, Melbourne, and Perth) in Australia. The sewer catchments for sampling included a range of sewage types (residential and commercial sewage), sewer structures (sewer lines, pump stations, siphons, and WWTP headworks), and chemical dosing treatments representative of conditions present in Australian sewer systems. The researchers analyzed all samples collected via absorption into Tenax sorbent tubes using GC/MS. The median and maximum concentrations reported by these researchers (see Appendix C) included values for ethylbenzene (Sydney: 2.37–1,650 µg/m^3; Melbourne: 0.3–44.2 µg/m^3; Perth: 3.55–80.3 µg/m^3), toluene (Sydney: 31.7–10,500 µg/m^3; Melbourne: 70.8–12,600 µg/m^3; Perth: 60.7–1,750 µg/m^3), tetrachloroethylene (Sydney: 18.3–24,800 µg/m^3; Melbourne: 1.05–72.6 µg/m^3; Perth: 1.05–357 µg/m^3), and trichloromethane (Sydney: 55.4–950 µg/m^3; Melbourne: 39.6–432 µg/m^3; Perth: 17.2–286 µg/m^3).

3.3.6 Sewer System, San Francisco, California

Roghani et al. (2018) reported the results of their sewer gas sampling over the years of 2014 to 2017 in an aged sanitary sewer infrastructure in the southern San Francisco Bay area. These researchers collected and analyzed gas samples from sewer manholes and cleanouts using several different methods, including TO-15 (grab), TO-17 (passive), Radiello® (passive), and the Autonomous Rugged Optical Multigas Analyzer (continuous monitoring). The TO-15 analytical results (2014) presented by these researchers indicated that gas concentrations from sewer manholes for TCE ranged from non-detect to 1,600 μg/m^3. The TO-17 analytical reports (2015) presented gas concentrations from sewer manholes for TCE that ranged from non-detect to 201.77 μg/m^3, tetrachloroethylene from non-detect to 182.79 μg/m^3, toluene from non-detect to 30.84 μg/m^3, and chloroform from non-detect to 2.69 μg/m^3. The TO-15 analytical reports (2015) presented gas concentrations from sewer manholes for TCE that ranged from non-detect to 500 μg/m^3, tetrachloroethylene from non-detect to 80 μg/m^3, toluene from non-detect to 100 μg/m^3, and chloroform from non-detect to 300 μg/m^3.

3.4. Case Study, Sampling, and Analysis Method: Hallandale Beach

In this study, gas-phase samples were collected in June 2019 from the City of Hallandale Beach sewer systems. Located in Broward County, Florida, the City of Hallandale Beach has approximately 38,000 residents and spans an area of approximately four square miles. The sewer system accumulates wastewater throughout the City and pumps to the City of Hollywood's SRWWTP for treatment and disposal from 15 sewer lift stations through four separate metered connections. The City's wastewater service area comprises four distinct geographic systems by force main networks: East, Central, West, and Three Islands. Florida International University was not able to accommodate the necessary equipment for data collection and analysis, and because of the limitations of personal funding, only six samples were collected. Laboratory services from SGS North America Inc. were procured using personal funds. A technician from SGS North America Inc. collected gas-phase samples from the West, Central, and East sewer systems of the City of Hallandale Beach. The technician collected two samples from each system from selected sewer manholes (SM1–SM6), as denoted in Figure 3. From each system, the technician collected one sample from the manhole nearest to a lift station and the second sample within less than 600 feet downstream. The six sewer manholes identified from SM1 to SM6 are shown in Figure 3. Furthermore, SM1 is the manhole nearest to the lift station LS-09, and the manhole SM2 is located within a 600-foot radius downstream. The SM3 is the nearest manhole to the lift station LS-08, and the manhole SM4 is located within a 450-foot radius downstream. The SM5 manhole is the nearest manhole to the lift station LS-06, and the manhole SM6 is located within 500 feet downstream. SGS North America Inc. collected and analyzed samples in accordance with USEPA Compendium Method TO-15. The technician collected gas-phase samples in specially-prepared canisters and analyzed them with GC/MS (USEPA, 1999).



Source: Adapted from Hazen, City of Hallandale Beach Wastewater Master Plan (2016)

Figure 3. Sampling area: City of Hallandale Beach.

The analysis process was as follows: First, a technician collected sewer air grab samples using stainless steel canisters (Silonite 1.4 L MiniCan) specially prepared and evacuated to 30 psi. To ensure an accurate and valid sample, before sampling, the technician leak-tested all canisters using a test field gauge attached to the canister, and the vacuum readings were 30 psi. By opening the canister to the atmosphere, the differential pressure caused the sample to flow into the canister for approximately 20 to 25 seconds. The technician collected all samples by holding the canisters at the same level at the lid of the manhole (see Figure 4).

Figure 4. Sample collection, June 2019.

After the collection of each sample, the technician closed the valve of the canister and measured the final pressure within the canister using the test gauge. The technician attached an identification tag to the canister (see Figure 5) and transported the canisters to SGS North America Inc., Houston’s laboratory for analysis. To assure the identity of the samples, the field technician completed the chain of custody form (see Appendix B), which represents the air sampling field data. The technician sent the chain of custody form to the laboratory facility with the canisters.

Figure 5. The final pressure of the canister was measured after sample collection.

Finally, technicians at SGS North America Inc.'s Houston laboratory analyzed and quantified all samples using GC-MS. I had several conversations with SGS North America staff to understand the methodology of performing the laboratory analysis. Once received by the laboratory, each canister was identified from the information in the chain of custody report, and the final pressure was checked to ensure no leaks appeared during transport. SGS stated that the technician quantified the concentrations of each sample using an internal standard calibration to ensure the quality of all the samples. Also, SGS explained that because one or multiple compounds were above the calibration curve of the instrument, or some interference was needed to be taken out of the system, some samples were run two times using different dilution factors (DF) from one to 10, as shown in Table 3. The information provided in Table 3 was extracted from the analytical report prepared by SGS North America. Although some air preconcentrator instruments can be operated while the canister is under a slight vacuum, others require the need to dilute the samples. According to USEPA Method TO-15, DF can be calculated using the following equation from the post-sampling pressure (before dilution), the final pressure (after dilution), and the atmospheric pressure in the laboratory.

$$DF = \frac{P\ after\ dilution + P\ lab\ athmosphere}{P\ lab\ atmosphere - P\ before\ dilution} \qquad \text{Equation 6}$$

A summary of the samples reported by SGS North America Inc. is presented in Appendix C, and the results from the analytical report dated June 27, 2019 are presented in Appendix D.

Table 3

Dilution Factors

ID	Field Sample ID	DF Run # 1	DF Run # 2	Volume	Date Sampled	Date Analyzed
SM1	LS 09-Wet Well	2	10	400 ml	06/12/2019	06/18/2019
SM2	NW 7AVE/NW 6 CT	4	10	400 ml	06/12/2019	06/18/2019
SM3	LS08	1	N/A	400 ml	06/12/2019	06/18/2019
SM4	SE 3AVE/SE 4ST	2	10	400 ml	06/12/2019	06/18/2019
SM5	LS06	1	N/A	400 ml	06/12/2019	06/18/2019
SM6	1013 NE 5th ST	4	N/A	400 ml	06/12/2019	06/18/2019

Note. DF = dilution factor.

3.5 Risk Assessment Method

Environmental health risk, in general, can either be a risk from carcinogens or risk from non-carcinogens (Niu et al., 2014). In this study, the levels for both carcinogenic and non-carcinogenic risks were assessed. It was assumed that the primary exposure pathway was inhalation intake for the duration of working in the sewer systems. The target carcinogens included benzene, carbon tetrachloride, chloroform, dichloromethane, ethylbenzene, methylene chloride, tetrachloroethylene, TCE, and vinyl chloride; chlorobenzene, chloromethane, and 1,4-dichlorobenzene are non-carcinogenic.

3.5.1 Cancer Risk Estimation Model

The carcinogenic risk was calculated using two models and compared results across the models. For the first model, the cancer risk (denoted by R) was estimated using the following equation (USEPA, 2009):

$$R = IUR \text{ x } EC \qquad \text{Equation 7}$$

where R is carcinogenic risk, IUR is the inhalation unit risk of a VOC (µg/m^3)$^{-1}$, and EC is the lifetime exposure concentration (µg/m^3). EC was calculated using the following equation (USEPA, 2009):

$$EC = \frac{CA \text{ x } ET \text{ x } EF \text{ x } ED}{AT} \qquad \text{Equation 8}$$

where CA is the concentration of the hazardous chemical in the air (µg/m^3), ET is the daily exposure time (hours/day), EF is the exposure frequency (days/year), ED is the exposure duration (years), and AT is the average time over which the cancer risk is evaluated (ED x 365 days/year x 24 hours/day, hours). The values for IUR used in this study were adopted from the USEPA's Integrated Risk Information System (IRIS; USEPA 2009). The IUR signifies the excess cancer risk over the background of a pollutant, and researchers typically express it as a risk or probability of cancer for a 70-year exposure per 1 µg pollutant per m^3. A 10^{-4} risk level corresponds to the upper end of the USEPA's generally acceptable risk range of $10^{-}6$ to 10^{-4} (40 C.F.R. § 300.430). Cancer risk values above the USEPA acceptable limit of 1×10^{-6} indicate cancer risk on humans exposed to the chemical hazard. Researchers recommend the 10^{-6} risk level for use as the point of departure for determining actions or remediation goals.

In the second model, researchers typically modify Equation 7 for specific exposure pathways. It was assumed that inhalation intake was the primary exposure pathway for sewer workers. Researchers have used the cancer risk model for chronic inhalation exposure equation adopted for this study in many health risk assessments (Durmusoglu et al., 2010; Guo et al., 2004; Yang et al., 2012; Yeh et al., 2011). Furthermore, the cancer risk equations to estimate the number of individuals likely to acquire cancer (because of their exposure to the pollutants of concern) in this study are as follows:

$$R = LAAD \text{ x } SF \qquad \text{Equation 9}$$

$$LADD = \frac{\text{CA x } 10^{-3} \text{ x IR x ET x EF x EW x ED}}{\text{LT x BW}} \qquad \text{Equation 10}$$

where LADD represents the lifetime average daily dose (mg/kg-day), SF is the slope factor (kg-day/mg), CA is the concentration of pollutant in air (µg/m^3), IR is the inhalation rate (m^3/hour), ET is the average exposure time (hours/time), EF is the average exposure frequency (time/week), EW is the exposure weeks (week/year), ED is the average working exposure duration (year), LT is the lifetime over which the cancer risk is evaluated (day), and BW is the body weight (kg).

3.5.2 Non-Cancer Risk Estimation Model

In the case of a non-carcinogenic effect, the risk characterization of an individual VOC by inhalation was evaluated by calculating the hazard quotient (HQ) using the following equation:

$$HQ = {}^{EC}/_{RfC} \qquad \text{Equation 11}$$

where EC is the lifetime exposure concentration (μg/m^3), and RfC is the reference concentration (μg/m^3), which is an estimate of continuous inhalation exposure to the human population that is likely to be without an appropriate risk of deleterious effects during a lifetime (USEPA, 2013). Researchers commonly consider, for non-carcinogenic compounds, values of HQ less than 1.0 to be negligible and HQ values larger or equal to 1.0 to indicate an appreciable non-cancer risk of health effects (LaGrega et al., 1994). Table 4 lists all values for IUR and the weight of evidence (WOE) used for the respective risk assessment process.

Table 4

Inhalation Unit Risk Values and Weight of Evidence

VOC	IARC weight of evidence[a]	IUR ($m^3/\mu g$)	Source
Benzene	1	2.2×10^{-6}	IRIS
Carbon tetrachloride	2B	6×10^{-6}	IRIS
Chlorobenzene	3	N.A.	-
Chloroform	2B	2.3×10^{-5}	IRIS
Chloromethane (methyl chloride)	3	N.A.	-
Dichloromethane (methylene chloride	2A	1×10^{-8}	IRIS
1,4-Dichlorobenzene	N.A.	N.A.	-
Ethylbenzene	2B	N.A.	IRIS
Tetrachloroethylene	2A	2.6×10^{-7}	IRIS
Trichloroethylene (trichloroethene)	1	4.1×10^{-6}	IRIS
Toluene	3	N.A.	IRIS
Vinyl chloride	1	4.4×10^{-6}	IRIS

Note. IRIS = USEPA's Integrated Risk Information System. *IUR* = the Inhalation Unit Risk. N.A. denotes information that is not available or that the IRIS Program does not assess.

[a] IARC = International Agency for Research on Cancer. CH = carcinogenic. 2A = probably carcinogenic. 2B = possibly carcinogenic. 3 = not classifiable. 4 = probably not carcinogenic.

The inhalation SF of each VOC of concern in this study was obtained from the California Environmental Protection Agency (CalEPA, 2012). The SF quantifies the relationship between dose and response, specifically the upper bound of 95% confidence level on increased cancer risk from lifetime exposure. The RfCs of the VOCs were adopted from IRIS of the USEPA. The RfC is an estimate of the concentration at which continuous inhalation exposure is likely to be without risk of harmful, non-cancer effects during a lifetime, as reported by the USEPA. Table 5 lists all values for SF and RfC.

Table 5

Toxicity Values for VOCs of Concern in This Study Used to Perform the Probabilistic Calculation of Cancer and Non-Cancer Risks (Source: Integrated Risk Information System [IRIS] & CalEPA).

VOC species	Inhalation SF (kg-day/mg)	RfC (mg/m^3)	Exposure pathway
Benzene	0.1	3×10^{-2}	Inhalation
Carbon tetrachloride	0.15	1×10^{-1}	Inhalation
Chlorobenzene[a]	N.A.	2×10^{-2}	Oral
Chloromethane (methyl chloride)	N.A.	9 x 10-2	Inhalation
Chloroform	0.019	1×10^{-2}	Oral
1,4-dichlorobenzene	0.04	8×10^{-1}	Inhalation
Dichloromethane (methylene chloride)	0.0035	6×10^{-1}	Inhalation
Ethylbenzene	0.0087	1	Inhalation
Tetrachloroethylene	0.021	4×10^{-2}	Inhalation
Trichloroethylene (trichloroethane)	0.007	2×10^{-3}	Inhalation
Toluene	N.A.	5	Inhalation
Vinyl chloride	0.27	1×10^{-1}	Inhalation

Note. SF = slope factor (obtained from CalEPA). RfC = reference concentration, adopted from USEPA IRIS. N.A. denotes information that is not available or that the IRIS Program does not assess.

[a] The RfC of chlorobenzene and chloroform has not been assessed under the USEPA IRIS Program as of now, and the chronic oral exposures as the reference doses were used.

3.5.3 Statistical Method and Sensitivity Analysis

In risk assessment, high uncertainty exists (Zhou et al., 2011). This uncertainty results primarily from the lack of knowledge about the variation of the parameters in the model (Niu et al., 2014). In order to consider uncertainties and their impacts on the estimation of expected risk, the Monte Carlo simulation and sensitivity analysis were performed using Crystal Ball software (version 11.2). This probabilistic method uses probability distributions to characterize variability or uncertainty in risk estimates that can use the whole range of input data as a random variable to give a probability distribution rather than a specific value (Niu et al., 2014; USEPA, 2001; Zhou et al., 2011). The principles of the Monte Carlo analysis to estimate human risk are as follows: (1) setting up probability distributions parameters and providing detailed information about the input distributions, (2) showing how the input distributions obtained represent uncertainty, and (3) performing sensitivity analysis to determine which input variables most influenced risk (i.e., contributed the most to the output variance; Pintar et al., 2010). Several researchers have used this method when conducting risk assessments (Bai et al., 2009; Liang & Liao, 2007; Niu et al., 2014; Wang et al., 2012, 2013; Yeh et al., 2011; Zhou et al., 2011). A Monte Carlo simulation result provides a confidence interval (5th and 95th quartiles) of the health risk for sewer workers exposed to hazardous air pollutants in the sewer workplace. *Risk Assessment Guidance for Superfund Volume III: Part A, Process for Conducting Probabilistic Assessment* (USEPA, 2001) includes detailed descriptions of all steps involved in conducting Monte Carlo simulations.

4. RESULTS AND DISCUSSION

4.1 Occurrence of VOCs in Sewer Systems in Florida

The information obtained from the analytical reports from the City of Orlando included separate reports from three WWTPs. The VOC concentrations from all reports were obtained from wastewater samples before entering the treatment processes. The samples from these three WWTPs (Orlando WCI, Orlando WCII, and Orlando Iron Bridge) were collected at four separate locations for each WWTP influent. For this reason, the VOC concentrations in the gas-phase were computed independently using the VOC concentrations identified in the liquid-phase to preserve the originality of the data. A similar approach was used for the information obtained from the City of Hollywood, which included separate reports from three of its large users. These large users are the City of Hallandale Beach, the Town of Pembroke Park, and Unincorporated Broward County. Because the wastewater flows from Hallandale Beach get pumped through four separate metered connections to Hollywood's sanitary sewer system, the reports listed VOC concentrations separately for each area. The analytical reports from Miami-Dade also included information collected from two locations, representing the flows from separate regions.

The VOC concentrations in all analytical reports were listed in mg/l. The gas-phase concentration values were computed using Equations 1 to 5, and the results were reported in $\mu g/m^3$ (Appendix F). Tables 6 to 12 include the computed gas-phase VOC mean concentrations (*M*) from each source and their respective standard deviations (*SD*), assuming equilibrium partitioning.

Table 6

Computed VOC Gas-Phased Concentrations (µg/m^3) From Orlando Conserv I (Appendix F)

	WCI-S1		WCI-S2		WCI-S3		WCI-S4	
VOC component	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Chloroform	0.39	0.08	0.64	0.21	0.34	0.18	0.52	0.22
1,4-Dichlorobenzene	0.41	0.14	0.32	0.11	0.42	0.25	0.42	0.25
Ethylbenzene	0.22	0.19	0.45	0.14	0.24	0.08	0.19	0.1
Methylene chloride	ND	-	0.53	0	0.34	0	2.04	0
Toluene	6.33	1.54	5.24	0.78	4.75	1.96	4.42	1.34

Note. ND = not detected; results are under the method detection limits reported in the reports.
M = mean concentration (µg/m^3). SD = standard deviation.

Table 7

Computed VOC Gas-Phased Concentrations (µg/m^3) From Orlando Conserv II (Appendix F)

	WCII-S1		WCII-S2		WCII-S3		WCII-S4	
VOC component	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Chloroform	0.95	0.22	0.93	0.09	1.09	0.12	0.79	0.17
1,4-Dichlorobenzene	0.43	0.1	0.50	0.13	0.48	0.07	0. 48	0.07
Ethylbenzene	0.38	0	0.32	0.14	0.47	0.13	0.67	0.43
Methylene chloride	0.15	1.0	2.42	1.68	1.02	0.3	ND	-
Tetrachloroethene	ND	-	0.38	0	ND	-	ND	-
Toluene	31.33	6.37	31.49	7.67	28.93	9.9	39.95	23.23

Note. ND = not detected; results are under the method detection limits reported in the reports.
M = mean concentration (µg/m^3). SD = standard deviation.

Table 8

Computed VOC Gas-Phased Concentrations (µg/m³) From Orlando Iron Bridge (Appendix F)

	OIB-S1		OIB-S2		OIB-S3		OIB-S4	
VOC component	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Chloroform	0.47	0.07	0.77	0.16	0.78	0.28	0.74	0.39
1,4-Dichlorobenzene	0.17	0.02	0.14	0.02	0.08	0.09	0.20	0.01
Ethylbenzene	0.19	0.05	0.15	0	0.23	0.01	0.25	0.2
Toluene	0.87	0.25	1.30	0.65	1.64	0.71	0.98	0.44

Note. ND = not detected; results are under the method detection limits reported in the reports.
M = mean concentration (µg/m³). SD = standard deviation.

Table 9

Computed VOC Gas-Phased Concentrations (µg/m³) From Palm Beach, Boca Raton, and Sunrise (Appendix F)

	West Palm Beach		Boca Raton		Sunrise	
VOC component	*M*	*SD*	*M*	*SD*	*M*	*SD*
Chloroform	0.76	0.16	1.25	0.02	2.81	3.12
1,4-Dichlorobenzene	0.72	0.17	ND	-	ND	-
Methylene chloride	ND	-	5.97	0	ND	-
Toluene	3.07	1.17	2.29	1.36	0.27	0

Note. ND = not detected; results are under the method detection limits reported in the reports.
M = mean concentration (µg/m³). SD = standard deviation.

Table 10

Computed VOC Gas-Phased Concentrations (µg/m^3) From Hallandale Beach (Appendix F)

	West		Central		East		Three Island	
VOC Component	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Chloroform	0.64	0.38	0.39	0.19	0.38	0.14	0.30	0.25
1,4-Dichlorobenzene	0.21	0.13	0.49	0.27	0.13	0.07	0.10	0.02
Toluene	0.16	0.02	1.10	0.91	0.35	0.06	0.35	0.11
Total xylenes	ND	-	2.66	0	ND	-	ND	-

Note. ND = not detected; results are under the method detection limits reported in the reports.
M = mean concentration (µg/m^3). SD = standard deviation.

Table 11

Computed VOC Gas-Phased Concentrations (µg/m^3) From Pembroke Park and Broward County (Appendix F)

	Pembroke Park		Broward County 1		Broward County 2	
VOC component	*M*	*SD*	*M*	*SD*	*M*	*SD*
Chloroform	1.99	0.98	0.38	0.19	0.31	0.17
1,4-Dichlorobenzene	0.72	0.31	0.3	0	0.42	0.39
Ethylbenzene	ND	-	3.08	1.46	ND	-
Methylene chloride	ND	-	0.6	0	0.18	0
Toluene	106.7	236.6	0.65	0.23	1.38	0.52

Note. ND = not detected; results are under the method detection limits reported in the reports.
M = mean concentration (µg/m^3). SD = standard deviation.

Table 12

Computed VOC Gas-Phased Concentrations (μg/m^3) From Miami-Dade (Appendix F)

	Miami-Dade 1		Miami-Dade 2	
VOC component	*M*	*SD*	*M*	*SD*
Chloroform	0.19	0.03	0.21	0.03
1,4-Dichlorobenzene	0.23	0	0.4	0
Tetrachloroethylene	2.14	0	ND	-
Toluene	1.35	0.5	1.16	0.17

Note. ND = not detected; results are under the method detection limits reported in the reports.
M = mean concentration (μg/m^3). SD = standard deviation.

The reports identified six predominant VOCs, and they are chloroform, 1,4-dichlorobenzene, ethylbenzene, methylene chloride, tetrachloroethylene, and toluene. Chloroform and toluene were present in all samples. The analytical reports from the selected sites included many other VOCs, but concentrations were below their detection limits. VOCs that were of interest in this study were benzene, chloroform, chlorobenzene, carbon tetrachloride, trichloroethene, and vinyl chloride.

4.2 Occurrence of VOCs in Sewer Systems in Hallandale Beach

The laboratory technicians analyzed a total of 52 VOC species from the gas-phase samples collected from Hallandale's sewer systems (represented in Figure 3) from six locations in the West, Central, and East systems. Table 13 lists the VOCs detected from the gas-phase sewer samples. This table was created by extracting the VOC species and their respective concentrations reported in the analytical report prepared by SGS North America Inc.

Table 13

Occurrence of VOCs and Concentrations (µg/m^3) From Hallandale Beach Sewer Systems

	West System		Central System		East System	
VOC component	SM1	SM2	SM3	SM4	SM5	SM6
Acetone	21	24.9	28.5	75.8	21	11
Chloroform	15	117	39	71.3	27	41
Chloromethane (Methyl chloride)	1.6*	5.6	1.4	5.6	2.9	1.7*
Dichlorodifluoromethane	2.5*	2.5*	2.5	3.1*	4.5	2.5*
1,4-Dichlorobenzene	2.2*	57	5.7	20	6.6	3.7*
Ethanol	7.5	329	12	188	6.0	7.5
Methylene chloride	1.4*	4.4*	15	22	2.2	1.1
Pentane	6.8	29	9.7	9.1	4.7	43.9
Propane	1.0*	2.7*	1.2	2.2	1.4	2.6*
Tetrachloroethene	895	2,410	1.2*	2.0*	2.3*	0.88*
Toluene	7.9	43	11	7.5	9	5.3*
Trichloroethene	0.23*	0.59*	4.4	1.1*	ND	ND
Total xylenes	0.48*	2.2*	4.0	2.3*	1.2*	0.78*

Note. ND = not detected. SM1 – SM6: samples identification
*Greater than method detection but less than the practical quantitation limit.

The ranges of these VOCs are as follows: acetone (11–75.5 µg/m^3), chloroform (15–117 µg/m^3), chloromethane (1.6–5.6 µg/m^3), dichlorodifluoromethane (2.5–4.5

µg/m^3), 1,4-dichlorobenzene (2.5–57 µg/m^3), ethanol (7.5–329 µg/m^3), methylene chloride (0.6–3.2 µg/m^3), pentane (4.7–43.9 µg/m^3), propane (1.0–2.7 µg/m^3), tetrachloroethene (0.88–2,410 µg/m^3), trichloroethene (0.23–4.4 µg/m^3), toluene (5.3–43 µg/m^3), and total xylenes (0.48–4 µg/m^3). Some values reported as "*" were greater than the MDL but less than the PQL. Moreover, the rest of the VOCs analyzed were below their MDL, and the laboratory technicians reported them as "U" (not detected).

4.3 Occurrence of VOCs in Sewer Systems Reported in the Literature From Past Studies

There are many studies on the VOCs and odors related to wastewater or sewer systems. In some previous work, researchers studied the source, composition, and concentration of VOCs emitted from sewer networks, sewer lift stations, WWTPs, composting facilities, solid waste incinerators, etc. However, in the current study, the goal was to identify VOCs reported in the literature from similar sewer networks and compare them to the results from Hallandale and other areas in Florida. Tables 14 to 18 summarize the results from five studies.

Huang et al. (2012) measured 71 VOCs in two main Kaohsiung municipal sewers during the winter and summer seasons. The results, presented in Table 14, include the overall mean concentrations of VOC species obtained from the two sewer networks. *M* represents the mean value, and *SD* represents the standard deviation.

Table 14

VOC Concentrations (µg/m^3) Reported by Huang et al. (2012)

	A-Sewer		B-Sewer	
VOC Component	*M*	*SD*	*M*	*SD*
Benzene	6.05	8.99	ND	-
Chloroform	13.83	9.83	10.66	8.00
Chloroethane (methyl chloride)	1.11	2.40	4.39	8.68
1,4-Dichlorobenzene	3.58	1.13	1.31	4.15
Ethylbenzene	9.04	17.95	53.19	50.46
Methylene chloride (dichloromethane)	5.71	5.01	3.51	2.98
Styrene	6.03	14.43	7.40	12.61
Tetrachloroethene	90.46	27.05	4.00	9.45
Toluene	94.23	57.38	147.53	103.09
Trichloroethylene (trichloroethene)	107.85	32.32	1.80	3.96
Vinyl chloride (chloroethene)	208.35	98.52	2.07	3.67

Note. ND = not detected; results are under the method detection limits reported in the reports. M = mean concentration (µg/m^3). SD = standard deviation.

Wang et al. (2012) studied VOC emissions from several sewer networks in Sydney, and the results are presented in Table 15, which includes the averages and ranges of minimum and maximum values for measured concentrations.

Table 15

VOC Concentrations (µg/m^3) Reported by Wang et al. (2012)

	Site 1		Site 2		Site 3		Site 4		Site 5	
VOC component	Avg	Range	Avg	Range	Avg	Range	Avg	Range	Avg	Range
Ethylbenzene	7.49	0.60–21.8	31.5	0.40–93.4	36.8	4.75–95.1	4.93	0.17–16.0	32.0	0.84–126
Tetrachloroethene (tetrachloroethylene)	2,592	125–11,178	449	8.40–1,336	1513	13.4–4,217	1,039	9.92–7,550	5,193	160–13,664
Toluene	24.7	0.22–104	40.4	0.54–141	49.6	0.12–173	23.8	1.47–107	42.6	0.92–148

Note. Avg = average value. Range = minimum value and maximum value.

Wang et al. (2012) reported VOC emissions from two sewer sites in Sydney. Table 16 presents the results and the averaged concentrations of target VOCs.

Table 16

Mean VOC Concentrations (µg/m³) Reported by Wang et al. (2012)

VOC component	S1-Sewer Upstream	S2-Sewer Line
Benzene	5.52	8.85
Chloroform	202.00	654.25
Toluene	111.33	61.15

Niu et al. (2014) estimated the potential health effects (for workers) of chlorobenzene, dichloromethane, hydrogen sulfide, and carbon disulfide in the emissions of wastewater pump stations in a residential area in Tianjin (in North China). Table 17 presents the sampling analysis results reported by these researchers.

Table 17

VOC Concentration Ranges (µg/m^3) Reported by Niu et al. (2014)

VOC component	Concentration range
Benzene	1.46 – 11.8
Chlorobenzene	7.40 – 89.95
Ethylbenzene	0.58 – 8.21
Methylene chloride (dichloromethane)	ND – 14.69
Toluene (methylbenzene)	0.15 – 12.14
Total xylenes	0.10 – 16.21
Hydrogen sulfide	ND – 87.50
Carbon disulfide	0.98 – 17.08

They concluded that chlorobenzene, hydrogen sulfide, carbon disulfide, and methylene chloride were the predominant odors in the wastewater pump stations, and their concentrations ranged from 7.40–89.95 µg/m^3, ND–87.50 µg/m^3, 0.98–17.08 µg/m^3, and ND–14.69 µg/m^3, respectively.

Sivret et al. (2016) monitored VOC emissions in the sewer headspace across 21 field monitoring sites in Sydney, Melbourne, and Perth, which represent climatically distinct regions of Australia. Table 18 includes only the concentrations of the VOCs targeted for this study.

Table 18
VOC Concentrations (μg/m^3) Reported by Sivret et al. (2016)

	City					
	Sydney		Melbourne		Perth	
VOC component	*Mdn*	Max	*Mdn*	Max	*Mdn*	Max
Chloroform	55.4	950	39.6	432	17.2	286
Ethylbenzene	2.37	1,650	0.30	44.2	3.55	80.3
1,4-Dichlorobenzene	1.05	834	1.05	469	45.5	568
Tetrachloroethene	18.3	24,800	1.05	72.6	1.05	357
Toluene	31.7	10,500	70.8	12,600	60.7	1,750

Mdn = median concentration (μg/m^3). Max = maximum concentration (μg/m^3).

During this study, the researchers identified 20 dominant VOCs, and the measured concentrations were generally less than 250 μg/m^3. Some VOCs (toluene, trimethylbenzene, and cymene) were present at higher concentrations in some of the cities, and the researchers identified significantly higher VOC concentrations at a low frequency (tetrachloroethylene).

4.4 Comparison of VOC Species and Concentrations Between Different Sources in Florida and From Past Studies

4.4.1 Comparison of Common VOCs Concentrations Between Gas-Phase and Liquid-phase Samples From Hallandale

The analysis of VOC data from gas-phase sampling sites in Hallandale indicates the presence of several VOCs classified as hazardous air pollutants by the USEPA. These pollutants are chloroform, 1,4-dichlorobenzene, ethylbenzene, methylene chloride, tetrachloroethene, toluene, trichloroethene, and total xylenes. Other VOCs identified in Hallandale were acetone, ethanol, chloromethane, dichlorodifluoromethane, pentane, and propane. These species were not considered for further discussion in this study since there is no information about their carcinogenicity in the USEPA's IRIS system. As seen in Table 10, the laboratory analytical reports identified only four kinds of VOCs from the wastewater liquid-phase samples from Hallandale, and they were chloroform, 1,4-dichlorobenzene, toluene, and total xylenes. These VOCs were also present in the gas-phase samples from sewer manholes in Hallandale. Nonetheless, some differences exist between the type of VOCs and their respective concentrations from the two types of samples. Chloroform, 1,4-dichlorobenzene, and toluene were present in most of the wastewater gas-phase and liquid-phase samples. However, their concentrations from gas-phase samples registered significantly higher values compared with the levels from liquid-phase samples. There are a few possible reasons to explain the difference. First, the VOC concentrations from wastewater samples in the liquid-phase were used to compute the gas-phase concentrations, and an equilibrium partitioning was assumed. This assumption may underestimate the precise values of the VOCs in the gas-phase since other factors may enhance volatilization. Second, the wastewater liquid-phase samples were obtained from upstream locations at the boundary limits between Hallandale and Hollywood. On the contrary, the gas-phase samples were collected from downstream sites in the proximity of sewer lift stations. As reported in the literature by Corsi (1997), since the wastewater usually flows over multiple drop structures before reaching the WWTP, a significant fraction of VOCs is most likely to be emitted from collection systems before reaching the

WWTP. A comparison of the VOC concentrations ranges (minimum and maximum values) between the liquid-phase and gas-phase samples are presented in Table 19.

Table 19

Ranges of VOC Concentrations (µg/m^3) From Liquid and Gas Phases From Hallandale

	East System		Central System		West System	
VOC Component	Liquid-phase samples	Gas-phase samples	Liquid-phase samples	Gas-phase samples	Liquid-phase samples	Gas-phase samples
Chloroform	0.21-0.55	27-41	0.20-0.61	39-71.3	0.21-1.06	15-117
1,4-Dichlorobenzene	0.08-0.23	3.7-6.6	0.31-0.89	5.7-20	0.09-0.35	2.2-57
Toluene	0.28-0.43	5.3-9.0	0.48-2.71	7.5-11	0.15-0.18	7.9-43

4.4.2 Chloroform Occurrence in Samples from Study Sites in Florida and Comparison With Values Reported in the Literature

Chloroform is an organic compound, and its chemical formula is $CHCl_3$. It is also known as trichloromethane or methyl trichloride. It is colorless, sweet-smelling, and very volatile, but it is not very soluble in water (ATSDR, 1997). According to the International Agency for Research in Cancer (IARC), chloroform has been classified as Group 2B, possibly carcinogenic. Also, according to the USEPA's IRIS, chloroform has been classified as Group B, a probable human carcinogen (USEPA, 1998a).

Chloroform was present in most of the samples from all the sites in Florida (Figure 6). The concentration levels for chloroform from the liquid-phase samples from Hallandale were below the 1 µg/m^3 range, while concentrations from gas-phase samples from manholes ranged from 15 to 117 µg/m^3. The highest level for chloroform was 117 µg/m^3, in a sample from the manhole in the West system, followed by the concentration at the manhole from the Central system, which was 71.3 µg/m^3. The reasons for the variation of the chloroform concentrations between liquid- and gas-phase samples from Hallandale was not part of this study. However, since chloroform is a chlorination byproduct produced during the disinfection of drinking water, it is most likely the reason to explain its presence in the wastewater samples. The chloroform concentrations from the liquid-phase samples from all other sources in Florida had similar values to Hallandale, and their ranges were below 1 µg/m^3. Exceptions were samples from Sunrise, where a maximum value was 7.92 µg/m^3, and Pembroke, with a maximum of 2.71 µg/m^3. Huang et al. (2012) reported comparable results to Hallandale. Chloroform concentrations (mean concentration ± standard deviation) measured by these researchers in two main municipal sewers in Kaohsiung, Taiwan were 13.83 ± 9.83 and 10.66 ± 8.0 µg/m^3. Wang et al. (2012) reported mean chloroform concentrations of 202 and 654.25 µg/m^3 in samples from two sewer sites in Sydney; these levels are similar to Sivret et al. (2016), who reported concentrations for chloroform measured in sewer headspace air samples from Sydney, Melbourne, and Perth. The maximum concentrations from these three cities were 950, 432, and 286 µg/m^3, respectively.

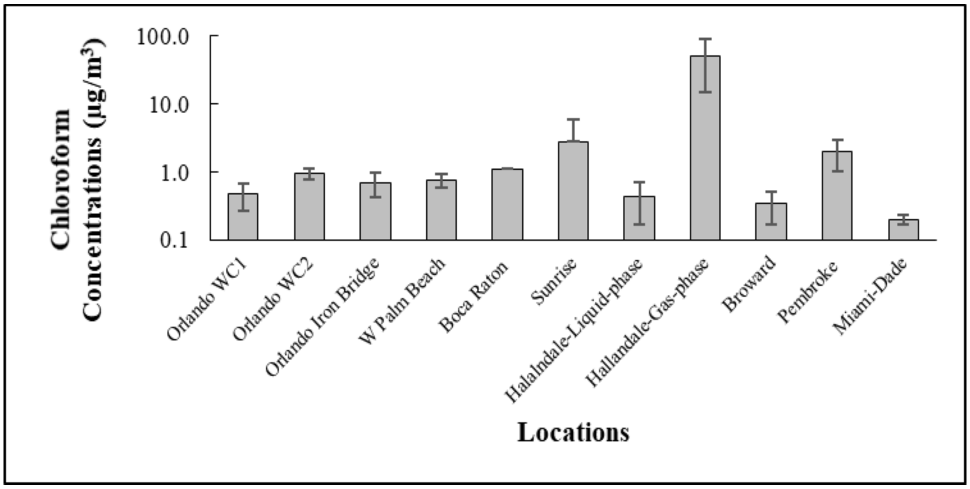


Figure 6. The occurrence of chloroform in wastewater samples from all study sites in Florida (mean concentrations in µg/m^3).

4.4.3. 1,4-Dichlorobenzene Occurrence in Samples From Study Sites in Florida and Comparison With Values Reported in the Literature

The VOC 1,4- dichlorobenzene is an organic compound, and its chemical formula is $C_6H_4Cl_2$. It has a strong odor and is used for manufacturing disinfectant, pesticide, and deodorant consumer products (ATSDR, 1997). According to the USEPA's IRIS, 1,4-dichlorobenzene has been classified as Group C, possible human carcinogen.

In all sites from Florida, 1,4-dichlorobenzene was present in most of the samples (Figure 7). The concentration levels for 1,4-dichlorobenzene from the liquid-phase samples from Hallandale were below the 1 µg/m^3 range, while concentrations from gas-phase samples from manholes ranged from 2.2 to 57 µg/m^3. The highest level for 1,4-dichlorobenzene was 57 µg/m^3 at the manhole from the West system, followed by the concentration at the sewer manhole from the Central system, which was 20 µg/m^3. The levels for 1,4-dichlorobenzene from sewer liquid-phase samples from all other sources from Florida had similar values to Hallandale, and their ranges were below 1 μg/m^3. Huang et al. (2012) reported comparable results to Florida and concluded that the concentrations (mean concentration ± standard deviation) for 1,4-dichlorobenzene were 3.58 ± 1.13 and 1.31 ± 4.15 μg/m^3 in two main municipal sewers in Kaohsiung, Taiwan. Sivret et al. (2016) also reported comparable concentrations for 1,4-dichlorobenzene, with a median value of 1.05 μg/m^3 measured in sewer headspace air from Sydney and Melbourne in Australia. Maximum concentrations for 1,4 -dichlorobenzene were reported as well by Sivret et al. (2016). These values were 834 μg/m^3 (Sydney), 469 μg/m^3 (Melbourne), and 568 μg/m^3 (Perth).

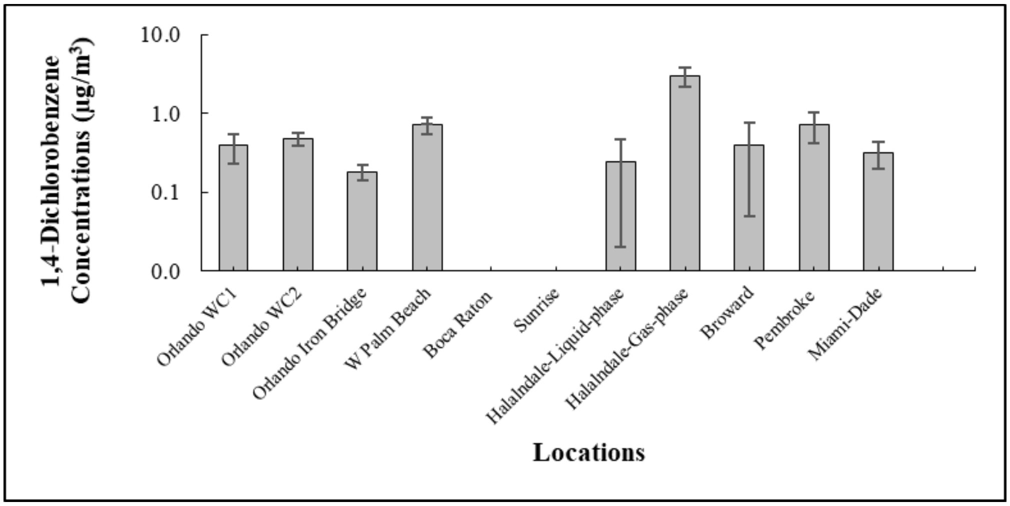


Figure 7. The occurrence of 1,4-dichlorobenzene in wastewater samples from all study sites in Florida (mean concentrations in μg/m^3).

4.4.4 Ethylbenzene Occurrence in Samples From Study Sites in Florida and Comparison With Values Reported in the Literature

Ethylbenzene is an organic compound, and its chemical formula is $C_6H_5C_2H_5$. It is a colorless liquid with an odor similar to gasoline, and it is highly flammable. Ethylbenzene is mostly consumed in the production of styrene, but it also can be found in some manufactured products, such as pesticides, paints, and inks. It is worth mentioning that ethylbenzene is often added to gasoline as an anti-knock agent. These types of applications of ethylbenzene may explain its appearance in the sewer systems. Small gasoline spills at gas stations, or even accidental gasoline spills, may find their way into the sewer systems through the runoff. According to the IARC, ethylbenzene has been classified as Group 2B, possibly carcinogenic. The USEPA has not determined ethylbenzene to be a carcinogen.

The laboratory analytical reports indicated the presence of ethylbenzene in a few locations throughout Florida (Figure 8), and the concentrations were generally lower than 1 $\mu g/m^3$, except the samples from Broward, in which the concentrations ranged from 2.05 to 4.11 $\mu g/m^3$; this result is comparable to Niu et al. (2014), who concluded that the concentration of ethylbenzene was from 0.58 to 8.21 $\mu g/m^3$ in a wastewater pump station in Tianjin. Other studies reported that ethylbenzene concentrations (mean concentration ± standard deviation) could range from 9.04 ± 17.95 to 53.19 ± 50.46 $\mu g/m^3$ in two sewer systems in Taiwan (Huang et al., 2012) and 16 to 126 $\mu g/m^3$ in five sewer systems in Sydney, Australia (Wang et al., 2012). Sivret et al. (2016) also reported comparable concentrations for ethylbenzene measured in sewer headspace air in three cities from

Australia; median values ranged from 0.30 to 3.55 µg/m^3. Maximum concentrations for ethylbenzene were reported as well by Sivret et al. (2016). These values were 1,650 µg/m^3 (Sydney), 44.2 µg/m^3 (Melbourne), and 80.3 µg/m^3 (Perth).

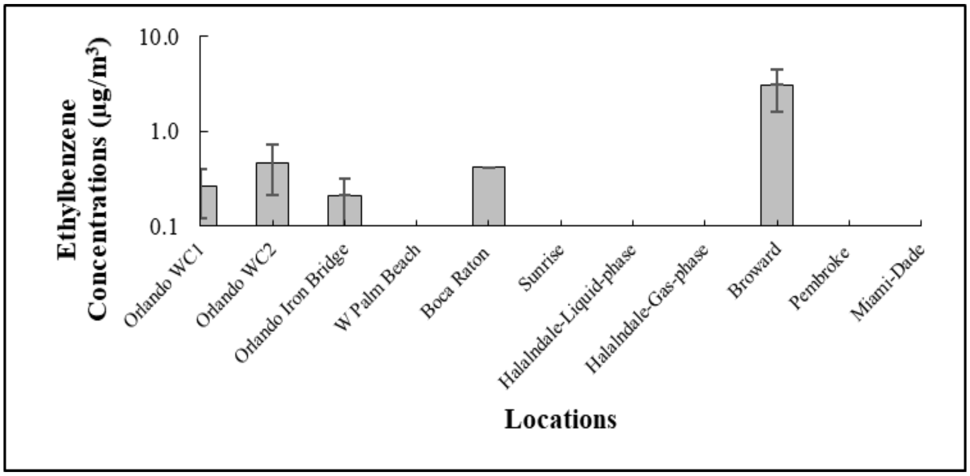


Figure 8. The occurrence of ethylbenzene in wastewater samples from all study sites in Florida (mean concentrations in µg/m^3). Missing values mean that the chemical was not detected.

4.4.5 Methylene Chloride Occurrence in Samples From Study Sites in Florida and Comparison With Values Reported in the Literature

Methylene chloride, also named dichloromethane, is an organochlorine compound, and its chemical formula is CH2Cl2. This volatile liquid has a moderately sweet aroma. Its primary use is as a solvent in the food industry and manufacturing. It can also be used as a paint stripper and as a degreaser. According to the IARC, methylene chloride has been classified as Group 2A, probably carcinogenic.

The laboratory analytical reports did not identify methylene chloride in the liquid-phase samples from Hallandale, but it was present in the gas-phase samples. This observation is potentially due to the lack of samples. Its high volatility may also explain the absence of this chemical in the liquid-phase samples, which were taken from upstream locations, as compared to the gas-phase samples locations. The highest concentrations for methylene chloride were in the gas-phase samples from the Central system, with values of 15 and 22 µg/m^3. The reports indicated values ranging from 0.15 to 5.28 µg/m^3 in Orlando's samples. Also, samples from Boca Raton registered a concentration of 5.97 µg/m^3. Huang et al. (2012) reported similar concentrations (mean concentration ± standard deviation) for methylene chloride of 5.71 ± 5.01 and 3.51 ± 2.98 µg/m^3 in two sewer systems from Taiwan. Also, Niu et al. (2014) reported comparative concentrations of methylene chloride, which ranged from non-detected to 14.69 µg/m^3 measured from odors emitted from an urban wastewater pump station in Tianjin, China. These values are similar to the concentrations obtained from the Central system in Hallandale (15 and 22 µg/m^3).

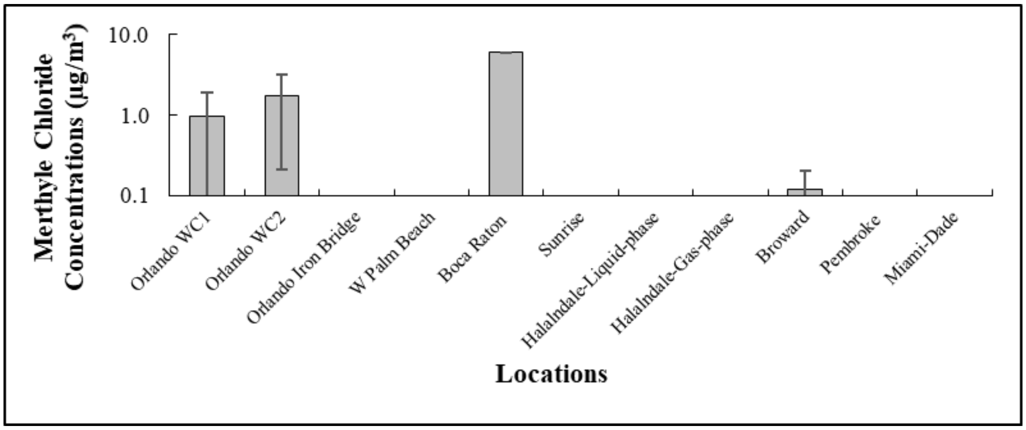


Figure 9. The occurrence of methylene chloride in wastewater samples from all study sites in Florida (mean concentrations in µg/m^3). Missing values mean that the chemical was not detected.

4.4.6 Tetrachloroethene Occurrence in Samples From Study Sites in Florida and Comparison With Values Reported in the Literature

Tetrachloroethene, also named tetrachloroethylene or perchloroethylene dichloromethane, is a chlorocarbon compound. Its chemical formula is Cl2C=CCl2. Tetrachloroethene is a colorless liquid, volatile, and very stable. Its primary use is for dry cleaning of fabrics, but it can also be used as a paint stripper or as a degreaser for metal parts in the automotive industry. According to the IARC, tetrachloroethene has been classified as Group 2A, probably carcinogenic.

The laboratory analytical reports rarely indicated tetrachloroethene in any of the study sites from Florida (Figure 10). Unusually high concentrations for tetrachloroethene were present in Hallandale in the gas-phase samples from the West system, ranging from 895 to 2,410 µg/m^3. There is no information available to be able to justify these concentrations of the tetrachloroethene.

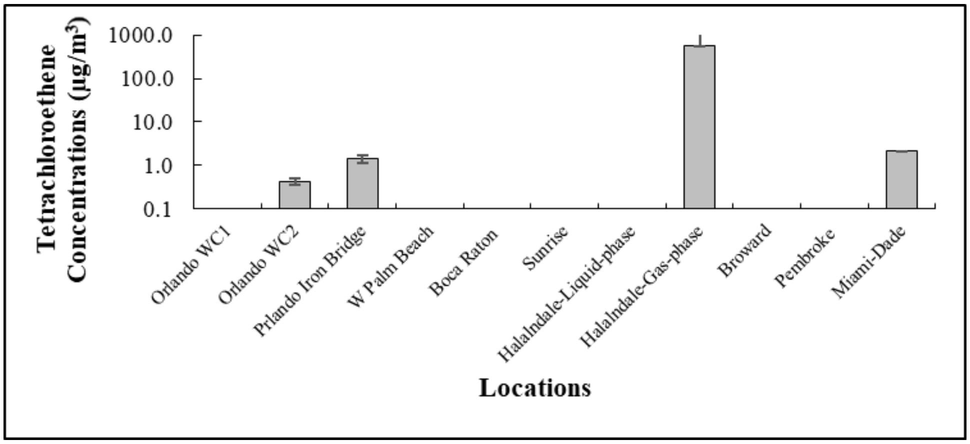


Figure 10. The occurrence of tetrachloroethene occurrence in wastewater samples from all study sites in Florida (mean concentrations in µg/m^3). Missing values mean that the chemical was not detected.

Huang et al. (2012) reported mean concentrations for tetrachloroethene of 90.46 ± 27.05 and 4.00 ± 9.45 µg/m^3. Sivret et al. (2016) measured significantly higher concentrations of tetrachloroethene in Sidney (24,800 µg/m^3), Perth (357 µg/m^3), and Melbourne (72.6 µg/m^3); these results are comparable to those of Wang et al. (2012), who concluded that the maximum concentrations of tetrachloroethene were from 4,217 to 13,664 µg/m^3.

4.4.7 Trichloroethene Occurrence in Samples From Study Sites in Florida and Comparison With Values Reported in the Literature

Trichloroethene, also named TCE, is a halocarbon compound. This chemical is a clear, non-flammable liquid and has a sweet smell. It is mostly used as an industrial solvent. According to the IARC, TCE was classified in 2014 as Group 1, carcinogenic.

The laboratory analytical reports did not identify trichloroethene in any of the samples from Florida. It only indicated small concentrations, ranging from non-detected to 4.4 µg/m^3, in the gas-phase samples in Hallandale. Huang et al. (2012) concluded that the concentrations (mean concentration ± standard deviation) for trichloroethene were from 107.85 ± 32.32 to 1.80 ± 3.96 µg/m^3.

4.4.8 Toluene Occurrence in Samples From Study Sites in Florida and Comparison With Values Reported in the Literature

Toluene, also named methylbenzene, is an aromatic hydrocarbon compound. This chemical is colorless, and its smell is similar to paint thinners. It is mostly used as a solvent and as an industrial feedstock. According to the IARC, toluene is classified as Group 3, not classifiable. Also, according to the USEPA, toluene has not been evaluated for carcinogenic potential due to insufficient information. In the early 1980s, Streicher et al. (1981) and Devathasan et al. (1984) reported that toluene was used as a recreational inhalant and caused severe neurological harm.

The toluene concentrations from liquid-phase samples from Hallandale were all below the 1 µg/m^3 range, except the sample from the Central system, in which the highest value was 2.71 µg/m^3. The concentrations measured in Hallandale from gas-phase samples ranged from 5.3 to 43 µg/m^3. The highest concentration of 43 µg/m^3 was in the West system. In general, the concentrations for toluene from all other sources from Florida were below 8 µg/m^3. The laboratory analytical reports identified higher concentrations in the samples from Orlando WCII, for which the values ranged from 12.8 to 65.5 µg/m^3. Figure 11 depicts the toluene concentrations identified in the study sites from Florida.

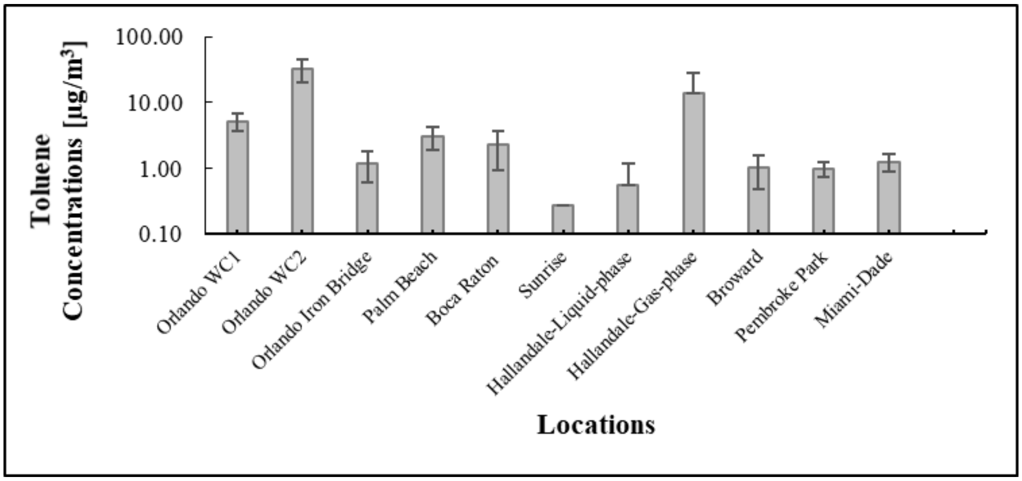


Figure 11. The occurrence of toluene in wastewater samples from all study sites in Florida (mean concentrations in µg/m^3).

Other studies showed comparable results to Florida. Niu et al. (2014) reported concentrations for toluene ranging from 0.15 to 12.14 µg/m^3, and Wang et al. (2012)

reported maximum concentrations for toluene ranging from 23.8 to 49.6 µg/m^3. Huang et al. (2012) reported concentrations (mean concentration ± standard deviation) for toluene of 94.23 ± 57.28 and 147.53 ± 103.09 µg/m^3. Also, Wang et al. (2012) reported mean concentrations for toluene of 61.15 to 111.33 µg/m^3. Sivret et al. (2016) reported higher levels of toluene, including median concentrations ranging from 31.7 to 70.8 µg/m^3 and maximum concentrations from 1,750 to 12,600 µg/m^3.

4.4.9 Total Xylenes Occurrence in Samples From Study Sites in Florida and Comparison With Values Reported in the Literature

Xylene is an aromatic hydrocarbon compound. Because the methyl groups vary on the benzene ring, there are three forms: meta-xylene (m-xylene), ortho-xylene (o-xylene), and para-xylene (p-xylene). This chemical is colorless and is a sweet-smelling liquid that can catch fire very quickly. It is mostly used as a solvent in the printing, rubber, and leather industries, but it also can be used as thinner for paints and as a cleaning agent. Often, xylenes can be found in small amounts in airplane fuel and gasoline.

The laboratory analytical reports identified a total xylenes concentration of 2.66 µg/m^3 only in the liquid-phase samples from the Central system in Hallandale, while concentrations from gas-phase samples from manholes ranged from 0.48 to 4 µg/m^3. The highest concentration value of 4 µg/m^3 was in the gas-phase samples from the Central system. A significantly higher concentration of 29.37 µg/m^3 was present in samples from Broward. As shown in Figure 12, the report identifies total xylenes only in a few locations throughout the study sites in Florida. Niu et al. (2014) reported similar results and concluded that the concentrations for total xylenes ranged from 0.10 to 16.21 µg/m^3. These concentrations were measured from odors emitted from urban wastewater pump stations in Tianjin, China.

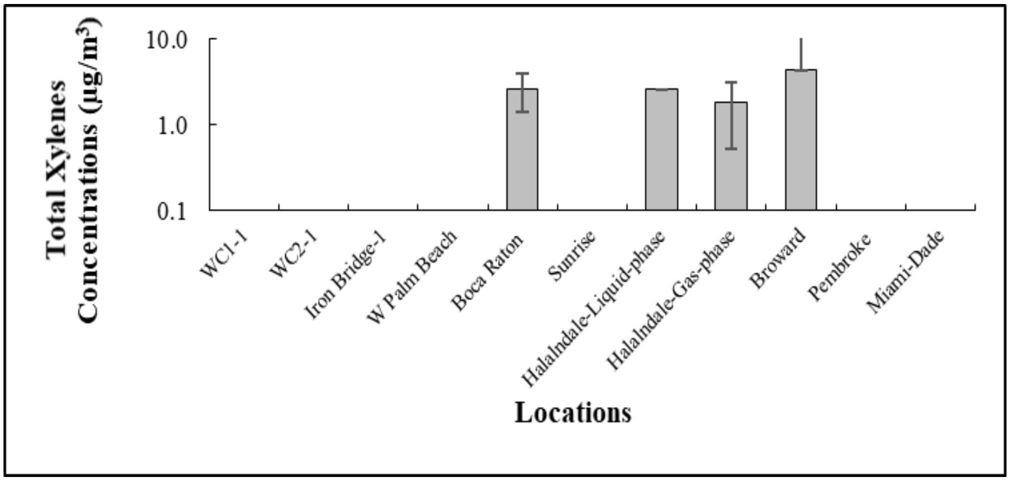


Figure 12. The occurrence of total xylenes in wastewater samples from all study sites in Florida (mean concentrations in µg/m^3). Missing values mean that the chemical was not detected.

4.5 Risk Assessment

The principle of which VOCs should be selected for risk estimation depends on their toxicity and concentration. In this study, both non-carcinogenic and carcinogenic risk levels were estimated. Although 52 kinds of common toxic VOCs were analyzed from Hallandale's gas-phase wastewater samples, only 13 types of VOCs were detected, as represented in Table 13. The rest of the 39 VOCs were below their detection limits. Among the 13 kinds of VOCs, the levels of tetrachloroethene, ethanol, and chloroform were the highest, followed by acetone, 1,4-dichlorobenzene, toluene, and methylene chloride. Because of their carcinogenicity classification, tetrachloroethene, chloroform, 1,4-dichlorobenzene, methylene chloride, and toluene were considered for evaluation of the potential health risks to sewer workers in Hallandale. The same hazardous pollutants were considered for estimating risks to the sewer workers in Orlando.

In this study, the non-carcinogenic and carcinogenic potential risk levels were estimated only for exposure conditions of the sewer workers in the Hallandale and Orlando sites. The concentrations of the VOCs identified from all other locations throughout Florida did not exceed the levels identified in Hallandale and Orlando. Furthermore, there was no need to estimate these health risk levels.

4.5.1 Risk Assessment Parameters

The parameters used for estimating the non-carcinogenic and carcinogenic risks are listed in Table 20. The ET was assumed based on the eight working hours per day. The EF was assumed based on the five working days per week and two weeks off vacation time. AT was ED (25 years) x 365 (days/year) x 24 (hours/day).

Table 20
Exposure Parameters and Their Values for the Sewer Workers

Parameter	Description	Value	Unit
ET	Daily exposure time	8	hour/day
EF	Exposure frequency	250	day/year
ED	Exposure duration	25	year
AT	Average time	219000	hour

When the risks were assessed using the Monte Carlo technique performed on Crystal Ball software, the distribution types for all the inputs were identified. Table 21 shows the selected types of probability distributions used in this study, including CA, IR, ET, EF, EW, ED, BW, LT, AT, SF, RfC, and IUR.

Based on the literature, there is significant support for the use of the lognormal distribution in describing chemical concentration data (Asante-Duah, 1993; Jia et al., 2008; Ott, 1990). In this study, the normality for the concentration of the VOCs identified in gas-phase samples from Hallandale Beach was verified through Kolmogorov–Smirnov and Shapiro–Wilk tests, commonly known as K–S tests (significance level = .05, *P* = 0.95), using SPSS software, version 25.0. The results given in Table 21 show that the concentrations for chloromethane, methylene chloride, and xylenes were normally distributed. For carbon tetrachloride, chloroform, 1,4-dichlorobenzene, toluene, and tetrachloroethylene, the data was not normally distributed since the significance values (sig) were very small. Because there was insufficient data, it is impossible to explain why the normality distribution failed to fit a normal distribution. Therefore, the lognormal distribution was used to describe the chemical contribution data for all risk calculations.

A phone questionnaire-based survey was conducted in different municipalities in southern Florida during January and February 2018 to determine the exposure parameters for sewer workers. Each subject was asked how many sewer workers are in their organization, the number of working hours per day, and the number of days per week spent in the outdoors performing sewer-related activities. According to the questionnaire results (Appendix G), the workers worked five days per week on eight-hour shifts or four days per week on 10-hour shifts. Values for ET ranged from six to 10 hours per day. Therefore, the triangular distribution was used to describe ET for the workers. The values for EF were four and five days per week, and the normal distribution was used. EW was considered to have a triangular distribution since the workers have stable holidays, sick time, and vacation days. The triangular distribution for the EW was also justified by Niu et al. (2014).

The mean values for IR, AT, LT, and BW were adopted from the USEPA Exposure Factors Handbook (USEPA, 2011). The mean for IR was selected from age groups of 21 to 71 years old and the mean BW for all adults (male, female, and all groups) combined. Previous studies assumed that IR had a normal distribution (Yeh et al., 2011). Thus, a normal distribution was used to describe IR characters.

Table 21

Distributions and Values of the Parameters in the Health Risk Assessment When Using the Monte Carlo Technique

Input parameter	Unit	Values (*M* ± *SD*)	Distribution	Range and explanation
CA	μg/m^3	Values	Lognormal	Shown in Table 13
IR	m^3/hour	0.65 ± 0.13	Normal	Standard deviation was taken as 20% of the mean; the mean value was adopted from the USEPA Exposure Factors Handbook (2011)
ET	hour/day	7.25 ± 1.19	Lognormal	(6, 8, 10) this study
EF	day/week	4.75 ± 0.43	Normal	(4, 5) this study
EW	week/year	42, 43, 44	Triangle	(42, 43, 44) this study
ED	year	22.97 ± 5.11	Lognormal	(10, 32) this study
BW	kg	80 ± 16	Lognormal	Standard deviation was taken as 20% of the mean; the mean value was adopted from USEPA (2011)
LT	year	75	Point	Adopted from USEPA (2011)
AT_{25}	hour	219,000	Point	25 years x 365 days/year x 24 hours/day
SF	kg-day/mg	Shown in Table 4	Triangle	(0, SF, SF)
RfC	mg/m^3	Shown in Table 4	Triangle	(0, RfC, RfC)
IUR	m^3/μg	Shown in Table 3	Triangle	(0, IUR, IUR)

Note. CA= gas-phase concentration. IR = inhalation rate. ET = average exposure time. EF = average exposure frequency. EW = exposure weeks. ED = average exposure duration. BW = body weight. LT = lifetime. AT = average time. SF = slope factor. RfC = reference concentration. IUR = inhalation unit risk.

Table 22

Tests for Normality for VOC Concentrations from Hallandale Beach

	Test for normality (K–S test)					
	Kolmogorov–Smirnov[a]			Shapiro–Wilk		
VOC species	Statistic	*df*	Sig.	Statistic	*df*	Sig.
Carbon tetrachloride	.433	6	.001		6	.003
Chloroform	.280	6	.153	.889	6	.311
Chloromethane (methyl chloride)	.265	6	.200*	.786	6	.044
1,4-dichlorobenzene	.336	6	.033	.713	6	.008
Methylene chloride	.218	6	.200*	.867	6	.215
Tetrachloroethene	.380	6	.007	.678	6	.004
Toluene	.415	6	.002	.622	6	.001
Xylenes	.191	6	.200*	.920	6	.506

[a] Lilliefors significance correction.
*This is a lower bound of the true significance.

The normal distribution, lognormal distribution, and triangle distribution for IUR and RfC were explored in this study. The extrapolation method for animal data or occupational studies, which results in uncertainty (USEPA, 2009), served as the basis for the IUR values for the target VOCs that were chosen for risk calculations, as reported by the USEPA's IRIS. Also, the USEPA's IRIS defines IUR as the upper-bound, excess lifetime cancer risk estimated to result from continuous exposure to the hazardous chemical at a concentration of 1 μg/m^3 in the air (USEPA, 2009). Furthermore, the zero value to lowest risk (minimum) was assigned, and it was assumed that the IUR values recommended by the USEPA represented the most likely values (maximum; Devon et al., 2004; McGavran et al., 1999). Some previous work studied the distributions of IUR and RfC (Niu et al. 2014). Durmusoglu et al. (2010) argued that triangle distribution for RfC and IUR was more likely to obtain reasonable results. Based on the references available, no reasonable assumptions were identified to consider the normal and lognormal distributions. Therefore, the triangle distribution was selected for the distribution of IUR and RfC.

4.5.2 Non-Carcinogenic Risk Assessment

For the non-carcinogenic effect, the hazardousness of an individual VOC by inhalation was estimated by calculation of the HQs expressed by Equation 11. The HQ was calculated for exposure to five chemical hazards identified in Hallandale and Orlando sites. Therefore, tetrachloroethene, chloroform, 1-4-dichlorobenzene, toluene, and methylene chloride were considered for calculating the non-carcinogenic risks. The ranges for the HQ for the five VOCs are presented in Table 23.

Table 23

Non-Carcinogenic Risk Assessment - Hazard Quotients (HQs)

	Ranges for Hazardous quotients (HQ)				
Exposure location	Tetrachloro-ethene	Chloroform	1,4-dichlorobenzene	Toluene	Methylene chloride
Hallandale liquid-phase	N.A.	0.05 – 0.02	N.A.	N.A.	N.A.
Hallandale gas-phase	0.007 – 13.76	0.34 – 2.67	0.001 – 1.01	0 – 0.02	0 – 0.008
Orlando liquid-phase	0.002 – 0.01	0.004 – 0.03	N.A.	0 – 0.003	0 – 0.002

Note. N.A. denotes that the chemical hazard was not present or that HQ values were too small to be reported.

Concentrations of tetrachloroethane, chloroform, 1,4-dichlorobenzene, toluene, and methylene chloride at different sample points from Hallandale and Orlando sites are listed in Tables 6, 7, 8, 10, and 13. The assessment of non-carcinogenic risks (Table 23) revealed that for all the exposure locations and VOCs identified in the liquid-phase samples, the HQ values were lower than the upper confidence limit (1.0). Furthermore, there are no health concerns for the sewer workers working under these exposures. On the contrary, HQ values for tetrachloroethene and chloroform are a reason for concern since some values exceeded the upper confidence limit of (1.0). Unusually high values for HQ were calculated for tetrachloroethene concentrations identified from the gas-phase samples from the West system in Hallandale (895 and 2,410 µg/m^3). The HQ values for these concentrations were 5.08 and 13.76, respectively. For these specific exposures, the HQ was also calculated for reduced amounts of ET (hour/day). This analysis was performed to determine the maximum number of hours that sewer workers can work with these exposures without health risks concerns. Furthermore, the HQ values under the threshold limit (1.0) were obtained when the ET did not exceed three hours per day.

4.5.3 Non-Carcinogenic Risk Assessment Using the Monte Carlo Technique - Hallandale Gas-Phase Exposure Concentrations

The Monte Carlo simulation, which is a probabilistic modeling technique, was applied when screening calculations using conservative point estimates were above the levels of concern. In this study, the Monte Carlo simulation was performed in Crystal Ball software to calculate the non-carcinogenic risk probability distributions based on the risk calculation method of the five VOCs expressed by Equation 11. Furthermore, the non-carcinogenic risks were analyzed only for the chemical hazards identified in the gas-phase samples from Hallandale.

Crystal Ball runs on Microsoft Excel and is an analytical tool that can assist in decision-making by performing simulations using spreadsheet models. The forecasts resulting from these simulations are helpful to quantify areas of risk. Figure 13 shows the necessary steps for using Crystal Ball, which include (a) build a spreadsheet model describing an uncertain situation, (b) run a simulation, and (c) analyze the results. The first step for the Monte Carlo simulation is to input each uncertain variable; this defines the possible value with a probability distribution, called an assumption.

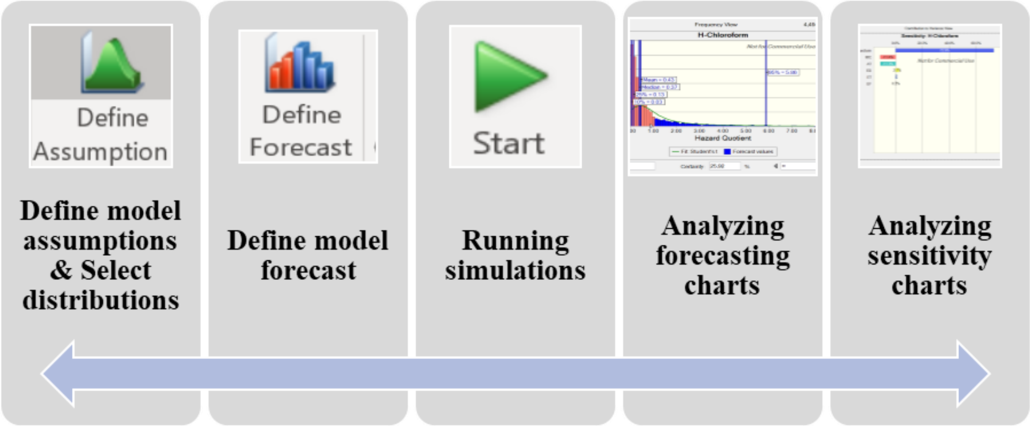


Figure 13. The basic process for quantifying risks using the Monte Carlo simulation on Crystal Ball software.

Table 21 lists the representative input values and distributions for the input variables used for the non-carcinogenic and carcinogenic risk assessment. Furthermore, the input values in the model were RfC, as listed in Table 5; CA, as listed in Table 13; ET; EF; ED; and AT. Details for ET, EF, ED, and AT input parameters were provided in Section 4.5.1. In the second step, Equation 11 was used to input the forecast model for the non-carcinogenic risk. As represented in Equation 11, the non-carcinogenic risk is expressed as HQ. For each forecast, Crystal Ball remembers the cell value for all the trials (scenarios).

In step 3, to ensure the stability of the results from the Monte Carlo method, 5,000 iterations were conducted for each hazard risk; the literature reported that this number of iterations was enough (Niu et al., 2014; Chen et al., 2011). In step 4, the results are displayed graphically and numerically by the Crystal Ball software, and they can be seen using different types of charts. There are six types of charts that can be created by the Crystal Ball, and they are assumption charts, forecast charts, sensitivity charts, overlay charts, trend charts, and scatter charts. These charts are the primary analysis tools for displaying results in Crystal Ball. In this study, the forecast chart was selected to analyze the risk. There are three types of forecast charts, and they are frequency, cumulative frequency, and reverse cumulative frequency. The frequency distribution type of chart was selected to display the results for the non-carcinogenic risk estimate.

Furthermore, Figure 14 shows the frequency distributions of the five odors' non-carcinogenic risks to the sewer workers. With Monte Carlo simulations, Crystal Ball displays results in a forecast chart that shows the entire range of possible outcomes and the likelihood of achieving each of them. Figure 14 shows the forecast results in graphical and numerical forms; these are the values generated for each forecast. They also show the probability of obtaining any value. Crystal Ball normalizes these probabilities to calculate certainty. The chance, or certainty, of any forecasting value falling between –Infinity and +Infinity is always 100%. However, the certainty of the HQ being at least one was used for all charts in Figure 14. In the chart preferences, the user has to select the line markers desired to be displayed in the graphs. Furthermore, the mean and median were selected, and for percentiles, 10%, 25%, and 95%, were chosen.

As seen in Figure 14, the non-carcinogenic risk frequency distributions for toluene, chloroform, and 1,4-dichlorobenzene fitted to logistic distribution, and tetrachloroethene and methylene chloride fitted to Student's *t* distribution. According to the risk assessment guidance, the 95th percentile was adopted as the upper confidence limit (USEPA, 2001). The 95th percentile of the total non-carcinogenic risk for the five VOCs was 31.13, which could pose a threat to human health because its estimated value is much higher than the acceptable upper confidence limit (1.0). The descending order of non-carcinogenic risk values of the five VOCs under the 95th percentile was tetrachloroethene, chloroform, 1,4-

dichlorobenzene, toluene, and methylene chloride. The 95th percentile of HQ for tetrachloroethene was 22.84, which represented 73.37% of the five totally; for chloroform, the 95th percentile of HQ was 8.22, representing 26.40%. The median and average values of HQ for tetrachloroethene were 1.35 and 3.59, respectively. Both surpassed the upper confidence limit (1.0). The probability that the HQ of tetrachloroethene was higher than 1.0 was 56.78%. This result means that the non-carcinogenic health effect of tetrachloroethene is significant. The median and average values of HQ for chloroform were 0.82 and 2.39, respectively. The probability that the HQ of chloroform was higher than 1.0 was 67.94%. Since the average value exceeded the upper confidence limit (1.0), the non-carcinogenic health effect of chloroform is also significant.

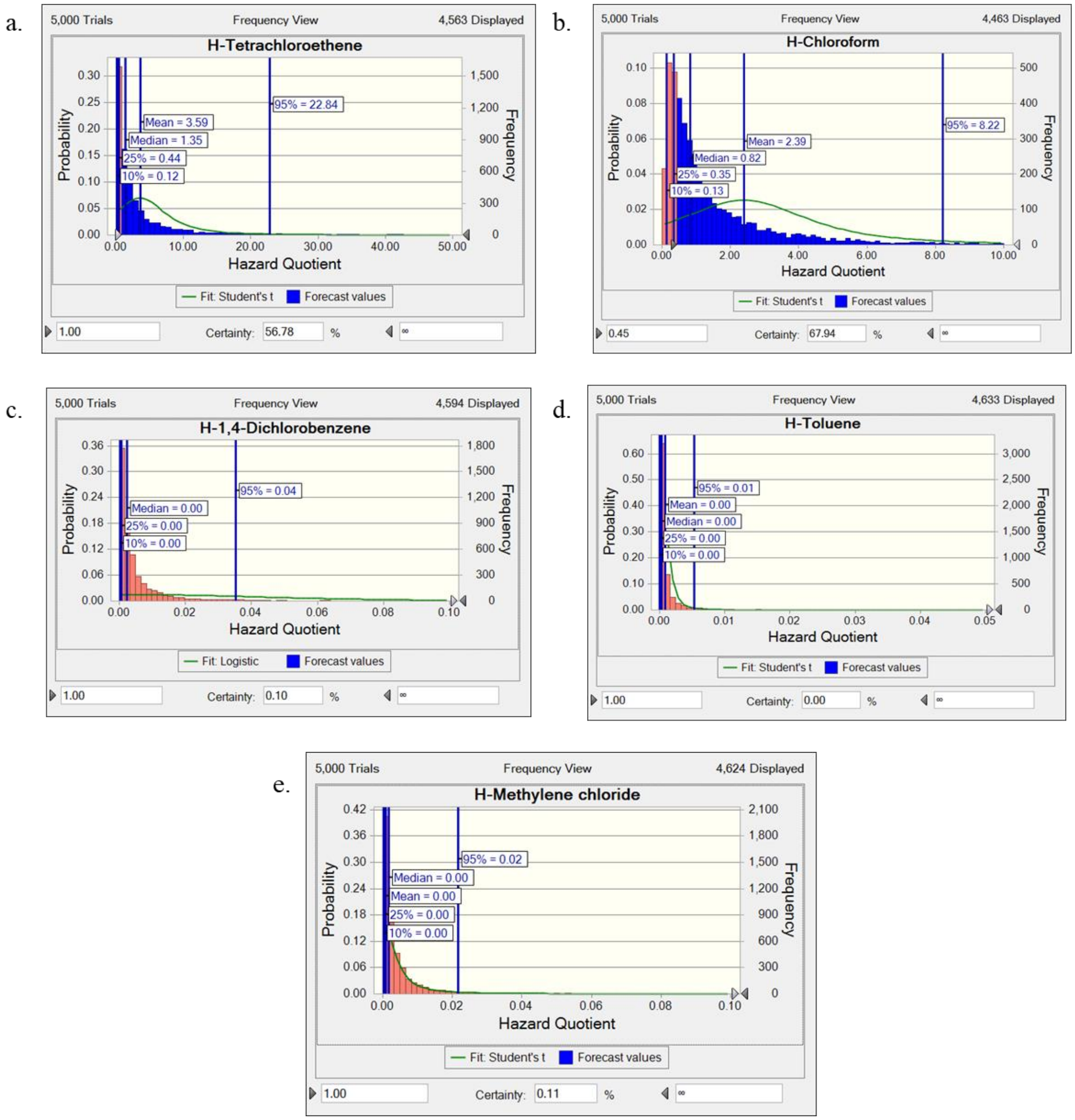


Figure 14. Hazard quotient (HQ) using a Monte Carlo simulation - Hallandale gas-phase exposure concentrations. Frequency distributions of non-carcinogenic risk for the five VOCs: (a) tetrachloroethene, (b) chloroform, (c) 1,4-dichlorobenzene, (d) toluene, and (e) methylene chloride.

Among the other three VOCs, 1,4-dichlorobenzene and methylene chloride had a low probability of 0.10% and 0.11%, respectively, for their HQ values being higher than the upper acceptable confidence limit of 1.0; their effects were considered to be negligible.

Also, the probability of the HQ being higher than 1.0 was 0.01% for toluene, which is very close to zero; its non-carcinogenic effect is also negligible.

The results reported above are based on the limited data obtained from VOC emissions from sewer manholes from three specific locations in Hallandale, and it cannot be assumed that these findings signify the entire city. Furthermore, they should raise concerns that possible health risks exist. Other researchers estimated non-carcinogenic effects for sewer workers exposed to VOCs. For example, Yang et al. (2012) examined the VOC emissions and the non-carcinogenic effects by inhalation intake from different processes from a WWTP in China. These researchers estimated HQ values toluene, xylenes, chloroform, TCE, carbon tetrachloride, and tetrachloroethene. The values for these VOCs were less than 1.0, indicating no health concerns. The HQ for benzene was above 1.0, which poses health concerns for the sewer workers. Niu et al. (2014) studied the VOC emissions from wastewater pump stations in Tianjin, China. These group of researchers performed a risk assessment to evaluate the potential health effects of four hazardous air pollutants (chloroform, methylene chloride, hydrogen sulfide, and carbon sulfide). They concluded that the non-carcinogenic risk exceeded the acceptable level of 1.0, raising health concerns to the sewer workers.

4.5.4 Non-Carcinogenic Risk Sensitivity Analysis

The Monte Carlo method provides the ability to perform a sensitivity analysis to determine which input variables influenced the risk the most. The results of the sensitivity analysis can be useful for utility managers to mitigate or lower the potential health risks of sewer workers.

The sensitivity chart is one of six charts produced by the Crystal Ball software. As represented in Figure 13, in step 5, a quantitative sensitivity analysis was conducted using the Crystal Ball software to evaluate the variability and uncertainty of input variables that contributed most significantly to excess lifetime cancer risk. The results are represented in the charts shown in Figure 15. There are two types of charts available under the sensitivity chart view menu bar. These charts are a contribution to the variance chart and rank correlation chart. The contribution to the variance chart type was selected. This type of chart is beneficial to identify what percentage of the uncertainty (variance) is caused by a specific assumption in the target forecast. This type of chart allows the user to select which assumptions they want to display. In all the charts presented in Figures 15 and 18, all assumptions (input parameters) were selected. Also, assumptions with a negative relationship have bars on the left side of the zero lines, and assumptions with a positive relationship have bars on the right side of the zero lines.

Figure 15 shows the effects of the non-carcinogenic risk sensitivity analyses for the five VOCs. Usually, one or two assumptions have the highest effect on the uncertainty of a forecast. For all five VOCs, the variable that contributed most to their non-carcinogenic risk values was CA. For chloroform, CA contributed most to its non-carcinogenic risk values (accounting for 73.1%). For tetrachloroethene, CA contributed 36.6%, and for 1,4-dichlorobenzene, toluene, and methylene chloride, CA contributed approximately 50% to their non-carcinogenic risk values (accounting for 50.2%, 51.8%, and 56.0%, respectively). Furthermore, this assumption should be further investigated, and efforts should be made to reduce its uncertainty and therefore its effect on the target forecast.

For all five VOCs, the sensitivity contributions of CA were positive values; therefore, there was a positive correlation between CA and the non-carcinogenic risk. A positive correlation means that if the CA increases, the risk also increases. Also, a positive correlation means that if one variable decreases, the second variable also decreases.

AT was the second most important parameter that contributed to the variance of non-carcinogenic risk values for all five VOCs. For 1,4-dichlorobenzene, toluene, and methylene chloride, AT contributed between 20 and 24% to their non-carcinogenic risk (accounting for -23.7%, -20.4%, and -21.8% respectively). For tetrachloroethene, AT had the largest contribution of -31.0%, and for chloroform, AT had the smallest contribution of -10.7%. The correlations between AT and the non-carcinogenic risk of all five VOCs were negative; therefore, there was a negative correlation between AT and the non-carcinogenic risk. A negative correlation between any variable and the non-carcinogenic risk means that if the variable increases, the non-carcinogenic risk decreases, or vice versa.

For RfC, its sensitivity had a significant contribution, accounting for approximately -20.3% of tetrachloroethene, -16.4% of 1,4-dichlorobenzene, -19.8% of toluene, and -15.6% of methylene chloride but only accounting for -11.8% of chloroform. Furthermore, the results showed that RfC had a negative correlation with the non-carcinogenic risk for the five VOCs. For ED, ET, and EF, the sensitivity contribution was generally between 1% and 6% for each variable. Also, the results showed that ED, ET, and EF had positive correlations with the non-carcinogenic risk for all five VOCs.

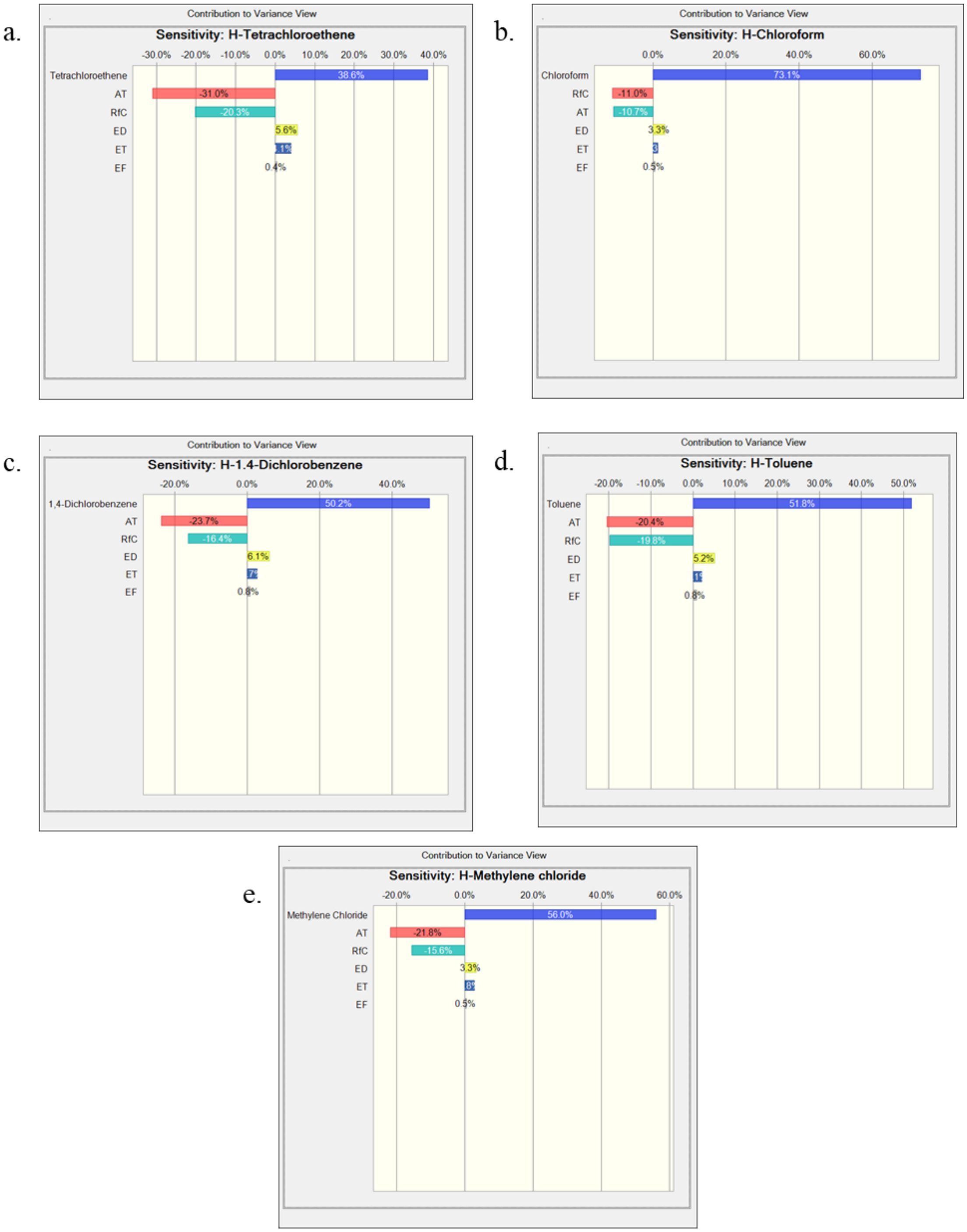


Figure 15. Non-carcinogenic risk sensitivity analysis results for five VOCs, Hallandale gas-phase exposure concentrations: (a) tetrachloroethene, (b) chloroform, (c) 1,4-dichlorobenzene, (d) toluene, and (e) methylene chloride. AT = average time. RfC =: reference concentration. ED = average exposure duration. ET = average exposure time. EF = average exposure frequency.

4.5.5 Carcinogenic Risk Assessment

According to the USEPA's WOE classification system for carcinogenicity, tetrachloroethene is classified as Group 2A (probably carcinogenic to humans), chloroform as Group 2B (possibly carcinogenic to humans), and methylene chloride as Group 2A (probably carcinogenic to humans). Any carcinogenic risk values above the USEPA acceptable limit of 1.0 x 10-6 indicate a high cancer risk on humans exposed to the hazardous chemical. Yeh et al. (2011) argued that an excess lifetime risk between 1.0 x 10^{-6} and 1.0 x 10^{-4} indicates potential risk, while larger than 1.0 x 10^{-4} indicates high potential health risks.

Because of the carcinogenicity classification and high concentrations of the three hazardous chemicals mentioned above, their carcinogenic risks were estimated in this study. The carcinogenic risks were calculated using the cancer model risk expressed by Equations 7 and 8. Concentrations of tetrachloroethane, chloroform, and methylene chloride at different sample points from Hallandale and Orlando sites are listed in Tables 6, 7, 8, 10, and 13. The estimated ranges for the carcinogenic risks for the three VOCs are presented in Table 24. The assessment of carcinogenic compounds (Table 23) revealed that, for tetrachloroethene and the exposures to the concentrations identified in the gas-phase samples in Hallandale, the carcinogenic risks values exceeded the upper confidence limit of 1.0 x 10^{-4} for potential high risk.

Carcinogenic risk values of 5.31 x 10^{-5} and 1.13 x 10^{-4} were calculated for exposure to the tetrachloroethylene concentrations identified in the West system in Hallandale (895 and 2,410 µg/m^3). Also, the carcinogenic risks for exposure to chloroform concentrations identified in the gas-phase samples in Hallandale ranged from 7.88 x 10^{-5} to 3.74 x 10^{-4}, which exceeded the acceptable risk levels. Furthermore, there are potential health concerns to the sewer workers working under these exposures. For these specific exposures, the carcinogenic risks were calculated for reduced values of ET (hours/day). Furthermore, the R values were decreased by approximately one order of magnitude when the ET was three hours per day.

The assessment for methylene chloride revealed that there are no health concerns under these exposures.

Table 24

Carcinogenic Risk Assessment – Carcinogenic Risk (R)

	Ranges for carcinogenic risks (R)		
Exposure location	Tetrachloroethene	Chloroform	Methylene chloride
Hallandale liquid-phase	N.A.	7.88×10^{-7} – 5.7×10^{-6}	N.A.
Hallandale gas-phase	7.12×10^{-8} – 1.43×10^{-4}	7.88×10^{-5} – 3.74×10^{-4}	2.51×10^{-9} – 5.08×10^{-8}
Orlando liquid-phase	9.19×10^{-8} – 1.05×10^{-7}	9.98×10^{-7} – 7.51×10^{-6}	7.76×10^{-10} – 1.21×10^{-8}

Note. N.A. = the chemical hazard was not present and there are no values for R.

4.5.6 Carcinogenic Risk Assessment Using the Monte Carlo Technique - Hallandale Gas-Phase Exposure Concentrations

Likewise, for the non-carcinogenic assessment, when the risk calculations were above the levels of concern when using conservative point estimates, the Monte Carlo simulation was applied. In this study, the Monte Carlo simulation performed in Crystal Ball software was used to calculate the carcinogenic risk probability distributions for the three carcinogens identified in the gas-phase samples from Hallandale. Therefore, a Monte

Carlo simulation was performed to quantify the uncertainty and its impact on the estimation of risk for sewer workers exposed to tetrachloroethane, chloroform, and methylene chloride.

The same steps, 1 to 4, as represented in Figure 13, were used for quantifying carcinogenic risk using a Monte Carlo simulation via Crystal Ball software. The representative values and distributions for the input variables used for the carcinogenic risk assessment are represented in Table 21.

First, the Monte Carlo simulation was used to estimate the carcinogenic risks using the first risk model, denoted by Equations 7 and 8. The input values in the model were IUR, as listed in Table 4; CA, as listed in Table 13; ET; EF; ED; and AT. The input values of ET, EF, ED, and AT are summarized in Table 21, and details for these parameters were provided in Section 4.5.1

Second, the Monte Carlo simulation was used to estimate carcinogenic risks using the second risk model, denoted by Equations 9 and 10. The input values in the model were SF as listed in Table 4, IR, CA as listed in Table 13, ET, EF, EW, ED, LT, and BW. The input values of ET, EF, EW, ED, LT, and BW are summarized in Table 21, and details for these parameters were provided in Section 4.5.1. Similar to the HQs represented in Figure 14, in the chart preferences for the carcinogenic risks (represented in Figure 16), the mean and median were selected, and for percentiles, 10%, 25%, and 95% were chosen. Five thousand iterations were conducted for each hazard risk to ensure the stability of the results from the Monte Carlo technique. The frequency distribution type of graph was selected to display the results for the carcinogenic risk estimate. In the chart preferences, by the model default, the scale is selected as “Auto,” but the chance, or certainty, of forecasting any value for the carcinogenic risk between –Infinity and +Infinity is always 100%. A fixed scale can be customized. Furthermore, the scale with minimum and maximum values was customized as appropriate.

The results from the two models were compared and discussed further. Figure 16 depicts the frequency distributions of the carcinogenic risks of tetrachloroethene, chloroform, and methylene chloride to the sewer workers, using the first model.

The frequency distributions of the carcinogenic risks of tetrachloroethene, chloroform, and methylene chloride to the sewer workers followed a logistic distribution type. The 95th percentile for workers exposed to tetrachloroethene was 1.32×10^{-4}, which exceeds the upper end of the USEPA's acceptable range of 1.0×10^{-6}. The probability that the risk of tetrachloroethene was between 1.0×10^{-6} and 1.0×10^{-4} was 85.48%. The 95th percentile of the carcinogenic risk for chloroform was 4.72×10^{-4}, which also exceeds the upper end of the USEPA's acceptable level of 1.0×10^{-6}. Also, the probability that the risk of chloroform was between 1.0×10^{-6} and 1.0×10^{-4} was 69.34%. Therefore, the results of the simulation showed that, for sewer workers exposed to high concentrations of tetrachloroethene and chloroform, the 95% probability excess lifetime risks were higher than 1.0×10^{-6}, indicating high potential health risks. The cancer risks associated with tetrachloroethene (1.32×10^{-4}) and chloroform (4.72×10^{-4}) were estimated for sewer workers without any ventilation and personal protection equipment.

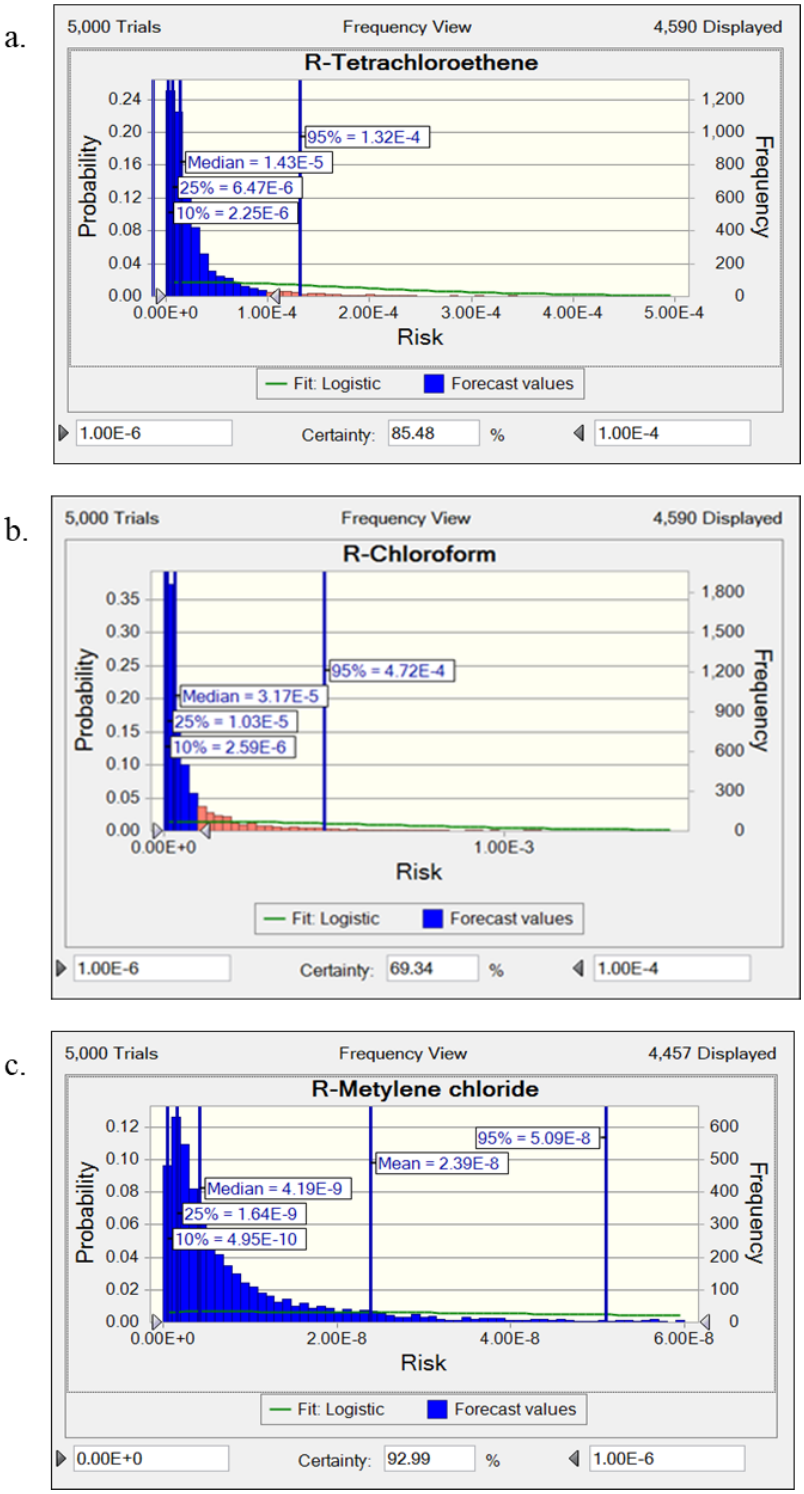


Figure 16. Carcinogenic risk (R) using a Monte Carlo simulation for Hallandale gas-phase exposure concentrations. The frequency distribution of carcinogenic risk using the first model (Equations 7 and 8) for (a) tetrachloroethene, (b) chloroform, and (c) methylene chloride.

As reported in the literature by Yeh et al. (2011), high cancer risks from the sewer air exposure have been estimated, and consequently, there is a need to protect the workers. These researchers concluded that wearing gas filtering equipment and ventilation for 15 minutes reduced the cancer risk for benzene ranging from 2.77–3.98 x 10^{-3} to 3.0–4.0 x 10^{-7} and for trichloromethane from 29.74–42.70 x 10^{-3} to 2.9–4.1 x 10^{-6}. Yeh et al. (2011) also argued that workspace safety for sewer workers could be attained through ensuring that workers wear protective breathing equipment and that there is good exhaust ventilation.

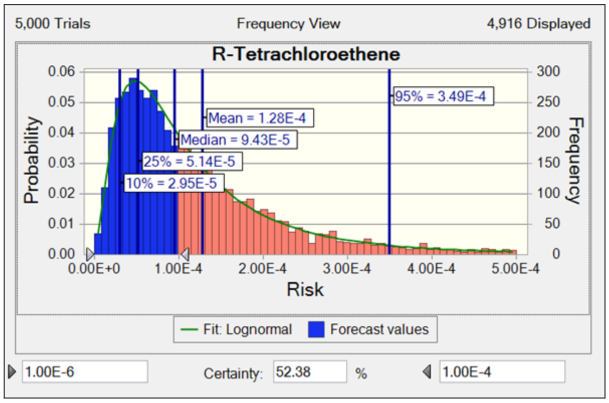
The 95th percentile of the carcinogenic risk for methylene chloride was 5.09 x 10^{-8}, which is much lower than the acceptable level of 1.0 x 10^{-6}. In addition, the probability that the risk of methylene chloride was lower than 1.0 x 10^{-6} was 92.99%. Therefore, the carcinogenic risk of methylene chloride is negligible and does not pose a health hazard to the sewer workers.

Figure 17 shows the frequency distributions of the carcinogenic risk of tetrachloroethene and chloroform chloride to the sewer workers using the second risk model. Because the frequency distribution of carcinogenic risk for methylene chloride was determined to be negligible using the first risk model, there was no need to estimate it again using the second model. As seen in Figure 17, the frequency distributions of the carcinogenic risk of tetrachloroethene and chloroform to the sewer workers were both fitted to a lognormal distribution. The 95th percentile for workers exposed to tetrachloroethene was 3.49 x 10^{-4}, which exceeds the USEPA acceptable level of 1.0 x 10^{-6}.

The probability that the risk of tetrachloroethene was between 1.0 x 10-6 and 1.0 x 10-4 was 52.38%. The 95th percentile of the carcinogenic risk for chloroform was 1.52

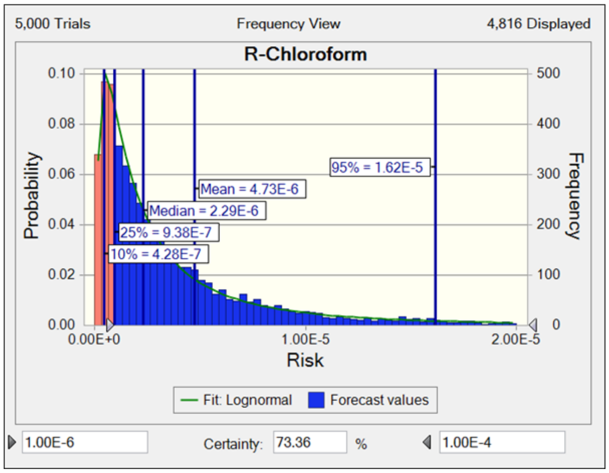
x 10-5, which indicates a potential health risk. Also, the probability that the risk of chloroform was between 1.0 x 10-6 and 1.0 x 10-4 was 73.36%. Based on the results from both risk models, the carcinogenic risk of tetrachloroethene exceeds the acceptable level of 1.0 x 10-6. Therefore, the carcinogenic risk of tetrachloroethane is estimated to pose a health hazard to the sewer workers. Since the results for the carcinogenic risk of chloroform from both risk models differed by a magnitude of one, a conservative approach was considered and concluded that chloroform poses a health hazard to the sewer workers in Hallandale.

a.



1.00E-6 Certainty: 52.38 % 1.00E-4

b.



1.00E-6 Certainty: 73.36 % 1.00E-4

Figure 17. Carcinogenic risk (R) using a Monte Carlo simulation - Hallandale gas-phase exposure concentrations. Frequency distribution of carcinogenic risk using the second model (Equations 9 and 10) for (a) tetrachloroethene and (b) chloroform.

The results reported for carcinogenic risk estimates are based on the limited data obtained from VOC emissions from sewer manholes from three specific locations in Hallandale, and it cannot be assumed that these findings signify the entire city.

Other researchers performed similar studies, and they estimated carcinogenic effects for sewer workers exposed to VOCs. Yang et al. (2012) examined the VOC emissions and carcinogenic effects by inhalation intake from different processes in a WWTP in China. These researchers estimated the carcinogenic risks for benzene, carbon tetrachloride, chloroform, and trichloroethene. The results for all four VOCs were below 10^{-5}, which means that the carcinogenic effects of these VOCs do not pose health concerns for the sewer workers. Niu et al. (2014) performed a risk assessment of four hazardous air pollutants (chloroform, methylene chloride, hydrogen sulfide, and carbon sulfide). The carcinogenic risk was estimated at approximately 5.5×10^{-8}, which is lower than the maximum acceptable level (1.0×10^{-6}). Yeh et al. (2011) studied the occurrence of VOC emissions in sewer networks in Taiwan. This group of researchers estimated the cancer risks of trichloromethane and benzene for sewer workers with and without personal protection. The cancer risks for workers without personal protection was assessed at $29.74–42.70 \times 10^{-3}$ for trichloromethane and $2.77–3.98 \times 10^{-3}$ for benzene. These values exceeded the acceptable levels, and these researchers recommended the use of personal protection equipment and the establishment of minimum time for general exhaust ventilation.

4.5.7 Carcinogenic Risk Sensitivity Analysis

As seen in Figure 18, CA accounted for the largest proportion of the carcinogenic risk values of tetrachloroethene, chloroform, and methylene chloride (accounting for 38.9%, 71.8%, and 56.8%, respectively).

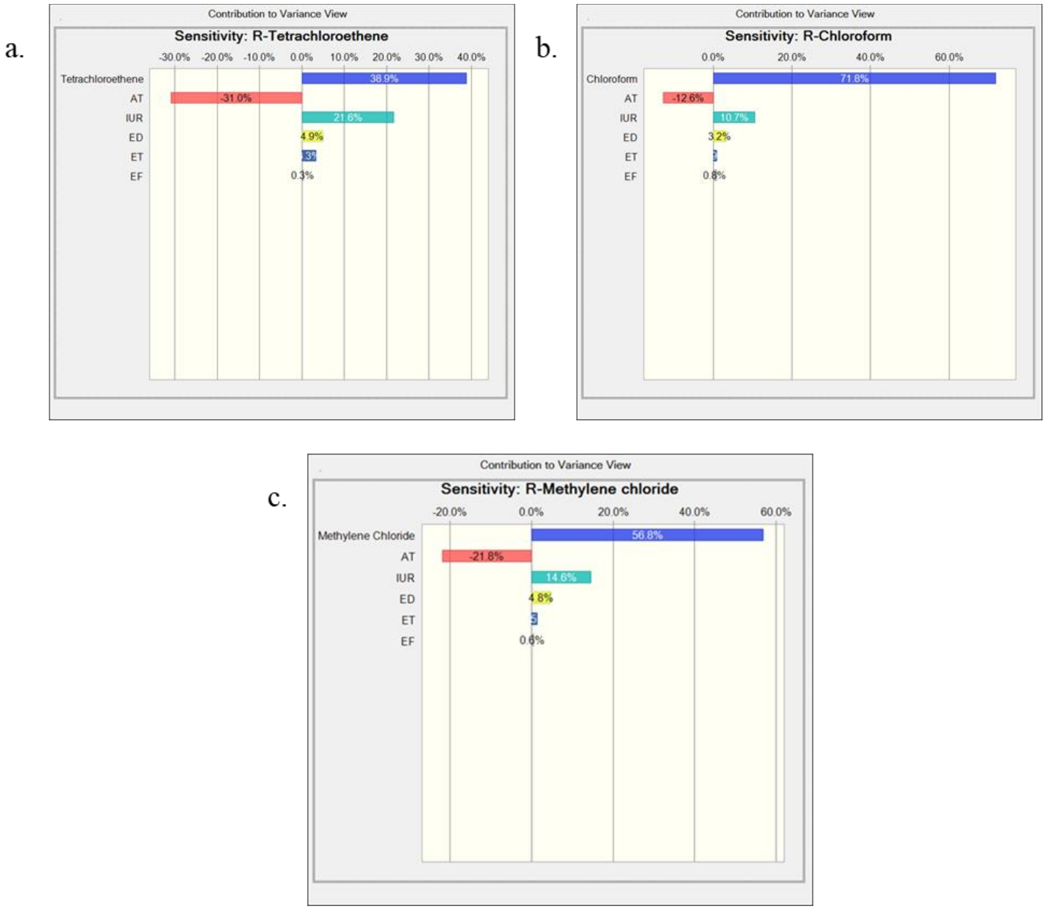


Figure 18. Carcinogenic risk sensitivity analysis results using the first model - Hallandale gas-phase exposure concentrations: (Equations 7 and 8) for: (a) tetrachloroethene, (b) chloroform, and (c) methylene chloride. AT = average time. IUR = inhalation unit risk. ED = average exposure duration. ET = average exposure time. EF = average exposure frequency.

The second most important parameter that contributed to the variance in risk estimation was AT (accounting for -31.0%, -12.6%, and -21.8%, respectively), and the results showed that AT had a negative correlation. IUR also contributed to the carcinogenic risk of the three VOCs, with 21.6% of tetrachloroethane, 10.7% of chloroform, and 14.6% of methylene chloride, with a positive correlation between IUR and the carcinogenic risk.

The contributions from ED, ET, and EF were relatively smaller, and the proportions were less than 5%. They made little contribution to the risks for tetrachloroethene, chloroform, and methylene chloride. These three variables were positively related to the carcinogenic risks for tetrachloroethene, chloroform, and methylene chloride.

For carcinogenic risk estimated using the second model (Equations 9 and 10), as represented in Figure 19, the CA accounted for the largest proportion of the carcinogenic risk values of tetrachloroethene and chloroform (49.5% and 77.7%, respectively). The variable with the second-largest contribution to carcinogenic risk was SF with 26.6% for tetrachloroethene and 11.9% for chloroform. For ED, their sensitivity contributions accounted for approximately 6.1% of tetrachloroethene but only accounted for 2.9% of chloroform. IR had a lower contribution to carcinogenic risk, with 5.5% of tetrachloroethane and 5.4% of chloroform. The results showed that CA, SF, ED, and IR had positive correlations with the carcinogenic risk for the two VOCs. The contributions from BW, ET, LT, EF, and EW were relatively smaller, and the proportions were approximately less than 5%. Moreover, these variables were likely to make little contribution to the risks of tetrachloroethene and chloroform (Figure 19).

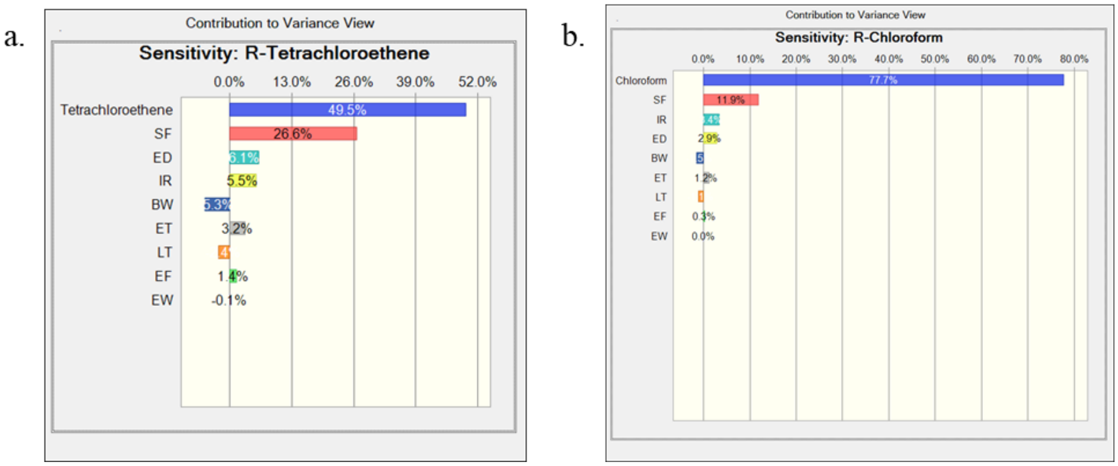


Figure 19. Carcinogenic risk sensitivity analysis using the second model - Hallandale gas-phase exposure concentrations (Equations 9 and 10) for (a) tetrachloroethene and (b) chloroform. SF = slope factor. ED = average exposure duration. IR = inhalation rate. BW = body weight. ET = average exposure time. LT = lifetime. EF = average exposure frequency. EW = exposure weeks.

Based on the sensitivity evaluations, the sensitivity contributions of each variable varied for each VOC's risks. CA contributed most to the non-carcinogenic risk for all five VOCs (tetrachloroethylene, chloroform, 1,4-dichlorobenzene, toluene, and methylene chloride).

Variables AT and RfC were also influential to the non-carcinogenic risk for all five VOCs. Also, CA contributed most to the carcinogenic risks of tetrachloroethene, chloroform, and methylene chloride. AT and RfC also influenced the carcinogenic risk for the three chemical hazards when the risk was estimated using the first model. When risk was estimated using the second model, SF and ED were influential variables to the carcinogenic risks for tetrachloroethene and chloroform.

4.5.8 Carcinogenic Risk Assessment Using the Monte Carlo Technique - Hallandale Liquid-Phase Exposure Concentrations

The carcinogenic risks for chloroform exposure identified in the liquid-phase samples in Hallandale ranged from 7.88 x 10^{-7} to 5.7 x 10^{-6}. Because some values were above the levels of concern of 1.0 x 10^{-6}, the Monte Carlo simulation was applied. The 95th percentile for workers exposed to chloroform was 9.36 x 10^{-6}, which exceeds the upper end of the USEPA's acceptable range of 1.0 x 10^{-6} (Figure 20). The probability that the risk of chloroform was between 1.0 x 10^{-6} and 1.0 x 10^{-4} was 53.06%. Therefore, the results of the simulation showed that, for sewer workers exposed to concentrations of chloroform, the 95% probability excess lifetime risks were higher than 1.0 x 10^{-6}, indicating a potential health risk.

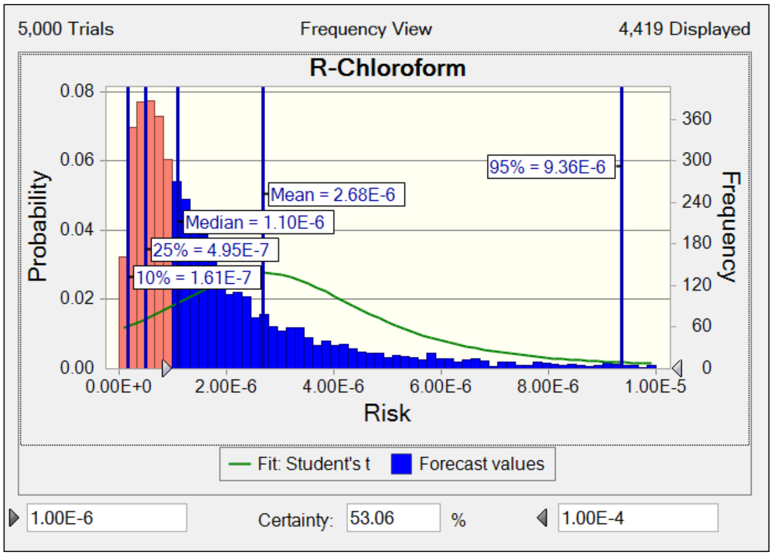
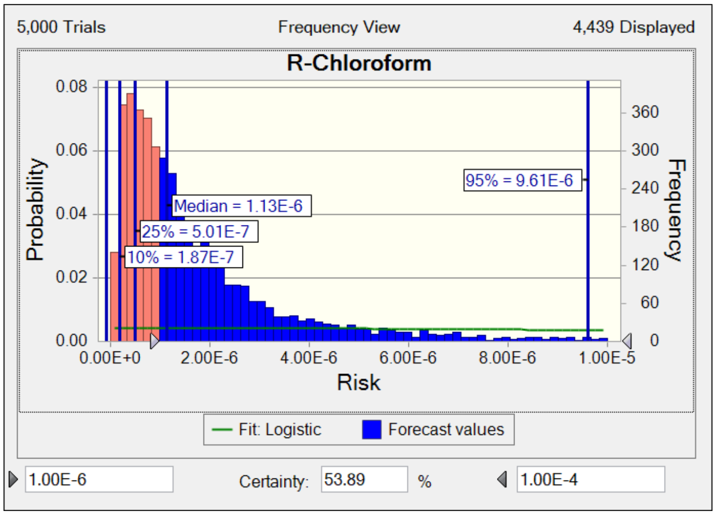


Figure 20. Carcinogenic risk (R) using a Monte Carlo simulation - Hallandale liquid-phase exposure concentrations. The frequency distribution of the carcinogenic risk for chloroform.

4.5.9 Carcinogenic Risk Assessment Using the Monte Carlo Technique - Orlando Liquid-Phase Exposure Concentrations

The carcinogenic risks for chloroform exposures identified in the liquid-phase samples in Orlando ranged from 9.98 x 10^{-7} to 7.51 x 10^{-6}. Because some values were above the levels of concern of 1.0 x 10^{-6}, a Monte Carlo simulation was applied. The 95th percentile for workers exposed to chloroform was 9.61 x 10^{-6}, which exceeds the upper end of the USEPA's acceptable range of 1.0 x 10^{-6} (Figure 21). The probability that the risk of chloroform was between 1.0 x 10^{-6} and 1.0 x 10^{-4} was 53.89%. Therefore, the results of the simulation showed that, for sewer workers exposed to concentrations of chloroform, the 95% probability excess lifetime risks were higher than 1.0 x 10^{-6}, indicating a potential health risk.



1.00E-6 Certainty: 53.89 % 1.00E-4

Figure 21. Carcinogenic risk (R) using a Monte Carlo simulation - Orlando liquid-phase exposure concentrations. The frequency distribution of the carcinogenic risk for chloroform.

5. CONCLUSIONS

This study generated a broad understanding of the occurrence of VOCs from Hallandale Beach's sewers networks and other governmental entities throughout the State of Florida that operate WWTP facilities. The biggest challenges of this study were identifying existing data and collecting new data for VOC concentrations in the sewer systems. It was challenging to obtain information from the authorities, most likely because of the sensitivity of this research. Also, sampling and analyzing gas-phase samples is very costly. It is recommended that researchers obtain funding assistance from the state or federal government agencies to support similar studies in the future. The limitations of data and the expensive costs of gas-phase samples may explain the lack of research on the risk assessments for sewer workers exposed to VOC emissions from sewer networks.

Health risk assessments of the exposure to VOCs (tetrachloroethene, chloroform, 1,4-dichlorobenzene, toluene, and methylene chloride) from sewer systems in Hallandale Beach and Orlando were conducted to give an understanding of the possible health effects for sewer workers. Chloroform, 1,4-dichlorobenzene, ethylbenzene, methylene chloride, tetrachloroethylene, toluene, and total xylenes were the predominant VOCs in wastewater influents of their respective WWTP from the City of Orlando, the City of West Palm Beach, the City of Boca Raton, the City of Sunrise, the Town of Pembroke Park, the City of Hallandale Beach, Broward County, and Miami-Dade County. The gas-phase sampling analysis from Hallandale indicated that chloroform, 1,4-dichlorobenzene, methylene chloride, toluene, and tetrachloroethene were the significant VOCs, and their concentrations ranged from 15 to 117 $\mu g/m^3$, 2.2 to 57 $\mu g/m^3$, 1.1 to 22 $\mu g/m^3$, 5.3 to 43 $\mu g/m^3$, and 0.88 to 2410 $\mu g/m^3$, respectively. Much smaller concentrations of chloroform, 1,4-dichlorobenzene, and toluene were identified in the liquid-phase samples in Hallandale (0.20 to 1.06 µg/m^3, 0.08 to 0.89 µg/m^3, and 0.15 to 2.71 µg/m^3, respectively). Because of this observation, the VOC concentrations from the wastewater influents before reaching the WWTP are not viable for the estimation of the potential health risks for the sewer workers. However, since these reports are readily available (as required by the WWTP permit requirements), they can be useful for governmental agencies as starting points for identifying chemical hazards and determining whether additional sampling is needed. Also, the analytical wastewater reports, including VOC concentrations from liquid-phase wastewater samples from Orlando, indicate that chloroform, 1,4-dichlorobenzene, and toluene were the predominant VOCs in the liquid wastewater influents. Their computed gas-phase concentrations ranged from 0.19 to 0.85 µg/m^3, 0.15 to 0.80 µg/m^3, and 0.60 to 65.50 µg/m^3, respectively.

Health risk assessments of the exposure to VOCs from sewer systems were carried out by performing evaluations of cancer and non-cancer risks associated with exposure by inhalation intake.

Calculating HQ using Equation 11 gave values less than unity for tetrachloroethene, chloroform, 1,4-dichlorobenzene, toluene, and methylene chloride concentrations identified in the liquid-phase samples from Hallandale and Orlando. This result implies that the non-carcinogenic effects have no health concerns for the sewer workers. On the contrary, calculating HQ using Equation 11 and the Monte Carlo technique gave values of more than unity value for tetrachloroethylene and chloroform for concentrations measured in the gas-phase samples from Hallandale, which suggests a high probability of health concerns in sewer workers. The calculated HQ for tetrachloroethylene and chloroform for concentrations measured in the gas-phase samples in Hallandale ranged from 0.007 to 13.76 and 0.34 to 2.67, respectively. As a result of the Monte Carlo simulation, the 95th percentile of the total non-carcinogenic risk for the five VOCs was 31.13, which could pose a threat to human health because it surpassed the acceptable upper confidence limit (1.0). The descending order of non-carcinogenic risk values for the five VOCs under the 95th percentile was tetrachloroethene, chloroform, 1,4-dichlorobenzene, toluene, and methylene chloride. These results mean that the non-carcinogenic health effects for sewer workers from exposures to tetrachloroethene and chloroform are significant.

The carcinogenic risks estimated by Equations 7 and 8 for tetrachloroethene concentrations measured in the liquid-phase samples from Hallandale and Orlando did not reveal health concerns. On the contrary, the carcinogenic risk for tetrachloroethylene for gas-phase concentrations from Hallandale ranged from 7.12 x 10^{-8} to 1.43 x 10^{-4}, which exceeded the acceptable USEPA level of 1 x 10^{-6}. Carcinogenic risks for chloroform for concentrations identified in the gas-phase samples from Hallandale and in the liquid-phase from Hallandale and Orlando also exceeded the acceptable level. The calculated carcinogenic risks for liquid-phase concentrations from Hallandale and Orlando ranged from 7.88 x 10^{-7} to 5.7 x 10^{-6} and 9.98 x 10^{-7} to 7.51 x 10^{-6}, respectively. The carcinogenic risk for chloroform for concentrations measured in the gas-phase samples in Hallandale ranged from 7.88 x 10^{-5} to 3.74 x 10^{-4}. A Monte Carlo simulation was used to estimate the carcinogenic risks to give a better understanding of the variability of exposure in the sewer systems and possible health effects on sewer workers. The 95th percentile of the carcinogenic risks for tetrachloroethene and chloroform from gas-phase concentrations in Hallandale was 1.32 x 10^{-4} and 4.72 x 10^{-4}, which exceeds the acceptable upper level of

1.0×10^{-6}. The 95th percentile of the carcinogenic risks for chloroform from liquid-phase concentrations in Hallandale and Orlando was 9.36×10^{-6} and 9.61×10^{-6}, respectively, which also exceeds the acceptable upper level.

It is essential to mention that in this study, the non-carcinogenic and carcinogenic risk results for tetrachloroethene and chloroform for the concentrations measured in the gas-phase samples in Hallandale are based on the limited data obtained from VOC emissions from six sewer manholes at specific locations (within 600 feet of three sewer lift stations). These findings should not be assumed that it represents the entire city.

The carcinogenic risk for methylene chloride was negligible and did not pose a health concern to the sewer workers.

Additional sampling and further investigation are being recommended in order to estimate the potential health risks of the sewer workers. Until such studies can be possible, it is recommended that sewer workers wear protective breathing equipment and that there is proper exhaust ventilation.

The sensitivity analysis from the Monte Carlo simulation demonstrated that the sensitivity of each input parameter varies with the type of VOC and risks. The CA accounted for the most significant proportion of the risk values. The second most important parameter that contributed to the variance in risk estimation was AT, which represented the average number of working hours per day. By lowering the values of CA and AT, the potential adverse health risks can be minimized.

The risk assessment in this research study is a conservative estimate because of the assumptions and limitations of the data. Governmental agencies should pay more attention to the VOC emissions from sewer networks, and such authorities must implement orders and policies for all sewer workers to follow a strict code of practice when performing inspections, repairs, and maintenance activities of the sewer systems. At the least, the use of personal protective equipment is recommended, based on the results of this study.

Finally, authorities of wastewater collection facilities and WWTPs should take the following steps in order to identify potential health risks for the sewer workers:

- Identify VOCs from the available data, when possible. More attention should be given to the VOCs classified by the IARC as Group 1 (carcinogenic), 2A (probably carcinogenic), and 2B (possibly carcinogenic).
- Compare the concentrations of VOCs with results from this study or other findings from the published literature.
- Perform additional sampling, as necessary.
- When significant VOC concentrations are identified, estimate the non-carcinogenic and carcinogenic risks using the methods described in this study or in the literature.
- Provide education and awareness to sewer workers of the possible VOC emissions from the sewer networks and potential health effects.
- As a precaution, recommend the wearing of gas filtering equipment.
- Develop education programs for residents and business owners for proper disposal of chemical hazards (to prevent their disposal in the sewer systems).

Finally, I hope that the results of this study can serve as both a reference and an interest for other researchers.

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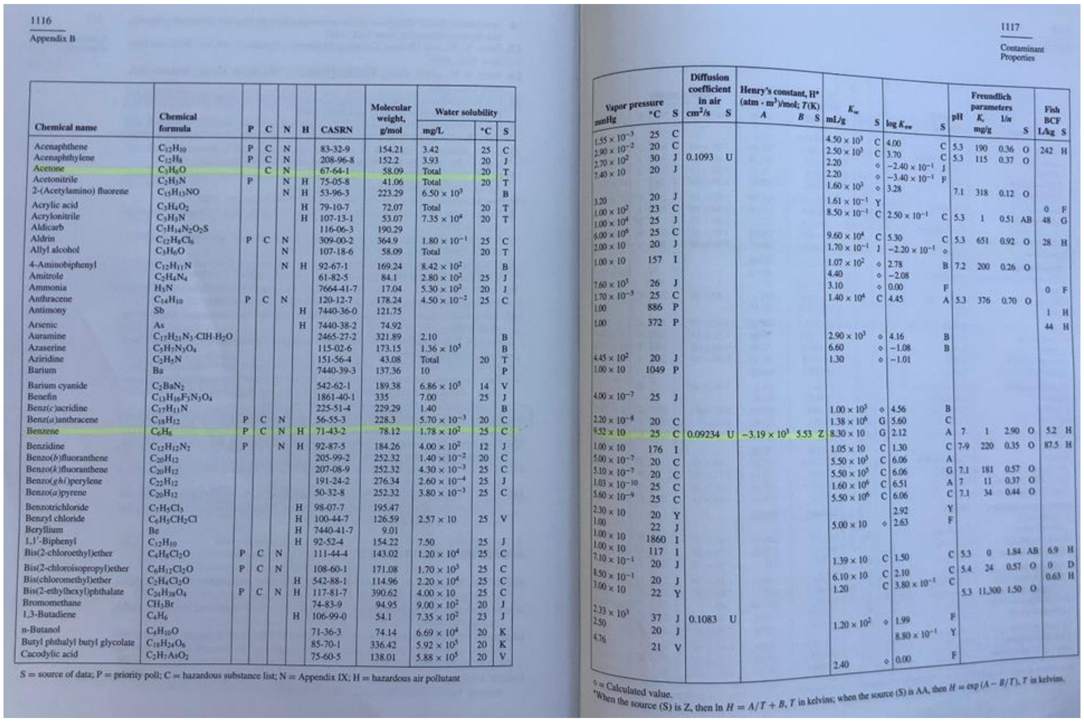
APPENDICES

APPENDIX A

Contaminant Properties (LaGrega et al., 1994, Appendix B, pp. 1116–1157)



1116
Appendix B

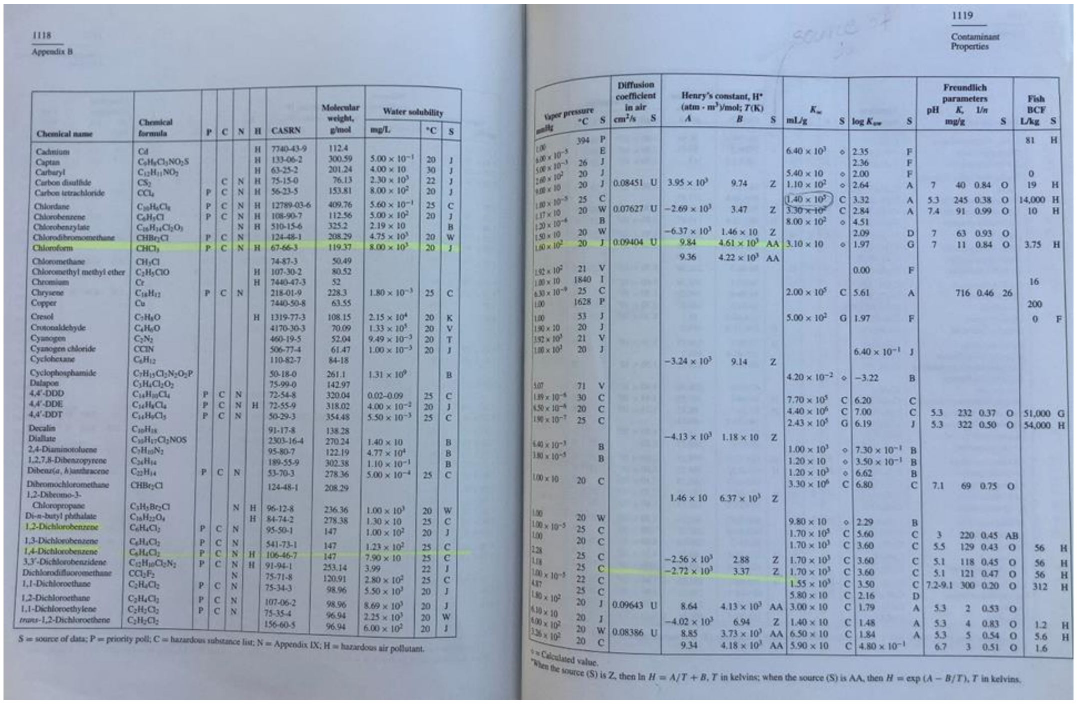
Chemical name	Chemical formula	P	C	N	H	CASRN	Molecular weight, g/mol	Water solubility mg/L	°C	S
Acenaphthene	$C_{12}H_{10}$	P	C	N		83-32-9	154.21	3.42	25	C
Acenaphthylene	$C_{12}H_8$	P	C	N		208-96-8	152.2	3.93	20	J
Acetone	C_3H_6O		C	N		67-64-1	58.09	Total	20	T
Acetonitrile	C_2H_3N	P		N	H	75-05-8	41.06	Total	20	T
2-(Acetylamino) fluorene	$C_{15}H_{13}NO$			N	H	53-96-3	223.29	6.50×10^3		B
Acrylic acid	$C_3H_4O_2$				H	79-10-7	72.07	Total	20	T
Acrylonitrile	C_3H_3N				H	107-13-1	53.07	7.35×10^4	20	T
Aldicarb	$C_7H_{14}N_2O_2S$					116-06-3	190.29			
Aldrin	$C_{12}H_8Cl_6$	P	C	N		309-00-2	364.9	1.80×10^{-1}	25	C
Allyl alcohol	C_3H_6O			N		107-18-6	58.09	Total	20	T
4-Aminobiphenyl	$C_{12}H_{11}N$			N	H	92-67-1	169.24	8.42×10^2		B
Amitrole	$C_2H_4N_4$					61-82-5	84.1	2.80×10^2	25	J
Ammonia	H_3N					7664-41-7	17.04	5.30×10^2	20	J
Anthracene	$C_{14}H_{10}$	P	C	N		120-12-7	178.24	4.50×10^{-2}	25	C
Antimony	Sb				H	7440-36-0	121.75			
Arsenic	As				H	7440-38-2	74.92			
Auramine	$C_{17}H_{21}N_3 \cdot ClH \cdot H_2O$					2465-27-2	321.89	2.10		B
Azaserine	$C_5H_7N_3O_4$					115-02-6	173.15	1.36×10^5		B
Aziridine	C_2H_5N					151-56-4	43.08	Total	20	T
Barium	Ba					7440-39-3	137.36	10		P
Barium cyanide	C_2BaN_2					542-62-1	189.38	6.86×10^5	14	V
Benefin	$C_{13}H_{16}F_3N_3O_4$					1861-40-1	335	7.00	25	J
Benz(*c*)acridine	$C_{17}H_{11}N$					225-51-4	229.29	1.40		B
Benz(*a*)anthracene	$C_{18}H_{12}$	P	C	N		56-55-3	228.3	5.70×10^{-3}	20	C
Benzene	C_6H_6	P	C	N	H	71-43-2	78.12	1.78×10^3	25	C
Benzidine	$C_{12}H_{12}N_2$	P		N	H	92-87-5	184.26	4.00×10^2	12	J
Benzo(*b*)fluoranthene	$C_{20}H_{12}$					205-99-2	252.32	1.40×10^{-2}	20	C
Benzo(*k*)fluoranthene	$C_{20}H_{12}$					207-08-9	252.32	4.30×10^{-3}	25	C
Benzo(*ghi*)perylene	$C_{22}H_{12}$					191-24-2	276.34	2.60×10^{-4}	25	J
Benzo(*a*)pyrene	$C_{20}H_{12}$					50-32-8	252.32	3.80×10^{-3}	25	C
Benzotrichloride	$C_7H_5Cl_3$				H	98-07-7	195.47			
Benzyl chloride	$C_6H_5CH_2Cl$				H	100-44-7	126.59	2.57×10	25	V
Beryllium	Be				H	7440-41-7	9.01			
1,1′-Biphenyl	$C_{12}H_{10}$				H	92-52-4	154.22	7.50	25	J
Bis(2-chloroethyl)ether	$C_4H_8Cl_2O$	P	C	N		111-44-4	143.02	1.20×10^4	25	C
Bis(2-chloroisopropyl)ether	$C_6H_{12}Cl_2O$	P	C	N		108-60-1	171.08	1.70×10^3	25	C
Bis(chloromethyl)ether	$C_2H_4Cl_2O$				H	542-88-1	114.96	2.20×10^4	25	C
Bis(2-ethylhexyl)phthalate	$C_{24}H_{38}O_4$	P	C	N	H	117-81-7	390.62	4.00×10	25	C
Bromomethane	CH_3Br					74-83-9	94.95	9.00×10^2	20	J
1,3-Butadiene	C_4H_6				H	106-99-0	54.1	7.35×10^2	23	J
n-Butanol	$C_4H_{10}O$					71-36-3	74.14	6.69×10^4	20	K
Butyl phthalyl butyl glycolate	$C_{18}H_{24}O_6$					85-70-1	336.42	5.92×10^5	20	K
Cacodylic acid	$C_2H_7AsO_2$					75-60-5	138.01	5.88×10^5	20	V

S = source of data; P = priority poll; C = hazardous substance list; N = Appendix IX; H = hazardous air pollutant

1117
Contaminant Properties

Chemical name	Vapor pressure mmHg	°C	S	Diffusion coefficient in air cm^2/s	S	Henry's constant, H* (atm · m^3/mol; T(K)) *A*	*B*	S	K_{oc} mL/g	S	log K_{ow}	S	Freundlich parameters pH	K_f mg/g	1/*n*	S	Fish BCF L/kg	S
Acenaphthene	1.55×10^{-3}	25	C						4.50×10^3	C	4.00	C	5.3	190	0.36	O	242	H
Acenaphthylene	2.90×10^{-2}	20	C						2.50×10^3	C	3.70	C	5.3	115	0.37	O		
Acetone	2.70×10^2	30	J	0.1093	U				2.20	◇	-2.40×10^{-1}	J						
Acetonitrile	7.40×10	20	J						2.20	◇	-3.40×10^{-1}	F						
2-(Acetylamino) fluorene									1.60×10^3	◇	3.28		7.1	318	0.12	O		
Acrylic acid	3.20	20	J						1.61×10^{-1}	Y							0	F
Acrylonitrile	1.00×10^2	23	C						8.50×10^{-1}	C	2.50×10^{-1}	C	5.3	1	0.51	AB	48	G
Aldicarb	1.00×10^4	25	J															
Aldrin	6.00×10^6	25	C						9.60×10^4	C	5.30	C	5.3	651	0.92	O	28	H
Allyl alcohol	2.00×10	20	J						1.70×10^{-1}	J	-2.20×10^{-1}	◇						
4-Aminobiphenyl	1.00×10	157	I						1.07×10^2	◇	2.78	B	7.2	200	0.26	O		
Amitrole									4.40	◇	−2.08							
Ammonia	7.60×10^3	26	J						3.10	◇	0.00	F					0	F
Anthracene	1.70×10^{-5}	25	C						1.40×10^4	C	4.45	A	5.3	376	0.70	O		
Antimony	1.00	886	P														1	H
Arsenic	1.00	372	P														44	H
Auramine									2.90×10^3	◇	4.16	B						
Azaserine									6.60	◇	−1.08	B						
Aziridine	4.45×10^2	20	J						1.30	◇	−1.01							
Barium	1.00×10	1049	P															
Barium cyanide																		
Benefin	4.00×10^{-7}	25	J															
Benz(*c*)acridine									1.00×10^3	◇	4.56	B						
Benz(*a*)anthracene	2.20×10^{-8}	20	C						1.38×10^6	G	5.60	C						
Benzene	9.52×10	25	C	0.09234	U	-3.19×10^3	5.53	Z	8.30×10	G	2.12	A	7	1	2.90	O	5.2	H
Benzidine	1.00×10	176	I						1.05×10	C	1.30	C	7-9	220	0.35	O	87.5	H
Benzo(*b*)fluoranthene	5.00×10^{-7}	20	C						5.50×10^5	C	6.06	A						
Benzo(*k*)fluoranthene	5.10×10^{-7}	20	C						5.50×10^5	C	6.06	G	7.1	181	0.57	O		
Benzo(*ghi*)perylene	1.03×10^{-10}	25	C						1.60×10^6	C	6.51	A	7	11	0.37	O		
Benzo(*a*)pyrene	5.60×10^{-9}	25	C						5.50×10^6	C	6.06	C	7.1	34	0.44	O		
Benzotrichloride	2.30×10	20	Y								2.92	Y						
Benzyl chloride	1.00	22	J						5.00×10	◇	2.63	F						
Beryllium	1.00×10	1860	I															
1,1′-Biphenyl	1.00×10	117	I															
Bis(2-chloroethyl)ether	7.10×10^{-1}	20	J						1.39×10	C	1.50	C	5.3	0	1.84	AB	6.9	H
Bis(2-chloroisopropyl)ether	8.50×10^{-1}	20	J						6.10×10	C	2.10	C	5.4	24	0.57	O	0	D
Bis(chloromethyl)ether	3.00×10	22	Y						1.20	C	3.80×10^{-1}	C					0.63	H
Bis(2-ethylhexyl)phthalate													5.3	11,300	1.50	O		
Bromomethane																		
1,3-Butadiene	2.33×10^3	37	J	0.1083	U				1.20×10^2	◇	1.99	F						
n-Butanol	2.50	20	J								8.80×10^{-1}	Y						
Butyl phthalyl butyl glycolate	4.76	21	V															
Cacodylic acid									2.40	◇	0.00	F						

◇ = Calculated value.
*When the source (S) is Z, then ln $H = A/T + B$, T in kelvins; when the source (S) is AA, then $H = \exp(A - B/T)$, T in kelvins.



1118
Appendix B

Chemical name	Chemical formula	P	C	N	H	CASRN	Molecular weight, g/mol	Water solubility mg/L	°C	S
Cadmium	Cd				H	7740-43-9	112.4			
Captan	$C_9H_8Cl_3NO_2S$				H	133-06-2	300.59	5.00×10^{-1}	20	J
Carbaryl	$C_{12}H_{11}NO_2$				H	63-25-2	201.24	4.00×10	30	J
Carbon disulfide	CS_2		C	N	H	75-15-0	76.13	2.30×10^3	22	J
Carbon tetrachloride	CCl_4	P	C	N	H	56-23-5	153.81	8.00×10^2	20	J
Chlordane	$C_{10}H_6Cl_8$	P	C	N	H	12789-03-6	409.76	5.60×10^{-1}	25	C
Chlorobenzene	C_6H_5Cl	P	C	N	H	108-90-7	112.56	5.00×10^2	20	J
Chlorobenzylate	$C_{16}H_{14}Cl_2O_3$			N	H	510-15-6	325.2	2.19×10		B
Chlorodibromomethane	$CHBr_2Cl$	P	C	N		124-48-1	208.29	4.75×10^3	20	W
Chloroform	$CHCl_3$	P	C	N	H	67-66-3	119.37	8.00×10^3	20	J
Chloromethane	CH_3Cl					74-87-3	50.49			
Chloromethyl methyl ether	C_2H_5ClO				H	107-30-2	80.52			
Chromium	Cr				H	7440-47-3	52			
Chrysene	$C_{18}H_{12}$	P	C	N		218-01-9	228.3	1.80×10^{-3}	25	C
Copper	Cu					7440-50-8	63.55			
Cresol	C_7H_8O				H	1319-77-3	108.15	2.15×10^4	20	K
Crotonaldehyde	C_4H_6O					4170-30-3	70.09	1.33×10^5	20	V
Cyanogen	C_2N_2					460-19-5	52.04	9.49×10^{-3}	20	T
Cyanogen chloride	CClN					506-77-4	61.47	1.00×10^{-3}	20	J
Cyclohexane	C_6H_{12}					110-82-7	84.18			
Cyclophosphamide	$C_7H_{15}Cl_2N_2O_2P$					50-18-0	261.1	1.31×10^9		B
Dalapon	$C_3H_4Cl_2O_2$					75-99-0	142.97			
4,4′-DDD	$C_{14}H_{10}Cl_4$	P	C	N		72-54-8	320.04	0.02–0.09	25	C
4,4′-DDE	$C_{14}H_8Cl_4$	P	C	N	H	72-55-9	318.02	4.00×10^{-2}	20	J
4,4′-DDT	$C_{14}H_9Cl_5$	P	C	N		50-29-3	354.48	5.50×10^{-3}	25	C
Decalin	$C_{10}H_{18}$					91-17-8	138.28			
Diallate	$C_{10}H_{17}Cl_2NOS$					2303-16-4	270.24	1.40×10		B
2,4-Diaminotoluene	$C_7H_{10}N_2$					95-80-7	122.19	4.77×10^4		B
1,2,7,8-Dibenzopyrene	$C_{24}H_{14}$					189-55-9	302.38	1.10×10^{-1}		B
Dibenz(*a, h*)anthracene	$C_{22}H_{14}$	P	C	N		53-70-3	278.36	5.00×10^{-4}	25	C
Dibromochloromethane	$CHBr_2Cl$					124-48-1	208.29			
1,2-Dibromo-3-Chloropropane	$C_3H_5Br_2Cl$			N	H	96-12-8	236.36	1.00×10^3	20	W
Di-n-butyl phthalate	$C_{16}H_{22}O_4$				H	84-74-2	278.38	1.30×10	25	C
1,2-Dichlorobenzene	$C_6H_4Cl_2$	P	C	N		95-50-1	147	1.00×10^2	20	J
1,3-Dichlorobenzene	$C_6H_4Cl_2$	P	C	N		541-73-1	147	1.23×10^2	25	C
1,4-Dichlorobenzene	$C_6H_4Cl_2$	P	C	N	H	106-46-7	147	7.90×10	25	C
3,3′-Dichlorobenzidene	$C_{12}H_{10}Cl_2N_2$	P	C	N	H	91-94-1	253.14	3.99	22	J
Dichlorodifluoromethane	CCl_2F_2			N		75-71-8	120.91	2.80×10^2	25	C
1,1-Dichloroethane	$C_2H_4Cl_2$	P	C	N		75-34-3	98.96	5.50×10^3	20	J
1,2-Dichloroethane	$C_2H_4Cl_2$	P	C	N		107-06-2	98.96	8.69×10^3	20	J
1,1-Dichloroethylene	$C_2H_2Cl_2$	P	C	N		75-35-4	96.94	2.25×10^3	20	W
trans-1,2-Dichloroethene	$C_2H_2Cl_2$					156-60-5	96.94	6.00×10^2	20	J

S = source of data; P = priority poll; C = hazardous substance list; N = Appendix IX; H = hazardous air pollutant.

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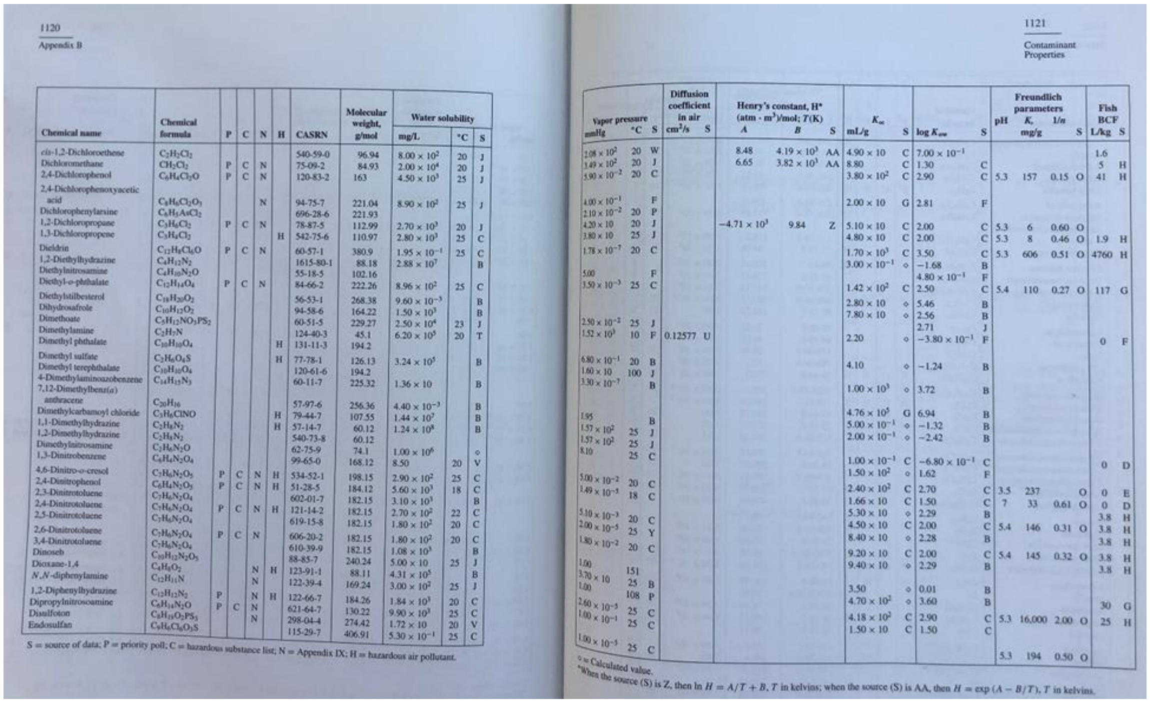
Contaminant Properties

source

Chemical name	Vapor pressure mmHg	°C	S	Diffusion coefficient in air cm^2/s	S	Henry's constant, H* (atm · m^3/mol; T(K)) *A*	*B*	S	K_{oc} mL/g	S	log K_{ow}	S	Freundlich parameters pH	K_f mg/g	1/*n*	S	Fish BCF L/kg	S
Cadmium	1.00	394	P														81	H
Captan	6.00×10^{-5}		E						6.40×10^3	◇	2.35	F						
Carbaryl	5.00×10^{-3}	26	J								2.36	F						
Carbon disulfide	2.60×10^2	20	J						5.40×10	◇	2.00	F					0	
Carbon tetrachloride	9.00×10	20	J	0.08451	U	3.95×10^3	9.74	Z	1.10×10^2	◇	2.64	A	7	40	0.84	O	19	H
Chlordane	1.00×10^{-5}	25	C						1.40×10^5	C	3.32	A	5.3	245	0.38	O	14,000	H
Chlorobenzene	1.17×10	20	W	0.07627	U	-2.69×10^3	3.47	Z	~~3.30×10^2~~	C	2.84	A	7.4	91	0.99	O	10	H
Chlorobenzylate	1.20×10^{-6}		B						8.00×10^2	◇	4.51							
Chlorodibromomethane	1.50×10	20	W			-6.37×10^3	1.46×10	Z			2.09	D	7	63	0.93	O		
Chloroform	1.60×10^2	20	J	0.09404	U	9.84	4.61×10^3	AA	3.10×10	◇	1.97	G	7	11	0.84	O	3.75	H
Chloromethane						9.36	4.22×10^3	AA										
Chloromethyl methyl ether	1.92×10^2	21	V								0.00	F						
Chromium	1.00×10	1840	I														16	
Chrysene	6.30×10^{-9}	25	C						2.00×10^5	C	5.61	A		716	0.46	26		
Copper	1.00	1628	P														200	
Cresol	1.00	53	J						5.00×10^2	G	1.97	F					0	F
Crotonaldehyde	1.90×10	20	J															
Cyanogen	3.92×10^3	21	V															
Cyanogen chloride	1.00×10^3	20	J								6.40×10^{-1}	J						
Cyclohexane						-3.24×10^3	9.14	Z										
Cyclophosphamide									4.20×10^{-2}	◇	−3.22	B						
Dalapon	5.07	71	V															
4,4′-DDD	1.89×10^{-6}	30	C						7.70×10^5	C	6.20	C						
4,4′-DDE	6.50×10^{-6}	20	C						4.40×10^6	C	7.00	C	5.3	232	0.37	O	51,000	G
4,4′-DDT	1.90×10^{-7}	25	C						2.43×10^5	G	6.19	J	5.3	322	0.50	O	54,000	H
Decalin						-4.13×10^3	1.18×10	Z										
Diallate	6.40×10^{-3}		B						1.00×10^3	◇	7.30×10^{-1}	B						
2,4-Diaminotoluene	3.80×10^{-5}		B						1.20×10	◇	3.50×10^{-1}	B						
1,2,7,8-Dibenzopyrene									1.20×10^3	◇	6.62	B						
Dibenz(*a, h*)anthracene	1.00×10	20	C						3.30×10^6	C	6.80	C	7.1	69	0.75	O		
Dibromochloromethane						1.46×10	6.37×10^3	Z										
1,2-Dibromo-3-Chloropropane	1.00	20	W						9.80×10	◇	2.29	B						
Di-n-butyl phthalate	1.00×10^{-5}	25	C						1.70×10^5	C	5.60	C	3	220	0.45	AB		
1,2-Dichlorobenzene	1.00	20	C						1.70×10^3	C	3.60	C	5.5	129	0.43	O	56	H
1,3-Dichlorobenzene	2.28	25	C			-2.56×10^3	2.88	Z	1.70×10^3	C	3.60	C	5.1	118	0.45	O	56	H
1,4-Dichlorobenzene	1.18	25	C			-2.72×10^3	3.37	Z	1.70×10^3	C	3.60	C	5.1	121	0.47	O	56	H
3,3′-Dichlorobenzidene	1.00×10^{-5}	22	C						1.55×10^3	C	3.50	C	7.2-9.1	300	0.20	O	312	H
Dichlorodifluoromethane	4.87	25	C						5.80×10	C	2.16	D						
1,1-Dichloroethane	1.80×10^2	20	J	0.09643	U	8.64	4.13×10^3	AA	3.00×10	C	1.79	A	5.3	2	0.53	O		
1,2-Dichloroethane	6.10×10	20	J			-4.02×10^3	6.94	Z	1.40×10	C	1.48	A	5.3	4	0.83	O	1.2	H
1,1-Dichloroethylene	6.00×10^2	20	W	0.08386	U	8.85	3.73×10^3	AA	6.50×10	C	1.84	A	5.3	5	0.54	O	5.6	H
trans-1,2-Dichloroethene	3.26×10^2	20	C			9.34	4.18×10^3	AA	5.90×10	C	4.80×10^{-1}		6.7	3	0.51	O	1.6	

◇ = Calculated value.
*When the source (S) is Z, then ln $H = A/T + B$, T in kelvins; when the source (S) is AA, then $H = \exp(A - B/T)$, T in kelvins.

(continued)

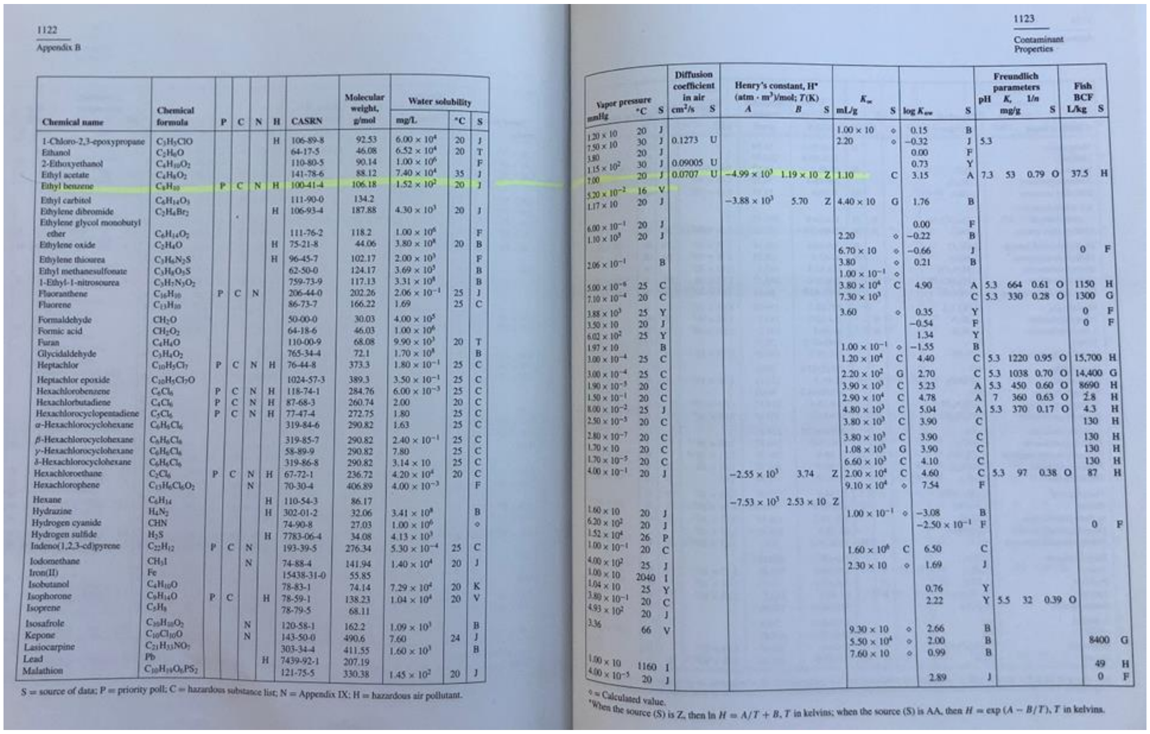


Chemical name	Chemical formula	P	C	N	H	CASRN	Molecular weight, g/mol	Water solubility			Vapor pressure			Diffusion coefficient in air		Henry's constant, H* (atm · m³)/mol; T(K)			K_{oc}				Freundlich parameters				Fish BCF	
								mg/L	°C	S	mmHg	°C	S	cm²/s	S	A	B	S	mL/g	S	log K_{ow}	S	pH	K_f mg/g	1/n	S	L/kg	S
cis-1,2-Dichloroethene	$C_2H_2Cl_2$					540-59-0	96.94	8.00×10^{2}	20	J	2.08×10^{2}	20	W			8.48	4.19×10^{3}	AA	4.90×10	C	7.00×10^{-1}						1.6	
Dichloromethane	CH_2Cl_2	P	C	N		75-09-2	84.93	2.00×10^{4}	20	J	3.49×10^{2}	20	J			6.65	3.82×10^{3}	AA	8.80	C	1.30	C					5	H
2,4-Dichlorophenol	$C_6H_4Cl_2O$	P	C	N		120-83-2	163	4.50×10^{3}	25	J	5.90×10^{-2}	20	C						3.80×10^{2}	C	2.90	C	5.3	157	0.15	O	41	H
2,4-Dichlorophenoxyacetic acid	$C_8H_6Cl_2O_3$			N		94-75-7	221.04	8.90×10^{2}	25	J	4.00×10^{-1}		F						2.00×10	G	2.81	F						
Dichlorophenylarsine	$C_6H_5AsCl_2$					696-28-6	221.93				2.10×10^{-2}	20	P															
1,2-Dichloropropane	$C_3H_6Cl_2$	P	C	N		78-87-5	112.99	2.70×10^{3}	20	J	4.20×10	20	J			-4.71×10^{3}	9.84	Z	5.10×10	C	2.00	C	5.3	6	0.60	O		
1,3-Dichloropropene	$C_3H_4Cl_2$				H	542-75-6	110.97	2.80×10^{3}	25	C	3.80×10	25	J						4.80×10	C	2.00	C	5.3	8	0.46	O	1.9	H
Dieldrin	$C_{12}H_8Cl_6O$	P	C	N		60-57-1	380.9	1.95×10^{-1}	25	C	1.78×10^{-7}	20	C						1.70×10^{3}	C	3.50	C	5.3	606	0.51	O	4760	H
1,2-Diethylhydrazine	$C_4H_{12}N_2$					1615-80-1	88.18	2.88×10^{7}		B									3.00×10^{-1}	◇	−1.68	B						
Diethylnitrosamine	$C_4H_{10}N_2O$					55-18-5	102.16				5.00		F								4.80×10^{-1}	F						
Diethyl-*o*-phthalate	$C_{12}H_{14}O_4$	P	C	N		84-66-2	222.26	8.96×10^{2}	25	C	3.50×10^{-3}	25	C						1.42×10^{2}	C	2.50	C	5.4	110	0.27	O	117	G
Diethylstilbesterol	$C_{18}H_{20}O_2$					56-53-1	268.38	9.60×10^{-3}		B									2.80×10	◇	5.46	B						
Dihydrosafrole	$C_{10}H_{12}O_2$					94-58-6	164.22	1.50×10^{3}		B									7.80×10	◇	2.56	B						
Dimethoate	$C_5H_{12}NO_3PS_2$					60-51-5	229.27	2.50×10^{4}	23	J	2.50×10^{-2}	25	J								2.71	J						
Dimethylamine	C_2H_7N					124-40-3	45.1	6.20×10^{5}	20	T	1.52×10^{3}	10	F	0.12577	U				2.20	◇	-3.80×10^{-1}	F					0	F
Dimethyl phthalate	$C_{10}H_{10}O_4$				H	131-11-3	194.2																					
Dimethyl sulfate	$C_2H_6O_4S$				H	77-78-1	126.13	3.24×10^{5}		B	6.80×10^{-1}	20	B						4.10	◇	−1.24	B						
Dimethyl terephthalate	$C_{10}H_{10}O_4$					120-61-6	194.2				1.60×10	100	J															
4-Dimethylaminoazobenzene	$C_{14}H_{15}N_3$					60-11-7	225.32	1.36×10		B	3.30×10^{-7}		B						1.00×10^{3}	◇	3.72	B						
7,12-Dimethylbenz(*a*)anthracene	$C_{20}H_{16}$					57-97-6	256.36	4.40×10^{-3}		B									4.76×10^{5}	G	6.94	B						
Dimethylcarbamoyl chloride	C_3H_6ClNO				H	79-44-7	107.55	1.44×10^{7}		B	1.95		B						5.00×10^{-1}	◇	−1.32	B						
1,1-Dimethylhydrazine	$C_2H_8N_2$				H	57-14-7	60.12	1.24×10^{8}		B	1.57×10^{2}	25	J						2.00×10^{-1}	◇	−2.42	B						
1,2-Dimethylhydrazine	$C_2H_8N_2$					540-73-8	60.12				1.57×10^{2}	25	J															
Dimethylnitrosamine	$C_2H_6N_2O$					62-75-9	74.1	1.00×10^{6}		◇	8.10	25	C						1.00×10^{-1}	C	-6.80×10^{-1}	C					0	D
1,3-Dinitrobenzene	$C_6H_4N_2O_4$					99-65-0	168.12	8.50	20	V									1.50×10^{2}	◇	1.62	F						
4,6-Dinitro-*o*-cresol	$C_7H_6N_2O_5$	P	C	N	H	534-52-1	198.15	2.90×10^{2}	25	C	5.00×10^{-2}	20	C						2.40×10^{2}	C	2.70	C	3.5	237		O	0	E
2,4-Dinitrophenol	$C_6H_4N_2O_5$	P	C	N	H	51-28-5	184.12	5.60×10^{3}	18	C	1.49×10^{-5}	18	C						1.66×10	C	1.50	C	7	33	0.61	O	0	D
2,3-Dinitrotoluene	$C_7H_6N_2O_4$					602-01-7	182.15	3.10×10^{3}		B									5.30×10	◇	2.29	B					3.8	H
2,4-Dinitrotoluene	$C_7H_6N_2O_4$	P	C	N	H	121-14-2	182.15	2.70×10^{2}	22	C	5.10×10^{-3}	20	C						4.50×10	C	2.00	C	5.4	146	0.31	O	3.8	H
2,5-Dinitrotoluene	$C_7H_6N_2O_4$					619-15-8	182.15	1.80×10^{2}	20	C	2.00×10^{-5}	25	Y						8.40×10	◇	2.28	B					3.8	H
2,6-Dinitrotoluene	$C_7H_6N_2O_4$	P	C	N		606-20-2	182.15	1.80×10^{2}	20	C	1.80×10^{-2}	20	C						9.20×10	C	2.00	C	5.4	145	0.32	O	3.8	H
3,4-Dinitrotoluene	$C_7H_6N_2O_4$					610-39-9	182.15	1.08×10^{3}		B									9.40×10	◇	2.29	B					3.8	H
Dinoseb	$C_{10}H_{12}N_2O_5$					88-85-7	240.24	5.00×10	25	J	1.00	151																
Dioxane-1,4	$C_4H_8O_2$			N	H	123-91-1	88.11	4.31×10^{5}		B	3.70×10	25	B						3.50	◇	0.01	B						
N,*N*-diphenylamine	$C_{12}H_{11}N$			N		122-39-4	169.24	3.00×10^{2}	25	J	1.00	108	P						4.70×10^{2}	◇	3.60	B					30	G
1,2-Diphenylhydrazine	$C_{12}H_{12}N_2$	P		N	H	122-66-7	184.26	1.84×10^{3}	20	C	2.60×10^{-5}	25	C						4.18×10^{2}	C	2.90	C	5.3	16,000	2.00	O	25	H
Dipropylnitrosoamine	$C_6H_{14}N_2O$	P	C	N		621-64-7	130.22	9.90×10^{3}	25	C	1.00×10^{-1}	25	C						1.50×10	C	1.50	C						
Disulfoton	$C_8H_{19}O_2PS_3$			N		298-04-4	274.42	1.72×10	20	V																		
Endosulfan	$C_9H_6Cl_6O_3S$					115-29-7	406.91	5.30×10^{-1}	25	C	1.00×10^{-5}	25	C										5.3	194	0.50	O		

S = source of data; P = priority poll; C = hazardous substance list; N = Appendix IX; H = hazardous air pollutant.

◇ = Calculated value.

*When the source (S) is Z, then $\ln H = A/T + B$, T in kelvins; when the source (S) is AA, then $H = \exp(A - B/T)$, T in kelvins.



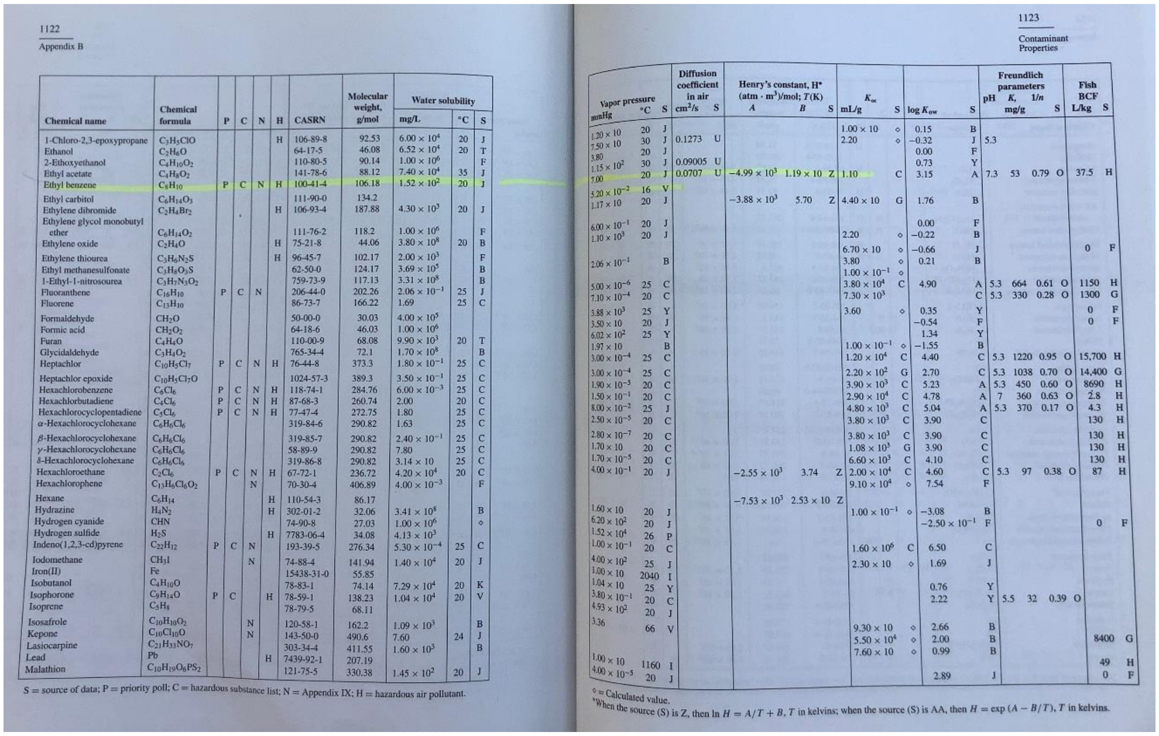
Chemical name	Chemical formula	P	C	N	H	CASRN	Molecular weight, g/mol	Water solubility			Vapor pressure			Diffusion coefficient in air		Henry's constant, H* (atm · m³)/mol; T(K)			K_{oc}				Freundlich parameters				Fish BCF	
								mg/L	°C	S	mmHg	°C	S	cm²/s	S	A	B	S	mL/g	S	log K_{ow}	S	pH	K_f mg/g	1/n	S	L/kg	S
1-Chloro-2,3-epoxypropane	C_3H_5ClO				H	106-89-8	92.53	6.00×10^{4}	20	J	1.20×10	20	J						1.00×10	◇	0.15	B						
Ethanol	C_2H_6O					64-17-5	46.08	6.52×10^{4}	20	T	7.50×10	30	J	0.1273	U				2.20	◇	−0.32	J	5.3					
2-Ethoxyethanol	$C_4H_{10}O_2$					110-80-5	90.14	1.00×10^{6}		F	3.80	20	J								0.00	F						
Ethyl acetate	$C_4H_8O_2$					141-78-6	88.12	7.40×10^{4}	35	J	1.15×10^{2}	30	J	0.09005	U						0.73	Y						
Ethyl benzene	C_8H_{10}	P	C	N	H	100-41-4	106.18	1.52×10^{2}	20	J	7.00	20	J	0.0707	U	-4.99×10^{3}	1.19×10	Z	1.10	C	3.15	A	7.3	53	0.79	O	37.5	H
Ethyl carbitol	$C_6H_{14}O_3$					111-90-0	134.2				5.20×10^{-2}	16	V															
Ethylene dibromide	$C_2H_4Br_2$				H	106-93-4	187.88	4.30×10^{3}	20	J	1.17×10	20	J			-3.88×10^{3}	5.70	Z	4.40×10	G	1.76	B						
Ethylene glycol monobutyl ether	$C_6H_{14}O_2$					111-76-2	118.2	1.00×10^{6}		F	6.00×10^{-1}	20	J								0.00	F						
Ethylene oxide	C_2H_4O				H	75-21-8	44.06	3.80×10^{8}	20	B	1.10×10^{3}	20	J						2.20	◇	−0.22	B						
Ethylene thiourea	$C_3H_6N_2S$				H	96-45-7	102.17	2.00×10^{3}		F									6.70×10	◇	−0.66	J					0	F
Ethyl methanesulfonate	$C_3H_8O_3S$					62-50-0	124.17	3.69×10^{5}		B	2.06×10^{-1}		B						3.80	◇	0.21	B						
1-Ethyl-1-nitrosourea	$C_3H_7N_3O_2$					759-73-9	117.13	3.31×10^{8}		B									1.00×10^{-1}	◇								
Fluoranthene	$C_{16}H_{10}$	P	C	N		206-44-0	202.26	2.06×10^{-1}	25	J	5.00×10^{-6}	25	C						3.80×10^{4}	C	4.90	A	5.3	664	0.61	O	1150	H
Fluorene	$C_{13}H_{10}$					86-73-7	166.22	1.69	25	C	7.10×10^{-4}	20	C						7.30×10^{3}			C	5.3	330	0.28	O	1300	G
Formaldehyde	CH_2O					50-00-0	30.03	4.00×10^{5}			3.88×10^{3}	25	Y						3.60	◇	0.35	Y					0	F
Formic acid	CH_2O_2					64-18-6	46.03	1.00×10^{6}			3.50×10	20	J								−0.54	F					0	F
Furan	C_4H_4O					110-00-9	68.08	9.90×10^{3}	20	T	6.02×10^{2}	25	Y								1.34	Y						
Glycidaldehyde	$C_3H_4O_2$					765-34-4	72.1	1.70×10^{8}		B	1.97×10		B						1.00×10^{-1}	◇	−1.55	B						
Heptachlor	$C_{10}H_5Cl_7$	P	C	N	H	76-44-8	373.3	1.80×10^{-1}	25	C	3.00×10^{-4}	25	C						1.20×10^{4}	C	4.40	C	5.3	1220	0.95	O	15,700	H
Heptachlor epoxide	$C_{10}H_5Cl_7O$					1024-57-3	389.3	3.50×10^{-1}	25	C	3.00×10^{-4}	25	C						2.20×10^{2}	G	2.70	C	5.3	1038	0.70	O	14,400	G
Hexachlorobenzene	C_6Cl_6	P	C	N	H	118-74-1	284.76	6.00×10^{-3}	25	C	1.90×10^{-5}	20	C						3.90×10^{3}	C	5.23	A	5.3	450	0.60	O	8690	H
Hexachlorbutadiene	C_4Cl_6	P	C	N	H	87-68-3	260.74	2.00	20	C	1.50×10^{-1}	20	C						2.90×10^{4}	C	4.78	A	7	360	0.63	O	2.8	H
Hexachlorocyclopentadiene	C_5Cl_6	P	C	N	H	77-47-4	272.75	1.80	25	C	8.00×10^{-2}	25	J						4.80×10^{3}	C	5.04	A	5.3	370	0.17	O	4.3	H
α-Hexachlorocyclohexane	$C_6H_6Cl_6$					319-84-6	290.82	1.63	25	C	2.50×10^{-5}	20	C						3.80×10^{3}	C	3.90	C					130	H
β-Hexachlorocyclohexane	$C_6H_6Cl_6$					319-85-7	290.82	2.40×10^{-1}	25	C	2.80×10^{-7}	20	C						3.80×10^{3}	C	3.90	C					130	H
γ-Hexachlorocyclohexane	$C_6H_6Cl_6$					58-89-9	290.82	7.80	25	C	1.70×10	20	C						1.08×10^{3}	G	3.90	C					130	H
δ-Hexachlorocyclohexane	$C_6H_6Cl_6$					319-86-8	290.82	3.14×10	25	C	1.70×10^{-5}	20	C						6.60×10^{3}	C	4.10	C					130	H
Hexachloroethane	C_2Cl_6	P	C	N	H	67-72-1	236.72	4.20×10^{4}	20	C	4.00×10^{-1}	20	J			-2.55×10^{3}	3.74	Z	2.00×10^{4}	C	4.60	C	5.3	97	0.38	O	87	H
Hexachlorophene	$C_{13}H_6Cl_6O_2$			N		70-30-4	406.89	4.00×10^{-3}		F									9.10×10^{4}	◇	7.54	F						
Hexane	C_6H_{14}				H	110-54-3	86.17									-7.53×10^{3}	2.53×10	Z										
Hydrazine	H_4N_2				H	302-01-2	32.06	3.41×10^{8}		B	1.60×10	20	J						1.00×10^{-1}	◇	−3.08	B						
Hydrogen cyanide	CHN					74-90-8	27.03	1.00×10^{6}		◇	6.20×10^{2}	20	J								-2.50×10^{-1}	F					0	F
Hydrogen sulfide	H_2S				H	7783-06-4	34.08	4.13×10^{3}			1.52×10^{4}	26	P															
Indeno(1,2,3-cd)pyrene	$C_{22}H_{12}$	P	C	N		193-39-5	276.34	5.30×10^{-4}	25	C	1.00×10^{-1}	20	C						1.60×10^{6}	C	6.50	C						
Iodomethane	CH_3I			N		74-88-4	141.94	1.40×10^{4}	20	J	4.00×10^{2}	25	J						2.30×10	◇	1.69	J						
Iron(II)	Fe					15438-31-0	55.85				1.00×10	2040	I															
Isobutanol	$C_4H_{10}O$					78-83-1	74.14	7.29×10^{4}	20	K	1.04×10	25	Y								0.76	Y						
Isophorone	$C_9H_{14}O$	P	C		H	78-59-1	138.23	1.04×10^{4}	20	V	3.80×10^{-1}	20	C								2.22	Y	5.5	32	0.39	O		
Isoprene	C_5H_8					78-79-5	68.11				4.93×10^{2}	20	J															
Isosafrole	$C_{10}H_{10}O_2$			N		120-58-1	162.2	1.09×10^{3}		B	3.36	66	V						9.30×10	◇	2.66	B						
Kepone	$C_{10}Cl_{10}O$			N		143-50-0	490.6	7.60	24	J									5.50×10^{4}	◇	2.00	B					8400	G
Lasiocarpine	$C_{21}H_{33}NO_7$					303-34-4	411.55	1.60×10^{3}		B									7.60×10	◇	0.99	B						
Lead	Pb				H	7439-92-1	207.19				1.00×10	1160	I														49	H
Malathion	$C_{10}H_{19}O_6PS_2$					121-75-5	330.38	1.45×10^{2}	20	J	4.00×10^{-5}	20	J								2.89	J					0	F

S = source of data; P = priority poll; C = hazardous substance list; N = Appendix IX; H = hazardous air pollutant.

◇ = Calculated value.

*When the source (S) is Z, then $\ln H = A/T + B$, T in kelvins; when the source (S) is AA, then $H = \exp(A - B/T)$, T in kelvins.

(continued)

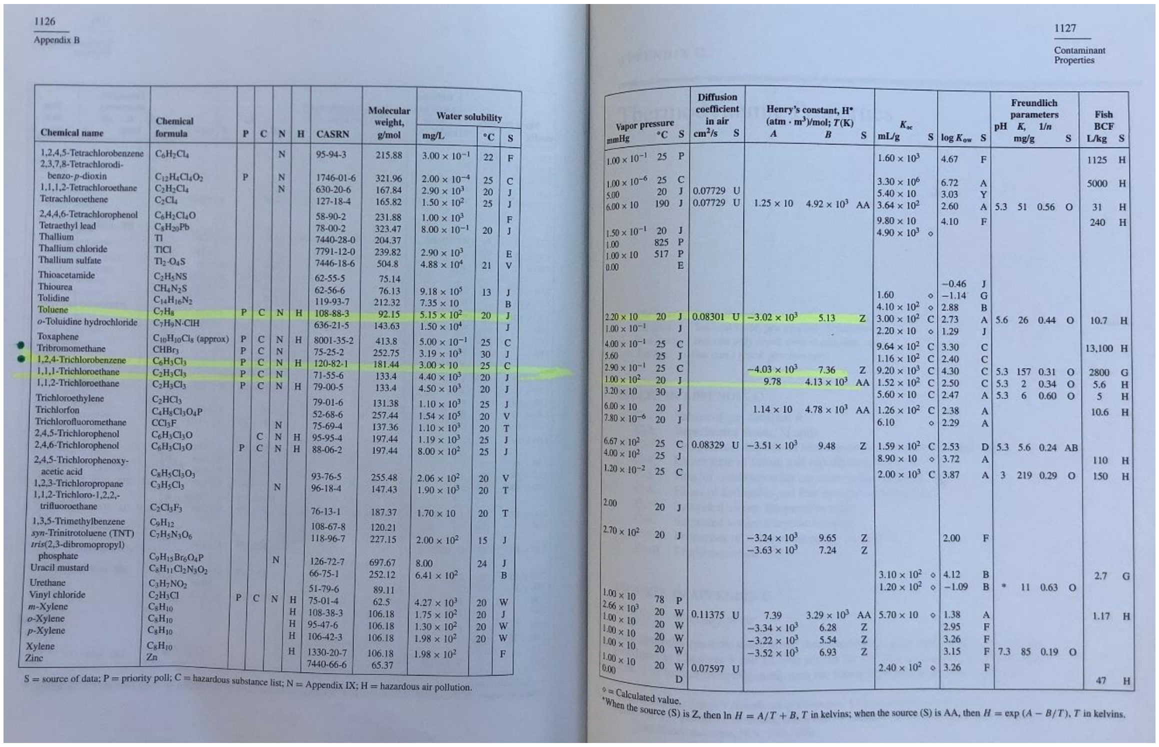


Chemical name	Chemical formula	P	C	N	H	CASRN	Molecular weight, g/mol	Water solubility			Vapor pressure			Diffusion coefficient in air		Henry's constant, H* (atm · m³)/mol; T(K)			K_{oc}				Freundlich parameters				Fish BCF	
								mg/L	°C	S	mmHg	°C	S	cm²/s	S	A	B	S	mL/g	S	log K_{ow}	S	pH	K, mg/g	1/n	S	L/kg	S
1-Chloro-2,3-epoxypropane	C_3H_5ClO				H	106-89-8	92.53	6.00×10^{4}	20	J	1.20×10	20	J						1.00×10	◇	0.15	B						
Ethanol	C_2H_6O					64-17-5	46.08	6.52×10^{4}	20	T	7.50×10	30	J	0.1273	U				2.20	◇	−0.32	J	5.3					
2-Ethoxyethanol	$C_4H_{10}O_2$					110-80-5	90.14	1.00×10^{6}		F	3.80	20	J								0.00	F						
Ethyl acetate	$C_4H_8O_2$					141-78-6	88.12	7.40×10^{4}	35	J	1.15×10^{2}	30	J	0.09005	U						0.73	Y						
Ethyl benzene	C_8H_{10}	P	C	N	H	100-41-4	106.18	1.52×10^{2}	20	J	7.00	20	J	0.0707	U	-4.99×10^{3}	1.19×10	Z	1.10	C	3.15	A	7.3	53	0.79	O	37.5	H
Ethyl carbitol	$C_6H_{14}O_3$					111-90-0	134.2				5.20×10^{-2}	16	V															
Ethylene dibromide	$C_2H_4Br_2$				H	106-93-4	187.88	4.30×10^{3}	20	J	1.17×10	20	J			-3.88×10^{3}	5.70	Z	4.40×10	G	1.76	B						
Ethylene glycol monobutyl ether	$C_6H_{14}O_2$					111-76-2	118.2	1.00×10^{6}		F	6.00×10^{-1}	20	J								0.00	F						
Ethylene oxide	C_2H_4O				H	75-21-8	44.06	3.80×10^{8}	20	B	1.10×10^{3}	20	J						2.20	◇	−0.22	B						
Ethylene thiourea	$C_3H_6N_2S$				H	96-45-7	102.17	2.00×10^{3}		F									6.70×10	◇	−0.66	J					0	F
Ethyl methanesulfonate	$C_3H_8O_3S$					62-50-0	124.17	3.69×10^{5}		B	2.06×10^{-1}		B						3.80	◇	0.21	B						
1-Ethyl-1-nitrosourea	$C_3H_7N_3O_2$					759-73-9	117.13	3.31×10^{8}		B									1.00×10^{-1}	◇								
Fluoranthene	$C_{16}H_{10}$	P	C	N		206-44-0	202.26	2.06×10^{-1}	25	J	5.00×10^{-6}	25	C						3.80×10^{4}	C	4.90	A	5.3	664	0.61	O	1150	H
Fluorene	$C_{13}H_{10}$					86-73-7	166.22	1.69	25	C	7.10×10^{-4}	20	C						7.30×10^{3}			C	5.3	330	0.28	O	1300	G
Formaldehyde	CH_2O					50-00-0	30.03	4.00×10^{5}			3.88×10^{3}	25	Y						3.60	◇	0.35	Y					0	F
Formic acid	CH_2O_2					64-18-6	46.03	1.00×10^{6}			3.50×10	20	J								−0.54	F					0	F
Furan	C_4H_4O					110-00-9	68.08	9.90×10^{3}	20	T	6.02×10^{2}	25	Y								1.34	Y						
Glycidaldehyde	$C_3H_4O_2$					765-34-4	72.1	1.70×10^{8}		B	1.97×10		B						1.00×10^{-1}	◇	−1.55	B						
Heptachlor	$C_{10}H_5Cl_7$	P	C	N	H	76-44-8	373.3	1.80×10^{-1}	25	C	3.00×10^{-4}	25	C						1.20×10^{4}	C	4.40	C	5.3	1220	0.95	O	15,700	H
Heptachlor epoxide	$C_{10}H_5Cl_7O$					1024-57-3	389.3	3.50×10^{-1}	25	C	3.00×10^{-4}	25	C						2.20×10^{2}	G	2.70	C	5.3	1038	0.70	O	14,400	G
Hexachlorobenzene	C_6Cl_6	P	C	N	H	118-74-1	284.76	6.00×10^{-3}	25	C	1.90×10^{-5}	20	C						3.90×10^{3}	C	5.23	A	5.3	450	0.60	O	8690	H
Hexachlorbutadiene	C_4Cl_6	P	C	N	H	87-68-3	260.74	2.00	20	C	1.50×10^{-1}	20	C						2.90×10^{4}	C	4.78	A	7	360	0.63	O	2.8	H
Hexachlorocyclopentadiene	C_5Cl_6	P	C	N	H	77-47-4	272.75	1.80	25	C	8.00×10^{-2}	25	J						4.80×10^{3}	C	5.04	A	5.3	370	0.17	O	4.3	H
α-Hexachlorocyclohexane	$C_6H_6Cl_6$					319-84-6	290.82	1.63	25	C	2.50×10^{-5}	20	C						3.80×10^{3}	C	3.90	C					130	H
β-Hexachlorocyclohexane	$C_6H_6Cl_6$					319-85-7	290.82	2.40×10^{-1}	25	C	2.80×10^{-7}	20	C						3.80×10^{3}	C	3.90	C					130	H
γ-Hexachlorocyclohexane	$C_6H_6Cl_6$					58-89-9	290.82	7.80	25	C	1.70×10	20	C						1.08×10^{3}	G	3.90	C					130	H
δ-Hexachlorocyclohexane	$C_6H_6Cl_6$					319-86-8	290.82	3.14×10	25	C	1.70×10^{-5}	20	C						6.60×10^{3}	C	4.10	C					130	H
Hexachloroethane	C_2Cl_6	P	C	N	H	67-72-1	236.72	4.20×10^{4}	20	C	4.00×10^{-1}	20	J			-2.55×10^{3}	3.74	Z	2.00×10^{4}	C	4.60	C	5.3	97	0.38	O	87	H
Hexachlorophene	$C_{13}H_6Cl_6O_2$			N		70-30-4	406.89	4.00×10^{-3}		F									9.10×10^{4}	◇	7.54	F						
Hexane	C_6H_{14}				H	110-54-3	86.17									-7.53×10^{3}	2.53×10	Z										
Hydrazine	H_4N_2				H	302-01-2	32.06	3.41×10^{8}		B	1.60×10	20	J						1.00×10^{-1}	◇	−3.08	B						
Hydrogen cyanide	CHN					74-90-8	27.03	1.00×10^{6}		◇	6.20×10^{2}	20	J								-2.50×10^{-1}	F					0	F
Hydrogen sulfide	H_2S				H	7783-06-4	34.08	4.13×10^{3}			1.52×10^{4}	26	P															
Indeno(1,2,3-cd)pyrene	$C_{22}H_{12}$	P	C	N		193-39-5	276.34	5.30×10^{-4}	25	C	1.00×10^{-1}	20	C						1.60×10^{6}	C	6.50	C						
Iodomethane	CH_3I			N		74-88-4	141.94	1.40×10^{4}	20	J	4.00×10^{2}	25	J						2.30×10	◇	1.69	J						
Iron(II)	Fe					15438-31-0	55.85				1.00×10	2040	I															
Isobutanol	$C_4H_{10}O$					78-83-1	74.14	7.29×10^{4}	20	K	1.04×10	25	Y								0.76	Y						
Isophorone	$C_9H_{14}O$	P	C		H	78-59-1	138.23	1.04×10^{4}	20	V	3.80×10^{-1}	20	C								2.22	Y	5.5	32	0.39	O		
Isoprene	C_5H_8					78-79-5	68.11				4.93×10^{2}	20	J															
Isosafrole	$C_{10}H_{10}O_2$			N		120-58-1	162.2	1.09×10^{3}		B	3.36	66	V						9.30×10	◇	2.66	B						
Kepone	$C_{10}Cl_{10}O$			N		143-50-0	490.6	7.60	24	J									5.50×10^{4}	◇	2.00	B					8400	G
Lasiocarpine	$C_{21}H_{33}NO_7$					303-34-4	411.55	1.60×10^{3}		B									7.60×10	◇	0.99	B						
Lead	Pb				H	7439-92-1	207.19				1.00×10	1160	I														49	H
Malathion	$C_{10}H_{19}O_6PS_2$					121-75-5	330.38	1.45×10^{2}	20	J	4.00×10^{-5}	20	J								2.89	J					0	F

S = source of data; P = priority poll; C = hazardous substance list; N = Appendix IX; H = hazardous air pollutant.

◇ = Calculated value.

*When the source (S) is Z, then $\ln H = A/T + B$, T in kelvins; when the source (S) is AA, then $H = \exp(A - B/T)$, T in kelvins.



Chemical name	Chemical formula	P	C	N	H	CASRN	Molecular weight, g/mol	Water solubility			Vapor pressure			Diffusion coefficient in air		Henry's constant, H* (atm · m³)/mol; T(K)			K_{oc}				Freundlich parameters				Fish BCF	
								mg/L	°C	S	mmHg	°C	S	cm²/s	S	A	B	S	mL/g	S	log K_{ow}	S	pH	K, mg/g	1/n	S	L/kg	S
1,2,4,5-Tetrachlorobenzene	$C_6H_2Cl_4$			N		95-94-3	215.88	3.00×10^{-1}	22	F	1.00×10^{-1}	25	P						1.60×10^{3}		4.67	F					1125	H
2,3,7,8-Tetrachlorodibenzo-p-dioxin	$C_{12}H_4Cl_4O_2$	P		N		1746-01-6	321.96	2.00×10^{-4}	25	C	1.00×10^{-6}	25	C						3.30×10^{6}		6.72	A					5000	H
1,1,1,2-Tetrachloroethane	$C_2H_2Cl_4$			N		630-20-6	167.84	2.90×10^{3}	20	J	5.00	20	J	0.07729	U				5.40×10		3.03	Y						
Tetrachloroethene	C_2Cl_4					127-18-4	165.82	1.50×10^{2}	25	J	6.00×10	190	J	0.07729	U	1.25×10	4.92×10^{3}	AA	3.64×10^{2}		2.60	A	5.3	51	0.56	O	31	H
2,4,4,6-Tetrachlorophenol	$C_6H_2Cl_4O$					58-90-2	231.88	1.00×10^{3}		F									9.80×10		4.10	F					240	H
Tetraethyl lead	$C_8H_{20}Pb$					78-00-2	323.47	8.00×10^{-1}	20	J	1.50×10^{-1}	20	J						4.90×10^{3}	◇								
Thallium	Tl					7440-28-0	204.37				1.00	825	P															
Thallium chloride	TlCl					7791-12-0	239.82	2.90×10^{3}		E	1.00×10	517	P															
Thallium sulfate	$Tl_2{\cdot}O_4S$					7446-18-6	504.8	4.88×10^{4}	21	V	0.00		E															
Thioacetamide	C_2H_5NS					62-55-5	75.14														−0.46	J						
Thiourea	CH_4N_2S					62-56-6	76.13	9.18×10^{5}	13	J									1.60	◇	−1.14	G						
Tolidine	$C_{14}H_{16}N_2$					119-93-7	212.32	7.35×10		B									4.10×10^{2}	◇	2.88	B						
Toluene	C_7H_8	P	C	N	H	108-88-3	92.15	5.15×10^{2}	20	J	2.20×10	20	J	0.08301	U	-3.02×10^{3}	5.13	Z	3.00×10^{2}	C	2.73	A	5.6	26	0.44	O	10.7	H
o-Toluidine hydrochloride	$C_7H_9N{\cdot}ClH$					636-21-5	143.63	1.50×10^{4}		J	1.00×10^{-1}		J						2.20×10	◇	1.29	J						
Toxaphene	$C_{10}H_{10}Cl_8$ (approx)	P	C	N	H	8001-35-2	413.8	5.00×10^{-1}	25	C	4.00×10^{-1}	25	C						9.64×10^{2}	C	3.30	C					13,100	H
Tribromomethane	$CHBr_3$	P	C	N		75-25-2	252.75	3.19×10^{3}	30	J	5.60	25	J						1.16×10^{2}	C	2.40	C						
1,2,4-Trichlorobenzene	$C_6H_3Cl_3$	P	C	N	H	120-82-1	181.44	3.00×10	25	C	2.90×10^{-1}	25	C			-4.03×10^{3}	7.36	Z	9.20×10^{3}	C	4.30	C	5.3	157	0.31	O	2800	G
1,1,1-Trichloroethane	$C_2H_3Cl_3$	P	C	N		71-55-6	133.4	4.40×10^{3}	20	J	1.00×10^{2}	20	J			9.78	4.13×10^{3}	AA	1.52×10^{2}	C	2.50	C	5.3	2	0.34	O	5.6	H
1,1,2-Trichloroethane	$C_2H_3Cl_3$	P	C	N	H	79-00-5	133.4	4.50×10^{3}	20	J	3.20×10	30	J						5.60×10	C	2.47	A	5.3	6	0.60	O	5	H
Trichloroethylene	C_2HCl_3					79-01-6	131.38	1.10×10^{3}	25	J	6.00×10	20	J			1.14×10	4.78×10^{3}	AA	1.26×10^{2}	C	2.38	A					10.6	H
Trichlorfon	$C_4H_8Cl_3O_4P$					52-68-6	257.44	1.54×10^{5}	20	V	7.80×10^{-6}	20	J						6.10	◇	2.29	A						
Trichlorofluoromethane	CCl_3F			N		75-69-4	137.36	1.10×10^{3}	20	T	6.67×10^{2}	25	C	0.08329	U	-3.51×10^{3}	9.48	Z	1.59×10^{2}	C	2.53	D	5.3	5.6	0.24	AB		
2,4,5-Trichlorophenol	$C_6H_3Cl_3O$		C	N	H	95-95-4	197.44	1.19×10^{3}	25	J	4.00×10^{2}	25	J						8.90×10	◇	3.72	A					110	H
2,4,6-Trichlorophenol	$C_6H_3Cl_3O$	P	C	N	H	88-06-2	197.44	8.00×10^{2}	25	J	1.20×10^{-2}	25	C						2.00×10^{3}	C	3.87	A	3	219	0.29	O	150	H
2,4,5-Trichlorophenoxyacetic acid	$C_8H_5Cl_3O_3$					93-76-5	255.48	2.06×10^{2}	20	V																		
1,2,3-Trichloropropane	$C_3H_5Cl_3$			N		96-18-4	147.43	1.90×10^{3}	20	T	2.00	20	J															
1,1,2-Trichloro-1,2,2,-trifluoroethane	$C_2Cl_3F_3$					76-13-1	187.37	1.70×10	20	T	2.70×10^{2}	20	J			-3.24×10^{3}	9.65	Z			2.00	F						
1,3,5-Trimethylbenzene	C_9H_{12}					108-67-8	120.21									-3.63×10^{3}	7.24	Z										
syn-Trinitrotoluene (TNT)	$C_7H_5N_3O_6$					118-96-7	227.15	2.00×10^{2}	15	J																		
tris(2,3-dibromopropyl) phosphate	$C_9H_{15}Br_6O_4P$			N		126-72-7	697.67	8.00	24	J									3.10×10^{2}	◇	4.12	B					2.7	G
Uracil mustard	$C_8H_{11}Cl_2N_3O_2$					66-75-1	252.12	6.41×10^{2}		B									1.20×10^{2}	◇	−1.09	B	*	11	0.63	O		
Urethane	$C_3H_7NO_2$					51-79-6	89.11				1.00×10	78	P															
Vinyl chloride	C_2H_3Cl	P	C	N	H	75-01-4	62.5	4.27×10^{3}	20	W	2.66×10^{3}	20	W	0.11375	U	7.39	3.29×10^{3}	AA	5.70×10	◇	1.38	A					1.17	H
m-Xylene	C_8H_{10}				H	108-38-3	106.18	1.75×10^{2}	20	J	1.00×10	20	W			-3.34×10^{3}	6.28	Z			2.95	F						
o-Xylene	C_8H_{10}				H	95-47-6	106.18	1.30×10^{2}	20	W	1.00×10	20	W			-3.22×10^{3}	5.54	Z			3.26	F						
p-Xylene	C_8H_{10}				H	106-42-3	106.18	1.98×10^{2}	20	W	1.00×10	20	W			-3.52×10^{3}	6.93	Z			3.15	F	7.3	85	0.19	O		
Xylene	C_8H_{10}				H	1330-20-7	106.18	1.98×10^{2}		F	1.00×10	20	W	0.07597	U				2.40×10^{2}	◇	3.26	F						
Zinc	Zn					7440-66-6	65.37				0.00		D														47	H

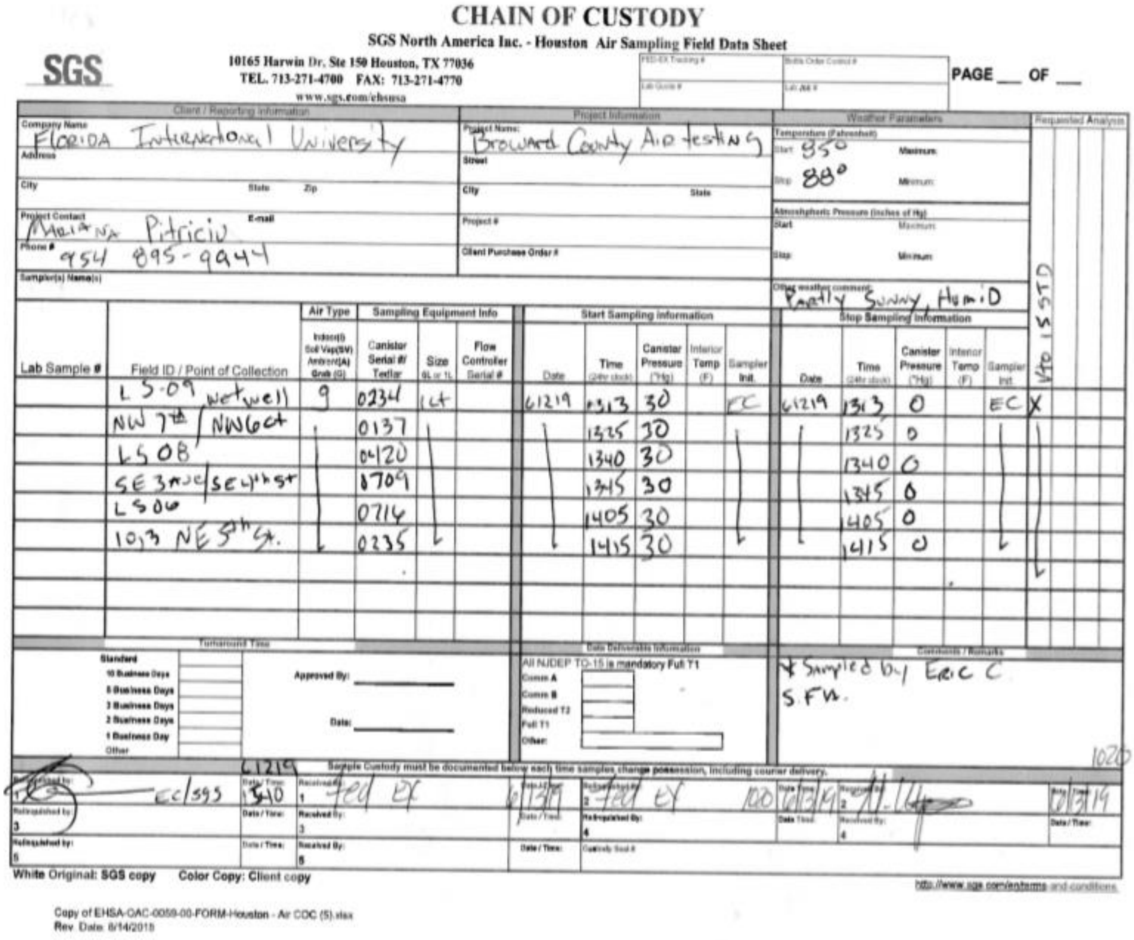
S = source of data; P = priority poll; C = hazardous substance list; N = Appendix IX; H = hazardous air pollution.

◇ = Calculated value.

*When the source (S) is Z, then $\ln H = A/T + B$, T in kelvins; when the source (S) is AA, then $H = \exp(A - B/T)$, T in kelvins.

APPENDIX B

Chain of Custody Samples Collection



CHAIN OF CUSTODY

SGS North America Inc. - Houston Air Sampling Field Data Sheet

SGS

10165 Harwin Dr, Ste 150 Houston, TX 77036
TEL. 713-271-4700 FAX: 713-271-4770
www.sgs.com/ehsusa

FED-EX Tracking #
Bottle Order Control #
Lab Quote #
Lab Job #

PAGE ___ OF ___

Client / Reporting Information

Company Name: FLORIDA International University
Address:
City: State: Zip:
Project Contact: Mariana Pitriciu E-mail:
Phone #: 954 895-9944
Sampler(s) Name(s):

Project Information

Project Name: Broward County Air testing
Street:
City: State:
Project #:
Client Purchase Order #:

Weather Parameters

Temperature (Fahrenheit)
Start: 85° Maximum:
Stop: 88° Minimum:

Atmospheric Pressure (inches of Hg)
Start: Maximum:
Stop: Minimum:

Other weather comments: Partly Sunny, Humid

Requested Analysis: Vto 15 STD

Lab Sample #	Field ID / Point of Collection	Air Type: Indoor(I) Soil Vap(SV) Ambient(A) Grab (G)	Sampling Equipment Info: Canister Serial #/ Tedlar	Size 6L or 1L	Flow Controller Serial #	Start Sampling Information: Date	Time (24hr clock)	Canister Pressure ("Hg)	Interior Temp (F)	Sampler Init.	Stop Sampling Information: Date	Time (24hr clock)	Canister Pressure ("Hg)	Interior Temp (F)	Sampler Init.	Vto 15 STD
	LS-09 wetwell	9	0234	1Lt		61219	1313	30		EC	61219	1313	0		EC	X
	NW 7th / NW 6ct		0137				1325	30				1325	0			
	LS 08		0420				1340	30				1340	0			
	SE 3 Ave / SE 4th st		0709				1345	30				1345	0			
	LS 06		0714				1405	30				1405	0			
	10,3 NE 5th St.		0235				1415	30				1415	0			

Turnaround Time

Standard
10 Business Days ☐
5 Business Days ☐
3 Business Days ☐
2 Business Days ☐
1 Business Day ☐
Other

Approved By: __________

Date: __________

Data Deliverable Information

All NJDEP TO-15 is mandatory Full T1
Comm A ☐
Comm B ☐
Reduced T2 ☐
Full T1 ☐
Other: ☐

Comments / Remarks

* Sampled by Eric C
S.FM.

1020

Sample Custody must be documented below each time samples change possession, including courier delivery.

Relinquished by: 1 EC/SGS	Date/Time: 61219 1340	Received by: 1 Fed Ex	Date/Time: 6/13/19	Relinquished by: 2 Fed Ex	Date/Time: 1020 6/13/19	Received by: 2	Date/Time: 6/13/19
Relinquished by: 3	Date/Time:	Received by: 3	Date/Time:	Relinquished by: 4	Date/Time:	Received by: 4	Date/Time:
Relinquished by: 5	Date/Time:	Received by: 5	Date/Time:	Custody Seal #			

White Original: SGS copy Color Copy: Client copy

http://www.sgs.com/en/terms-and-conditions

Copy of EHSA-QAC-0059-00-FORM-Houston - Air COC (5).xlsx
Rev Date: 8/14/2018

APPENDIX C

Sample Summary - SGS North America Inc.

Sample number	Collected date	Time	By	Received	Type	Client sample ID
FA65082-1	6/12/2019	13:13	EC	6/13/2019	Air	LS 09 WET WELL
FA65082-2	6/12/2019	13:25	EC	6/13/2019	Air	NW 7TH/NW6CT
FA65082-3	6/12/2019	13:40	EC	6/13/2019	Air	LS08
FA65082-4	6/12/2019	13:45	EC	6/13/2019	Air	SE 3AVE/SE 4TH ST
FA65082-5	6/12/2019	14:05	EC	6/13/2019	Air	LS06
FA65082-6	6/12/2019	14:15	EC	6/13/2019	Air	1013 NE 5TH ST

APPENDIX D

Sample Results (μg/m³) – MS Volatile (TO-15)
SGS North America Inc. (June 27, 2019)

	Client sample ID					
	LS09 WET WELL	NW7THCT/ NW6CT	LS08	SE3AVE/ SE4ST	LS06	1013 NE 5TH ST
	Lab sample ID					
	FA65082-1	FA65082-2	FA65082-3	FA65082-4	FA65082-5	FA65082-6
Acetone	21[a]	24.9[a]	28.5[a]	75.8[a]	21[a]	11[a]
Acrolein	0.69 I[a]	0.87 I[a]	0.62 I[a]	0.57 I[a]	0.44 I[a]	0.39 I[a]
Acrylonitrile	0.093 U[a]	0.18 U[a]	0.072 I[a]	0.093 U[a]	0.046 U[a]	0.18 U[a]
Allyl chloride	0.14 U[a]	0.28 U[a]	0.072 U[a]	0.14 U[a]	0.072 U[a]	0.28 U[a]
1,3-Butadiene	0.15 U	0.29 U	0.075 U	0.15 U	0.075 U	0.29 U
Benzene	0.27 I	1.2 I	0.61 I	0.51 I	0.23 I	0.27 I
Benzyl Chloride	0.12 I	0.27 I	0.082 I	0.12 U	0.077 I	0.31 I
Bromodichloromethane	0.24 I[a]	2.9 I[a]	1.4 I[a]	1.9 I[a]	0.94 I[a]	1.3 I[a]
Bromoform	0.28 U	0.56 U	0.14 U	0.28 U	0.17 I	0.56 U
Bromomethane	0.19 U	0.37 U	0.093 U	0.19 U	0.093 U	0.37 U
2-Butanone	0.88 I	0.77 I	1.1 I	0.59 I	0.71 I	0.47 I
n-Butylbenzene	0.11 U[a]	0.22 U[a]	0.077 I[a]	0.11 U[a]	0.055 I[a]	0.22 U[a]
sec-Butylbenzene	0.15 U[a]	0.31 U[a]	0.077 U[a]	0.15 U[a]	0.077 U[a]	0.31 U[a]
Carbon disulfide	0.26 I[a]	3.1 I[a]	1.5 I[a]	1.7 I[a]	3.0[a]	2.7 I[a]
Carbon tetrachloride	0.51 I[a]	2.6 I[a]	0.82 I[a]	0.88 I[a]	0.88 I[a]	0.75 I[a]
Chlorobenzene	0.17 U	1.8 I	0.33 I	0.32 I	0.36 I	0.33 U
Chloroethane	0.12 I	0.95 I	0.32 I	2.0 I	0.37 I	0.95 I
Chloroform	15	117	39	71.3	27	41
Chloromethane	1.6 I	5.6	1.4	5.6	2.9	1.7 I
Cyclohexane	0.11 I[a]	0.32 I[a]	1.1 I[a]	0.089 U[a]	0.11 I[a]	0.18 U[a]
Dibromochloromethane	0.26 U[a]	0.52 U[a]	0.15 I[a]	0.26 U[a]	0.14 I[a]	0.52 U[a]
1,1-Dichloroethane	0.13 U	0.27 U	0.069 U	0.13 U	0.069 U	0.27 U
1,1-Dichloroethene	0.15 U	0.36 I	0.11 I	0.37 I	0.11 I	0.36 I
1,2-Dibromoethane	0.27 U	0.54 U	0.13 U	0.27 U	0.13 U	0.54 U
1,1-Dibromoethane	0.15 U[b]	0.31 U[b]	0.077 U[b]	0.15 U[b]	0.077 U[b]	0.31 U[b]
1,2-Dichloroethane	0.14 U	0.28 U	0.23 I	0.21 I	0.65 I	0.28 U
1,2-Dichloropropane	0.23 U	0.46 U	0.12 U	0.23 U	0.12 U	0.46 U
1,4-Dioxane	0.19 U	0.40 U	0.097 U	0.19 U	0.097 U	0.40 U

(continued)

	Client sample ID					
	LS09 WET WELL	NW7THCT/ NW6CT	LS08	SE3AVE/ SE4ST	LS06	1013 NE 5TH ST
	Lab sample ID					
	FA65082-1	FA65082-2	FA65082-3	FA65082-4	FA65082-5	FA65082-6
Dichlorodifluoromethane	2.5 I	2.5 I	2.5	3.0 I	4.5	2.5 I
trans-1,2-Dichloroethene	0.22 U	0.44 U	0.11 U	0.22 U	0.11 U	0.44 U
cis-1,2-Dichloroethene	0.15 U	0.39 I	2.8	0.33 I	0.19 I	0.31 U
cis-1,3-Dichloropropene	0.14 U	0.27 U	0.068 U	0.14 U	0.068 U	0.27 U
1,2-Dichlorobenzene	0.19 U	0.38 U	0.096 U	0.28 I	0.40 I	0.96 I
1,3-Dichlorobenzene	0.14 U	0.29 U	0.072 U	0.14 U	0.072 U	0.29 U
1,4-Dichlorobenzene	2.2 I	57	5.7	20	6.6	3.7 I
trans-1,3-Dichloropropene	0.18 U	0.36 U	0.091 U	0.18 U	0.091 U	0.36 U
1,2-Dichlorotetrafluoroethane	0.29 U	0.59 U	0.15 U	0.29 U	0.15 U	0.59 U
Di-Isopropyl ether	0.092 U[a]	0.18 U[a]	0.046 U[a]	0.092 U[a]	0.046 U[a]	0.18 U[a]
Ethanol	7.5[a]	329[a]	12[a]	188[a]	6.0[a]	7.5[a]
Ethylbenzene	0.13 I	0.48 I	0.69 I	0.29 I	0.28 I	0.21 U
Ethyl Acetate	0.13 U[a]	0.65 I[a]	1.3 I[a]	0.65 I[a]	0.26 I[a]	0.27 U[a]
Ethyl tert-butyl ether	0.10 U[a]	0.20 U[a]	0.050 U[a]	0.10 U[a]	0.050 U[a]	0.20 U[a]
4-Ethyltoluene	0.47 U[a]	0.93 U[a]	0.24 U[a]	0.47 U[a]	0.24 U[a]	0.93 U[a]
Heptane	0.20 I	1.8 I	0.53 I	0.41 I	0.41 I	2.2 I
Hexachloro-1,3-butadiene	0.23 U	0.47 U	0.12 U	0.23 U	0.12 U	0.47 U
Hexane	0.39 I[a]	1.9 I[a]	0.74 I[a]	0.81 I[a]	0.67 I[a]	1.5 I[a]
2-Hexanone	0.15 I	0.28 I	0.22 I	0.18 I	0.12 I	0.20 U
Isopropylbenzene	0.30 U[a]	0.59 U[a]	0.15 U[a]	0.30 U[a]	0.15 U[a]	0.59 U[a]
Isopropanol	1.4 I[a]	4.4 I[a]	15[a]	22[a]	2.2 I[a]	1.1 I[a]
p-Isopropyltoluene	0.19 I[b]	3.3 I[b]	0.88 I[b]	0.55 I[b]	1.8 I[b]	1.4 I[b]
Methylene chloride	0.66 I	1.8 I	3.2	1.4 I	0.94 I	1.1 I
4-Methyl-2-pentanone	0.12 U	0.24 U	0.57 I	0.14 I	0.082 I	0.24 U
Methyl tert-butyl ether	0.10 U	0.27 I	0.33 I	0.34 I	0.27 I	0.36 I
Methyl methacrylate	0.11 U[a]	0.21 U[a]	0.094 I[a]	0.11 U[a]	0.053 U[a]	0.21 U[a]
Naphthalene	0.40 U[a]	0.79 U[a]	4.1[a]	0.40 U[a]	0.27 I[a]	0.79 U[a]
Pentane	6.8[a]	29[a]	9.7[a]	9.1[a]	4.7[a]	43.9[a]
n-Propylbenzene	0.14 U[a]	0.93 I[a]	0.14 I[a]	0.29 I[a]	0.083 I[a]	0.27 U[a]
Propene	1.0 I[a]	2.7 I[a]	1.2[a]	2.2[a]	1.4[a]	2.6 I[a]
Styrene	0.21 U	0.42 U	0.11 I	0.21 U	0.11 U	0.42 U
1,1,2,2-Tetrachloroethane	0.20 U	0.40 U	0.10 U	0.20 U	0.10 U	0.40 U
1,1,1-Trichloroethane	0.16 U	0.33 U	0.082 U	0.16 U	0.082 U	0.33 U
1,1,2-Trichloroethane	0.29 U	0.60 U	0.15 U	0.29 U	0.15 U	0.60 U

(continued)

	Client sample ID					
	LS09 WET WELL	NW7THCT/ NW6CT	LS08	SE3AVE/ SE4ST	LS06	1013 NE 5TH ST
	Lab sample ID					
	FA65082-1	FA65082-2	FA65082-3	FA65082-4	FA65082-5	FA65082-6
1,2,4-Trichlorobenzene	0.30 U	0.61 U	0.16 U	0.30 U	0.16 U	0.61 U
1,1,2-Trichlorotrifluoroethane	0.61 I	1.0 U	0.61 I	0.59 I	0.61 I	1.0 U
1,2,4-Trimethylbenzene	0.34 I	4.1 I	0.79 I	1.2 I	0.49 I	0.69 I
1,3,5-Trimethylbenzene	0.25 U	1.6 I	0.32 I	1.3 I	0.16 I	0.49 U
2,2,4-Trimethylpentane	0.19 I	0.65 I	0.24 I	0.26 I	0.29 I	0.61 I
t-Butyl alcohol	0.22 I[a]	0.36 I[a]	1.0 I[a]	0.27 I[a]	0.36 I[a]	0.36 I[a]
Tert-amyl methyl ether	0.088 U[a]	0.17 U[a]	0.042 U[a]	0.088 U[a]	0.042 U[a]	0.17 U[a]
Tetrachloroethene	895	2410	1.2 I	2.0 I	2.3 I	0.88 I
Tetrahydrofuran	1.0 I[a]	0.35 U[a]	0.28 I[a]	0.18 U[a]	0.26 I[a]	0.35 U[a]
Toluene	7.9	43.0	11	7.5	9.0	5.3 I
Trichloroethene	0.23 I	0.59 I	4.4	1.1 I	0.081 U	0.32 U
Trichlorofluoromethane	1.3 I	1.3 I	1.4 I	1.4 I	1.5 I	1.3 I
Vinyl acetate	0.29 I	0.39 U	0.26 I	0.25 I	0.21 I	0.39 U
Vinyl Bromide	0.096 U	0.19 U	0.048 U	0.096 U	0.048 U	0.19 U
Vinyl chloride	0.19 U	0.41 I	0.092 U	0.19 U	1.0 I	2.4 I
m- & p-Xylene	0.39 U	1.5 I	2.3	1.7 I	0.83 I	0.78 U
o-Xylene	0.18 U	0.69 I	1.7 I	0.61 I	0.39 I	0.36 U
Xylenes, Total	0.48 I	2.2 I	4.0	2.3 I	1.2 I	0.78 I

APPENDIX E

VOC Concentrations (µg/L) From Analytical Reports From City of Orlando, City of West Palm Beach, City of Boca Raton, City of Sunrise, City of Sunrise, City of Hallandale Beach, Town of Pembroke Park, Unincorporated Broward County, and Miami-Dade County (2014, 2015, 2016, 2017, and 2018)

Table E1

Orlando Conserv I - 2014; Method USEPA 624 (Concentrations in mg/l)

VOC species	WCI-S1 10/24/2014	WCI-S2 10/24/2014	WCI-S3 10/24/2014	WCI-S4 10/24/2014
Chloroform	2.7	5.1	3.5	3
1,4-Dichlorobenzene	4.3	2.6	6.2	4.4
Acetone USEPA 8260B	110	52	130	43
Toluene	29	17	23	16
Methylene chloride				2.6
Trichlorobenzene		11		

Table E2

Orlando Conserv II - 2014; Method USEPA 624 (Concentrations in mg/l)

VOC species	WCII-S1 10/16/2014	WCII-S2 10/16/2014	WCII-S3 10/16/2014	WCII-S4 10/16/2014
Chloroform	8.9	7.2	7.7	3.8
1,4-Dichlorobenzene	2.5	3.1	3.3	3.3
Acetone USEPA 8260B	72	79	130	210
Toluene	130	150	150	240
Methylene chloride		11	13	

Table E3

Iron Bridge - 2014; Method USEPA 624 (Concentrations in mg/l)

VOC species	Iron Bridge-1 10/10/2014	Iron Bridge-2 10/10/2014	Iron Bridge-3 10/10/2014	Iron Bridge-4 10/10/2014
Chloroform	3.1	3.7	5.5	3.3
1,4-Dichlorobenzene	1.4	0.97	1.9	1.5
Acetone USEPA 8260B	220	360	420	320
Toluene	2.4	2.4	5	1.8
Methylene chloride	2.2	2.9	3.2	2.8

Table E4

Orlando Conserv I - 2015; Method USEPA 624(Concentrations in mg/l)

VOC species	WCI-S1 10/2/2015	WCI-S2 10/2/2015	WCI-S3 10/2/2015	WCI-S4 10/2/2015
Chloroform	3	5.8	1.8	1.8
1,4-Dichlorobenzene	3.1	2.9	2.7	2
Acetone USEPA 8260B	76	32	37	27
Toluene	24	19	16	12
Methylene chloride			4 (I)	
Ethylbenzene	1.1	1.1	0.91 (I)	0.90 (I)

Table E5

Orlando Conserv II - 2015; Method USEPA 624 (Concentrations in mg/l)

VOC species	WCII-S1 10/9/2015	WCII-S2 10/9/2015	WCII-S3 10/9/2015	WCII-S4 10/9/2015
Chloroform	4.9	6	6.5	5
1,4-Dichlorobenzene	3.8	5	4.8	4.4
Toluene	130	130	130	120
Methylene chloride		62	15	
Ethylbenzene	1.2	1.2	1.1	2.5
Dichlorobromoethane	0.6 (I)	0.9 (I)	1.2	0.8 (I)

Table E6

Iron Bridge - 2015; Method USEPA 624 (Concentrations in mg/l)

VOC species	Iron Bridge-1 11/9/2015	Iron Bridge-2 11/9/2015	Iron Bridge-3 11/9/2015	Iron Bridge-4 11/9/2015
Chloroform	4	6.4	8.2	4.6
Toluene	4.5	5.8	5.1	3.8
Ethylbenzene	0.7 (I)	0.47 (I)	0.73 (I)	1.5
Tetrachloroethylene	1.8	2.1	2.4	1.5

Table E7

Orlando Conserv I - 2016; Method USEPA 624 (Concentrations in mg/l)

VOC species	WCI-S1 10/21/2016	WCI-S2 10/21/2016	WCI-S3 10/21/2016	WCI-S4 10/21/2016
Chloroform	1.8	3.4	1.3	5.8
1,4-Dichlorobenzene	3.6	3.2	2.5	3.3
Total Xylene	0.62 I			
Toluene	19	16	8	12
Methylene Chloride				18

Table E8

Orlando Conserv II - 2016; Method USEPA 624 (Concentrations in mg/l)

VOC species	WCII-S1 11/11/2016	WCII-S2 11/11/2016	WCII-S3 11/11/2016	WCII-S4 11/11/2016
Chloroform	5.6	6.7	7.4	6.3
1,4-Dichlorobenzene	3.8	3.6	3.7	3.6
Toluene	120	100	99	95

Table E9

Iron Bridge - 2016; Method USEPA 624 (Concentrations in mg/l)

VOC species	Iron Bridge-1 10/18/2016	Iron Bridge-2 10/18/2016	Iron Bridge-3 10/18/2016	Iron Bridge-4 10/18/2016
Chloroform	2.7	4.7	5	3.6
1,4-Dichlorobenzene	1.2	1.2	0.90 (I)	1.6
Toluene	2.2	2.6	2.9	2.4
m- & p-Xylene				0.64 (I)

Table E10

Orlando Conserv I - 2017; Method USEPA 624(Concentrations in mg/l)

VOC species	WCI-S1 10/13/2017	WCI-S2 10/13/2017	WCI-S3 10/13/2017	WCI-S4 10/13/2017
Chloroform	2.7	2.6	1.3	3.1
Toluene	16	23	14	17
Methylene chloride				24
Ethylbenzene		1.7	0.57 (I)	0.54 (I)
Benzene		1.4		

Table E11

Orlando Conserv II - 2017; Method USEPA 624 (Concentrations in mg/l)

VOC species	WCII-S1 11/2/2017	WCII-S2 11/2/2017	WCII-S3 11/2/2017	WCII-S4 11/2/2017
Chloroform	6.1	5.8	8.7	5
Toluene	120	120	96	230
Methylene chloride		28	16	
Ethylbenzene		0.48 (I)		0.59 (I)

Table E12

Iron Bridge - 2017; Method USEPA 624 (Concentrations in mg/l)

VOC species	Iron Bridge-1 11/2/2017	Iron Bridge-2 11/2/2017	Iron Bridge-3 11/2/2017	Iron Bridge-4 11/2/2017
Chloroform	3.3	5.4	6.8	4
Toluene	3.3	4.9	7.2	4
Ethylbenzene				0.49 (I)

Table E13

Orlando Conserv I - 2018; Method USEPA 624 (Concentrations in mg/l)

VOC species	WC1 Inf Grab 1 10/27/2018	WC1 Inf Grab 2 10/27/2018	WC1 Inf Grab 3 10/27/2018	WC1 Inf Grab 4 10/27/2018
Chloroform	3.2	4.4	3.8	4.1
1,4-Dichlorobenzene	1.8	1.2	1.8	0.11 (I)
Acetone USEPA 8260B				
Toluene	28	21	26	24
Methylene chloride		6.2 (I)		
Ethylbenzene	0.27 (I)			0.30 (I)
Benzene	0.25 (I)			
Xylene	0.86	0.58	0.7	0.62

Table E14

Orlando Conserv II - 2018; Method USEPA 624 (Concentrations in mg/l)

VOC species	WCII-S1 10/18/2018	WCII-S2 10/18/2018	WCII-S3 10/18/2018	WCII-S4 10/18/2018
Chloroform	6.9	6	7.2	6.8
Toluene	74	77	55	47
Methylene chloride	1.8 (I)			
Ethylbenzene	1.2	1.3	1.9	3.2

Table E15

Iron Bridge - 2018; Method USEPA 624 (Concentrations in mg/l)

VOC species	Iron Bridge-1 9/25/2018	Iron Bridge-2 9/25/2018	Iron Bridge-3 9/25/2018	Iron Bridge-4 9/25/2019
Chloroform	2.9	6	5	3.6
Toluene	3.5	8.1	9.8	5.9
Ethylbenzene	0.47 (I)	0.42 (I)	0.69 (I)	0.37 (I)

Table E16

City of West Palm Beach; Method USEPA 624 (Concentrations in mg/l)

VOC species	2014	2015	2016	2017	2018
Chloroform	4.15	4.75	5.1	6.7	
1,4-Dichlorobenzene	4.2	5.5	3.5	2.4	
Chlorobenzene	0.33	0.2	0.4		
Toluene	8	8.1	17.1	11.8	

Table E17

City of Boca Raton; Method USEPA 624 (Concentrations in mg/l)

VOC species	3/10/2014 29.3 °C	7/1/2015 30.6 °C	6/23/2016 29.4 °C	11/14/2017 27.8 °C	9/22/2018 29.9 °C
Chloroform	8.4			7.4	
Ethylbenzene	1				
Tetrachloroethylene (PCE)	1.1				
Methylene Chloride			59		
Methyl tert-butyl ether (MTBE)					7.3
Toluene	4.2			4.3	
Trichloroethane	1.9				
Vinyl Chloride	0.84 (I)				
Xylene-mp	4	7.3 (U)			
Xylene-o	1.1	5.3 (I)			
Xylene (total)	5.1	11			

Table E18

City of Sunrise; Method USEPA 524.2 (Concentrations in mg/l)

VOC species	2/28/2014 25.2 °C	2/3/2015 21 °C	2/9/2016 23.9 °C	2/14/2017 27.4 °C	2/15/2018 28.8 °C
Chloroform	53.7	29.2	12.4	3.5	1.9
Bromodichloromethane	18.5		37.5	14.5	2
Bromoform			42.4	30.1	7
Dibromochloromethane	3.5		76.5	33.1	5.8
Toluene				0.93	
Total trihalomethane (calc.)	75.7	61.2	169	81.2	16.7

Table E19

City of Hallandale Beach (9/23/2014); Method USEPA 624.1(Concentrations in mg/l)

VOC species	Central 27.3 °C	West 28.2 °C	East 29.1 °C	3 Island 29.5 °C
Chloroform	0.74 (I)	1.2	1.2	0.58 (I)
1,4-Dichlorobenzene	0.87 (I)	2.2	0.65 (I)	0.9 (I)
1,2-Dichlorobenzene				
Toluene	0.96 (I)	2.1	0.50 (U)	0.5 (I)
m- & p-Xylene		5.6		
o-Xylene		2.4		
Xylene (Total)		8.1		

Table E20

City of Hallandale Beach (9/9/2015); Method USEPA 624.1(Concentrations in mg/l)

VOC species	Central 30.8 °C	West 33.1 °C	East 31.3 °C	3 Island 31.6 °C
Toluene	1.1	7.8	0.5 (U)	1.3

Table E21

City of Hallandale Beach (9/9/2016); Method USEPA 624.1(Concentrations in mg/l)

VOC species	Central 34.7 °C	West 32.9 °C	East 31.3 °C	3 Island 28.36 °C
1,4-Dichlorobenzene	1.3	2.2	5.4	1.2
1,2-Dichlorobenzene		5.6		
Toluene	1.4			
m- & p-Xylene	1.1	1.4	0.5 (U)	0.58 (I)

Table E22

City of Hallandale Beach (11/7/2017); Method USEPA 624.1 (Concentrations in mg/l)

VOC species	Central 29.1 °C	West 29.3 °C	East 28.4 °C	3 Island 27.7 °C
Chloroform	2.4	3.4	4.8	4
1,4-Dichlorobenzene		2.4	1.4	
1,2-Dichlorobenzene				
Toluene	1.4	2.5	0.59 (I)	1.1

Table E23

City of Hallandale Beach (8/23/2018); Method USEPA 624.1 (Concentrations in mg/l)

VOC species	Central 31.6 °C	West 30.8 °C	East 25.9 °C	3 Island 30.6 °C
Chloroform	1.7	1.4	2.5	1.2
1,4-Dichlorobenzene		2.7		
Toluene	0.91 (I)	2.7	0.54 (I)	1.4
m- & p-Xylene				

Table E24

City of Hallandale Beach (11/7/2017); Method USEPA 624.1 (Concentrations in mg/l)

VOCs species	Location 1 29.1 °C	Location 2 29.3 °C	Location 3 28.4 °C	Location 4 27.7 °C
Chloroform	2.4	3.4	4.8	4
1,4-Dichlorobenzene		2.4	1.4	
1,2-Dichlorobenzene				
Toluene	1.4	2.5	0.59 (I)	1.1

Table E25

Town of Pembroke Park; Method USEPA 624 (Concentrations in mg/l)

VOC species	8/13/2014 33.0 °C	8/12/2015 36.4°	8/25/2016 34.1 °C	8/15/2017 32.4 °C	8/22/2018 33.0 °C
Chloroform	12.7	1.8	11.7	7.6	3.5
Chlorobenzene	13.9				
Bromodichloromethane			3.2		0.88
Dibromochloromethane			5		
1,4-Dichlorobenzene	5.81 (I)	6.3	4.8	2.6	2.6
Toluene	1530	2.5	3.7	2.1	2.6

Table E26

Broward County; Method USEPA 624 (Concentrations in mg/l)

VOC species	6/4/2014 30.6 °C Site 1	6/3/2014 30.1 °C Site 2	4/22/2015 30.1 °C Site 1	4/22/2015 30.0 °C Site 2	6/2/2016 31.1 °C Site 1	6/2/2016 32.5 °C Site 2
Chloroform		1.73	1.37	2.38	1.49	0.74
1,4-Dichlorobenzene		0.75	2.03	1.73		
Ethylbenzene			9.86		4.67	
Toluene	2.04	0.91	2.17	1.43	2.3	1.18
Total Xylenes	10.1		84		36	

Table E27

Broward County; Method USEPA 624 (Concentrations in mg/l)

VOC species	4/27/2017 28.7 °C Site 1	4/27/2017 28.6 °C Site 2	5/31/2018 28.3 °C Site 1	5.31/2018 28.3 °C Site 2
Chloroform	1.83	2.9	3.89	0.74
Dichloromethane (Methylene Chloride)	1.78	0.65		
Dibromochloromethane		0.54		
1,4-Dichlorobenzene		0.97		1.06
Toluene	2.9	2.56	0.88	2.04
Total Xylenes	1.5			

Table E28

Miami-Dade; Method USEPA 624 (Concentrations in mg/l)

VOC species	2/27/2014 Site 1	2/27/2014 Site 2	2/19/2015 Site 1	2/19/2015 Site 2	2/24/2016 Site 1	2/24/2016 Site 2
Chloroform	1.9	1.8		1.6	1.6	2.3
Toluene	7.5	5	4.9	5.2	4.1	4.6
Methylene Chloride						

Table E29

Miami-Dade; Method USEPA 624 (Concentrations in mg/l)

VOC species	2/8/2017 Site 1	2/8/2017 Site 2	2/16/2018 Site 1	2/16/2018 Site 2
Chloroform	1.3	1.6	1.9	1.9
1,4-Dichlorobenzene			2.1	3.6
Tetrachloroethene			2.9	
Toluene	8.6	6	3.8	4

APPENDIX F
Computed VOCs Gas-Phase Concentration (µg/m^3)

Table F1

Hallandale Beach

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m3)/ (mol · K)	H_C	C_g (µg/m^3)
Chloroform										
Location 1	1.3	34.7	307.7	0.0000825	9.84	4610	AA	0.005845	0.2303	0.55
	0.74	27.3	300.3	0.0000825	9.84	4610	AA	0.004041	0.1631	0.21
	2.4	29.1	302.1	0.0000825	9.84	4610	AA	0.004428	0.1777	0.43
	1.7	31.6	304.6	0.0000825	9.84	4610	AA	0.005019	0.1997	0.34
Location 2	1.2	28.2	301.2	0.0000825	9.84	4610	AA	0.004230	0.1702	0.20
	2.2	32.9	305.9	0.0000825	9.84	4610	AA	0.005352	0.2121	0.47
	3.4	29.3	302.3	0.0000825	9.84	4610	AA	0.004473	0.1793	0.61
	1.4	25.9	298.9	0.0000825	9.84	4610	AA	0.003760	0.1525	0.21
Location 3	1.2	29.1	302.1	0.0000825	9.84	4610	AA	0.004428	0.1777	0.21
	5.4	31.3	304.3	0.0000825	9.84	4610	AA	0.004944	0.1969	1.06
	4.8	28.4	301.4	0.0000825	9.84	4610	AA	0.004274	0.1719	0.82
	2.5	25.9	298.9	0.0000825	9.84	4610	AA	0.003760	0.1525	0.38
Location 4	1.2	28.3	301.3	0.0000825	9.84	4610	AA	0.004252	0.1711	0.21
	4	27.7	300.7	0.0000825	9.84	4610	AA	0.004124	0.1662	0.66
	1.2	30.6	303.6	0.0000825	9.84	4610	AA	0.004775	0.1906	0.23
1,4-Dichlorobenzene										
Location 2	2.2	28.2	301.2	0.0000825	-2720	3.37	Z	0.003481	0.1401	0.31
	5.6	32.9	305.9	0.0000825	-2720	3.37	Z	0.003999	0.1584	0.89
	2.4	29.3	302.3	0.0000825	-2720	3.37	Z	0.003597	0.1442	0.35
	2.7	30.8	303.8	0.0000825	-2720	3.37	Z	0.003760	0.1500	0.41
Location 3	1.4	28.4	301.4	0.0000825	-2720	3.37	Z	0.003502	0.1408	0.20

(continued)

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/(mol · K)	A	B	Source	H (atm · m^3)/(mol · K)	H_C	C_g (µg/m^3)
1,2-Dichlorobenzene	1.4	34.7	307.7	0.0000825	-2560	2.88	Z	0.004340	0.1710	0.24
Toluene										
Location 1	1.1	30.8	303.8	0.0000825	-3020	5.13	Z	0.008142	0.3248	0.36
	1	34.4	307.4	0.0000825	-3020	5.13	Z	0.009147	0.3607	0.36
	1.4	29.1	302.1	0.0000825	-3020	5.13	Z	0.007699	0.3089	0.43
	1.7	31.6	304.6	0.0000825	-3020	5.13	Z	0.008357	0.3326	0.57
Location 2	2.1	28.2	301.2	0.0000825	-3020	5.13	Z	0.007472	0.3007	0.63
	7.8	33.1	306.1	0.0000825	-3020	5.13	Z	0.008773	0.3474	2.71
	1.4	32.9	305.9	0.0000825	-3020	5.13	Z	0.008717	0.3454	0.48
	2.5	29.3	302.3	0.0000825	-3020	5.13	Z	0.007750	0.3107	0.78
	2.7	25.9	298.9	0.0000825	-3020	5.13	Z	0.006917	0.2805	0.76
Location 4	1.3	31.6	304.6	0.0000825	-3020	5.13	Z	0.008357	0.3326	0.43
	1.1	27.7	300.7	0.0000825	-3020	5.13	Z	0.007349	0.2962	0.33
	1.4	30.6	303.6	0.0000825	-3020	5.13	Z	0.008089	0.3229	0.45
Xylenes										
Location 2	8.1	28.2	301.2	0.0000825	-3340	6.28	Z	0.008156	0.3282	2.66

Table F2

Town of Pembroke Park

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (µg/m^3)
Chloroform	1.8	36.4	309.4	0.0000825	9.84	4610	AA	0.006347	0.2486	0.45
	12.7	33	306	0.0000825	9.84	4610	AA	0.005378	0.2130	2.71
	11.7	34.1	307.1	0.0000825	9.84	4610	AA	0.005677	0.2241	2.62
	7.6	32.4	305.4	0.0000825	9.84	4610	AA	0.005222	0.2072	1.58
	3.5	33	307.1	0.0000825	9.84	4610	AA	0.005677	0.2241	2.62
1,4-Dichlorobenzene	2.6	33	306	0.0000825	-2720	3.37	Z	0.004010	0.1589	0.41
	2.6	32.4	305.4	0.0000825	-2720	3.37	Z	0.003941	0.1564	0.41
	4.8	34.1	307.1	0.0000825	-2720	3.37	Z	0.004140	0.1634	0.78
	6.3	36.4	309.4	0.0000825	-2720	3.37	Z	0.004422	0.1732	1.09
	5.81	33	306	0.0000825	-2720	3.37	Z	0.004010	0.1589	0.92
Toluene	2.1	32.4	305.4	0.0000825	-3020	5.13	Z	0.008577	0.3404	0.71
	2.5	36.4	309.4	0.0000825	-3020	5.13	Z	0.009747	0.3818	0.95
	2.6	33	306	0.0000825	-3020	5.13	Z	0.008745	0.3464	0.90
	3.7	34.1	307.1	0.0000825	-3020	5.13	Z	0.009060	0.3576	1.32
Chlorobenzene	13.9	33	306	0.0000825	-2690	3.47	Z	0.004889	0.1936	2.69

Table F3

Broward County Unincorporated

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (µg/m^3)
Chloroform										
S1	1.37	30.1	303.1	0.0000825	9.84	4610	AA	0.004656	0.1862	0.26
	1.49	31.1	304.1	0.0000825	9.84	4610	AA	0.004895	0.1951	0.29
	1.83	28.7	301.7	0.0000825	9.84	4610	AA	0.004339	0.1743	0.32
	3.89	28.4	301.4	0.0000825	9.84	4610	AA	0.004274	0.1719	0.67
S2	1.73	30.1	303.1	0.0000825	9.84	4610	AA	0.004656	0.1862	0.32
	2.38	30	303	0.0000825	9.84	4610	AA	0.004633	0.1853	0.44
	0.74	32.5	305.5	0.0000825	9.84	4610	AA	0.005247	0.2082	0.15
	2.9	28.6	301.6	0.0000825	9.84	4610	AA	0.004317	0.1735	0.50
	0.74	28.3	301.3	0.0000825	9.84	4610	AA	0.004252	0.1711	0.13
1,4-Dichlorobenzene										
S1	2.03	30.1	303.1	0.0000825	-2720	3.37	Z	0.003683	0.1473	0.30
S2	0.75	30.1	303.1	0.0000825	-2720	3.37	Z	0.003683	0.1473	0.11
	1.73	30	303	0.0000825	-2720	3.37	Z	0.003672	0.1469	0.25
	1.69	32.5	305.5	0.0000825	-2720	3.37	Z	0.003952	0.1568	0.27
	0.97	28.6	301.6	0.0000825	-2720	3.37	Z	0.003523	0.3848	0.14
	1.06	28.3	301.3	0.0000825	-2720	3.37	Z	0.003491	1.0378	0.15
Toluene										
S1	2.04	30.6	303.6	0.0000825	-3020	5.13	Z	0.008089	0.3229	0.66
	2.17	30.1	303.1	0.0000825	-3020	5.13	Z	0.007957	0.3182	0.69
	2.3	31.1	304.1	0.0000825	-3020	5.13	Z	0.008222	0.3277	0.75
	2.9	28.7	301.7	0.0000825	-3020	5.13	Z	0.007597	0.3052	0.89
	0.88	28.4	301.4	0.0000825	-3020	5.13	Z	0.007522	0.3025	0.27
S2	1.43	30	303	0.0000825	-3020	5.13	Z	0.007931	0.3173	0.45
	0.91	30.1	303.1	0.0000825	-3020	5.13	Z	0.007957	0.3182	0.29
	1.2	32.5	305.5	0.0000825	-3020	5.13	Z	0.008605	0.3414	0.41
	2.56	28.6	301.6	0.0000825	-3020	5.13	Z	0.007572	0.3043	0.78
	2.04	28.3	301.3	0.0000825	-3020	5.13	Z	0.007497	0.3016	0.62

(continued)

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (µg/m^3)
Ethylbenzene										
S1	4.67	31.1	304.1	0.0000825	-4990	11.9	Z	0.011009	0.4388	2.05
	9.86	30.1	303.1	0.0000825	-4990	11.9	Z	0.010428	0.4170	4.11
Xylenes										
S1	10.1	36.6	309.6	0.0000825	-3340	6.28	Z	0.011019	0.4314	4.36
	84	30.1	303.1	0.0000825	-3340	6.28	Z	0.008743	0.3497	29.37
	36	31.1	304.1	0.0000825	-3340	6.28	Z	0.009066	0.3614	13.01
	1.5	28.7	301.7	0.0000825	-3340	6.28	Z	0.008307	0.3338	0.50
S2	0.9	30.1	303.1	0.0000825	-3340	6.28	Z	0.008743	0.3497	0.31
Methylene chloride										
S1	0.652	28.6	301.6	0.0000825	6.65	3820	AA	0.002440	0.0981	0.06
S2	1.78	28.7	301.7	0.0000825	6.65	3820	AA	0.002450	0.0984	0.18

Table F4

City of Sunrise

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (µg/m^3)
Chloroform	1.9	28.8	301.8	0.0000825	9.84	4610	AA	0.004361	0.1752	0.33
	3.5	27.4	300.4	0.0000825	9.84	4610	AA	0.004061	0.1639	0.57
	12.4	23.9	296.9	0.0000825	9.84	4610	AA	0.003389	0.1384	1.72
	29.2	21.0	294.0	0.0000825	9.84	4610	AA	0.002908	0.1199	3.50
	53.7	25.2	298.2	0.0000825	9.84	4610	AA	0.003627	0.1474	7.92
Toluene	0.93	27.4	300.4	0.0000825	-3020	5.13	Z	0.007275	0.2936	0.27

Table F5

City of West Palm Beach

	C_l (μg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (μg/m^3)
Chloroform	4.15	25.0	298.0	0.0000825	9.84	4610	AA	0.003589	0.1460	0.61
	4.75	25.0	298.0	0.0000825	9.84	4610	AA	0.003589	0.1460	0.69
	5.1	25.0	298.0	0.0000825	9.84	4610	AA	0.003589	0.1460	0.74
	6.7	25.0	298.0	0.0000825	9.84	4610	AA	0.003589	0.1460	0.98
Toluene	8	25.0	298.0	0.0000825	-3020	5.13	Z	0.006710	0.2729	2.18
	8.1	25.0	298.0	0.0000825	-3020	5.13	Z	0.006710	0.2729	2.21
	17.1	25.0	298.0	0.0000825	-3020	5.13	Z	0.006710	0.2729	4.67
	11.8	25.0	298.0	0.0000825	-3020	5.13	Z	0.006710	0.2729	3.22
1,4-Dichlorobenzene	4.2	30.1	303.1	0.0000825	-2720	3.37	Z	0.003683	0.1473	0.62
	5.5	30	303	0.0000825	-2720	3.37	Z	0.003672	0.1469	0.81
	3.5	32.5	305.5	0.0000825	-2720	3.37	Z	0.003952	0.1568	0.55
	2.4	28.6	301.6	0.0000825	-2720	3.37	Z	0.003523	0.1416	0.34

Table F6

Boca Raton

	C_l (μg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (μg/m^3)
Chloroform	8.4	25.6	298.6	0.0000825	9.84	4610	AA	0.003703	0.1503	1.26
	7.4	27.8	300.8	0.0000825	9.84	4610	AA	0.004145	0.1670	1.24
Toluene	4.2	29.9	302.9	0.0000825	-3020	5.13	Z	0.007905	0.3163	1.33
	4.3	25.6	298.6	0.0000825	-3020	6.13	Z	0.018614	0.7556	3.25
Ethylbenzene	1	29.9	302.9	0.0000825	-4990	11.9	Z	0.010316	0.4128	0.41
Xylenes	5.1	29.9	302.9	0.0000825	-3340	6.28	Z	0.008680	0.3473	1.77
	11	27.8	300.8	0.0000825	-3340	6.28	Z	0.008037	0.3239	3.56
Methylene chloride	59	29.4	302.4	0.0000825	6.65	3820	AA	0.002523	0.1011	5.97
Trichloroethane	1.9	29.9	302.9	0.0000825	9.78	4130	AA	0.021177	0.8474	1.61
Vinyl chloride	0.84	29.9	302.9	0.0000825	7.39	3290	AA	0.031065	1.2431	1.04

Table F7

Orlando Iron Bridge

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (µg/m^3)
Chloroform										
WC1-Grab 1	2.7	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.39
	3	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.44
	1.8	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.26
	2.7	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.39
	3.2	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.47
WC1-Grab 2	5.8	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.85
	5.8	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.85
	3.4	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.50
	2.6	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.38
	4.4	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.64
WC1-Grab 3	3.5	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.51
	1.8	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.26
	1.3	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.19
	1.3	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.19
	3.8	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.55
WC1-Grab 4	3	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.44
	1.8	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.26
	5.8	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.85
	3.1	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.45
	4.1	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.60
WC2-Grab 1	8.9	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	1.30
	4.9	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.72
	5.6	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.82
	6.1	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.89
	6.9	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	1.01

(continued)

	C_l (μg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/(mol · K)	A	B	Source	H (atm · m^3)/(mol · K)	H_C	C_g (μg/m^3)
WC2-Grab 2	7.2	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	1.05
	6	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.88
	6.7	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.98
	5.8	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.85
	6	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.88
WC2-Grab 3	7.7	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	1.12
	6.5	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.95
	7.4	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	1.08
	8.7	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	1.27
	7.2	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	1.05
WC2-Grab 4	3.8	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.55
	5	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.73
	6.3	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.92
	5	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.73
	6.8	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.99
IB Grab 1	3.1	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.45
	4	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.58
	2.7	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.39
	3.3	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.48
	2.9	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.42
IB Grab 2	3.7	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.54
	6.4	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.93
	4.7	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.69
	5.4	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.79
	6	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.88
IB Grab 3	5.5	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.80
	8.2	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	1.20

(continued)

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/(mol · K)	A	B	Source	H (atm · m^3)/(mol · K)	H_C	C_g (µg/m^3)
IB Grab 3	35	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.73
	2.9	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.42
	5	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	1.73
IB Grab 4	3.3	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.48
	4.6	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.67
	3.6	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.53
	4	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.58
	3.6	25	298	0.0000825	9.84	4610	AA	0.003589	0.1460	0.53
1,4-Dichlorobenzene										
WC1-Grab 1	4.3	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.55
	3.1	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.40
	3.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.46
	1.8	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.23
WC1-Grab 2	2.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.33
	2.9	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.37
	3.2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.41
	1.2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.15
WC1-Grab 3	6.2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.80
	2.7	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.35
	2.5	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.32
	1.8	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.23
WC1-Grab 4	4.4	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.57
	2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.26
	3.3	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.42
WC2-Grab 1	2.5	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.32
	3.8	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.49
	3.8	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.49

(continued)

	C_l (μg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (μg/m^3)
WC2-Grab 2	3.1	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.40
	5	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.64
	3.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.46
WC2-Grab 3	3.3	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.42
	4.8	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.62
	3.7	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.48
WC2-Grab 4	3.3	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.42
	4.4	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.57
	3.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.46
IB Grab 1	1.4	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.18
	1.2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.15
IB Grab 2	0.97	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.12
	1.2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.15
IB Grab 3	1.9	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.24
IB Grab 4	1.5	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.19
	1.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.21
Toluene										
WC1-Grab 1	29	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	7.91
	24	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	6.55
	19	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	5.19
	16	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	4.37
	28	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	7.64
WC1-Grab 2	17	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	4.64
	19	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	5.19
	16	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	4.37
	23	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	6.28
	21	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	5.73

(continued)

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (µg/m^3)
WC1-Grab 3	23	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	6.28
	16	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	4.37
	8	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	2.18
	14	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	3.82
	26	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	7.10
WC1-Grab 4	16	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	4.37
	12	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	3.27
	12	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	3.27
	17	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	4.64
	24	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	6.55
WC2-Grab 1	130	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	35.48
	130	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	35.48
	120	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	32.75
	120	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	32.75
	74	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	20.20
WC2-Grab 2	150	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	40.94
	130	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	35.48
	100	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	27.29
	120	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	32.75
	77	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	21.01
WC2-Grab 3	150	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	40.94
	130	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	35.48
	99	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	27.02
	96	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	26.20
	55	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	15.01

(continued)

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (µg/m^3)
WC2 -Grab 4	240	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	65.50
	120	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	32.75
	95	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	25.93
	230	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	62.77
	47	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	12.83
IB Grab 1	2.4	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	0.65
	4.5	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	1.23
	2.2	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	0.60
	3.3	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	0.90
	3.5	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	0.96
IB Grab 2	2.4	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	0.65
	5.8	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	1.58
	2.6	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	0.71
	4.9	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	1.34
	8.1	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	2.21
IB Grab 3	5	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	1.36
	5.1	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	1.39
	2.9	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	0.79
	7.2	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	1.96
	9.8	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	2.67
IB Grab 4	1.8	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	0.49
	3.8	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	1.04
	2.4	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	0.65
	4	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	1.09
	5.9	25	298	0.0000825	-3020	5.13	Z	0.006710	0.2729	1.61

(continued)

	Cl (µg/m3)	Temperature (C)	Temperature (K)	R (atm · m3)/ (mol · K)	A	B	Source	H (atm · m3)/ (mol · K)	HC	Cg (µg/m3)
Methylene chloride (dichloromethane)										
WC1-Grab 2	6.2	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	0.53
WC1-Grab 3	4	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	0.34
WC1-Grab 4	24	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	2.04
WC2-Grab 1	1.8	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	0.15
WC2-Grab 2	11	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	0.94
	62	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	5.28
	19	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	1.62
	28	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	2.38
	22	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	1.87
WC2-Grab 3	13	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	1.11
	15	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	1.28
	8.1	25	298	0.0000825	6.65	3820	AA	0.002094	0.0852	0.69
Ethylbenzene										
WC1-Grab 1	1.1	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.35
	0.27	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.09
WC1-Grab 2	1.1	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.35
	1.7	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.54
WC1-Grab 3	0.91	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.29
	0.57	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.18
WC1-Grab 4	0.9	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.29
	0.54	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.17
	0.3	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.10
WC2-Grab 1	1.2	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.38
	1.2	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.38

(continued)

	Cl (µg/m3)	Temperature (C)	Temperature (K)	R (atm · m3)/ (mol · K)	A	B	Source	H (atm · m3)/ (mol · K)	HC	Cg (µg/m3)
WC2-Grab 2	1.2	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.38
	0.48	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.15
	1.3	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.42
WC2-Grab 3	1.4	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.45
	1.1	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.35
	1.9	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.61
WC2-Grab 4	2.5	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.80
	0.59	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.19
	3.2	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	1.02
IB Grab 1	0.7	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.22
	0.47	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.15
IB Grab 2	0.47	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.15
	0.47	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.15
IB Grab 3	0.73	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.23
	0.69	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.22
IB Grab 4	1.5	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.48
	0.49	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.16
	0.37	25	298	0.0000825	-4990	11.9	Z	0.007868	0.3200	0.12
1,4-Dichlorobenzene										
WC1-Grab 1	4.3	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.55
	3.1	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.40
	3.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.46
	1.8	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.23

(continued)

	C_l (μg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/(mol · K)	A	B	Source	H (atm · m^3)/(mol · K)	H_C	C_g (μg/m^3)
WC1-Grab 2	2.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.33
	2.9	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.37
	3.2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.41
	1.2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.15
WC1-Grab 3	6.2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.80
	2.7	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.35
	2.5	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.32
	1.8	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.23
WC1-Grab 4	4.4	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.57
	2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.26
	3.3	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.42
WC2-Grab 1	2.5	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.32
	3.8	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.49
	3.8	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.49
WC2-Grab 2	3.1	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.40
	5	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.64
	3.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.46
WC2-Grab 3	3.3	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.42
	4.4	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.57
	3.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.46
WC2-Grab 4	3.3	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.42
	4.4	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.57
	3.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.46
IB Grab 1	1.4	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.18
	1.2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.15
IB Grab 2	0.97	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.12
	1.2	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.15

(continued)

	C_l (µg/m^3)	Temperature (C)	Temperature (K)	R (atm · m^3)/ (mol · K)	A	B	Source	H (atm · m^3)/ (mol · K)	H_C	C_g (µg/m^3)
IB Grab 3	1.9	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.24
	0.9	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.12
IB Grab 4	1.5	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.19
	1.6	25	298	0.0000825	-2720	3.37	Z	0.003159	0.1285	0.21
Tetrachloroethylene (tetrachloroethene)										
WC2-Grab 2	0.51	25	298	0.0000825	12.5	4920	AA	0.018132	0.7375	0.38
WC2-Grab 4	0.64	25	298	0.0000825	12.5	4920	AA	0.018132	0.7375	0.47
IB Grab 1	1.8	25	298	0.0000825	12.5	4920	AA	0.018132	0.7375	1.33
IB Grab 2	2.1	25	298	0.0000825	12.5	4920	AA	0.018132	0.7375	1.55
IB Grab 3	2.4	25	298	0.0000825	12.5	4920	AA	0.018132	0.7375	1.77
IB Grab 4	1.5	25	298	0.0000825	12.5	4920	AA	0.018132	0.7375	1.11

Table F8

Miami Dade County

	C_l (µg/m^3) min/max	Temperature (C)	Temperature (K)	R (atm · m^3)/(mol · K)	A	B	Source	H (atm · m^3)/(mol · K)	H_C	C_g (µg/m^3)
Chloroform										
S1	1.9	20	293	0.0000825	9.84	4610	AA	0.002757	0.1140	0.22
	1.6	20	293	0.0000825	9.84	4610	AA	0.002757	0.1140	0.18
	1.3	20	293	0.0000825	9.84	4610	AA	0.002757	0.1140	0.15
	1.9	20	293	0.0000825	9.84	4610	AA	0.002757	0.1140	0.22
S2	1.8	20	293	0.0000825	9.84	4610	AA	0.002757	0.1140	0.21
	1.6	20	293	0.0000825	9.84	4610	AA	0.002757	0.1140	0.18
	2.3	20	293	0.0000825	9.84	4610	AA	0.002757	0.1140	0.26
	1.6	20	293	0.0000825	9.84	4610	AA	0.002757	0.1140	0.18
	1.9	20	293	0.0000825	9.84	4610	AA	0.002757	0.1140	0.22
1,4-Dichlorobenzene										
S1	2.1	20	293	0.0000825	-2720	3.37	Z	0.002703	0.1118	0.23
S2	3.6	20	293	0.0000825	-2720	3.37	Z	0.002703	0.1118	0.40
Toluene										
S1	7.5	20	293	0.0000825	-3020	5.13	Z	0.005644	0.2335	1.75
	4.9	20	293	0.0000825	-3020	5.13	Z	0.005644	0.2335	1.14
	4.1	20	293	0.0000825	-3020	5.13	Z	0.005644	0.2335	0.96
	8.6	20	293	0.0000825	-3020	5.13	Z	0.005644	0.2335	2.01
	3.8	20	293	0.0000825	-3020	5.13	Z	0.005644	0.2335	0.89
S2	5	20	293	0.0000825	-3020	5.13	Z	0.005644	0.2335	1.17
	5.2	20	293	0.0000825	-3020	5.13	Z	0.005644	0.2335	1.21
	4.6	20	293	0.0000825	-3020	5.13	Z	0.005644	0.2335	1.07
	6	20	293	0.0000825	-3020	5.13	Z	0.005644	0.2335	1.40
	4	20	293	0.0000825	-3020	5.13	Z	0.005644	0.2335	0.93
Tetrachloroethylene (tetrachloroethene)										
S1	2.9	25	298	0.0000825	12.5	4920	AA	0.018132	0.7375	2.14

APPENDIX G

Phone-Based Survey Results

This survey was conducted via phone. The following questions were asked:

Q1: How many sewer workers performing maintenance, testing, and inspections activities your organization has?
Q2: How many days per week the sewer workers are performing the activities mentioned above?
Q3: How many hours the sewer workers are performing the activities mentioned above?
Q4: What is the average time off per year (to include vacation days, sick days, holidays)?

Name of Municipality/County	Contact Person	Date Contacted	Q1 No. of workers	Q2 day/week	Q3 hour/day	Q4 week/year
City of Hallandale Beach	Director of Public Works	1/23/2018	6	5	6 to 8	(*)42 to 44
City of Margate	Engineer	2/6/2018	6	4	8 to 10	42 to 44
City of Hollywood	Director of Public Utilities	1/9/2018	15	4	8 to 10	42 to 44
City of Miami	Director of Public Works	1/5/2018	10	5	6 to 8	42 to 44
City of North Miami	Former Assistant Public Works Director	1/5/2018	16	5	6 to 8	42 to 44
City of Boca Raton	Director, Utility Services	1/4/2018	6	5	6 to 8	42 to 44
Broward County	Enterprise Director Operation (Water and Sewer)	2/27/2018	30	5	6 to 8	42 to 44
City of Pembroke Pines	Environmental Services Director	1/5/2018	8	4	8 to 10	42 to 44
Total			97			

(*) Vacation: 2 weeks is standard; for people working more than 7 to 10 years, vacation can extend to 3 weeks. Sick time: 0 to 12 days. Holidays: 10 to 12 days. Training: 2 to 4 days. Other events or equipment maintenance: 1 to 2 weeks.

VITA

MARIANA PITIRICIU

Hallandale Beach, Florida

1990 – 1995	B.S., Mechanical Engineering University of Petroleum & Gas Ploiesti, Romania
2003 – 2004	M.S., Environmental Engineering Florida International University Miami, Florida
2013 – 2019	Doctoral Candidate Florida International University Miami, Florida

Licensed civil engineer and project management professional with remarkable experience in planning, budgeting, design, construction, and administration of capital improvements projects (water, sewer, public facilities, water treatment plant, airport infrastructure). Profound experience in the practice of civil engineering, project management, contracts and proposal negotiations, design, plan review, cost estimation, planning, contract administration, and legalities for public works engineering functions. Deep knowledge of techniques used in municipal stormwater, water, sewer, bridges, roadway, ADA projects, budgetary, contract negotiation, and bid process principles. Remarkable skills in reviewing plans, directing work, and formulating precise reports. Knowledge of the National Flood Insurance Program (NFIP), Community Rating System (CRS) and National Pollutant Discharge Elimination System (NPDES).

- P.E. – Professional Engineer License - State of Florida P.E. Lic. No: 67384
- PMP – Project Management Professional - PMP Number 1589210
- CFM – Certified Floodplain Manager - Number: 24989
- Qualified Stormwater Management Inspector
- FEMA, IS-100, IS-200, and IS-700

Construction Project Management Supervisor Jan. 2018 – Present
Broward County Aviation Department, Fort Lauderdale-Hollywood Int. Airport

Project Manager supervisor for airport capital projects exceeding one billion dollars; contact administrator for design and construction of large projects (Terminal Modernization, Airport Expansion, Landside and Airside improvements, and Utility Infrastructure); design proposals and construction contracts negotiations.

Assistant Director of Public Works/City Engineer June 2014 – Jan. 2018
City of Hallandale Beach
City Engineer Feb. 2005 – June 2014
City of Miami Gardens

Administrative, supervisory, and professional engineering work necessary to manage the Engineering Division of Public Works Department, which incorporates the functions of engineering, budget preparation, design, construction administration, project management, utility master plans, plan review, floodplain management, National Pollutant Discharge Elimination System (NPDES), Geographic Information System, and to fulfill the statutory obligations and ensures engineering-related compliance to engineering standards, government regulations, and codes. Coordinates and undertakes the development or update of the Transportation, Water, Sewer and Stormwater Comprehensive Master Plans and the Capital Improvement Program.

- PMI – Project Management Institute
- ASCE – American Society of Civil Engineering
- AEEE – American Association of Airport Executives
- ASFPM – Association of State Floodplain Managers
- APWA – American Public Works Associations
- APWA – Board Member of South Florida Branch; 2016 – Present
- APWA - Scholarship and Awards Committee Chair; 2015 – Present
- Academy of Graduates for Integrative Learning Experiences (AGILE), Florida International University, 2014
- Selected for the Broward County Leadership Roundtable Program by the FLL Airport Development Officer, 2019–2020
- Selected as a Subject Matter Expert by the Project Management Institute (PMI) to review white papers and presentation submissions for the PMI Global North America and EMEA Congresses, 2015 – Present
- Attended the PMI Global Congresses North America and EMEA (London, UK, 2015; Orlando, Barcelona, Spain, 2016; San Diego, California, USA, 2016; Rome, Italy, 2017, Berlin, Germany, 2018, California, USA, 2018)
- Obtained recognition annually from PMI for volunteering work, 2015 – Present
- Attended several ASCE annual conferences, 2006 – Present
- Attended International Congress of Engineering Infrastructure, Canal de Panama, 2012