ADDIS ABABA UNIVERSITY

AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT

Evaluation of Formation and Health Risks of Disinfection By-Products in Drinking Water Supply of Ggaba Waterworks, Kampala, Uganda

By:

Annitah Nshemereirwe

July, 2021

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A thesis submitted to the Africa Center of Excellence for Water Management in partial fulfillment of the requirement for the degree of Master of Science in Water Management with specialization in Water Supply and Sanitation.

July, 2021

DECLARATION

I, Annitah Nshemereirwe, hereby declare that this thesis has been done by myself and where information is sourced has been acknowledged in the text.

Annitah Nshemereirwe GSR/8425/12

Signature........................ Date...13/07/2021...

CERTIFICATE OF APPROVAL

The undersigned, certify that this thesis titled ***Evaluation of Formation and Health Risks of Disinfection By-Products in Drinking Water Supply of Ggaba Waterworks, Kampala Uganda*** is a result of the authors work, and that to the best of our knowledge it has not been submitted for any other academic qualification within Addis Ababa University or elsewhere. The thesis is acceptable in form and content, and that satisfactory knowledge of the field covered by thesis was demonstrated by the candidate through oral examination held on 16th June 2021 at African Center of Excellence for Water Management (ACEWM) Addis Ababa University, Ethiopia.

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DEDICATION

I dedicate this study to my late grandfather Professor James Patrick Ntozi Manyenye who passed away on the 19th May 2021 and my Guardian Aunt Caroline Korutaro Victoria Chomi who also passed away on the 19th June 2021. May their souls rest in Eternal Peace. Thank you for the support towards my education and Career. Forever in my heart. Till we meet again.

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ABSTRACT

In developing countries, the evaluation of DBPs has been neglected because most water utility companies focus on microbial elimination. As a result, this study aimed at evaluating THMs formation, their concentration, the effect of other water quality parameters and estimation of the associated potential health risks in drinking water. The study considered evaluation of THMs because they are the most common, and are used as indicators for total DBPs concentration. The USEPA 524.2 method was used to quantify THMs in water while utilizing the headspace purge and trap coupled with a GC-MS technique. The THMs identified were chloroform in the concentration ranging from 11.87-33.98 µg/L and 11.23-39.30 µg/L at the treatment plant and along the distribution system respectively. Bromodichloromethane was in the range from 0.78-9.43 µg/L and 0.89-9.49 µg/L at the treatment plant and along the distribution system, respectively. The concentrations of THMs found in water were within NWSC, WHO and USEPA guidelines. Running a Pearson correlation, to find the relation between water parameters; TOC, $UV_{254,}$ bromide concentration, temperature had a positive and significant correlation, pH had a positive but non-significant correlation while the residual chlorine had a negative but significant correlation. Potential health risk was evaluated using the WHO index and the USEPA risk estimation model. WHO index was 0.4104 which was less than unity indicating no noncarcinogenic risk to human health in the study area. The human lifetime carcinogenic risk of THMs due to the oral ingestion, dermal and inhalation were 2.54×10^{-5}, 9.08×10^{-6} and 8.29×10^{-6} for females and 2.44×10^{-5}, 1×10^{-5} and 7.96×10^{-6} for males, the values were within the USEPA acceptable low risk range of $1\times 10^{-6} < CR < 5.1 \times 10^{-5}$. Also, the hazard quotient was less than unity, indicating no adverse health effects due to exposure to THMs in Kampala western zone.

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ACRONYMS

ANOVA	Analysis of Variance
APHA	American Public Health Association
BDCM	Bromodichloromethane
CSF	Cancer Slope Factor
CR	Cancer risk
DBP	Disinfection by Products
DBCM	Dibromochloromethane
DOC	Dissolved Organic Carbon
DPD	Diethylphenyldiamine
EPA	Environmental Protection Agency
GC	Gas Chromatography
HAAs	Haloacetic Acids
HANs	Haloacetic Nitriles
HOCL	Hypochlorous Acid
HS-GC-MS	Headspace Gas Chromatographic Mass Spectrometry
IRIS	Integrated Risk Information System
LADD	Lifetime Average Daily Dose
LLE-GC-ECD	Liquid-Liquid Extraction Gas Chromatographic Electron Capture Detection
LLE-GC-MS	Liquid-Liquid Extraction Gas Chromatographic Mass Spectrometry
LSD	Least Significant Difference
LVEMP	Lake Victoria Environmental Management Program
MCL	Maximum Contaminant Level
NOM	Natural Organic Matter
NWSC	National Water and Sewerage Corporation
OCl^-	Hypochlorite ion
P&T-GC-MS	Purge and Trap Gas Chromatographic Mass Spectrometry

POC	Particulate Organic Carbon
RSD	Relative Standard Deviation
SE	Standard error
THMs	Trihalomethanes
TTHMs	Total trihalomethanes
TOC	Total Organic Carbon
USEPA	United States Environmental Protection Agency
UBOS	Uganda Bureau of Statistics
UN	United Nations
UNICEF	United Nations Children's Fund
UV_{254}	Ultraviolet absorbance at 254nm
WHO	World Health Organization

1.0 INTRODUCTION

1.1 Background

Availability and accessibility of safe, affordable drinking water and sanitation services are not only human basic needs but also human rights. The human rights agenda necessitates that the water required for domestic consumption must be safe and free from micro-organisms, chemical and radiological hazards that threaten human health (UN-Water, 2019). Despite safe drinking water being a basic human right, there are populations that do not have access to safe drinking water. In 2015, 2.1 billion people worldwide did not use a safely managed drinking water facility, whereas 844 million people still lacked a basic drinking water facility (WHO/UNICEF, 2017). Also, the coverage of safe drinking water supply varies across regions; 94% for European countries and 24% for sub–Saharan Africa countries (UN-Water, 2019).

Urban areas in developing countries are facing challenges in provision of adequate and safe drinking water. This is attributed to more rapid population growth, and urbanization, which Africa has experienced over the past two decades in comparison to other regions (Bahri et al., 2016). The rapid population growth has led to an increase in water demand hence intermittent water supply. The intermittent water supply leads to reduced water supply pressures and also the water is highly susceptible to contamination (Vairavamoorthy, 2007). Also, there is increased pollution of water sources attributed to poor solid waste and wastewater management practices in urban centers (Jain, 2012). Furthermore, there is a challenge of climate change and this has led to extreme weather events such as floods that lead to damage of the water supply infrastructure hence water loss. Whereas droughts reduce the water levels leading to deterioration of water quality and quantity of the water resources (Howard et al., 2016). Due to the polluted water sources, the water utility companies incur high treatment costs to provide safe water to the population.

Water utility companies are mandated to provide clean, safe potable drinking water to the population. To meet this requirement, disinfection by chlorination, ozonation, and ultraviolet light methods are used to kill pathogens including viruses and bacteria to ensure the water is free from disease-causing microorganisms hence, fit for human consumption. Disinfection by chlorination is the most widely used method for the inactivation of pathogenic microorganisms in water because it’s readily available, easy to use, relatively low cost, and its ability to form residual chlorine along the distribution system to avoid recontamination (USEPA, 2011). This method provides hygienically quality drinking water.

Worldwide and Africa in particular, there is increasing pollution of surface water caused by point and non-point sources, which increases the organic matter load in the raw water abstracted for treatment (Fayiga et al., 2018). When the organic matter reacts with chlorine in the water in the form of hypochlorous acid and hypochlorite, there is the formation of unwanted DBPs predominantly trihalomethanes (THMs) and haloacetic acids (HAAs) (Durmishi et al., 2015). THMs are categorized into four compounds namely chloroform ($CHCl_3$), bromoform ($CHBr_3$), dibromochloromethane ($CHClBr_2$), bromodichloromethane ($CHBrCl_2$). The chloroform takes the highest proportion of THMs in drinking water (Ristoiu et al., 2009) .

Trihalomethanes formation is affected by the water source, bromide concentration, temperature, organic matter, pH, and residual chlorine (Guo et al., 2016). The natural organic matter (NOM) consists of chemical compounds categorized as hydrophilic part comprised of carbohydrates, amino acids, and a hydrophobic part consisting of fulvic and humic acids. The hydrophobic part comprises of 50-90% total dissolved organic carbon (DOC) in surface water, and is predominated by humic materials (Pérez et al., 2017). The humic materials are resistant to biodegradation and instead they react with chlorine to form increased levels of THMs (Tak & Vellanki, 2018). Chlorine reacts with aromatic compounds such as humic acids by electrophilic substitution. Electrophilic aromatic substitution is an organic reaction where an atom attached to an aromatic system that is hydrogen is substituted by an electrophile hence formation of THMs (Bond et al., 2012).

The Maximum Contaminant Level (MCL) for total THMs in drinking water is 100 μg/L according to World Health Organization (WHO) guidelines (WHO, 2012). Drinking water with THMs at the MCL level of 0.1 mg/L signifies a chance of 1 in 1,000,000 carcinogenic risks based on a drinking rate of 1.5-2 liters per day for 70 years (Du et al., 2001). Disinfecting water by chlorination to protect the public health from water-borne diseases poses health risks such as carcinogens, and reproductive disorder in humans (Boorman et al., 1999; Richardson, 2011; Pan et al., 2014). This is a concern that requires to be addressed by engineers, chemists, and policymakers in a way that elimination of pathogens is achieved and also no increase in the formation of DBPs in water supply systems that pose health risks (Boorman et al., 1999). Epidemiological studies have indicated health risks such as colon, rectal, bladder cancers associated with disinfection by products whereas non carcinogenic health risks included delayed pregnancies, stillbirth, fetal loss among US women who had been exposed to DBPs (Villanueva et al., 2015).

Most developing countries have neglected the formation of the DBPs in drinking water and instead only focus on the microbiological WHO guidelines for drinking water (Durmishi et al., 2015). In Uganda, like any other developing country, surface water sources have become polluted. National Water and Sewerage Corporation (NWSC) is the public water utility company mandated to supply piped water and provide sewerage services across Uganda. Most municipal water supplies utilize disinfection by chlorination as part of the water treatment processes. Ggaba waterworks is the largest water supply for Kampala City supplying 226 cubic meters per day to approximately 2,551,299 million people and utilizes Lake Victoria as its water source (NWSC, 2019).

Lake Victoria contains organic matter either from autochthonous sources where the organic matter is created in the interior of the water column from algae and phytoplankton activities, or from allochthonous sources where the organic matter is created from inputs getting into the water from outside the water body such as the discharge of industrial and municipal wastewater effluents, drainage, and runoff from agricultural fields near the lake shores (Deirmendjian et al., 2020). The allochthonous sources are dominated by hydrophobic contents therefore the formation of THMs is inevitable (Tak & Vellanki, 2018). According to the Lake Victoria Environmental Management Program (LVEMP), the organic matter levels in Lake Victoria were 7.5 mg/L (LVEMP, 2005). In addition, a recent study carried out found out that the dissolved organic carbon was 23 mg/L in bays and 18.5 mg/L in open waters of Lake Victoria (Deirmendjian et al., 2020).

From the literature reviewed, no study on DBPs has been done at the Ggaba waterworks and along the distribution system. The study considered evaluation of THMs because they are the most common, regulated compounds and are used as an indicator for total DBPs concentration (Whitaker et al., 2003). Therefore, there was a need to evaluate the THMs in drinking water at the Ggaba waterworks, along the distribution system, and estimate the potential health risks associated with THMs in drinking water.

1.2 Problem Statement

In Uganda, National Water and Sewerage Corporation is facing a challenge of heavy pollution of the surface water sources due to point and non-point pollution sources. Due to this, the organic matter load in raw water sources has increased. Disinfection by chlorination is the most used method to ensure the safety of drinking water. Despite the advantages of chlorine, using it in the presence of organic matter leads to the formation of DBPs such as trihalomethanes which are carcinogenic to humans once consumed in water in quantities above the set guidelines (Ferreira & Cunha, 2012). The increased organic matter overloads the conventional water treatment system therefore an operational gap that leads to an increase in formation of DBPs. Previously, a study was carried out at Masaka waterworks to determine the characteristics and levels of the natural organic matter in raw water sources and along the treatment train (Kalibbala et al., 2011). Also, another study was carried out at Palorinya surface water treatment plant in a refugee settlement in northern Uganda which aimed at characterizing the DBPs levels (Ali et al., 2019). However, the occurrence of the DBPs formation along the distribution system has not been considered in previous studies. In addition, there is a gap in finding the relation between the water quality parameters and the formation of DBPs at the treatment plant and along the distribution system. There is no research carried out concerning the formation of DBPs at Ggaba waterworks in Uganda. Furthermore, no attempt has been made to estimate the potential health risk associated with THMs in drinking water. Therefore, there is a need to carry out a study to evaluate formation of DBPs considering THMs in drinking water at the Ggaba waterworks and along the distribution system, find the influence of other water quality parameters on the formation of DBPs, and to estimate the potential health risk associated with THMs.

1.3 Objectives of the Study

1.3.1 Main Objective

To evaluate the formation and health risks of disinfection by-products in drinking water supply at Ggaba waterworks and along the distribution system.

1.3.2 Specific Objectives

1. To determine the concentration of trihalomethanes in drinking water at Ggaba waterworks and along the distribution system.

2. To assess the relation between water quality parameters and formation of trihalomethanes.

3. To evaluate potential health risks associated with trihalomethanes.

1.4 Research Questions

1. What is the concentration of trihalomethanes in drinking water at Ggaba waterworks and along the distribution system?

2. What is the relation between water quality parameters and formation of trihalomethanes?

3. What are the potential health risks associated with trihalomethanes?

1.5 Scope of the Study

The study was limited to evaluate THMs at the Ggaba waterworks and along the distribution system Kampala water western zone Uganda. The study was to find out the THMs concentration, assessed the relation between water quality parameters and formation of THMs, and evaluated the potential health risk associated with THMs. The study was conducted for a period of 3 months from January to March 2021.

1.6 Significance of the Study

The research will fill the knowledge gap about the THMs formation at the Ggaba waterworks and along the distribution system, this knowledge will be used in decision making. NWSC Kampala Uganda will embrace the culture of continuous monitoring for THMs formation at other waterworks and along the distribution system.

After the study, if the potential health risks associated with the concentration of THMs in water is negligible, the customers will have confidence in the product being supplied by NWSC. On another hand, if the concentration of THMs in the water leads to potential health risks, then NWSC Ggaba waterworks water quality department will have to ensure that the subsequent processes before disinfection are performed effectively to minimize formation of THMs.

2.0 LITERATURE REVIEW

2.1 Disinfection Technologies

Disinfection is a treatment process applied in water to kill pathogens including viruses, bacteria, and other microorganisms in water to protect the consumers from water-borne diseases. There are various disinfection techniques ranging from non-chemical that is ultraviolet light radiation to chemical methods such as the use of chlorine and its compounds, chloramines, and ozone (Saqib Ishaq et al., 2019).

2.1.1 Ultraviolet Light Disinfection

Water to be treated is passed through the disinfection chamber, the microorganisms in water absorb the ultraviolet light and the cells are damaged. This method has the ability to destroy the giardia and cryptosporidium cells (USEPA, 2011). Figure 2.1 illustrates the assembly of the ultraviolet light disinfection.

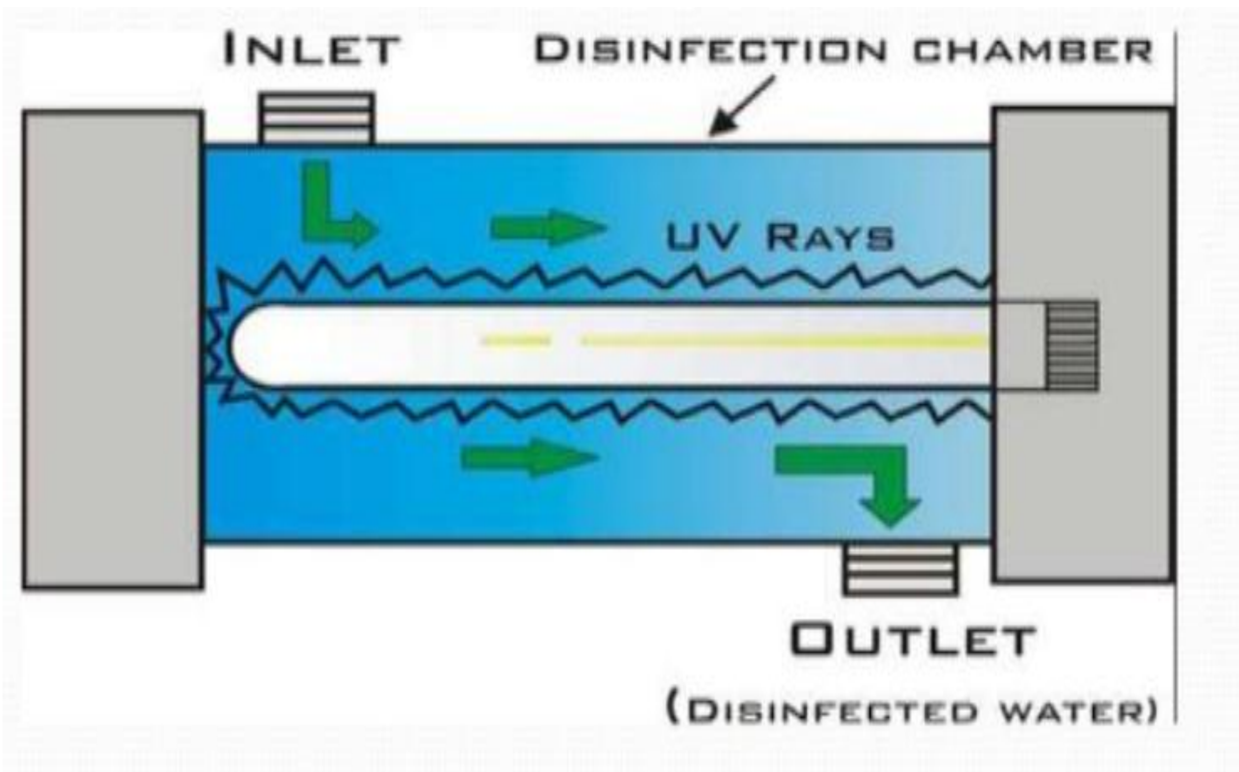

Figure 2.1: Ultraviolet Light Assembly Adopted from (Gowri, 2015)

2.1.2 Ozonation

Ozone is a widely used disinfectant in European countries and it's a strong oxidizing agent. Ozone is generated on-site passing oxygen through an electric field. After generation, the ozone is injected into the water to be treated and it dissolves and oxidizes microorganism cells hence killing the pathogens (Zierler, 1992; Saqib Ishaq et al., 2019). A typical ozonation process is presented in Figure 2.2 below.

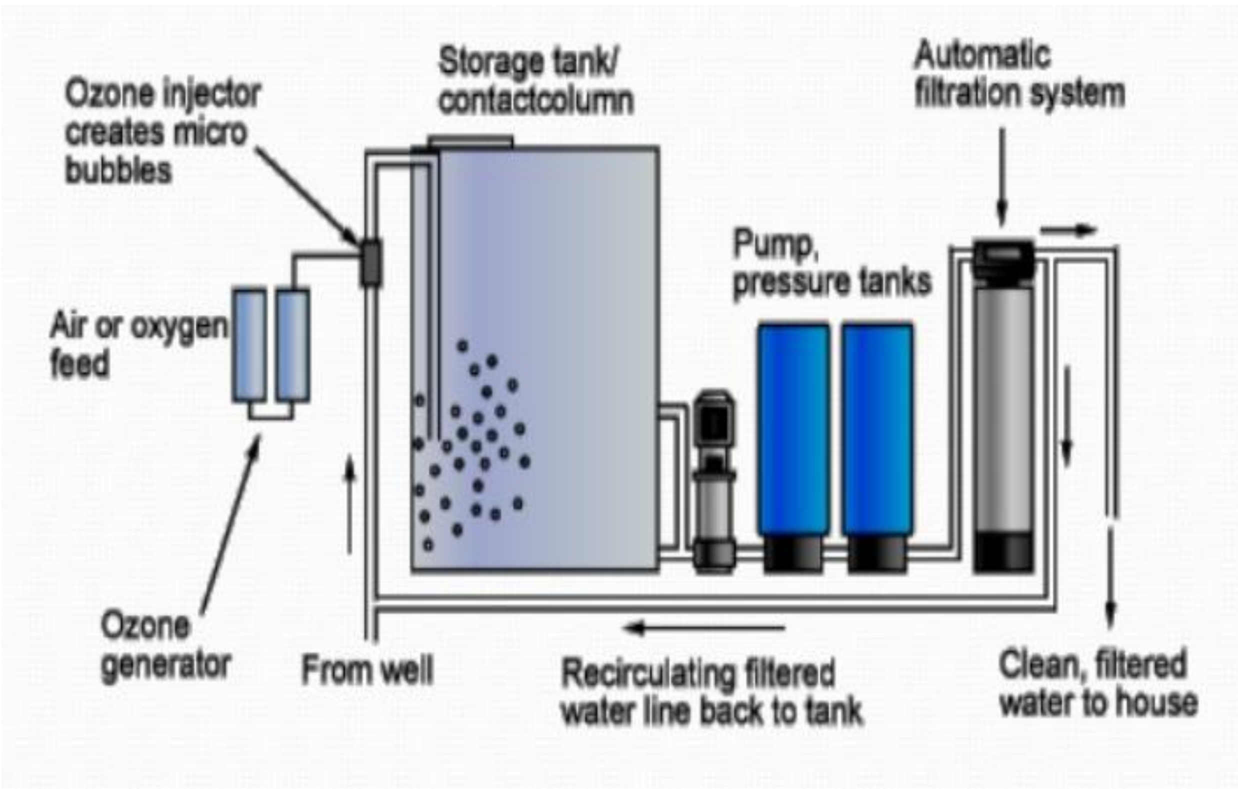

Figure 2.2: Ozonation Process Adapted from (Gowri, 2015)

2.1.3 Chlorine and its Compounds

Chlorine is the most widely used disinfectant. When chlorine is added to water, there is the formation of hypochlorous acid and hypochlorite ion. The hypochlorous acid (HOCl) is electrically neutral and hypochlorite ion (OCl^-) is electrically negative, the two species behave differently. Chlorine inhibits enzymatic activity and inactivates bacteria and viruses. Pathogen shells carry a natural negative electrical charge and these surfaces are easily infiltrated by the electrically neutral hypochlorous acid than the negatively charged hypochlorite ion. Hypochlorous acid effectively destroys pathogens (Zierler, 1992).

Chlorine Gas as a Disinfectant

Chlorine gas is a greenish gas whereby under high pressure it can be converted into liquid. Chlorine gas is used for the disinfection of water. Its main advantage is the ability to work as a primary and secondary disinfectant (Saqib Ishaq et al., 2019). Equation 2.1 shows the reaction between chlorine gas and water.

$$Cl_2 + H_2O \leftrightarrow H^+ + Cl^- + HOCl \tag{2.1}$$

Chlorination (Sodium hypochlorite)

The solution comprises 10-15% of concentration chlorine (Muhammed, 2018). It is used as a disinfectant and effective as chlorine. Equation 2.2 shows the reaction between sodium hypochlorite and water.

$$2NaOCl + 2H_2O \leftrightarrow 2NaOH + HOCl + OCl^- + H^+ \tag{2.2}$$

Calcium hypochlorite

Calcium hypochlorite is mainly in the form of solid that is granules, pellets, powder. The granular is in the form of chlorinated lime or High-Test Hypochlorite (HTH) whereby the concentration of chlorine is 65-70% (USEPA, 2011). Equation 2.3 shows the reaction between calcium hypochlorite and water.

$$CaOCl_2 + 2H_2O \leftrightarrow CaOH_2 + 2HOCl \tag{2.3}$$

Chloramines as disinfectants

Chloramines are chemical compounds formed by a combination of chlorine and ammonia in water. Chloramines are weak disinfectants and they are seldom used as a primary disinfectant (USEPA, 2011). Chloramines are used as a secondary disinfectant for long distribution systems.

Table 2.1 compares the different disinfection technologies used in water treatment versus their corresponding operational parameters.

Table 2.1: Compares Disinfection Technologies versus Operational Parameters

		Disinfection technology			
#	**Parameter**	**Ultraviolet Radiation**	**Chlorination**	**Ozonation**	**Chloramines**
1	Operating cost	High cost	Relatively low cost	High costs	Relatively low cost
2	Availability	Hardly	Readily	Hardily	Readily
3	Effectiveness	Highly effective kills bacteria, viruses, giardia, cryptosporidium	Highly effective in activating pathogens except giardia, cryptosporidium	Highly effective kills bacteria, viruses, giardia, cryptosporidium.	Inactivates pathogens
4	Ability to form residuals	No residuals	Forms residual chlorine	No residuals	No residuals
5	Formation of DBPs	No by-products	THMs, HAAs formed	No by-products	Reduced DBPs
6	Odour and taste	Lower odour and taste	Unique odour and taste	No taste and odour problems	Lower taste and odour
7	Energy requirement	High energy required	No energy	Energy required	No energy
8	Chemical requirement	No chemicals	Chemicals required	No chemical	Chemicals required

Source: (EPA (Ireland), 2011; Saqib Ishaq et al., 2019)

2.2 Disinfection By-Products in Drinking Water

Disinfection by-products result from a chemical reaction between disinfectants and natural organic matter (NOM) present in natural water. NOM is a composite of organic material present in all-natural surface waters. NOM is generated from the breakdown of matter in the environment surrounding the fresh surface water such as leaves and aquatic plants. Total organic carbon (TOC) is taken as a good pointer of the existence of NOM in natural water. TOC consists of dissolved organic carbon (DOC) and particulate organic carbon (POC), of which DOC makes up approximately 99% of the TOC (Pérez et al., 2017 ; Ewaid, 2019).

2.2.1 Mechanism of Disinfection by Product Formation

The primary disinfection by-products are formed from the breakage under chlorine influence of polyphenol ring through the three paths a, b and c, as seen in Figure 2.3.

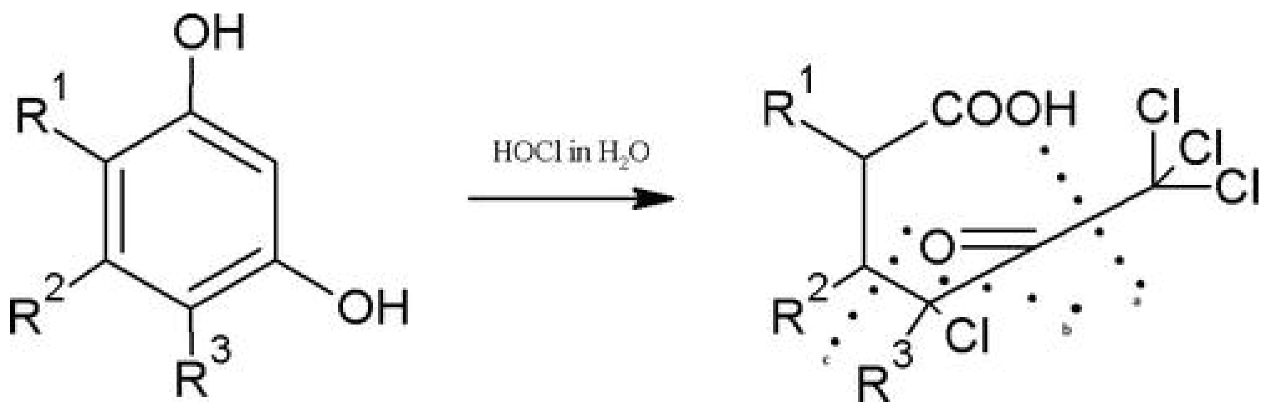

Figure 2.3: Mechanism of Formation of Disinfection by Product Adopted from (Rosero-moreano, 2018).

Whenever the breakage is through path a, there is formation of halomethanes, whereas path b with addition of a hydroxide, the haloacetic acids are formed. Path c leads to the formation of haloketones. The primary disinfection by products in the presence of bromine or iodine react and form bromohalomethane, iodotrihalomethane, and haloacetonitriles (Rosero-moreano, 2018). The DBPs formation likely is directly associated to the levels of NOM in natural water and the quantity of disinfectant used in the disinfection process. Table 2.2 below shows the disinfection by products formed in drinking water while utilizing different types of disinfectants.

Table 2.2: Disinfection By-Products in Drinking Water

Disinfectant	Significant Organo halogenated by- Products	Significant Inorganic by- Products	Significant Non-halogenated by -Products
Chlorine /hypochlorites	Trihalomethanes	Chlorate for hypochlorites	Aldehydes
	Haloacetic Acids		Cyanoalkanoic Acids,
	Haloacetic Nitriles		Alkanoic Acids
	Chloropicrin		Benzene
	Chloral hydrate		Carboxylic Acids
	Chlorophenols		
Chloramines	Haloacetic Nitriles	Nitrate	Aldehydes
	Cyanogen chloride	Nitrite	Ketones
	Organic chloramines	Chlorate	
	Chloramine acids	Hydrazine	
	Chloral acids		
	Chloral hydrate		
	Haloketones		
Ozone	Bromoform	Chlorate	
	Monobromomethane	Iodate	Aldehydes
	Dibromoacetone	Bromate	Ketones
	Cyanogen bromide	Hydrogen peroxide	Ketoacidosis
		Ozonates	Carboxylic acids

Source:(Pérez et al., 2017)

The use of chlorine for disinfection leads to the formation of THMs, HAAs, and Haloaceticnitriles (HANs). The two main categories of DBPs regulated by the United States Environmental Protection Agency (USEPA) are the four forms of THMs that are bromoform, chloroform, dibromochloromethane, bromodichloromethane and the five forms of HAAs that are dichloroacetic acid, trichloroacetic acid, chloroacetic acid, bromoacetic acid, and dibromoacetic acid (Clark & Boutin, 2001; Richardson, 2011). Between THMs and HAAs, THMs predominate in drinking water (Al-Mudhaf & Abu-Shady, 2008 ; Durmishi et al., 2015 ; Fakour & Lo, 2018).

THMs are used as an indicator for total DBPs concentration in drinking water (Whitaker et al., 2003). Therefore, the study evaluated THMs as the DBPs in drinking water.

2.3Trihalomethanes in Drinking Water

Dating back in the 1970s, Rook discovered that chlorine reacted with dissolved organic materials in water to form chlorination disinfection byproducts known as trihalomethanes (THMs) (Hrudey & Fawell, 2015). Trihalomethanes are colorless, volatile in liquids, and soluble in water.

THMs are halogen substituted single carbon complexes having a general chemical formula CHX_3, where X is usually chlorine or bromine or mixture of the two. THMs occur in the following four forms: Chloroform (CF) $CHCL_3$, bromoform (BF) $CHBr_3$, dibromochloromethane (DBCM) $CHBr_2Cl$, and bromodichloromethane (BDCM) $CHCl_2Br$ (Ristoiu et al., 2009).

Chloroform is a commonly occurring THM found in drinking water. Chloroform is an organic compound with chemical structure $CHCl_3$, a molecular weight of 119.386 g/mol, it does not have color but has an ether odor, and a density of 1.4788 g/cm^3 (Boorman et al., 1999 ; Pérez et al., 2017).

Dibromochloromethane (DBCM) is the second most commonly occurring THM. It has chemical structure $CHClBr_2$, the molecular weight of DBCM is 208.28 g/mol, yellow, sweet odor compound, the density of 2.451 g/cm^3 (Pérez et al., 2017).

Bromodichloromethane (BDCM) is the least common THM. BDCM can dissolve in water and evaporate into the air therefore the amount found in drinking water is lower as compared to other trihalomethanes. BDCMs with chemical structure $CHBrCl_2$, the molecular weight of 163.823 g/mol, the colorless, nonflammable, density of 1.98 g/cm^3 (Pérez et al., 2017).

Bromoform is the second least common THM. It is a non-flammable, pale yellow, sweet odor, the chemical structure of $CHBr_3$, the molecular weight of 252.731 g/mol, the density of 2.89 g/cm^3 and is slightly soluble in water (Pérez et al., 2017).

The natural organic matter and chlorine undergo a complex reaction as seen in Figure 2.4 that indicates the trihalomethanes formation pathway in drinking water.

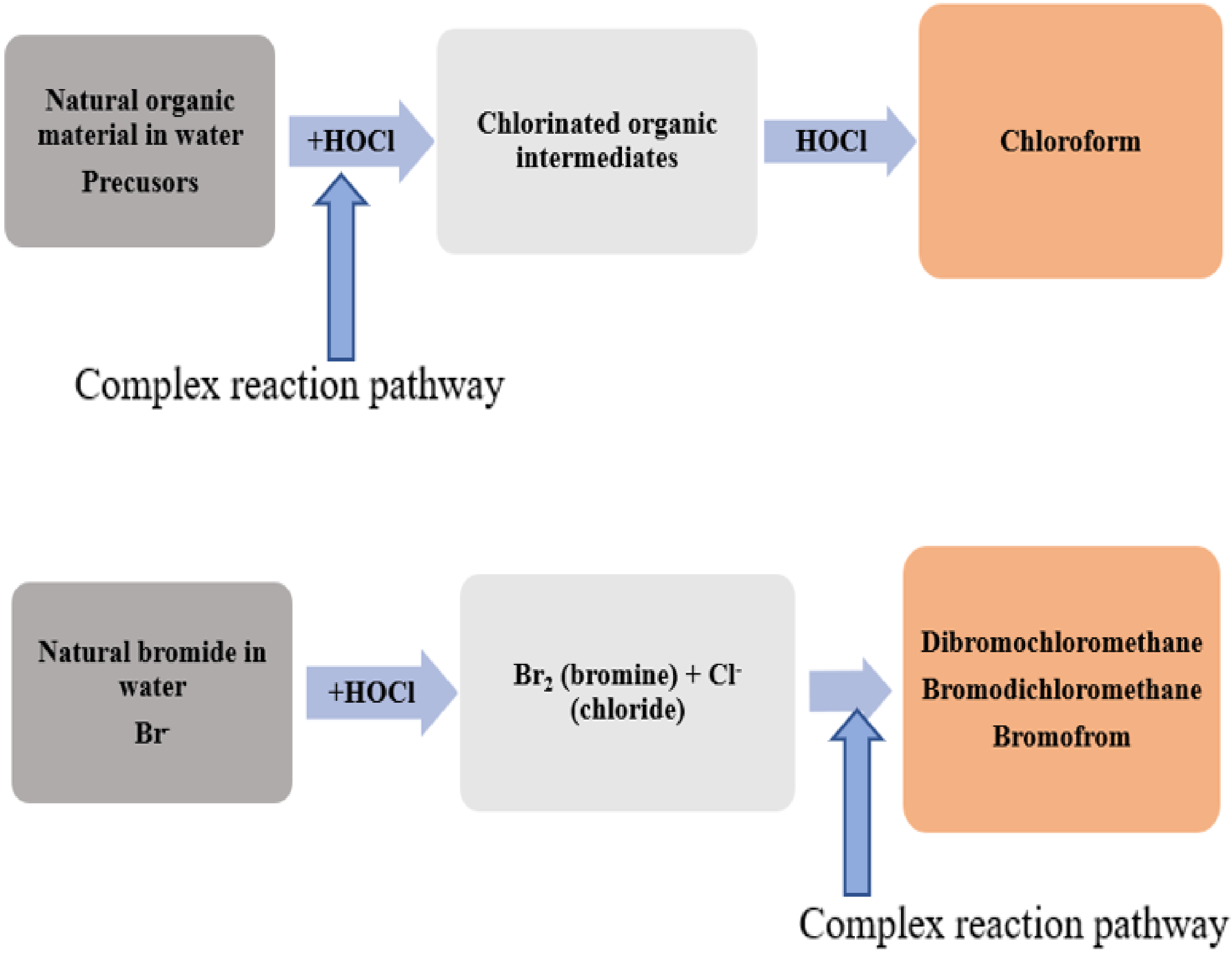

Figure 2.4: Formation of Trihalomethanes Pathway Adopted from (Pérez et al., 2017).

The natural organic matter in presence of hypochlorous acid undergo a complex reaction to form chloroform. THMs are the dominant DBPs in chlorinated drinking water, therefore they are considered as an indicator of the presence of other DBPs (Whitaker et al., 2003). Also, of the four THMs, chloroform is the most occurring and has been detected in several studies (Rodriguez et al., 2003). In the existence of bromides in the water, brominated THMs are formed in high concentrations compared to chloroform (Wang et al., 2017).

Drinking chlorinated water containing THMs has adverse health effects such as being carcinogenic, causing reproductive, nervous system complications as reported from numerous studies (Boorman et al., 1999; Pan et al., 2014; Durmishi et al., 2015). THMs have been categorized as carcinogens by the USEPA into three groups; group B1 includes chloroform (possible human carcinogens with limited human data), group B2 includes bromodichloromethane and bromoform (probable human carcinogen with sufficient animal data), and then group C consists of dibromochloromethane (possible human carcinogen) (Pardakhti et al., 2011).

2.3.1 Methods of Measurement of Trihalomethanes in Drinking Water

There are numerous ways to determine THMs in drinking water. The Gas Chromatography (GC) in combination with either Electron Capture Detection (ECD) or Mass Spectrometry Detection (MSD) is the most used method to determine THMs in drinking water (Pérez et al., 2017). The THMs concentration ranges from ng/l to µg/l, therefore, it's of great importance to carry out preconcentration of the analyte to obtain THMs amounts that are measurable. The preconcentration is done to improve the sensitivity, accuracy, reliability of the analysis for THMs (Pérez Pavón et al., 2008). Conventional procedures such as liquid-liquid extraction (LLE), headspace and purge and trap (P&T) are commonly used for water sample preparation in water analysis using GC (Ahmad & Mechor, 2012).

Liquid-Liquid Extraction

This is the most commonly used method for the separation of THMs from the water samples. The process of extracting compounds is achieved by the addition of anhydrous sodium sulfate. This increases the ionic strength of solution thus facilitating the extraction of THMs due to salting-out effect (Pérez Pavón et al., 2008). The extracted solvent is directly injected into the GC. However, despite the advantages of being a simple, relatively low-cost investment technique, its time consuming, there is formation of emulsions and requires a large amount of solvents to exhaust the analytes from the water sample. Also, the solvents used are toxic in nature therefore posing adverse effect to the environment. In addition, sample manipulation is high, therefore loss of the compounds of interest may occur due to their high volatility (Kanchanamayoon, 2015).

Purge & Trap

This method doesn’t require organic solvents and is set in line with the chromatographic system therefore analysis is done in a closed system (Pérez Pavón et al., 2008). An inert gas is passed through the aqueous sample to volatilize the THMs. Compounds that have low water solubility, higher vapor pressure than water are transferred to the gaseous phase. The compounds are brushed from the purging device and are trapped into a short column containing a sorbent. After a given period, the trapped compounds are thermally desorbed and directed into the GC column and separated based on their retention (EPA, 1979).

A previous study carried out in Greece compared the performance of the analytical methods for the determination of DBPs (THMs, HANs, halo ketones, chloral hydrate, and chloropicrin) in drinking water. The LLE–GC– ECD, LLE–GC–MS, P&T–GC–MS, HS–GC–MS techniques were used to analyze the drinking water samples. Among these, LLE–GC–ECD technique demonstrated to be the most sensitive for the determination of DBPs in drinking water, followed by LLE–GC–MS (Nikolaou et al., 2002).

Recently, a study has been carried out using the LLE-GC-MS to determine the THMs concentration in seven villages of Marvdasht Far in Iran. The study revealed that the mean concentrations of chloroform, bromoform, dibromochloromethane, and bromodichloromethane in all samples during spring as 22.25, 11.42, 5.95, and 7.43 μg/L, respectively, and the summer values were 14.69, 7.55, 3.95 and 3.93 μg/L, respectively. Also, the mean concentration of total THMs was 47.06 μg/L in spring and 31.13 μg/L in summer. The THMs concentrations for two seasons were compared using paired and one-sample t-tests and the study revealed there was no significant difference between total THMs concentration in spring and summer. All the THMs concentrations were less than the USEPA's 80 µg/l (Nasiri et al., 2020).

A study carried out in Egypt to determine the concentration of THMs in drinking water using EPA Method 551.1 Four communities sited in Alexandria were selected for study and the THMs concentrations ranged from 12 to 74 µg/L which met the Egyptian THMs drinking water standard of 100 µg/l (Abdullah, 2014).

From the literature reviewed, the LLE method is the most used in extraction of THMs, however, due to the requirement of large quantities of organic solvents which are toxic in nature, time consuming process, and formation of emulsions, the purge and trap extraction technique was coupled with a GC-MS in the determination of THMs in drinking water in this study.

Working Principle of the Purge and Trap GC-MS technique

According to the user manual, the inert gas purges the sample and the volatile compounds are transferred and adsorbed into a trap. The trap is heated adequately to desorb the volatile compounds, these compounds are transferred by the carrier gas into the GC column. In the GC column separation of different chemical compounds is according to their volatility and polarity. As the vaporized compounds pass through the column, the oven where the column resides gradually increases in temperature through the pre-programmed method (Patil & Ramaswamy, 2017). The GC column has a stationary phase and a mobile phase, these two phases interact and compounds are separated according to their ability to partition between the phases. The highly volatile compounds leave the GC column faster and have less retention time. At the end of the column, the compounds hit the detector and proportional peaks of each compound are recorded on a chromatogram. The height and area of each peak are directly proportional to the concentration of the compound in the sample.

Furthermore, in the MS the molecules are hit with 70 electron volts, this leads to breaking of molecular ions into fragment ions (Patil & Ramaswamy, 2017). The ions pass through a magnetic field that filters them based on the mass. The detector counts each number of ions associated with the specific mass of the fragments; the information is sent to the computer where the mass spectrum is recorded. The spectrum shows each individual compound within a sample this provides the blue print of the compound's chemical identity.

2.3.2 Factors Influencing Trihalomethanes Formation in Drinking Water

Effect of pH

Water pH greatly influences the formation and quantity of DBPs formed. A recent study revealed that at pH of less than 6.5 the HAAs formation was high compared to THMs formation (Hung et al., 2017). In another study carried out to assess formation of THMs in chlorinated water, it was reported that high pH levels of 6 to 8 led to an increase in THMs concentration (Özdemir et al., 2013).

Effect of Natural Organic Matter

Natural organic matter (NOM) is comprised of a mixture of organic compounds that occur in a water body and mostly derived from living or decomposed flora and fauna within the water column or from the surrounding environment (Tak & Vellanki, 2018). The NOM consists of humic material that is the non-polar or non humic material which is polar. Humic material is categorized into humic acids and fulvic acids. Fulvic acids have lower molecular weight and are less aromatic, have higher oxygen content, and higher carboxylic acid. Humic acids have a larger molecular weight and are predominantly darker in color. Non-humic materials are largely made up of proteins, and amino acids, sugars, and polysaccharides (Nikolaou et al., 2001).

The existence of NOM in chlorinated drinking water reacts with chlorine to form THMs. Increased NOM leads to the increased formation of THMs especially chloroform (Pérez et al., 2017). An experiment was carried out in Saudi Arabia to investigate the effect of organic matter distribution in the formation of THMs revealed that the high molecular weight NOM (humic acids) led to an increase in the formation of THM-chloroform, whereas the brominated THMs formation was decreased. Also, at lower molecular weights of NOM, the chloroform formation was reduced (Chowdhury, 2013).

Owing to the complexity of the natural organic matter, the quantification of NOM are characterized by water parameters such as total organic carbon (TOC) content, ultraviolet absorbance at the wavelength of 254 nm (Klymenko et al., 2016). Generally, natural organic matter exists in dissolved, colloidal, and particulate forms, and is quantified in terms of total organic carbon (TOC) (Nikolaou et al., 2001).

Ultraviolet absorbance at a wavelength of 254 nm is usually used to depict the structure of the natural organic matter existing in water. A high UV_{254} means there is a high concentration of aromatic material in the water which consist of the primary sites that react with chlorine to form DBPs (Stéphanie, 2020). According to a study carried out in China on factors influencing DBPs formation in drinking water, the increased TOC and UV_{254} levels led to the increased formation of THMs, where the TOC and UV_{254} levels were low, the THMs formation was low (Ye et al., 2009).

Effect of Residual Chlorine

Residual chlorine is maintained in the water distribution system to protect the water from recontamination of harmful microbes, and as guided by WHO the residual chlorine should be within a range of 0.2-0.5 mg/l (WHO, 2012). Former studies indicated a high THMs formation at levels where the residual chlorine was greater and less than the WHO drinking water quality guideline requirement (Pérez et al., 2017).

Effect of Bromide Concentration

The existence of naturally occurring inorganic bromide ions in water leads to the formation of brominated THMs. The low molecular weight fractions of natural organic matter (non humic) are more reactive with bromide ion than the high molecular weight fractions so it tends to remain in finished water (Chowdhury, 2013). When the bromide ion concentration is high, the brominated THMs formation increases. This is because the free chlorine oxidizes the bromide ion and leads to the formation of hypobromous acid. This hypobromous acid reacts with organic matter hence, the formation of more brominated THMs (Guo et al., 2016).

Effect of Retention time

The retention time is the amount of time treated water remains within the distribution system before it is used. The more the water is in contact with chlorine, the more the THMs and HAAs are formed. Recent study carried out in Cairo, revealed that higher concentration of THMs were formed at longer retention times (Abdullah et al., 2014).

Effect of Temperature

Generally, the rate of chemical reactions increases with increase in temperature. Due to this, DBP formation increases with increasing temperature since the rate of reaction between disinfectants and natural organic matter are faster in warm water (Hua & Reckhow, 2008). Also, during high temperatures, the chlorine decay easily occurs therefore this necessitates increased dose of chlorine to ensure an adequate residual chlorine within the distribution system (WHO, 2012). From studies conducted, DBP formation during chlorination is more in warm temperatures (Hua & Reckhow, 2008).

According to the literature reviewed, the factors influencing THMs formation such as pH, bromide concentration, organic matter (TOC, UV_{254}), residual chlorine, and temperature were adopted in this study.

2.4 Potential Health Risk Associated with Trihalomethanes

2.4.1 Trihalomethanes and Human Health Risk

According to investigations carried out in the early 1980's, there are human health risks linked with exposure to DBPs in disinfected water (Anderson, 1983). THMs have been categorized as carcinogens by the USEPA into three groups; group B1 includes chloroform (possible human carcinogens with limited human data), group B2 includes bromodichloromethane and bromoform (probable human carcinogen with sufficient animal data), and then group C consists of dibromochloromethane (possible human carcinogen) (Pardakhti et al., 2011). Human exposure to THMs is likely to be through ingestion, inhalation, or dermal absorption from drinking water (Mishra et al., 2014). In addition, THMs have been utilized to measure exposure to DBPs because not only are they the primary drivers of cancer risk, but also THMs are carcinogens and their concentrations have been correlated with other DBPs (Li & Mitch, 2018).

2.4.2. Guidelines for Trihalomethanes in Drinking Water

According to WHO every human despite their age, social, economic status must have a right to access an acceptable supply of safe drinking water (WHO, 1996). Due to this, WHO developed guideline values for THMs in drinking water (chloroform 200 µg/L, bromodichloromethane 60 µg/L, dibromochloromethane 100 µg/L, bromoform 100 µg/L) (WHO, 2012). The guideline values are not standards, but each country has a right to state obligatory restrictions according to local or national environmental, social, economic, and cultural situations and the occurrence of waterborne diseases. Also, WHO considers potential health effects associated with exposure to the four THMs compounds concurrently and conditions that the sum of each individual THM concentration divided by its guideline value cannot be greater than one (WHO, 2012).

2.4.3 Potential Health Risk Associated with Trihalomethanes in Drinking Water

Potential health risks associated with THMs in water are evaluated by two approved models namely World Health Organization Index model for additive toxicity and the USEPA approved risk assessment model (Pardakhti et al., 2011 ; Salih & Al-azzawi, 2016). USEPA risk assessment model estimates the toxic and carcinogenic risks associated with THMs in water. The estimation of the toxic risk is through computation of hazard quotient. It is through exposure assessment that the carcinogenic risks are estimated. The human is exposed to THMs through drinking water, skin contact, and inhalation when the THMs volatilize into the air. The population exposure factors such as water consumption rate, bathing exposure time, bodyweight are necessary and also toxicological data obtained from the Integrated Risk Information System (IRIS) database are required during exposure assessment (Ferreira & Cunha, 2012).

A study was carried out in Brazil to find out the risk associated with THMs in tap water. The researcher used the USEPA risk assessment model to carry out a multi-pathway analysis for the cancer risk by ingestion, inhalation, and dermal adsorption. The study revealed that the mean cancer risk was 3.6×10^{-4}, which was higher than the USEPA limit. The researchers concluded that there was a cancer risk mostly contributed by inhalation to the population of Fortaleza. However, the hazard quotient value was less than one which indicated that there were no noncancer effects (Viana & Cavalcante, 2009).

Recently, a study was carried out in Baghdad City to find out the carcinogenic risk of THMs in the main drinking water sources. The researchers used the USEPA risk assessment model and the results revealed that the lifetime cancer risk is 10^{-4}, which was about 100 times higher than the USEPA limit of 10^{-6}. This means that about 1 in 10,000 residents in Baghdad City are likely to develop cancer due to the daily consumption of water containing THMs in his/her lifetime (Ewaid et al., 2018).

In a study carried out in Egypt to assess the potential risk from THMs water supply, the researcher found that cancer risk due to chloroform and bromoform THM species was in the acceptable range of less than 10^{-6}, whereas the bromodichloromethane and dibromochloromethane the cancer risk was greater than 10^{-6} based on the USEPA risk assessment model. Also, the hazard quotient was less than one, signifying that no non-cancer health effects are anticipated due to THMs in Egypt drinking water (Abdullah, 2014). According to a study carried out in Ethiopia in the towns of Jimma and Agaro, the cancer risk estimated ranged from 1.098×10^{-4} to 3.14×10^{-4} for Jimma town and from 1.96×10^{-5} to 3.84×10^{-4} for Agaro town. The cancer risk values were greater than $1\text{x}10^{-6}$ WHO acceptable risk of cancer in drinking water. The researcher estimated that the cancer risk for only chloroform was due to ingestion and inhalation exposure route. The researcher concluded that the cancer risk value may be much higher than the calculated value if the estimation for all known THMs and other routes of exposure are put into consideration (Ambelu et al., 2017).

Several studies have been carried out in developed countries, including in Europe about the DBPs in drinking water. But for developing countries, the studies have been a neglected case since the main focus of water utility companies in developing countries is to ensure the water is chlorinated to kill pathogens and maintain residual chlorine in the distribution system. This avoids recontamination of water along the pipelines with viruses and bacteria hence protecting the population from water-borne diseases (Durmishi et al., 2015).

In Uganda, a study was carried out at Masaka waterworks to determine the characteristics and levels of the NOM in raw water sources and along the treatment train (Kalibbala et al., 2011). Also, another study carried out at Palorinya surface water treatment plant in a refugee settlement in Northern Uganda aimed at characterizing the DBPs levels (Ali et al., 2019). The previous research done in Uganda has not looked at the occurrence of the THMs formation along the distribution system, and there is also a gap concerning the relation between the other water quality parameters and the formation of THMs along the municipal water supply distribution system. Although Ggaba water works is the main and biggest treatment plant in Kampala Uganda, there is no research with focus on the THMs formation potential. Furthermore, the associated potential health risk with THMs has not been reported. Thus, there is a need to carry out a study to evaluate the THMs in drinking water at the Ggaba waterworks and along the distribution system and evaluate the potential health risk associated with THMs.

3.0 MATERIALS AND METHODS

3.1 Description of the Study Area

Kampala is the capital city of Uganda located in the central region. Ggaba water works is located in the Murchison Bay on the shores of Lake Victoria in Makindye Division approximately, 11km away from the central business district. Ggaba waterworks is the main water treatment plant supplying Kampala, Kira, and Mukono Municipalities (Kalibbala et al., 2019). Figure 3.1 below shows the study area and the location of the sampling points.

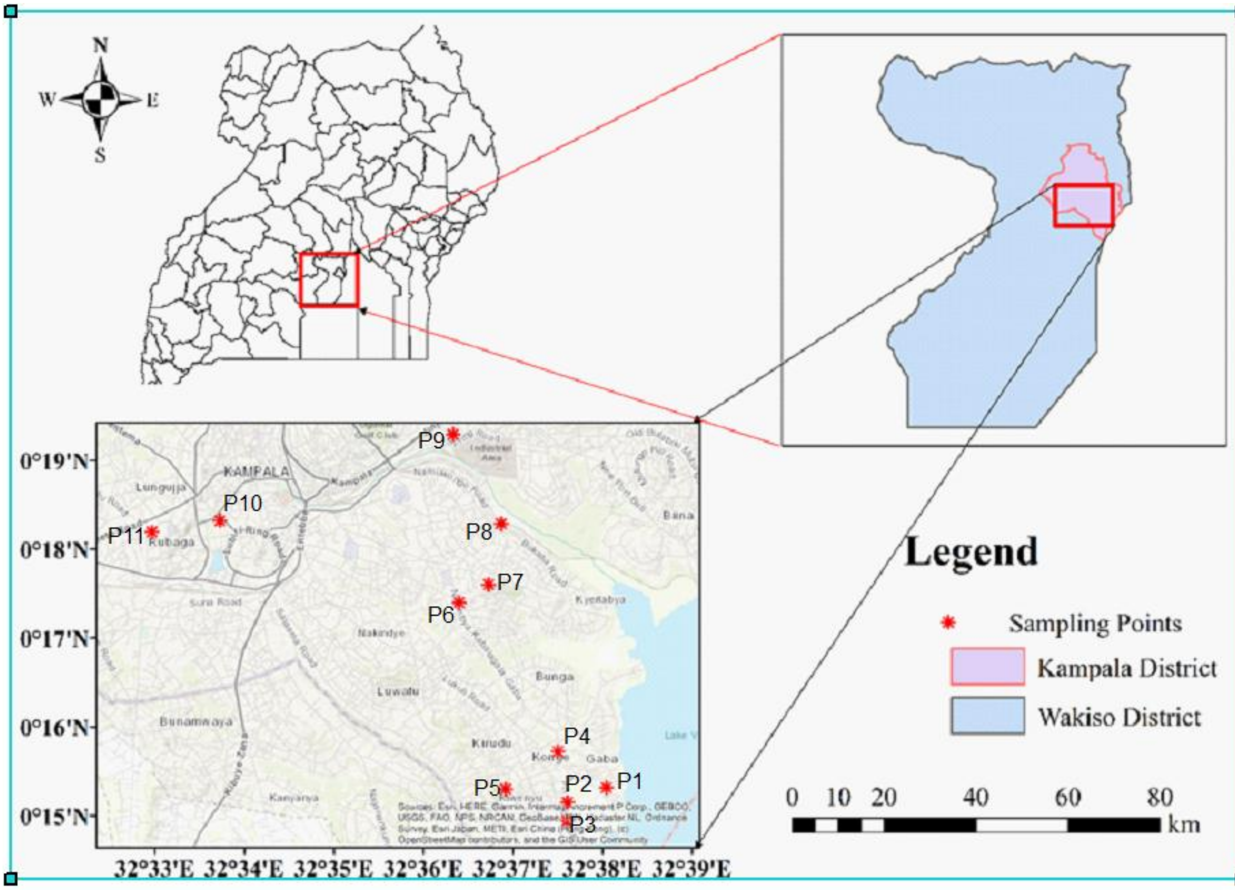

Figure 3.1: A Map of the Study Area and Sampling Points

Conventional water treatment is utilized at Ggaba water works and includes raw water screening, pre-chlorination, coagulation, flocculation, clarification, filtration, pH adjustment, post chlorination (Niwagaba et al., 2019). Approximately 226 cubic meters per day of water is pumped to eight distribution reservoirs serving about 420,000 customers. According to NWSC, Kampala water service coverage is divided into two zones; Kampala water eastern zone and

Kampala water western zone for easy management. The study was carried out in the Kampala water western zone and sampling points are detailed in Table 3.1.

Table 3.1: Coordinates for the Sampling Points

ID	Sample Point Description	Eastings	Northings
P1	Raw water	458479	27901
P2	Filtered Water	459287	28211
P3	Final treated Water	458282	28968
P4	Munyonyo Public tap	458464	27523
P5	Buziga tank point	457202	28181
P6	Kansanga Market	456231	32050
P7	Muyenga Tank E point	456845	32424
P8	Namuwongo Market	457106	33687
P9	Bugolobi Public tap	456107	35541
P10	Kabakanjjagala Road Public tap	451282	33751
P11	Rubaga Tank B point	449874	33517

The study area in the western zone has approximately 18,500 households (NWSC, 2019).

3.2 Research Design

This study was interested in determining the concentration of THMs in drinking water, assessing the relation between water quality parameters and formation of THMs. Furthermore, it aimed at evaluating the potential health risks associated with THMs. Therefore, the study followed a quantitative research approach.

3.3 Sampling Strategy

Eleven sampling points were selected from the NWSC Kampala western zone existing water sampling points. Three sampling points were selected from the treatment plant; raw water, filtered water before post chlorination and the finished water after post chlorination. Eight sampling points were selected along the water distribution system. The trihalomethane concentration along the distribution system was categorized into three; points near the treatment plant P4 and P5 these points were 2, 4 km respectively away from the plant while intermediate points P6, P7 and P8 were 8, 10 and 13 km respectively away from the plant. The farther points P9, P10 and P11 were 14.6, 15.9 and 16.6 km respectively away from the treatment plant. These points were selected because they were easily accessible, were tapping from the main pipeline therefore constant water supply and the points hadn't been re-chlorinated within the network. Also, points were selected by taking points that were active points and not dead ends. The grab samples were collected on Monday's weekly between 8:30 am and 12:30 pm because at this time water production was at its peak. The sample collection lasted a period of twelve weeks during January, February and March 2021. The samples were collected in duplicates from each of the eleven sampling points and total number of collected samples were one hundred thirty- two for the entire study period.

Household Survey Sample Size Determination

The sample size for the households surveyed was determined using equation 3.1 (Kothari, 2004). This is because the study population was large therefore sample sizing was used to come up with a small size which was a representative of the study population.

$$n = \frac{(Z_{\alpha/2})^2 \times N}{(Z_{\alpha/2})^2 + 4N \times e^2} \qquad (3.1)$$

Where, n- sample size, N number of households, $Z_{\alpha/2}$ Z value at the confidence level 95% and e- acceptable error 5%. Simple random sampling was used to select households that were surveyed so as to avoid biased results.

3.3.1 Sample Collection Procedures

The researcher followed the USEPA Method 524.2 sampling procedures to collect samples for THMs. The water samples for THM analysis were collected in duplicates in 40 mL glass vials with polypropylene screw caps and Teflon-faced septa. The vials were carefully washed, rinsed and put in an oven 100 ^{0}C for an hour before sampling. Sodium thiosulphate (3 mg) were added to the THMs sample bottles to eliminate further formation of THMs. Before collecting samples from the sampling points, the taps were opened for about 3-5 minutes to ensure that the water was direct from the main distribution system. The vials were carefully and completely filled to the brim without allowing air bubbles and sample over flow to avoid loss of THMs due to their volatility. After sampling, the vials were put in a cooler box and kept at 4 °C as they were transported from the field to the laboratory. The samples were kept at same temperature until analysis which was done within 48 hours. Figures 7.13 and 7.14 in Appendix C show the researcher collecting samples from the Ggaba water treatment plant and along the distribution system respectively.

The water samples for determination of water parameters such as total organic carbon, bromide ions, UV_{254} were collected in duplicates in 250 mL glass bottles and analyzed according to standard methods (APHA, 2012). The water parameters such as pH, residual chlorine, total chlorine and temperature were measured in situ.

3.4 Data Collection Methods

3.4.1 Primary Data Collection

Primary data was collected by carrying out laboratory analysis and field test analysis. For the concentration of trihalomethanes, total organic carbon, and bromide concentration and UV_{254} were measured in the laboratory. Whereas the pH, temperature, residual chlorine was measured in the field. Also, the body weights, heights of the study population were measured.

3.4.2 Secondary Data Collection

Secondary data was collected by reviewing of published journal articles, theses, textbooks, and other relevant material useful to the study. Exposure factors required in equations 3.5, 3.7, and 3.9 such as aspirated air, permeability coefficient, and volatilization factor were obtained from the existing USEPA guideline data, and also the online Integrated Risk Information System. Also, the life expectancy (exposure duration) of the Uganda population was obtained from the Uganda Bureau of Statistics.

3.5 Analytical Methods

3.5.1 Determination of Trihalomethanes Concentration in Drinking Water

Trihalomethanes present in water and their concentration were quantified in the laboratory within 48 hours after sample collection. THMs were measured using an automatic head space purge and trap system coupled to a gas chromatography mass spectrometry detector. A headspace purge and trap technique specifically purge and trap was used in the extraction of THMs because it doesn't require use of solvents, and it's a fast technique. The gas chromatography ensures compounds in the sample are chromatographically separated depending on their volatility and polarity, while the mass spectrometer confirms the occurrence of the compounds according to their mass fragments.

Using the Purge and trap GC-MS to Measure Trihalomethanes in Water Samples

The 20 ml vial containing a sample sealed with a Teflon-lined septum was placed in the head space sampling unit heat chamber at 60 ^{o}C to equilibrate for about 5 minutes. The sample was transferred using a nitrogen carrier gas, displacing the gas phase in the vial through a heated transfer line into a gas sampling loop. The contents of the sample loop were then adsorbed onto the trap- carbon tri-bed concentrator and then desorbed onto the GC column for analysis using MS as a detector. The GC capillary column length 15 m, internal diameter 0.25 mm and 1.0 µm film thickness was used in the chromatographic separation. The GC temperature profile was set to start temperature of 60 °C and held for 2 minutes and 30 seconds; with temperature increase to 100 ^{o}C at a rate of 10 °C/min, a final temperature increase to 180 °C at a rate of 26 °C/min. Injector and detector temperature were 230 °C and 250 °C, respectively. The carrier gas, nitrogen, was set in constant flow mode at 16.7 mL/s to the GC column. The whole process took a maximum of 10 minutes. The molecular ions (M^{+}) for chloroform, bromoform, dibromochloromethane, and bromodichloromethane were detected at mass / charge of 83, 173, 129, and 83 following a 70-electron volts high-energy ionization. The mass spectra obtained for the trihalomethanes are shown in Figures 7.9, 7.10, 7.11, and 7.12 for chloroform, bromoform, dibromochloromethane and bromodichloromethane, respectively in Appendix B.

The chromatograms were recorded on the computer, the peak areas of individual THMs are proportional to the individual THMs concentrations in µg/L. Figure 7.15 in Appendix C illustrates the operation of a head space purge and trap coupled with a GC-MS to measure trihalomethanes in drinking water.

A stock standard containing 400 mg/L of each of the 4 THMs; chloroform, bromodichloromethane, bromoform and dibromochloromethane Spexcertiprep brand was used. To prepare the calibration standard of 10 µg/L, 0.5 µL was measured using a micro syringe. The 0.5 µL was transferred to a 20 mL volumetric flask and filled to mark using deionized water. The mixture was transferred to a 40 mL vial making it ready for analysis. This was repeated for calibration standards of 20, 50, 100 µg/L as seen in Table 3.2.

Table 3.2: Calibration Standards

Calibration Level	**Calibration Standard Concentration (µg/L)**	**Stock Standard Concentration (mg/L)**	**Volume of Stock Standard (µL)**
1	10	400	0.5
2	20	400	1
3	50	400	2.5
4	100	400	5

Before the target samples were analyzed, the GC-MS was calibrated by running THMs standards of 10, 20, 50 and 100 µg/L in order to find out the response of the instrument to the known concentrations. The chromatograms were recorded on the computer, the peak areas of individual THMs are proportional to the individual THMs concentrations in µg/L (APHA, 2012). The four-point calibration curves were plotted over the well-known concentration range. The retention time and peak areas for each individual THMs were recorded as seen in Table 3.3.

Table 3.3: Peak Area of the Calibration Standards and Known Concentrations

Retention time	1 min 06 sec	1 min 41 sec	2 min 47 sec	4 min 20 sec
Concentration µg/L	**Chloroform peak area**	**Bromodichloromethane peak area**	**Dibromochloromethane peak area**	**Bromoform peak area**
100	274,600,800	196,528,768	227,142,400	171,452,672
50	135,496,160	105,153,464	121,799,992	88,043,680
20	66,395,140	42,011,180	45,550,256	31,934,830
10	29,783,624	32,866,116	22,359,488	14,535,222

The linear regression of peak area versus concentration for the individual THMs gave good fit R^2 of 0.9978, 0.9971, 0.998 and 0.993 for chloroform, bromodichloromethane, dibromochloromethane and bromoform as shown in Figures 7.1, 7.2, 7.3 and 7.4, respectively in Appendix A1.

In addition, running the calibration standards, chromatograms were generated as indicated in Appendix A2, Figures 7.5, 7.6, 7.7 and 7.8 for 10, 20, 50 and 100 µg/L calibration standards, respectively. The chromatograms show all the four compounds present in each standard run.

A set of eight samples of volume 20 mL were spiked with a 50 µL from a 400-mg/L standard concentration. Table 3.4 summarizes the unspiked and spiked samples that were run, relative standard deviation (RSD) of 3.48 % for chloroform and 7.92 % for bromodichloromethane for spiked samples indicating a high precision since RSD < 20%. Also, the rate of recovery for chloroform ranged from 95 % to 108 % while for bromodichloromethane ranged from 97% to 103% indicating high accuracy level for the technique. The head space purge and trap coupled with GC-MS technique had a detection limit of 0.02 µg/L.

Table 3.4: Precision and Accuracy of the HS P&T GC-MS

	Unspiked sample		**Spiked sample**			
No.	**Chloroform Concentration µg/L**	**BDCM concentration µg/L**	**Chloroform concentration µg/L**	**BDCM concentration µg/L**	**Chloroform % Recovery**	**BDCM % Recovery**
1	16.26	9.35	17.34	10.37	108	102
2	16.47	7.89	17.43	8.89	96	100
3	15.09	7.11	16.15	8.09	106	98
4	15.75	8.85	16.79	9.88	104	103
5	16.54	7.67	17.49	8.64	95	97
6	16.69	8.25	17.65	9.24	96	99
7	17.09	8.35	18.08	9.32	99	97
8	16.77	7.76	17.73	8.74	96	98
Mean	16.33	8.15	17.33	9.15	100	99.5
STD	0.637	0.708	0.603	0.725	5.226	2.259
RSD %	3.90	8.69	3.48	7.92		

3.5.2 Determination of Water Quality Parameters in Drinking Water

Total Organic Carbon (TOC)

The TOC measurements were done in the laboratory following Standard Method 5310C (APHA, 2012). The TOC was analyzed using a laboratory total organic carbon analyzer model Sievers M5310C. Heated-Persulphate Oxidation method was used in the measurement of total organic carbon. The organic carbon is oxidized to CO_2 by persulphate in the presence of heat to 95-100 ºC, CO_2 is purged from the sample, dried and transferred with carrier gas (Nitrogen) to the non-dispersive infrared NDIR detector. Figure 7.16 in Appendix C shows the researcher operating the laboratory organic carbon analyzer to measure TOC in the drinking water.

Ultraviolet Absorbance at Wavelength 254 nm

The Ultraviolet absorbance at wave length 254 nm (UV_{254}) measurement was carried out in the laboratory using standard method 5910B (APHA, 2012). Ultraviolet absorbance was measured at 254 nm wavelength using a DR spectrophotometer model (Cecil-400) with a 10mm long quartz cell. Organic free water UV_{254} absorbance value was used as reference. Figure 7.17 in Appendix C shows the researcher operating a DR spectrophotometer to measure the ultraviolet 254 nm absorbance in drinking water.

Bromide Concentration

The bromide concentration was determined in the laboratory using the phenol red colorimetric method 4500 C (APHA, 2012). All the laboratory analysis was conducted at Ggaba National Water and Sewerage Corporation laboratory and the THMs measurement were done at the Ministry of Water and Environment water quality laboratory Entebbe.

In-situ Water Parameter Quality Tests

Some parameters were measured in the field because the transportation and storage affect their properties. For example, the pH, temperature, residual chlorine and total chlorine were determined in the field (APHA, & Greenberg, 1999).

Residual chlorine and total chlorine

The residual chlorine was measured in the field using a potable palinest chlorometer while utilizing the diethylphenyldiamine DPD tablets one and two to measure residual chlorine and total chlorine, respectively. Figure 7.18 in Appendix C shows the researcher measuring the residual and total chlorine using a chlorine meter in drinking water.

Water pH and Temperature

The water temperature and pH were measured in the field using a portable pH meter following Standard Method (APHA, 2012). The pH meter was calibrated before use with standard pH 4.0, 7.0 and 10.0 buffer solutions. The pH meter also determined the water temperature. Figure 7.19 in Appendix C shows the researcher measuring pH and water temperature in the drinking water.

3.5.3 Potential Health Risk Estimation for Trihalomethanes

The potential health risk associated with trihalomethanes were estimated using two models as detailed below.

World Health Organization Index (I_{WHO})

World Health Organization Index is an estimation for additive toxicity for THMs. The Index was used to estimate the toxic risk associated with chlorinated water. For compliance, the index should be less than one (WHO, 2012). WHO index was computed using Equation 3.2.

$$I_{WHO} = \frac{C_{CF}}{GV_{CF}} + \frac{C_{BDCM}}{GV_{BDCM}} + \frac{C_{BF}}{GV_{BF}} + \frac{C_{DBCM}}{GV_{DBCM}} \leq 1 \qquad (3.2)$$

where, C is the concentration of chloroform, bromodichloromethane, bromoform, and dibromochloromethane as measured from the study. GV is the WHO guideline values. According to WHO guideline values for THMs in drinking water (chloroform 200 µg/L, bromodichloromethane 60 µg/L, dibromochloromethane 100 µg/L, bromoform 100 µg/L) (WHO, 2012). The values were used in the estimation of the WHO index.

USEPA Risk Estimation Method

This method involves estimating the toxic and carcinogenic risks. The toxic risk is defined as the Hazard Quotient (HQ) (Ferreira & Cunha, 2012). Hazard quotient was computed using Equation 3.3.

$$HQ = \frac{Total\ amount\ ingested}{BW \times ET \times RfD} \quad (3.3)$$

where, BW-Body Weight kg, ET-Exposure Time days/year, RfD is the reference dose mg/kg/day.

The total amount of chemical ingested depends on the specific population exposure factors such as THMs concentration in water, drinking water consumption rate, exposure frequency, exposure duration. The reference doses were obtained from toxicological studies of exposure that demonstrate critical effect as stipulated by the Integrated Risk Information System database (Ferreira & Cunha, 2012). Also, bodyweight and exposure time were required to compute the hazard quotient. Therefore, a survey was carried out to determine the exposure factors such as average bodyweight of the population in the study area.

Carcinogenic Risk Estimation

Carcinogenic risk assessment is commonly considered that the risk is proportional to the total lifetime dose. The exposure system of measurement used to estimate the carcinogenic risk assessment was the lifetime average daily dose (LADD) (Ewaid et al., 2018). The LADD and the Cancer Slope Factors (CSF) were used to estimate individual excess cancer risk. LADD is an estimate of the daily intake of a carcinogenic agent throughout the whole life of an individual. The CSF is the gradient of the line of the dose-response curve derived from laboratory toxicological studies, and values for each individual THM were obtained from the USEPA IRIS database (Ferreira & Cunha, 2012). There are several ways in which the human is exposed to carcinogens, that is through ingestion, skin contact, and inhalation. The following computations according to USEPA guideline were used to compute the carcinogenic risks for different exposure routes (Pardakhti et al., 2011).

Carcinogenic Risk through Ingestion.

The carcinogenic risk through ingestion of trihalomethanes in drinking water was computed using Equations 3.4 and 3.5.

$$THM\ carcinogenic\ risk\ by\ ingestion = LADD_{Ingestion} \times CSF_{Ingestion} \quad (3.4)$$

$$LADD_{Ingestion} = \frac{THM\ concentration \times ER \times EF \times ED}{BW \times AT} \quad (3.5)$$

where, ER-Exposure rate, water consumption rate liters/day, EF-Exposure Frequency days of the year for water consumption, ED -Exposure duration that is equivalent to the life expectancy of the population, BW-Body Weight kg, AT- Average Exposure Time days/year.

Carcinogenic Risk through Skin Contact

The carcinogenic risk through skin contact was computed using Equations 3.6 and 3.7.

$$THM\ carcinogenic\ risk\ by\ skin\ contact = LADD_{skin\ contact} \times CSF_{skin\ contact} \quad (3.6)$$

$$LADD_{skin\ contact} = \frac{THM\ concentration \times BSA \times PC \times ED \times EF \times ET}{BW \times AT} \quad (3.7)$$

where, BSA- Body surface area m^2, PC-Permeability coefficient cm/hr, ET- Exposure time in the shower minutes/day.

The body surface area for the Kampala western zone was computed according to Equation 3.8 (Reading & Freeman, 2005)

$$BSA = \frac{1}{6}(BWH)^{0.5} \quad (3.8)$$

where BW is body weight and H is height.

Carcinogenic Risk through Inhalation

The cancer risk through inhalation was considered for chloroform (USEPA, 1991). The risk was computed using Equation 3.9 and 3.10.

$$THM\ carcinogenic\ risk\ inhalation = LADD_{inhalation} \times CSF_{inhalation} \quad (3.9)$$

$$LADD_{skin\ contact} = \frac{Chloroform\ concentration \times AA \times VF \times ED \times EF \times ET}{BW \times AT} \quad (3.10)$$

where, AA- Aspirated air m^3/day, VF-Volatilization factor for chloroform l/m^3

Total carcinogenic risk for all the three exposure routes was computed by summing up individual exposure risks as illustrated in Equation 3.11.

$$Cancer\ risk = Risk_{ingestion} + Risk_{dermal\ contact} + Risk_{\ Inhalation} \quad (3.11)$$

According to USEPA, the cancer risk is divided into four categories that is if CR < 1×10^{-6} the risk is negligible, 1×10^{-6} < CR< 5.1×10^{-5} acceptable low risk, 5.1×10^{-5} < CR < 1×10^{-4} acceptable high risk and if CR > 1×10^{-4} then the risk is unacceptable (Legay et al., 2011).

Exposure factors required in equations 3.3, 3.5, 3.7, 3.8 and 3.10 such as aspirated air, permeability coefficient, and volatilization factor were obtained from the existing USEPA guideline data as shown in Table 3.5. Also, the life expectancy (exposure duration) of the Uganda population was obtained from the Uganda Bureau of Statistics (UBOS). Also, factors such as body weight, body surface area were obtained through a survey carried out in Kampala western zone.

Table 3.5: Exposure Factors for the Exposure Assessment

Exposure factor	Notation	Unit	Value	Reference
THM Conc. in water	CF	μg/L	CF: 19.91	This study
	BDCM		BDCM: 7.86	
Exposure rate	ER	L/day	2	(USEPA, 1997)
Exposure frequency	EF	days/ year	365	(Abbas et al., 2015)
Exposure duration	ED	year	Female: 64.5	(UBOS, 2013)
			Male: 62. 8	
Average exposure time	AT	days/year	Female: 64.5 × 365	(Lee et al., 2004) (Abbas et al., 2015)
			Male: 62.8 × 365	
Body weight	BW	Kg	Female: 67.1	This study
			Male: 70.5	
Surface area	SA	m^2	Female: 1.69	This study
			Male: 1.84	
Exposure time	ET	min/day	35	(USEPA 1997)
Aspirated air	AA	m^3 per day	20	(Semerjian & Dennis, 2008)
Volatilization factor for chloroform	VF	L/m^3	0.5	(Semerjian & Dennis, 2008)
Permeability Coefficient	PC	cm/h	CF- 0.00683	(IRIS, 2012)
			BDCM-0.00402	

Also, to use the USEPA model for estimating the potential health risk, the cancer slope factors and the reference doses for the compounds of chloroform and bromodichloromethane were obtained from the online integrated risk information system (IRIS) as shown in Table 3.6.

Table 3.6: Carcinogenic Slope Factors and Reference Doses for the Individual THMs

Chemical compound	Cancer groups	Carcinogenic Slope Factor (CSF) (mg/kg day)		Reference dose RfD	Reference
		Oral/ dermal	**Inhalation**		
Chloroform	B1	3.1×10^{-2}	8.05×10^{-5}	0.01	(IRIS, 2012)
Bromodichloromethane	B2	6.2×10^{-2}		0.02	(IRIS, 2012)

3.6 Data Quality Control

The National water and sewerage corporation laboratory standard operating procedures were followed during sample collection and analysis. The samples were collected and analyzed in duplicates to ensure reproducibility of results and average values were reported. Also, sample spiking was done to determine the accuracy and precision rates of the purge and trap GC-MS technique. All the instruments used were calibrated to ensure that instrument readings were accurate with reference to established standards during the study. The data obtained during the study (TOC, pH, residual chlorine) was cross referenced with the historical data from National Water and Sewerage Corporation Central laboratory Kampala and the data differed by ± 0.5 for TOC, ± 0.2 for residual chlorine and ± 0.1 – 0.4 for pH from the historical data.

3.7 Data Analysis

Quantitative data collected was analyzed using Microsoft Office Excel and Minitab computer package version 20 for Windows. The data was summarized and tabulated using Microsoft excel where the mean, standard errors for the data were computed. Also, a one-way analysis of variance (ANOVA) was computed using Excel to determine whether the mean differences of total trihalomethanes for the different points were significant or not. Minitab was used to determine the Pearson correlation coefficients, carry out regression analysis between variables and plotting the scatter graphs for the data.

3.8 Ethical Considerations

Great care was taken to ensure that the respondents were kept completely anonymous in the research.

There were no conflicts of interests during the study.

Adequate level of confidentiality of the research data was ensured.

4.0 RESULTS AND DISCUSSION

4.1 Trihalomethane Concentration at the Treatment Plant and Water Distribution System

The concentration of trihalomethanes were measured at the Ggaba Water Works and along the water distribution system.

4.1.1 Trihalomethane Concentration at the Ggaba Water Treatment Plant

The results of the THMs measurement at the Ggaba Water treatment plant are summarized in Table 4.1. During the study period from January to March 2021, only chloroform and bromodichloromethane species of trihalomethanes were identified in the drinking water at the treatment plant. The chromatograms obtained for raw water, filtered water and final water are indicated in Figures 7.20, 7.21 and 7.22 respectively in Appendix D.

Table 4.1: Trihalomethanes Concentration along the Ggaba Water Treatment Plant

Parameter	**Chloroform µg/L**			**Bromodichloromethane µg/L**			**Total trihalomethanes µg/L**		
Point	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
Mean	ND	10.53	19.86	ND	4.18	4.59	ND	14.72	24.45
± SE		0.88	2.34		0.73	0.59		1.53	2.39
Min		3.99	11.87		0.69	0.78		4.68	14.96
Max		14.42	33.98		8.99	9.43		23.41	38.65
NWSC standard									**80.00**
WHO Guideline		**200**	**200**		**60**	**60**			**100**
USEPA standard									**80**

The mean chloroform, bromodichloromethane and total trihalomethane concentration obtained at the treatment plant were all within the NWSC, WHO and USEPA acceptable drinking water standard. The data was normally distributed therefore, a single factor Analysis of variance

(ANOVA) statistical test in Table 4.2 was carried out to determine whether the difference between mean concentrations of TTHMs for points P2 and P3 were statistically significant or not.

Table 4.2: ANOVA between the Mean Concentrations of TTHMs at P2 and P3

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
P2	12	176.5812	14.7151	28.0408
P3	12	293.3978	24.44981	68.28477

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	568.5875	1	568.5875	11.80554	0.00236	4.30095
Within Groups	1059.581	22	48.16278			
Total	1628.169	23				

From the one-way ANOVA test, it indicated that the difference between mean concentrations of TTHMs at points P2 and P3 were statistically significant ($p \leq 0.05$).

There were no trihalomethanes in the raw water because for trihalomethane to form, there should be precursors of natural organic matter in presence of chlorine. However, the raw water received at the plant did not have chlorine hence absence of trihalomethanes in raw water samples. The filtered water had trihalomethanes because of the pre-chlorination process done at the treatment plant. The pre- chlorination is done to reduce on the algae that is in the raw water source. The final treated water showed an increase in total trihalomethanes because of the post chlorination done at the water treatment plant to ensure pathogens are killed and also maintain a given concentration of residual chlorine along the distribution system.

Generally, the trend of individual THMs found at Ggaba water works showed that chloroform concentration levels were higher than the bromodichloromethane concentration levels. The chloroform concentration at the water works contributed 81.2% to the TTHMs compared to 18.8% contributed by bromodichloromethane. This means chloroform dominated the TTHMs. This result has been supported by a study carried out in Ethiopia where it was found out that the chloroform concentrations were higher than other THMs in Hossana water supply system. (Zelelew et al., 2018). Also, another study carried out in Cairo Egypt found higher chloroform concentration levels compared to other THMs in the water (Abdullah et al., 2014). The low levels of bromodichloromethane were attributed to low levels of bromide concentration in the water source.

4.1.2 Trihalomethane Concentration along the Water Distribution System

Table 4.3 summarizes the results of THMs measurement for near, intermediate and far points along the water distribution system. The chromatograms obtained for points P4, P5, P6, P7, P8, P9, P10 and P11 are indicated in Figures 7.23, 7.24, 7.25, 7.26, 7.27, 7.28, 7.29 and 7.30, respectively in Appendix D.

Table 4.3: Trihalomethane Concentration along the Water Distribution System

		Near Points		**Intermediate points**			**Far points**		
Parameter/Point		P4	P5	P6	P7	P8	P9	P10	P11
Chloroform (µg/L)	Mean	16.16	17.77	19.17	19.21	20.76	20.8	23.07	22.39
	SE±	0.59	0.56	1.93	1.2	1.25	1.36	1.47	2.05
	Min	12.49	14.85	11.23	12.31	11.45	11.23	14.8	13.12
	Max	19.87	21.79	28.12	24.79	27.43	26.88	35.65	39.3
BDCM (µg/L)	Mean	5.68	5.7	7.31	7.58	7.74	9.59	8.79	10.5
	SE±	0.51	0.43	1.15	0.84	0.98	1.1	0.68	1.0
	Min	2.78	2.95	2.38	0.89	1.85	2.79	4.53	4.99
	Max	9.03	7.65	13.56	10.61	11.6	15.49	11.83	14.42
TTHMs (µg/L)	Mean	21.84	23.47	26.49	26.79	28.5	30.38	31.86	32.89
	SE±	0.95	0.88	2.81	1.64	2.07	2.21	1.77	2.93
	Min	18.23	17.8	16.45	19.76	15.77	16.57	19.33	18.4
	Max	28.9	29.44	41.18	35.4	39.03	39.75	41.87	53.72

Along the distribution system, only chloroform and bromodichloromethane species of trihalomethanes were identified in the drinking water as seen on the chromatograms in Appendix D. The mean chloroform, bromodichloromethane and total trihalomethane concentration obtained along the water distribution system were all within the NWSC, WHO and USEPA acceptable drinking water standards. The mean total trihalomethanes concentration increased in order P11 > P10 > P9 > P8 > P7 > P6 > P5 > P4. This is because the longer the distance, the contact time between residual chlorine and the organics in water increased hence increased formation of total trihalomethanes (Saidan et al., 2013; Zelelew et al., 2018). Also, there was an increased level of TOC along the water distribution system and this was attributed to cracked pipes that let in foreign matter into the piped water. In addition, during repair of cut pipes, leaks and bursts if after the repairs there is no pipe line flushing, this is a source of foreign matter into the water distribution system. Furthermore, along the pipeline there is presence of biofilm and this attributes to the organic matter hence TOC levels (NRC, 2007).The presence of the organic matter and residual chlorine along the water distribution system attributes to the increased formation of trihalomethanes

A single factor ANOVA statistical test in Table 4.4 was carried out to determine whether the difference between mean concentrations of TTHMs for near points P4 and P5 were statistically significant or not.

Table 4.4: ANOVA between the Mean Concentrations of TTHMs for Near points

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
P4	12	262.0689	21.83908	10.9381
P5	12	281.664	23.472	9.370297

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	15.9986	1	15.9986	1.575566	0.22257	4.30095
Within Groups	223.3923	22	10.1542			
Total	239.3909	23				

From the one-way ANOVA test, it indicated that the difference between mean concentrations of TTHMs for near points P4 and P5 were not statistically significant ($p \geq 0.05$).

A single factor ANOVA statistical test in Table 4.5 was carried out to determine whether the difference between mean concentrations of TTHMs for intermediate points P6, P7 and P8 were statistically significant or not.

Table 4.5: ANOVA between the Mean Concentrations of TTHMs for Intermediate Points

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
P6	12	317.828	26.48567	95.03183
P7	12	321.5085	26.79237	32.33197
P8	12	341.9558	28.49632	51.22245

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	28.16083	2	14.08041	0.236531	0.790688	3.284918
Within Groups	1964.449	33	59.52875			
Total	1992.61	35				

From the one-way ANOVA test, it indicated that the difference between mean concentrations of TTHMs for the intermediate P6, P7 and P8 were not statistically significant ($p \geq 0.05$).

A single factor ANOVA statistical test in Table 4.6 was carried out to determine whether the difference between mean concentrations of TTHMs for far points P9, P10 and P11 were statistically significant or not.

Table 4.6: ANOVA between the Mean Concentrations of TTHMs for Far points

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
P9	12	364.6058	30.38382	58.79116
P10	12	382.2656	31.85547	37.40862
P11	12	394.6701	32.88917	102.7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	38.04438	2	19.02219	0.286911	0.752432	3.284918
Within Groups	2187.898	33	66.29994			
Total	2225.942	35				

From the one-way ANOVA test, it indicated that the difference between mean concentrations of TTHMs for far points P9, P10, and P11 were not statistically significant ($p \geq 0.05$).

Generally, the trend of individual THMs found along the distribution network showed that chloroform concentration levels were higher than the bromodichloromethane concentration levels. The chloroform concentration along the water distribution system contributed 73.9%,72.8% and 67.5% to the total THMs for near, intermediate and far points respectively, while 26.1%, 27.2% and 32.5% were contributed to bromodichloromethane along near, intermediate and far points along the distribution system. This implied the chloroform dominated the TTHMs. The low levels of bromodichloromethane are attributed to low levels of bromide ions in the water source. This result has been supported by a study carried out in Ethiopia by Zelelew et al. (2018) who found out that the chloroform concentrations; 28.1 – 35.5 µg/L were higher than other THMs of dibromochloromethane; 20.10 – 30.01 µg/L in Hosanna water supply system. A study done in Pakistan drinking water supply found out that chloroform concentration was higher than other THMs (Abbas et al., 2015). Also, another study carried out in Cairo Egypt found higher chloroform concentration levels compared to other THMs in the water; chloroform levels ranged from 12.8 to 74.2 µg/L whereas bromodichloromethane ranged from 4.27 to 23.4 µg/L (Abdullah et al., 2014).

The relationship between the trihalomethanes and distance away from the plant is illustrated in the Figure 4.1.

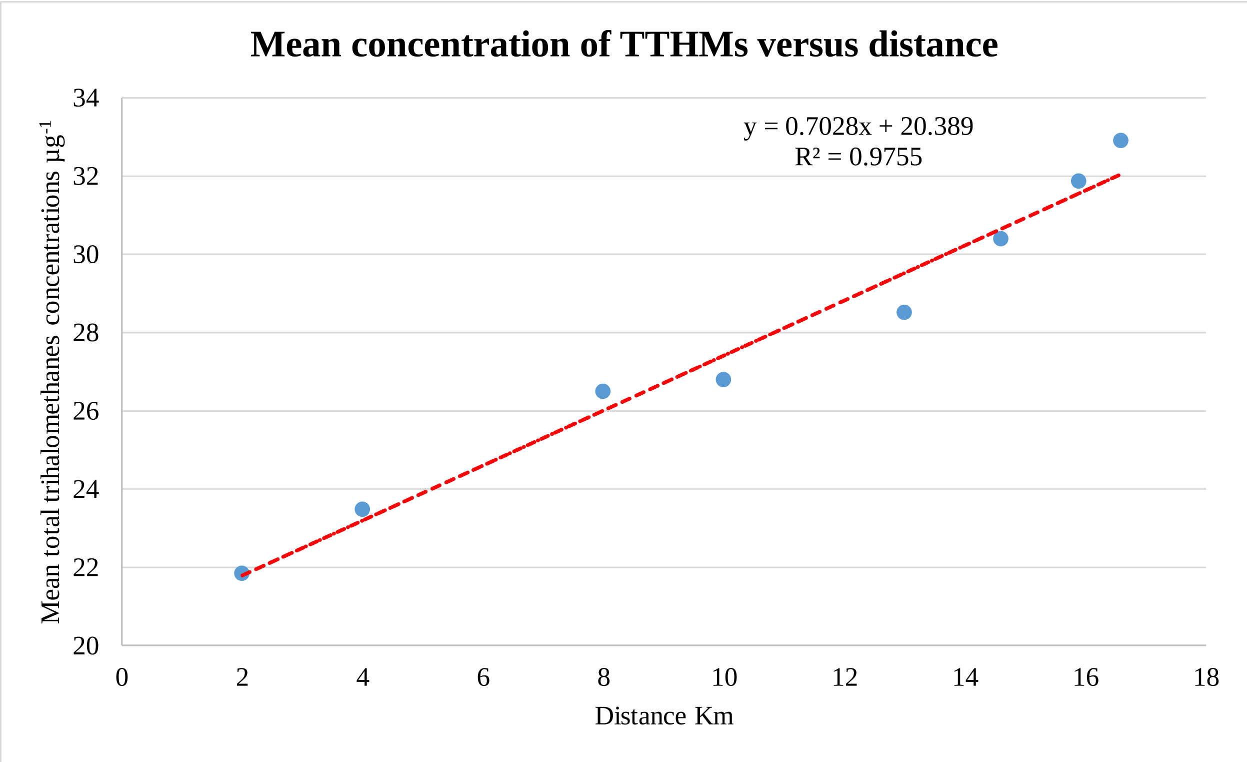

Figure 4.1: Mean Concentration of TTHMs at Different Points versus the Distance

As illustrated in Figure 4.1 above, there is a strong and significant correlation between distance and THMs formation according to Pearson correlation $r = 0.974$, p value $= 0.001 < 0.05$. This means there is a linear relationship between THMs formation and distance if residual chlorine is present and organic matter is present. Also, as we move along the distribution system, there may be points of contamination due to cracked pipes that allow the entry of organics into the water. However, as the distance further increases if there is no re-chlorination, the THMs formation reduces due to decay of chlorine.

Generally, the total trihalomethanes increased as we moved from the water treatment plant to far points along the distribution system. The mean concentrations of total trihalomethanes at P11 > P10 > P9 > P8 > P7 > P6 > P5 > P4: 32.89 > 31.86 > 30.83 >28.5 >26.79 >26.49 >23.47 >21.84.

The increase of TTHMs is attributed to the increased contact time of water in the pipe hence ample time for the reaction between residual chlorine and natural occurring organics (Saidan et al., 2013). This is supported by a study done in Canada on spatial and temporal evolution of trihalomethanes in three water distribution systems, where the researchers found out that the water at the extremes of the distribution systems had high trihalomethanes compared to points near the plant (Rodriguez & Sérodes, 2001). Also another study carried out in Iran on monitoring of THMs concentration in Isfahan water distribution system found out that more trihalomethanes were formed as the distance away from the treatment plant increased (Mohammadi et al., 2015). In addition, according to Li & Mitch, (2018) DBP concentrations show significant spatial variability along the water distribution system, because the disinfection by- products continue to form within the distribution system.

Also, a one-way ANOVA statistical test in Table 4.7 was carried out to determine whether the difference between mean concentrations of TTHMs for the plant, near, intermediate points and, far points along the distribution system were significant or not.

Table 4.7: ANOVA between Mean of TTHMs at the Plant and the Distribution System

ANOVA: Single factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Plant	24	454.35	18.93125	50.82009
Near points	32	737.33	23.04156	9.582833
intermediate points	32	902.52	28.20375	55.05072
Far points	32	1015.16	31.72375	64.10046

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2682.115802	3	894.0386	20.10004	1.46833E-10	2.682809
Within Groups	5159.616584	116	44.47945			
Total	7841.732387	119				

From the one-way ANOVA test, it indicated that the difference between mean concentrations of TTHMs at the plant, near, intermediate points and, far points along the water distribution system were all statistically significant ($p \leq 0.05$).

Furthermore, to find out whether there are differences between the individual groups, a Fishers least significant difference (LSD) test at 95% confidence level was carried out. Mean 4, mean 3 mean 2 and mean1 representing means at far, intermediate points, near and plant, respectively. Table 4.8 summarizes the differences in means between the groups versus the least square difference.

Table 4.8: Differences in Group Means versus the Least Square Difference

Mean 4-Mean 1	12.79	>	3.5
Mean 4-Mean 2	8.68	>	3.5
Mean 4-Mean 3	3.52	>	3.5
Mean 3-Mean 1	9.27	>	3.5
Mean 3-Mean 2	5.16	>	3.5
Mean 2-Mean 1	4.11	>	3.5

All the differences in means between each group were still statistically significant since the absolute differences between the means were greater than LSD of 3.5.

From the study, it’s important to note that the mean concentration of THMs along the distribution system was higher than the mean THMs at Ggaba water treatment plant. This is attributed to the fact that the chlorine is still reacting at the treatment plant. This result is same as that obtained in the study carried out in Ontario water system, the researchers found out that the mean concentrations of THMs were higher in the distribution system compared to the mean concentrations at water treatment plant (Chowdhury et al., 2008).

4.2 The Relation between Water Quality Parameters and Formation of Trihalomethanes

4.2.1 Water Quality Characteristics for the Ggaba Water Treatment Plant

Water quality parameters influence the trihalomethanes formed therefore its necessary to know the water quality parameters of the raw water source and after water treatment has been done. Table 4.9 summarizes the results of the water quality parameters for the raw water at Ggaba water treatment plant.

Table 4.9: Water Quality Characteristics for Raw Water at Ggaba Plant

Parameter	N	Mean	± SE	Min	Max
Temperature (^{o}C)	12	26.01	0.232	25	27.3
pH	12	7.6	0.077	7.08	8
TOC (mg/L)	12	7.22	0.258	6.2	8.4
UV_{254} (cm^{-1})	12	0.11	0.003	0.09	0.13
Bromide (mg/L)	12	0.3	0.005	0.28	0.33

The TOC values ranged from 6.2 to 8.4 mg/L for Lake Victoria. The high organic matter is contributed by natural organic substances, agricultural runoff, industrial and municipal wastewater discharges (Deirmendjian et al., 2020). The THMs weren't present in the raw water because the raw water had no chlorine. The UV_{254} ranged from 0.094 to 0.137 cm^{-1}, the high UV_{254} means there is a high concentration of aromatic material in the water which consist of the primary sites that react with chlorine to form DBPs (Stéphanie, 2020). Bromide values in Lake Victoria ranged from 0.28 to 0.3 mg/L. Lake Victoria being a surface water source, bromide levels are contributed by anthropogenic activities that is wastewater treatment effluents, agricultural herbicides, municipal waste incinerators, and pharmaceuticals (Wang et al., 2017).

Table 4.10 summarizes the water quality parameters for filtered water; this was treated water before post chlorination.

Table 4.10: Water Quality Characteristics for Filtered Water

Parameter	N	Mean	±SE	Min	Max
Free chlorine (mg/L)	12	0.28	0.059	0.05	0.63
Total Chlorine (mg/L)	12	0.52	0.062	0.11	0.77
Temperature (^{o} C)	12	26.15	0.244	25.00	27.70
pH	12	6.76	0.046	6.57	7.11
TOC (mg/L)	12	2.46	0.122	1.89	3.19
UV_{254} (cm^{-1})	12	0.03	0.002	0.02	0.04
Bromide (mg/L)	12	0.24	0.011	0.16	0.29
Chloroform (µg/L)	12	10.53	0.883	3.99	14.42
BDCM (µg/L)	12	4.18	0.732	0.69	8.99
TTHMs (µg/L)	12	14.72	1.529	4.68	23.41

The residual chlorine was detected in filtered water ranging from 0.05 to 0.63 mg/L the residual chlorine is contributed by the pre-chlorination process done at the plant aimed at reducing the algae in the raw water. Furthermore, presence of chlorine led to the formation of THMs in the filtered water. Among the four trihalomethanes, only chloroform and bromodichloromethane were identified in the filtered water. The concentration levels of chloroform ranged from 3.99 to 14.42 µg/L, bromodichloromethane concentration ranged from 0.69 to 8.99 µg/L and total trihalomethanes concentration ranged from 4.68 to 23.41 µg/L. The TOC values ranged from 1.88 to 3.18 mg/L this implies the treatment processes reduced the organic matter but it is not completely removed. The UV_{254} ranged from 0.019 to 0.038 cm^{-1}, the values are lower than the raw water implying a reduction in the aromatic material in the filtered water. Bromide concentration ranged from 0.16 to 0.29 mg/L, indicating a reduction in the bromide levels compared to the raw water. The statistical difference between the mean concentrations of bromides for the raw water and filtered water were tested using ANOVA single factor in Table 4.10.

Table 4.10: ANOVA between Bromide Concentrations for Raw and Filtered Water

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Raw water	12	3.6	0.3	0.000255
Filtered water	12	2.885	0.24	0.001353

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.021301	1	0.021301	26.50445	3.68E-05	4.30095
Within Groups	0.017681	22	0.000804			
Total	0.038982	23				

From the one-way ANOVA test, it indicated that the difference between mean concentrations of bromide concentrations for raw water and filtered water were statistically significant ($p \leq 0.05$). Despite the reduction in bromide concentration, NWSC does not monitor bromides present in the water. Table 4.11 summarizes the water quality characteristics of the final treated water at Ggaba water treatment plant.

Table 4.11: Water Quality Characteristics for the Final Treated Water

Parameter	**N**	**Mean**	**±SE**	**Min**	**Max**	**NWSC standard**
Free chlorine (mg/L)	12	0.89	0.103	0.52	1.46	0.8-1
Total Chlorine (mg/L)	12	1.08	0.101	0.58	1.56	
Temperature (^{o} C)	12	26.58	0.262	25	28.1	
pH	12	6.64	0.058	6.33	6.96	6.5 - 7
TOC (mg/L)	12	2.25	0.184	1.4	3.5	2 .0– 4.0
UV_{254} (cm^{-1})	12	0.02	0.002	0.014	0.037	
Bromide (mg/L)	12	0.2	0.015	0.096	0.278	
Chloroform (µg/L)	12	19.86	2.341	11.87	33.98	80
BDCM (µg/L	12	4.59	0.64	0.79	9.43	80
TTHMs (µg/L)	12	24.45	2.385	14.96	38.65	80

Final treated water is the water after post chlorination, pH had been adjusted and the water was ready to leave the plant to the distribution network. The concentration levels of chloroform ranged from 11.87 to 33.98 µg/L, bromodichloromethane concentration ranged from 0.79 to 9.43 µg/L and total trihalomethanes concentration ranged from 14.96 to 38.65 µg/L. On comparing the final treated water concentrations of THMs to filtered water the final water had higher concentrations and this is contributed by the post chlorination process. All the water quality characteristics for final treated water were all within the NWSC drinking water standards as indicated in Table 4.12 above. However, parameters such as bromide, UV_{254} are not directly monitored at the plant.

4.2.2 Water Quality Characteristics along the Distribution System

Table 4.12 summarizes the water quality characteristics along the water distribution system. The parameters were measured because the study was interested in assessing the relation between other water quality parameters and the formation of THMs.

Table 4.12: Water Quality Characteristics along the Water Distribution System

Parameter	N	Mean	±SE	Min	Max	NWSC standard
Free chlorine (mg/L)	96	0.41	0.02	0.01	0.78	0.2-0.5
Total Chlorine (mg/L)	96	0.56	0.026	0.01	1.13	-
Temperature (^{o}C)	96	26.47	0.121	24.8	29.2	-
pH	96	6.93	0.014	6.64	7.47	6.5-7
TOC (mg/L)	96	2.81	0.039	1.89	3.71	2.0-4.0
UV_{254} (cm^{-1})	96	0.03	0.001	0.013	0.05	-
Bromide (mg/L)	96	0.25	0.03	0.12	3.1	-
Chloroform (µg/L)	96	19.92	0.524	11.23	39.3	80
BDCM (µg/L)	96	7.86	0.34	0.89	15.49	80
TTHMs (µg/L)	96	27.78	0.787	15.77	53.72	80

The water quality parameters obtained along the distribution system showed they are within the NWSC drinking water guidelines. The TOC concentration along the distribution system ranged from 1.89 to 3.7 mg/L with a mean concentration of 2.81mg/L. The increase in the TOC along the distribution system is attributed to cracked pipes that let in foreign matter into the piped water. Also, during repair of cut pipes, leaks and bursts if after the repairs there is no pipe line flushing, this is a source of foreign matter into the water distribution system. In addition, along the pipeline there is presence of biofilm and this contributes to the organic matter hence TOC levels (NRC, 2007). The mean trihalomethane concentration along the distribution system was more than the trihalomethanes formed at the treatment plant. This is because the reaction between residual chlorine and organic matter is still taking place along the distribution system.

4.2.3. Relationship between Water Quality Parameters and Trihalomethanes Formation

To determine the relationship between trihalomethanes and water quality parameters, a Pearson correlation was performed. Table 4.13 illustrates the correlation coefficients r between the total trihalomethanes and other drinking water quality parameters.

Table 4.13: Pearson Correlation Matrix for the Water quality Parameters

Parameter	Residual chlorine (mg/L)	Total Chlorine (mg/L)	Temp (^oC)	pH	TOC (mg/L)	UV_{254} (cm^{-1})	Bromide (mg/L)	Chloroform (µg/L)	BDCM (µg/L)
Total Chlorine (mg/L)	0.847								
Temperature (^{o}C)	-0.256	-0.241							
pH	-0.241	-0.118	0.149						
TOC (mg/L)	-0.422	-0.318	0.28	0.3					
UV_{254} (cm^{-1})	-0.425	-0.29	0.248	0.1	0.336				
Bromide (mg/L)	-0.238	-0.23	0.833	0.037	0.186	0.308			
Chloroform (µg/L)	-0.294	-0.259	0.863*	0.089	0.305	0.234	0.841		
BDCM (µg/L)	-0.329	-0.237	0.8*	0.059	0.283	0.341	0.984*	0.725	
TTHMs (µg/L)	-0.332	-0.272	0.905*	0.097	0.324	0.280	0.873*	0.95*	0.883*

Correlations at 95% confidence level

* Strong positive correlations

Furthermore, Table 4.14 illustrates the statistical significance of the relationship between water quality parameters and trihalomethanes.

Table 4.14: P-values between Trihalomethanes and Water Quality Parameters

Dependent Variable	Independent Variable	P-Value
Chloroform (µg/L)	Residual chlorine (mg/L)	0.004
Bromodichloromethane (µg/L)	Residual chlorine (mg/L)	0.001
TTHMs (µg/L)	Residual chlorine (mg/L)	0.001
Chloroform (µg/L)	Total Chlorine (mg/L)	0.011
Bromodichloromethane (µg/L)	Total Chlorine (mg/L)	0.021
TTHMs (µg/L)	Total Chlorine (mg/L)	0.008
Chloroform (µg/L)	Temperature (^{o}C)	0
Bromodichloromethane (µg/L)	Temperature (^{o}C)	0
TTHMs (µg/L)	Temperature (^{o}C)	0
Chloroform (µg/L)	pH	0.387
Bromodichloromethane (µg/L)	pH	0.566
TTHMs (µg/L)	pH	0.348
Chloroform (µg/L)	TOC (mg/L)	0.002
Bromodichloromethane (µg/L)	TOC (mg/L)	0.005
TTHMs (µg/L)	TOC (mg/L)	0.001
Chloroform (µg/L)	UV_{254} cm^{-1}	0.022
Bromodichloromethane (µg/L)	UV_{254} cm^{-1}	0.001
TTHMs (µg/L)	UV_{254} cm^{-1}	0.006
Chloroform (µg/L)	Bromide (mg/L)	0
Bromodichloromethane (µg/L)	Bromide (mg/L)	0
TTHMs (µg/L)	Bromide (mg/L)	0
TTHMs (µg/L)	Chloroform (µg/L)	0
TTHMs (µg/L)	Bromodichloromethane (µg/L)	0

P-value < 0.05 implies a statistically significant relationship between the two variables.

The relationship between the total trihalomethanes and residual chlorine was illustrated on a scatter plot in Figure 4.2.

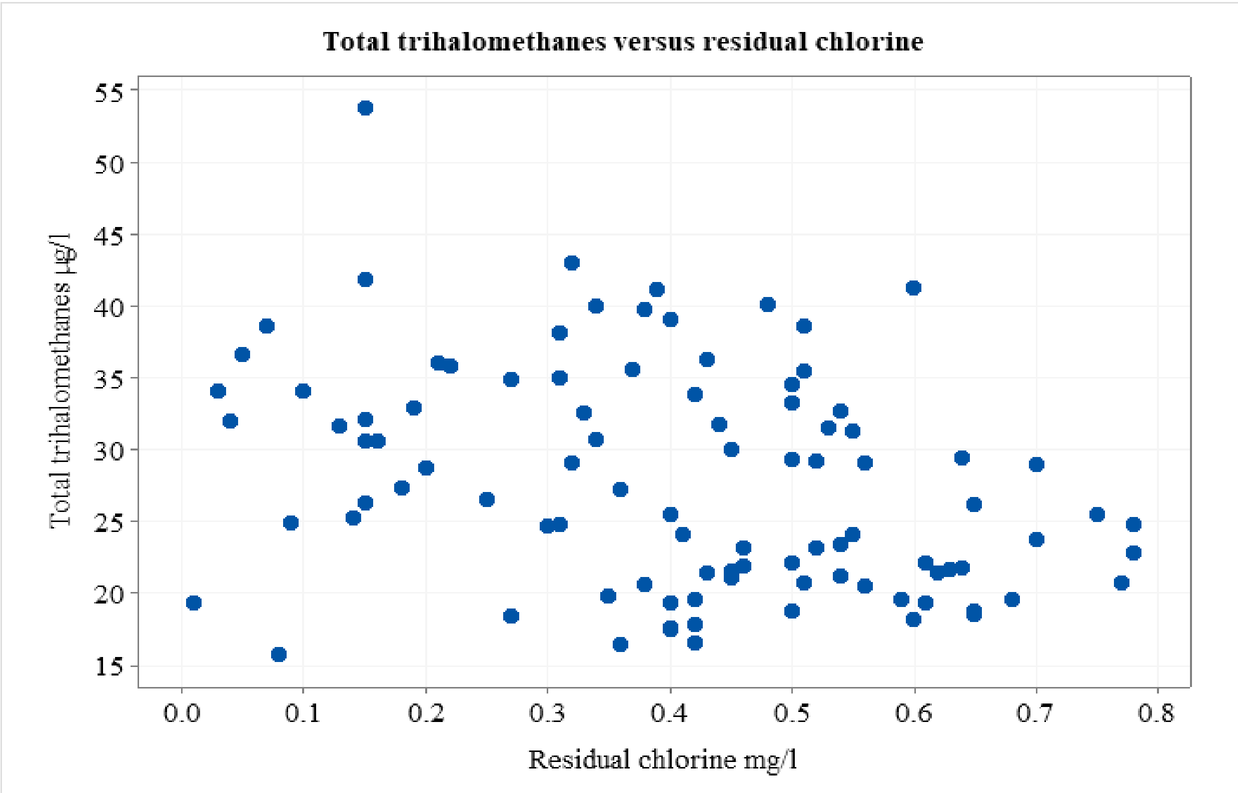

Figure 4.2: Scatter Plot of Total Trihalomethanes Versus Residual Chlorine

Using Pearson correlation method, weak, negative but significant correlation of r=-0.332, p = 0.001 < 0.05 was obtained between total trihalomethanes and residual chlorine. Generally, as the residue chlorine content decreased, the concentration of THMs increased. This is because presence of chlorine in water dissociates into hypochlorous acid and hypochlorite ion species which are pH dependent. Whenever conditions are acidic, hypochlorous acid is dominant, while when the conditions are alkaline hypochlorite ion dominates. During the study, pH values in drinking water ranged from 6.6 to 7.5. Thus, hypochlorous acid was more dominant than hypochlorite ion. Therefore, the hypochlorous acid reacted with the organic matter to form THMs. In this case when THM concentration increases, the concentration of hypochlorous acid decreased, hence reduced residual chlorine. Several studies have been conducted and have reported the same trend where the reduced residual chlorine was associated with an increased trihalomethanes formation (Abdullah et al., 2003 ; Kowalska et al., 2007; Ye et al., 2009 ;

Ramavandi et al., 2015). Also, due to other factors such as chlorine decay, quantities of chlorine doses could possibly affect the relationship between residual chlorine and trihalomethanes concentration. This is supported from the literature by other studies that have found out contrary to our study, a positive correlation between total trihalomethanes and residual chlorine (Zelelew et al., 2018 ; Nadali et al., 2019). This is explained by increased chlorine doses lead to increased available residual chlorine hence increased trihalomethanes formed (Saidan et al., 2013).

Figure 4.3 illustrates the relationship between total trihalomethanes and total organic carbon in drinking water.

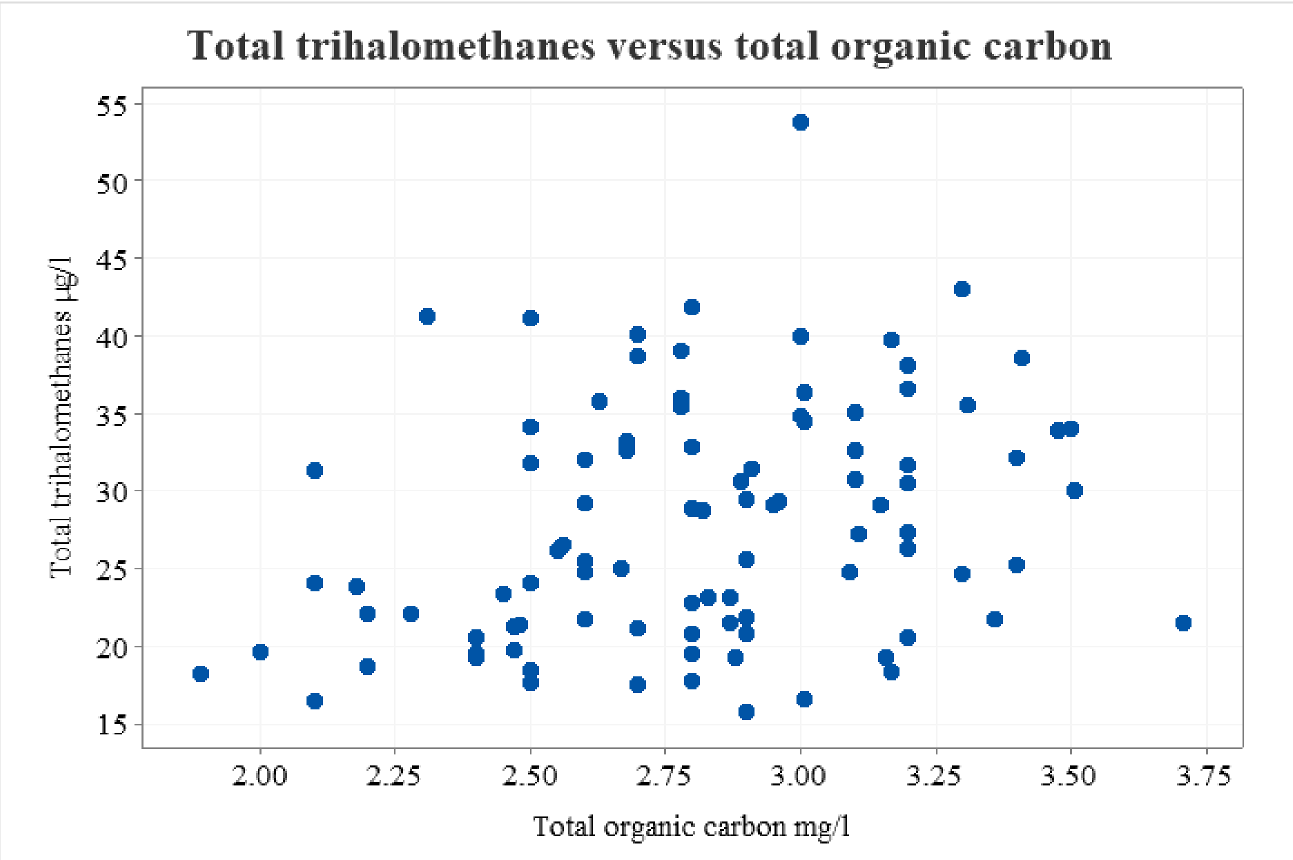

Figure 4.3: Scatter Plot of Total Trihalomethanes Versus TOC

Using a Pearson correlation method, weak, positive but significant correlation r=0.324, p value =0.001 < 0.05 was obtained between total trihalomethanes and TOC as seen in Table 4.14 and Table 4.15. The trend showed that points that had high total organic carbon, there was an increase in total trihalomethanes formed. This implies that the natural organic matter present in the water favors formation of trihalomethanes. According to Abdullah et al. (2003), the hydrophobic part of the natural organic matter is majorly responsible for the THMs formation since the part readily reacts with chlorine. Also, several studies have been carried out and found out that trihalomethanes and total organic matter have a low, positive and significant correlation (Abdullah et al., 2003; Ye et al., 2009; Saidan et al., 2013; Souaya et al., 2015). On contrary to this study, other studies have been carried out and found TOC and THMs have a negative correlation explanation being not all the organic compounds present in water lead to formation of trihalomethanes. Furthermore, the total organic carbon measurements don't distinguish between the various chemical compounds comprised in the DBP precursor (Mohammadi et al., 2015; Zelelew et al., 2018; Nadali et al., 2019).

The relationship between total trihalomethanes and pH in drinking water was illustrated in Figure 4.4.

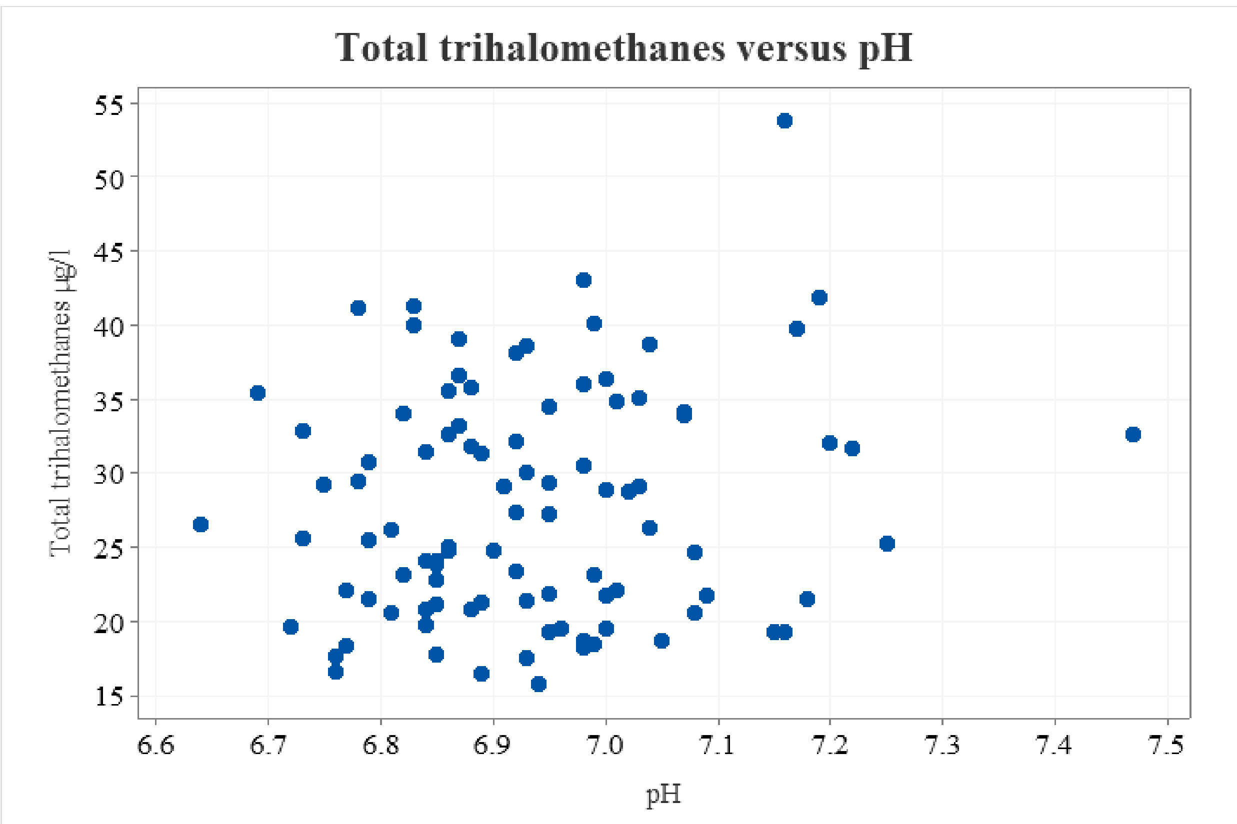

Figure 4.4: Scatter Plot of Total Trihalomethanes Versus pH

Using Pearson correlation method, a very weak positive but non-significant correlation r = 0.097, p value = 0.348 > 0.05 was obtained between total trihalomethanes and pH for the study. The pH values were in a narrow range from 6.6 to 7.5. This is because the pH is strictly maintained in the acceptable limits, therefore the very weak correlation between pH and trihalomethanes formation. However, previous studies have found out that as the pH levels increased from 6 to 9, the total trihalomethanes formed increases (Ye et al., 2009; Saidan et al., 2013; Souaya et al., 2015; Zelelew et al., 2018). This is because higher pH levels favor base-catalyzed hydrolysis of the halogenated group of which THMs are part (Bond et al., 2012). In addition, according to Bond et al. (2012), when the pH levels are 5 and below being acidic conditions, studies have indicated a decrease in trihalomethanes formation.

A linear regression analysis was used to obtain the relationship between total trihalomethanes and bromide concentration as illustrated in Figure 4.5.

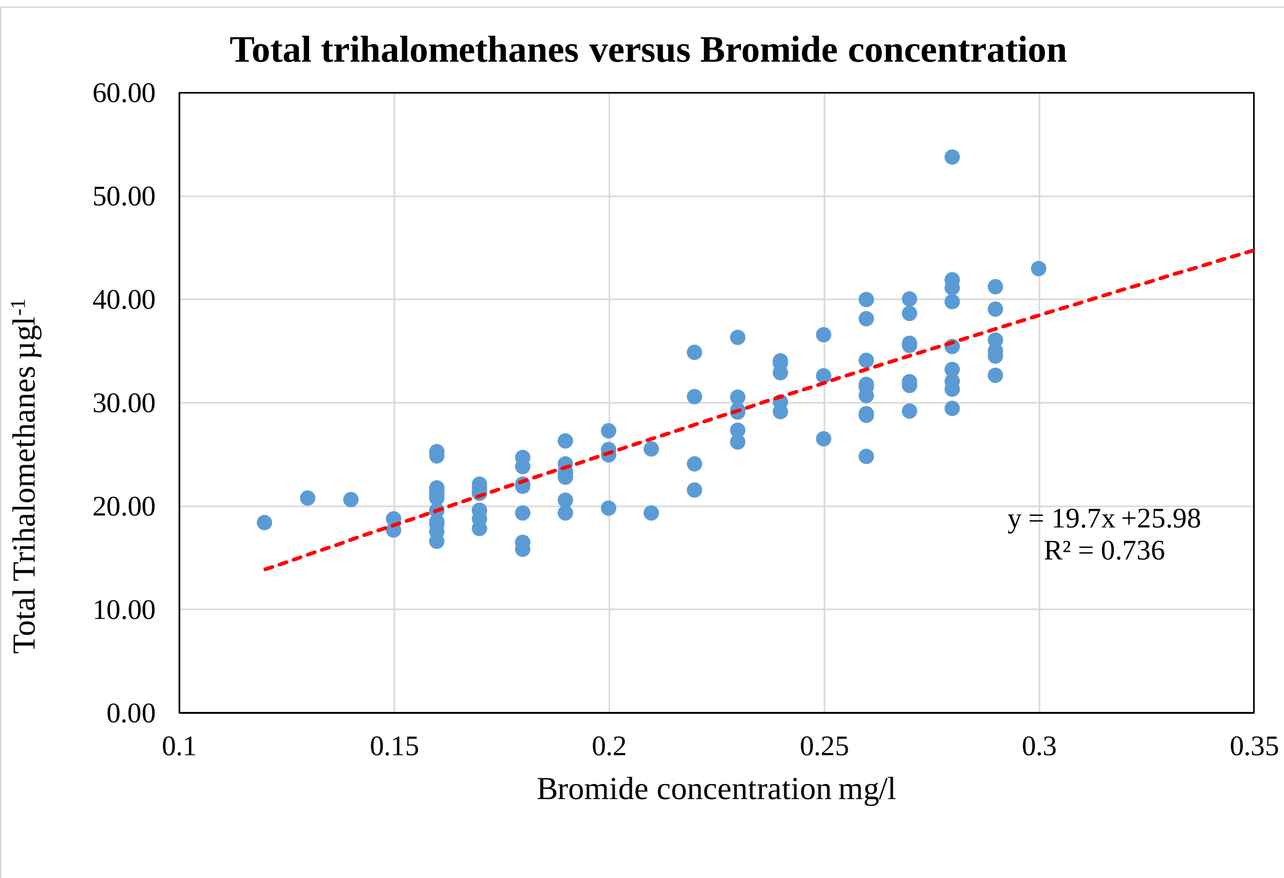

Figure 4.5: Scatter Plot of Total Trihalomethanes Versus Bromide Concentration

Using Pearson correlation method, a strong positive but significant correlation r = 0.873, p value = 0.00 < 0.05 was obtained between total trihalomethanes and bromide concentration. From the study, it showed an increase in the bromide concentrations led to increased total trihalomethanes this is contributed by an increase in the formation of bromodichloromethane. This is explained by presence of bromide in water is oxidized to bromine that reacts with natural organic matter to form brominated THMs (Kujlu et al., 2020). Several researchers have found out that slight increase in bromide concentrations leads to increase in total trihalomethanes (Ristoiu et al., 2009 ;Ye et al., 2009 ; Souaya et al., 2015).

The relationship between total trihalomethanes and ultraviolet absorbance at 254 nm was illustrated in Figure 4.6.

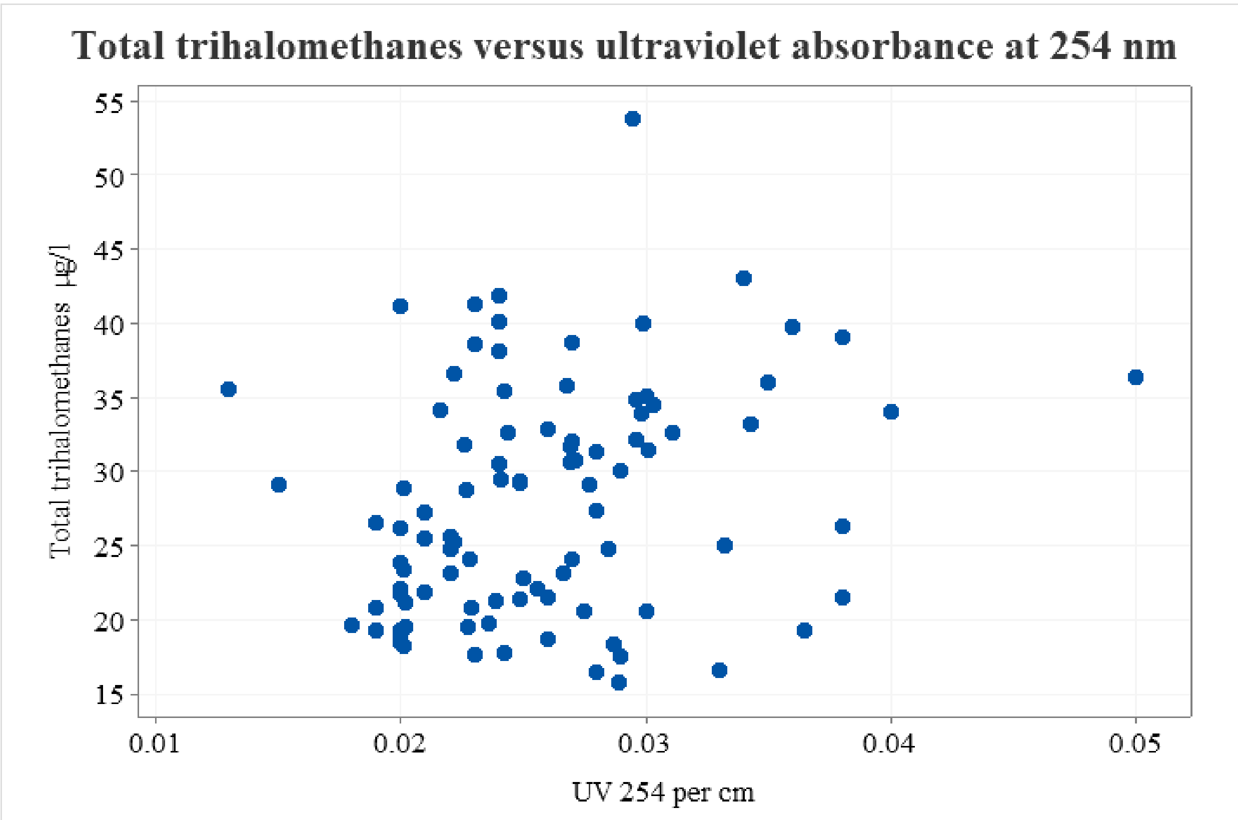

Figure 4.6: Scatter Plot of Total Trihalomethanes Versus UV_{254}

Using Pearson correlation method, weak, positive but significant correlation r =0.280, p value = 0.006 < 0.05 was obtained between total trihalomethanes and ultraviolet absorbance at 254 nm. Generally, high UV_{254} values led to an increase in the formation of trihalomethanes. This is explained by a high UV_{254} means there is a high concentration of aromatic material in the water which consist of the primary sites that react with chlorine to form DBPs (Stéphanie, 2020). According to a study carried out in China on factors influencing DBPs formation in drinking water, the increased UV_{254} levels led to the increased formation of THMs, whereas whenever the UV_{254} levels were low, the THMs formation was low (Ye et al., 2009).

Figure 4.7 illustrates the relationship between total trihalomethanes and temperature. From Figure 4.7, it indicates there is a linear relationship between the two variables

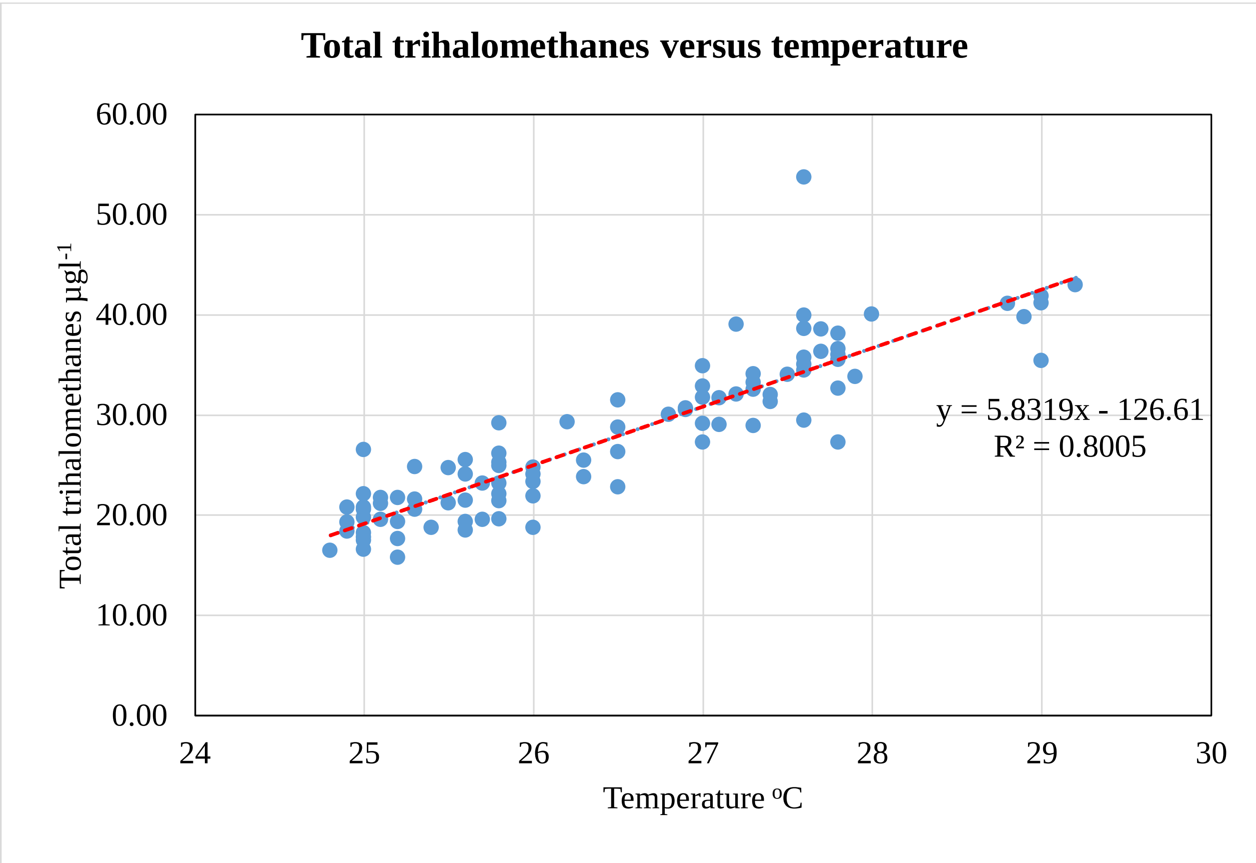

Figure 4.7: Scatter Plot of Total Trihalomethanes Versus Temperature

The regression equation Y=5.8X-126.6 relates the total trihalomethanes and the temperature in drinking water. Using Pearson correlation method as seen in Table 4.13 above, a strong positive and significant correlation r=0.905, p value = 0.00 < 0.05 was obtained between total trihalomethanes and temperature. Generally, the trend on the plot from the study showed that as temperatures increased, the total trihalomethanes formed also increased. This is explained by an increase of temperature quickens the reaction rate between organic matter present in water and the chlorine (Ramavandi et al., 2015). Several studies have been conducted to investigate factors affecting trihalomethanes formation in drinking water results indicated that increased temperatures led to increase in trihalomethanes formed (Saidan et al., 2013; Ramavandi et al., 2015; Zelelew et al., 2018).

4.3 Evaluation of Potential Health Risks Associated with Trihalomethanes

The exposure and assessment of the cancer risk was calculated based on the mean concentration of the individual trihalomethanes found in the water; chloroform 19.92 µg/l and bromodichloromethane 7.86 µg/l and the mean total trihalomethanes concentration 27.77 µg/l during the three months study.

4.3.1 Word Health Organization Index for Non-Carcinogenic Risks for Trihalomethanes

The WHO index for additive toxicity was calculated using equation 3.2 in Chapter 3. The trihalomethanes resulted into a WHO index of 0.4104 which was less than one. Due to this, the additive toxicity of THM levels in the Kampala water western zone is compliant with the WHO THM guideline. According to the WHO index, the value showed that the levels of THMs in water do not pose any non-carcinogenic risk to the residents in the Kampala western zone. Several studies have been done and the WHO index for additive toxicity was less than unity meaning the concentrations did not pose any adverse toxic health impacts (Semerjian & Dennis, 2008 ; Salih & Al-azzawi, 2016 ; Ewaid et al., 2018).

4.3.2 USEPA Carcinogenic Risk Assessment

The sample size for Kampala water western zone was computed using Equation 3.1 in Chapter 3. The computed sample size was three hundred seventy-six people. Table 4.15 summarizes the age, body weight, height and body surface area for females and males in the study population.

Table 4.15: Description of the Kampala Western Zone Population

Female					
Variable	**Total Count**	**Mean**	**±SE**	**Min**	**Max**
Age	188	37.77	0.629	24	75
BW (Kg)	188	67.06	0.38	55.5	81
Height (cm)	188	158.77	0.193	154	164
BSA (m^2)	188	1.69	0.004	1.56	1.88
Male					
BW (Kg)	188	70.653	0.416	59.9	88
Age	188	40.899	0.798	28	82
Height (cm)	188	164.07	0.263	156	172
BSA (m^2)	188	1.844	0.005	1.65	1.98

The survey provided a representative body weight and height for Kampala water western zone population. The average body weights obtained for male and females were 70.6 and 67.1 kg respectively while the average heights were 164 and 158.8 cm for males and females respectively. The surface body area was computed using Equation 3.8, this resulted into 1.84 and 1.69 m^2 surface area for males and females respectively. The results obtained in the study are supported by USEPA, (1997) standards of 70 kg for an adult body weight, and body surface area of 1.9 and 1.69 for males and females respectively. To carry out the USEPA carcinogenic risk assessment, various exposure factors were obtained from Table 3.5 and 3.6. Also, according to Uganda Bureau of Statistics, the average life expectancy for Ugandans were 62.8 and 64.5 years for males and females respectively. These factors were used in the computation of the carcinogenic risks.

1. **Hazard Quotient Evaluation for THMs**

The hazard quotient for individual THMs were computed using Equation 3.3, the HQ chloroform was 0.0577 which is less than one, while the HQ bromodichloromethane was 0.0114 which is less than one. Therefore, the THM concentrations found in the distribution system do not pose any adverse developmental and non-carcinogenic risks for CF, and BDCM to the Kampala water western zone residents during the study period according to USEPA guidelines. Several studies have used the hazard quotient to evaluate the risk and results showed that there were no non carcinogenic risks (Viana & Cavalcante, 2009 ; Karim et al., 2013; Abdullah, 2014 ; Ewaid et al., 2018).

2. **Different Exposure Route Evaluations of Lifetime Cancer Risks for THMs.**

The humans are exposed to THMs in three different routes; oral, dermal and inhalation routes. The computation for the lifetime carcinogenic risk for THMs were obtained using exposure factors in Tables 3.5 and 3.6 substituted in Equations 3.4 to 3.10 as illustrated in Chapter 3. Table 4.16 summarizes the carcinogenic risks through oral, dermal and inhalation routes for females and males computed for the study population.

Table 4.16: The Lifetime Carcinogenic Risks Associated with Trihalomethanes in Water

	FEMALE			
Chemical compound	**Oral exposure risk**	**Dermal exposure risk**	**Inhalation exposure risk**	**Total Risk**
Chloroform	1.82×10^{-5}	7.37×10^{-6}	8.29×10^{-6}	3.39×10^{-5}
Bromodichloromethane	7.20×10^{-6}	1.71×10^{-6}		8.91×10^{-6}
Total Risk	2.54×10^{-5}	9.08×10^{-6}	8.29×10^{-6}	4.28×10^{-5}
	MALE			
Chemical compound	**Oral exposure risk**	**Dermal exposure risk**	**Inhalation exposure risk**	**Total Risk**
Chloroform	1.75×10^{-5}	8.12×10^{-6}	7.96×10^{-6}	3.36×10^{-5}
Bromodichloromethane	6.91×10^{-6}	1.89×10^{-6}		8.80×10^{-6}
Total Risk	2.44×10^{-5}	1×10^{-5}	7.96×10^{-6}	4.24×10^{-5}

According to USEPA, the cancer risk is divided into four categories that is $CR < 1\times 10^{-6}$ negligible, $1\times 10^{-6} < CR < 5.1 \times 10^{-5}$ acceptable low risk, $5.1 \times 10^{-5} < CR < 1\times 10^{-4}$ acceptable high risk and $CR > 1\times 10^{-4}$ unacceptable risk (Legay et al., 2011).

Oral Route Evaluations of Lifetime Carcinogenic Risk for THMs

The cumulative carcinogenic risk through oral route for total THMs were 2.44×10^{-5} and 2.54×10^{-5} for male and female respectively, which lies within the USEPA acceptable low risk range of 1×10^{-6} < carcinogenic risk < 5.1×10^{-5}. The oral carcinogenic risk is within the acceptable low risk range same as a study carried out in Pakistan (Siddique et al., 2015). The carcinogenic risk through oral route was shown in Table 4.16 for male and female respectively. The lifetime carcinogenic risks computed for chloroform was found to be 1.75×10^{-5} and 1.82×10^{-5} for male and female respectively, which gives a 71.6% contribution in carcinogenic risk through the oral route. Whereas the lifetime carcinogenic risks computed for bromodichloromethane was found to be 6.91×10^{-6} and 7.20×10^{-6} for male and female respectively, which gives a 28.3% contribution in carcinogenic risk through the oral route. A study carried out in India showed that chloroform had the highest percentage contribution of 56% to total ingestion carcinogenic risks (Mishra et al., 2014). Generally, the oral carcinogenic risk was higher in females than males this is contributed by the high life expectancy of the Ugandan females compared to the males. Chloroform presents a great carcinogenic risk though within the acceptable low risk range compared to bromodichloromethane because the concentration of chloroform was much higher than for bromodichloromethane in the water samples during the study.

Dermal Route Evaluations of Lifetime Carcinogenic Risk for THMs

The cumulative carcinogenic risk through dermal route for total trihalomethanes was 1×10^{-5} and 9.08×10^{-6} for male and female respectively which lies within the USEPA acceptable low risk range of $1\times 10^{-6} <$ carcinogenic risk $< 5.1 \times 10^{-5}$. A study carried out in Abadan gave the same range of acceptable low risk for the dermal route of trihalomethanes in water (Kujlu et al., 2020). The carcinogenic risk through dermal route is shown in Table 4.16 for male and female respectively. The lifetime carcinogenic dermal risks computed for chloroform was found to be 8.12×10^{-6} and 7.37×10^{-6} for male and female respectively, which gives 81.2% contribution in carcinogenic risk through the dermal route. Whereas the lifetime carcinogenic risks computed for bromodichloromethane was found to be 1.89×10^{-6} and 1.71×10^{-6} for male and female respectively, which gives 18.8% contribution in carcinogenic risk through the dermal route. Chloroform presents a great risk though within the acceptable low risk range compared to bromodichloromethane because the concentration of chloroform was much higher than for bromodichloromethane in the water samples during the study.

Inhalation Route Evaluations of Lifetime Carcinogenic Risk for THMs

The estimation of trihalomethane carcinogenic risk through inhalation route was conducted for chloroform only, this is because chloroform is highly volatile (Siddique et al., 2015). The carcinogenic risk through inhalation route was 7.96×10^{-6} and 8.29×10^{-6} for male and female respectively which lies within the USEPA acceptable low risk range of $1\times 10^{-6} <$ carcinogenic risk < 5.1 × 10^{-5}. The inhalation carcinogenic risk of chloroform was in the acceptable low risk this was contributed by the generally low concentration chloroform in the study area. However compared to previous studies done in Abadan and India the inhalation carcinogenic risk of chloroform was found to be in an acceptable high risk range (Mishra et al., 2014 ; Kujlu et al., 2020).

Total Carcinogenic Risk for THMs

The results indicated in Table 4.16 above, there is a higher carcinogenic risk through oral route that is 2.44 × 10^{-5}, followed by 1 × 10^{-5} for dermal route and finally 7.96 ×10^{-6} for inhalation route in males also there is a higher carcinogenic risk through oral route that is 2.54 × 10^{-5}, followed by 9.08 × 10^{-6} for dermal route and finally 8.29 ×10^{-6} for inhalation route in females. According to several studies carried out indicated the carcinogenic risk of trihalomethanes through oral route > dermal route > inhalation route (Lee et al., 2004 ; Semerjian & Dennis, 2008 ; Ewaid et al., 2018). Total carcinogenic risk through the routes of oral, dermal and inhalation for male and female were 4.24 × 10^{-5} and 4.28 × 10^{-5} respectively which lies within the USEPA acceptable low risk range of 1× 10^{-6} < carcinogenic risk < 5.1 × 10^{-5}. Therefore, the water consumed in the Kampala western zone has a low carcinogenic acceptable risk.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

During the study, only two trihalomethane species were present in the water that is chloroform and bromodichloromethane. The two species were present at the water treatment plant and the water distribution system. The trihalomethanes found present in water were chloroform ranging from 11.87-33.98 µg/L and 11.23-39.3 µg/L at the treatment plant and along the distribution system respectively and bromodichloromethane ranging from 0.78-9.43 µg/L and 0.89-9.15.49 µg/L at the treatment plant and along the distribution system respectively. The concentrations of THMs found in the Kampala water western zone were within NWSC (80 µg/L), WHO (200 µg/L for chloroform and 60 µg/L for bromodichloromethane), and USEPA (80 µg/L) guidelines. Among the trihalomethane species present in the water chloroform had the highest contribution to total trihalomethanes compared to bromodichloromethane. The mean concentrations at the plant and along the distribution system were all statistically significant.

Running a Pearson correlation to find the relation between water parameters TOC, UV_{254}, bromide concentration, temperature, pH, and residual chlorine and formation of THMs. The correlation showed $r = 0.324$ and $p = 0.001$ for TOC, $r = 0.28$ and $p = 0.006$ for $UV_{254,}$ $r=0.873$ $p=0.00$ for bromide concentration, $r=0.905$ $p=0.00$ for temperature, $r=0.097$ $p=0.348$ for pH and $r=-0.332$ $p=0.001$ for residual chlorine. The TOC, $UV_{254,}$ had weak positive but significant correlation however, bromide concentration and temperature had a strong positive and significant correlation with trihalomethanes formation. In addition, pH had a very weak positive but non-significant correlation while the residual chlorine had weak negative but significant correlation with trihalomethanes formation.

Potential health risks associated with trihalomethanes were evaluated using the WHO index and the USEPA model. WHO index was 0.4104 which was less than unity indicating no noncarcinogenic risk to human health in the study area. Also, the hazard quotient was less than unity, indicating no adverse health effects due to exposure to THMs in Kampala western zone. The human lifetime carcinogenic risk of THMs due to the oral ingestion, dermal and inhalation were 2.54×10^{-5}, 9.08×10^{-6} and 8.29×10^{-6} for females and 2.44×10^{-5}, 1×10^{-5} and 7.96×10^{-6} for males the values were within the USEPA acceptable low risk range of $1\times 10^{-6} < CR < 5.1 \times$

10^{-5}. Therefore, the residents in the Kampala Water western zone are consuming water that has a low acceptable carcinogenic risk according to USEPA guidelines.

5.2 Recommendations

There is need for a continuous monitoring program for trihalomethanes at Ggaba water treatment plant and also along the distribution system. This is necessary so as to balance the use of chlorine to kill pathogens while putting in consideration the minimization of formation of trihalomethanes.

Chlorine use as a disinfectant should continue to be used but the team at the Ggaba water treatment plant should ensure that all the treatment units preceding disinfection are operating effectively such that the total organic matter is reduced. Thus, this will lead to further reduction in the formation of trihalomethanes formed.

The water distribution network maintenance team should ensure that the water lines are flushed after repairs to reduce entry of foreign materials into the pipe network. In addition, the end points along the distribution system should be flushed periodically to push out any dirt that has accumulated within the pipeline.

The study showed that the lifetime cancer risk was within the acceptable low risk range according to USEPA guideline, therefore there is need to control the formation of THMs so as to have the risk reduced to negligible risk.

A study to monitor the other chlorination by-products in chlorinated drinking water; such as halo acetic acids, halo aldehydes, halo-ketones at Ggaba water treatment plant and other water treatment plants supplying other districts should be done. In addition, a study needs to be carried out including the seasonal variations and distribution of THMs concentrations at the plant and along the water distribution system.

NWSC should have an inhouse capacity building for measuring and controlling THMs formation at the water treatment plants and along water distribution system for all areas.

There is need for National Environmental Management Authority to enforce the regulations on effluent discharges from industrial, waste water treatment plants into the water sources. This will in turn reduce on the organics getting into the raw water sources.

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7.0 APPENDIX

Appendix A1: Calibration Curves for the Individual Trihalomethanes

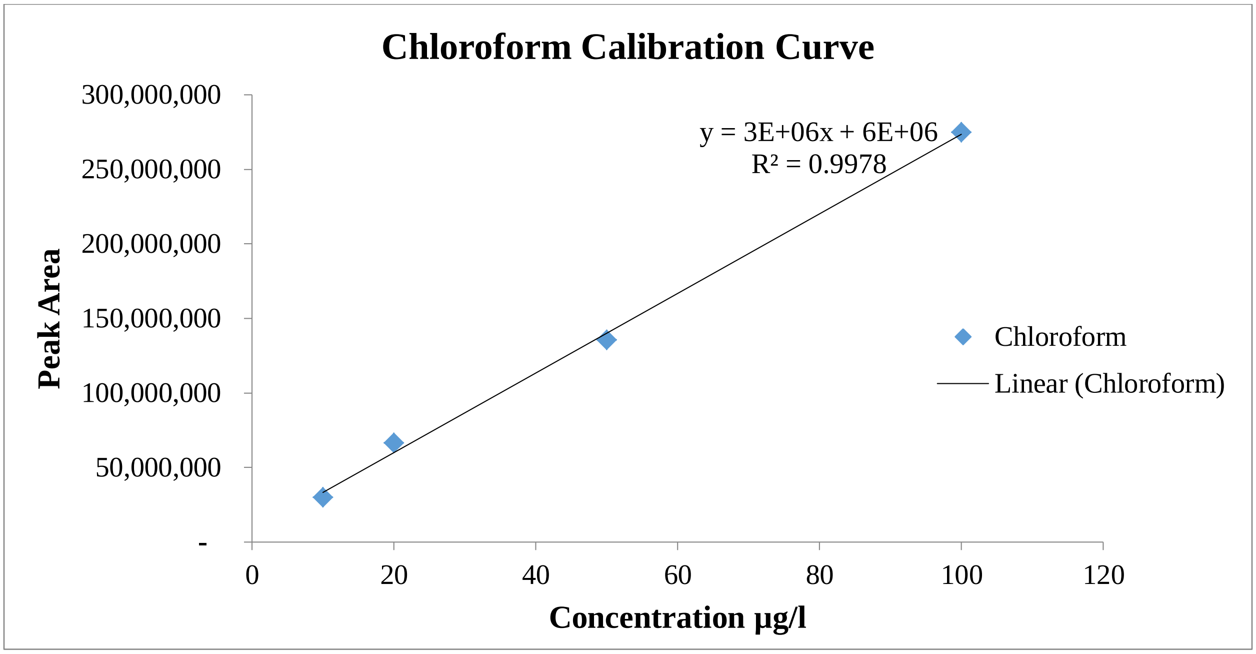


Figure 7.1: Calibration Curve for Chloroform

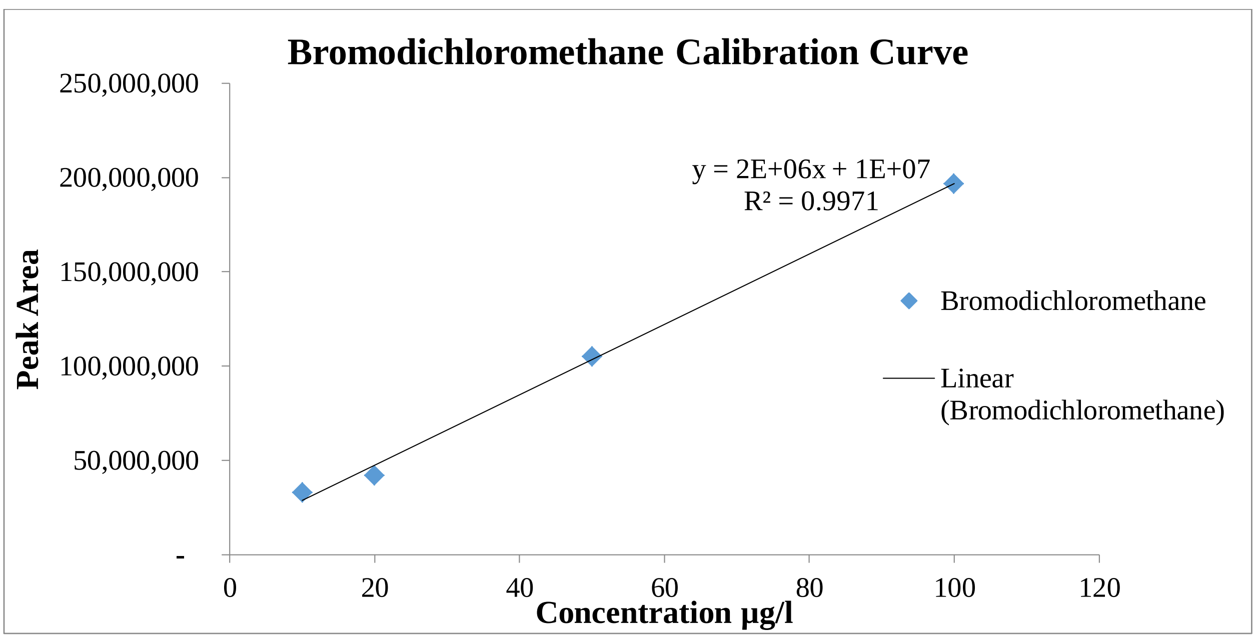


Figure 7.2: Calibration Curve for Bromodichloromethane

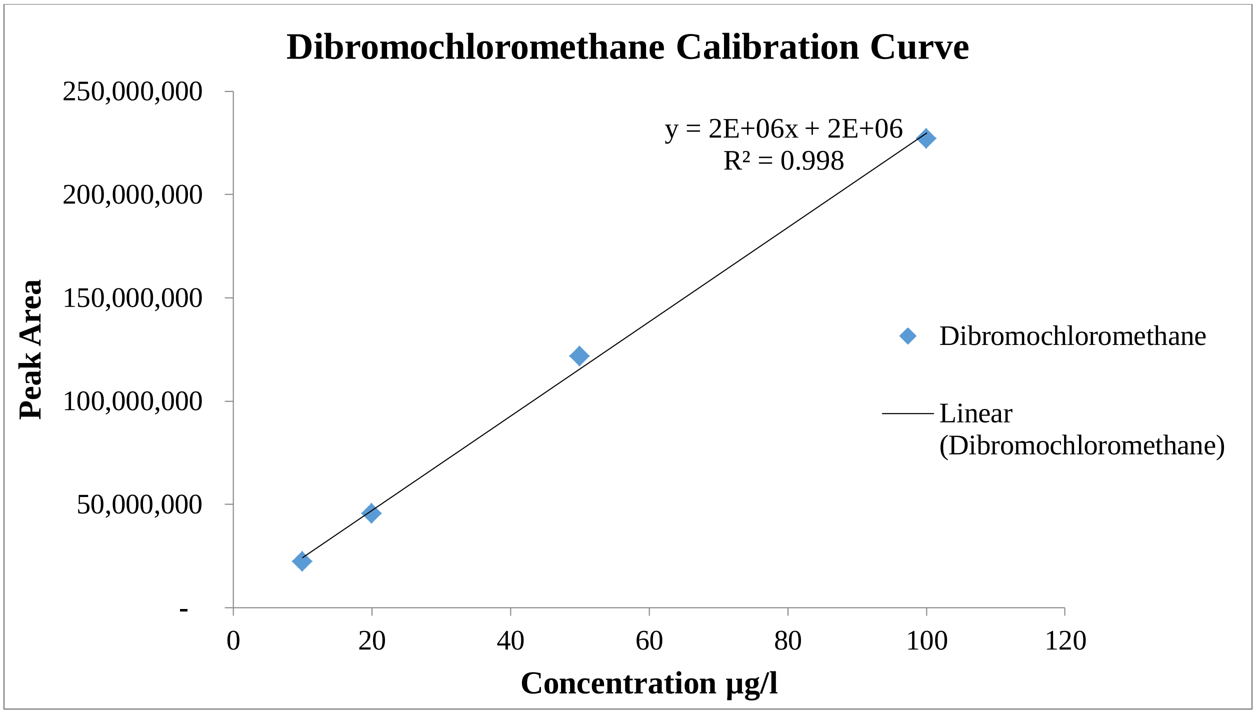


Figure 7.3: Calibration Curve for Dibromochloromethane

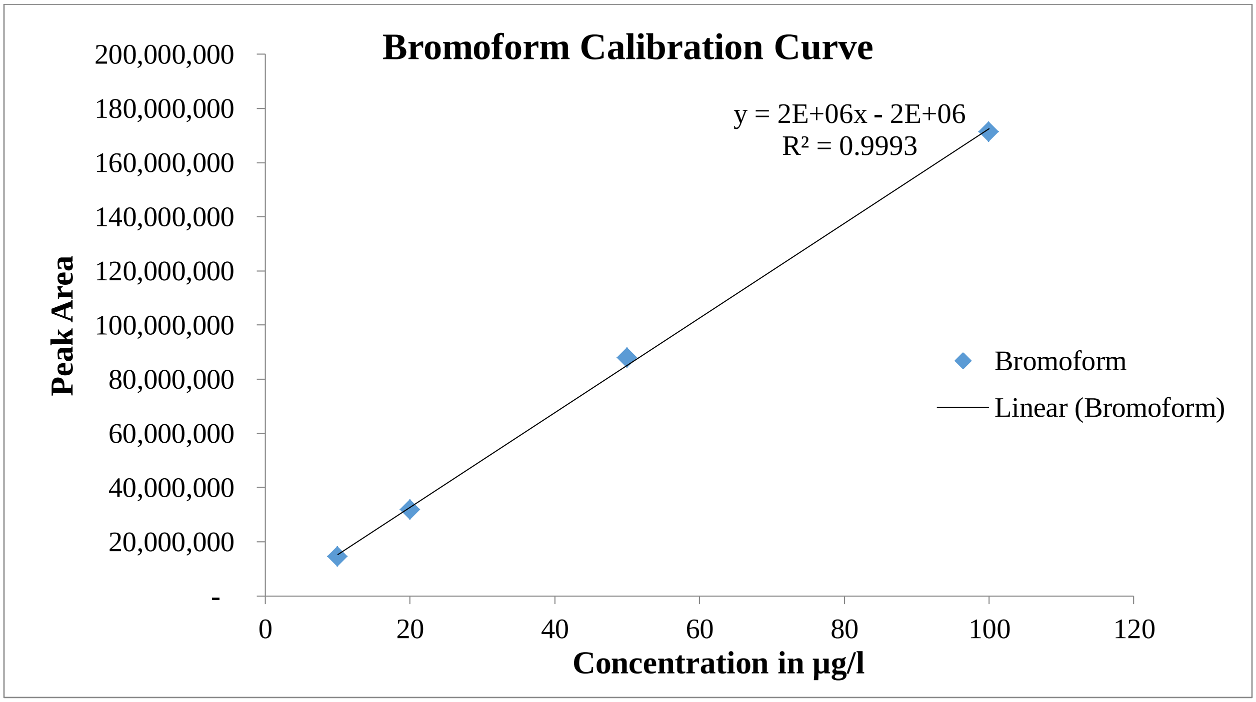


Figure 7.4: Calibration Curve for Bromoform

Appendix A2: Chromatograms for Standards

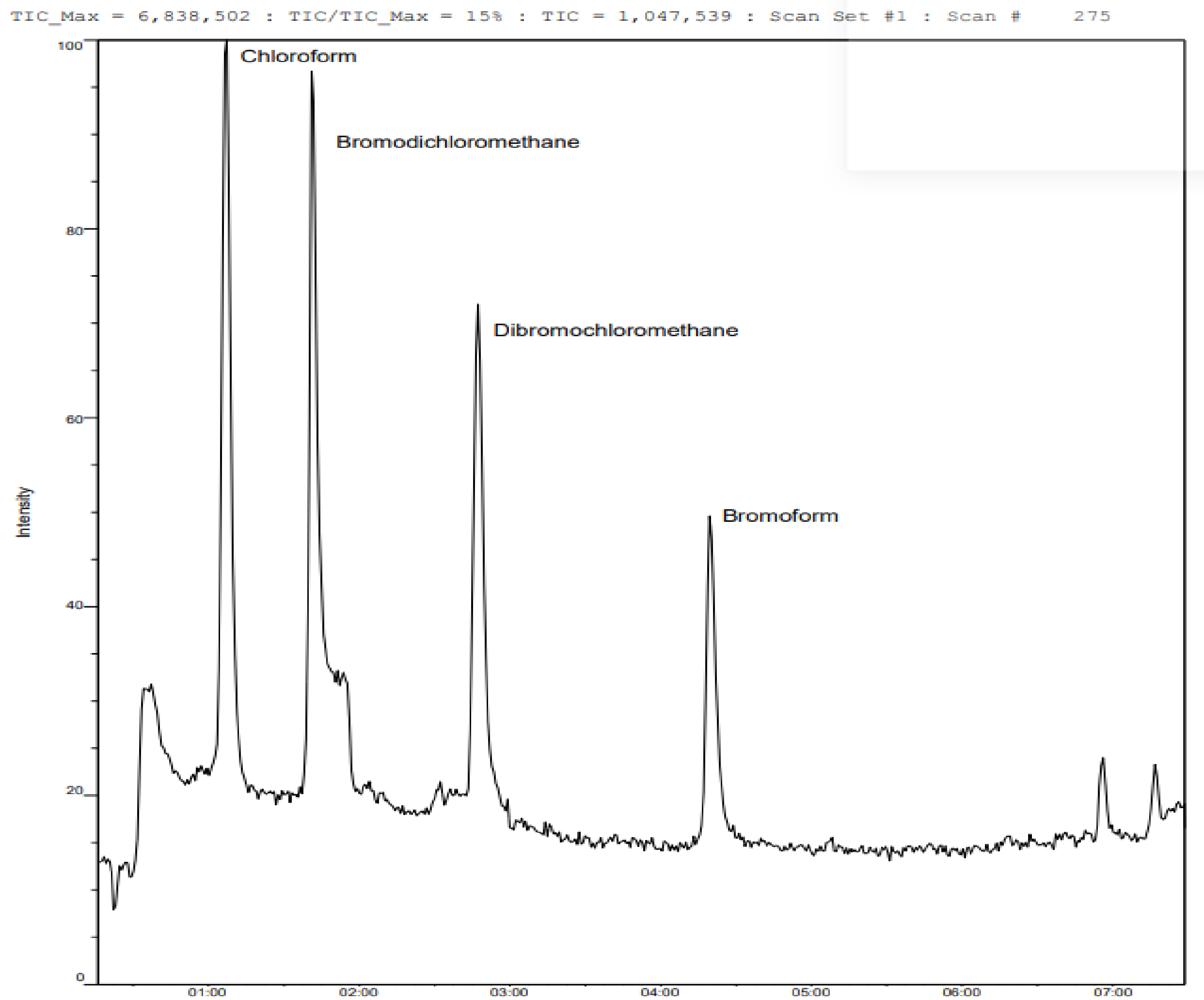


Figure 7.5: Chromatograms for 10 µg/l Calibration Standard

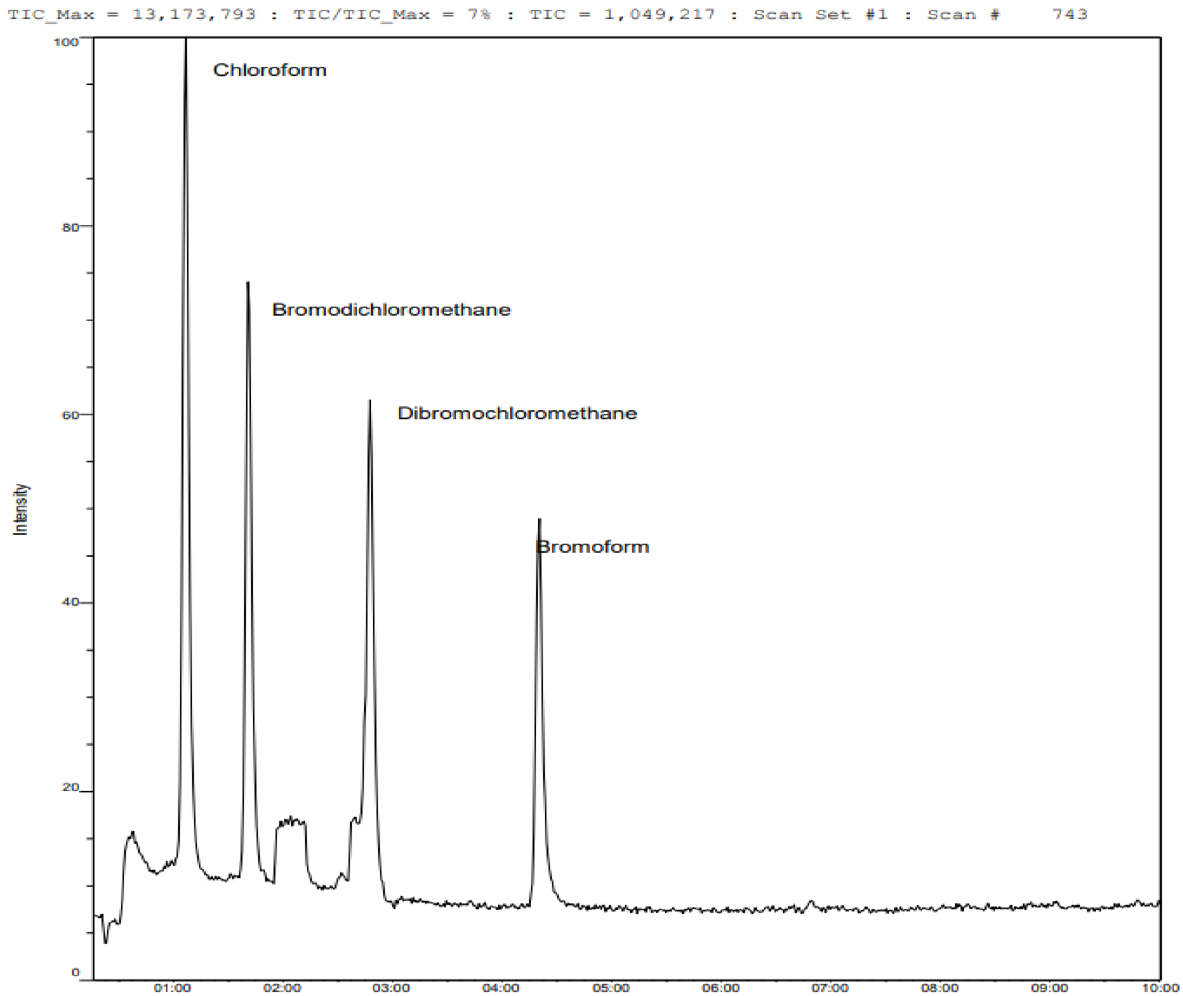


Figure 7.6: Chromatogram for 20 µg/l Calibration Standard

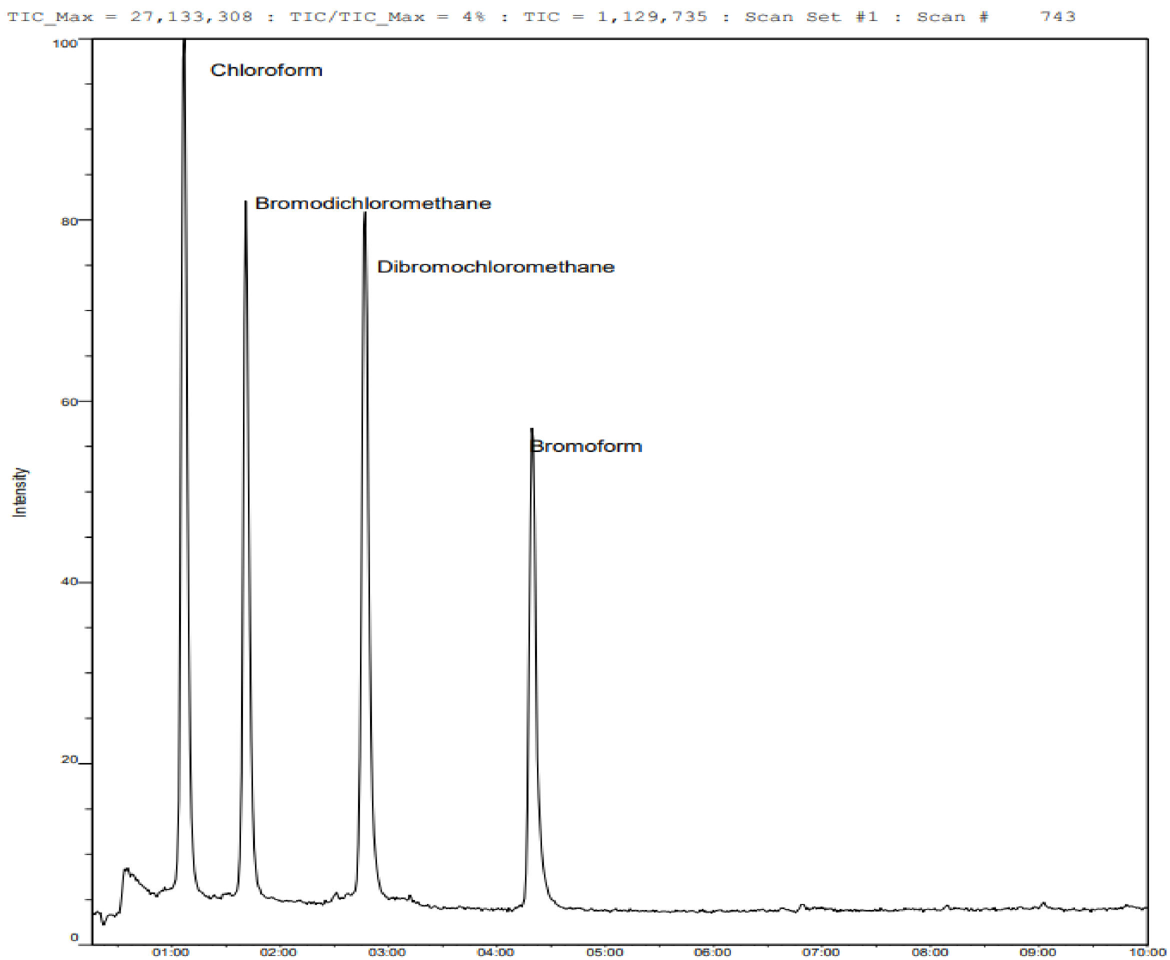


Figure 7.7: Chromatogram for 50 µg/l Calibration Standard

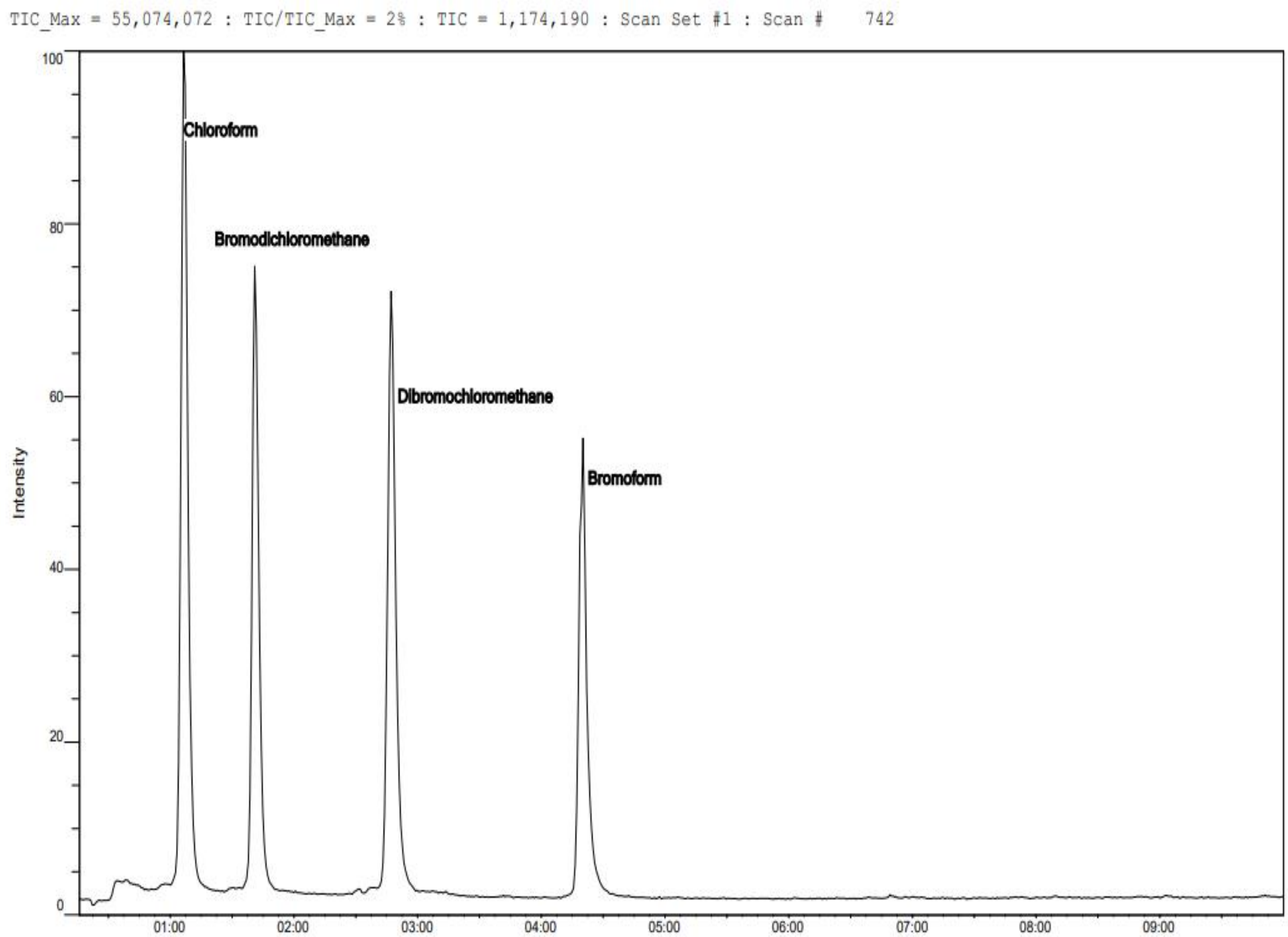


Figure 7.8: Chromatogram for 100 µg/l Calibration Standard

Appendix B: Mass Spectra Obtained for the Individual Trihalomethanes

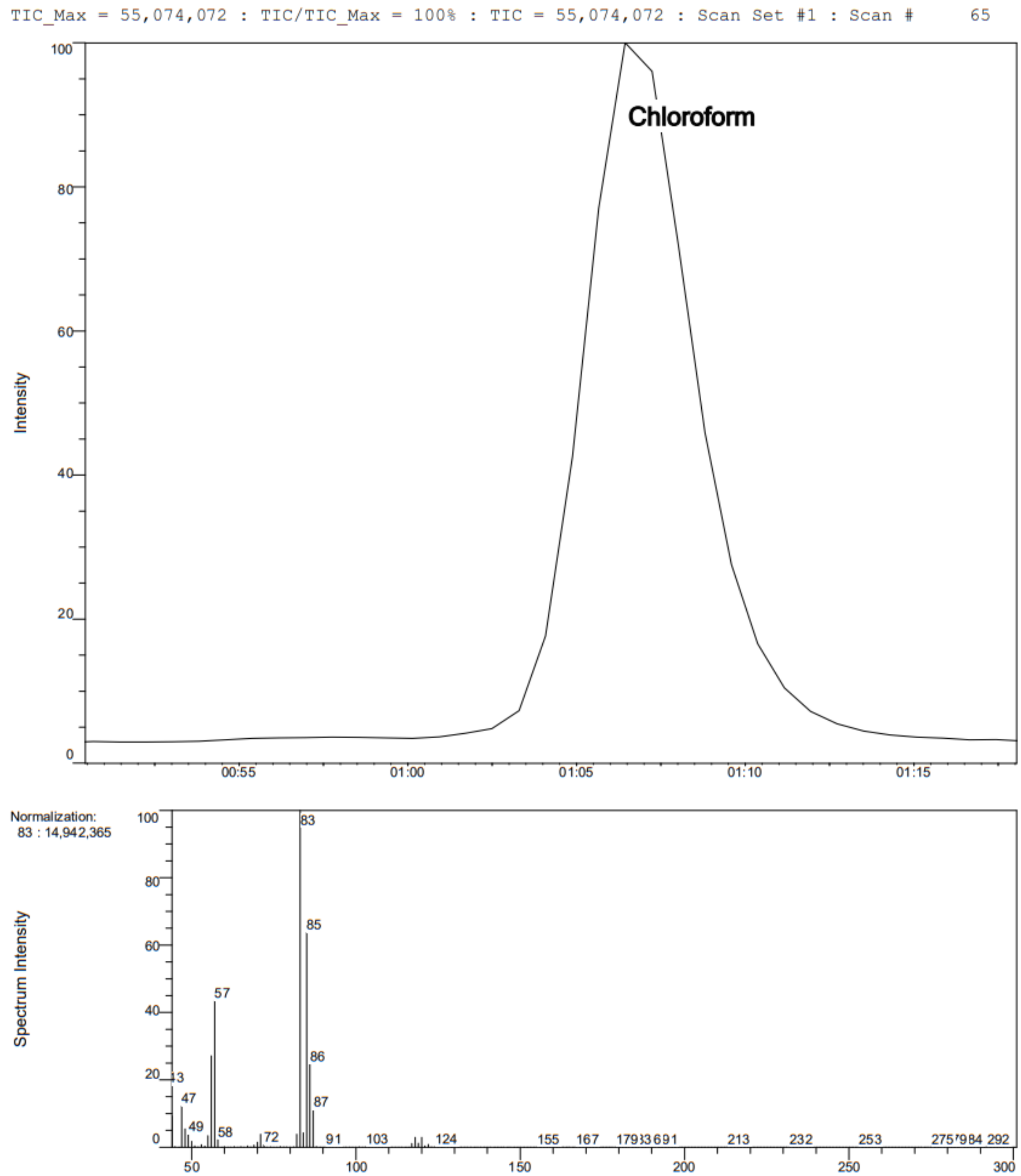


Figure 7.9: Mass Spectrum Obtained for Chloroform

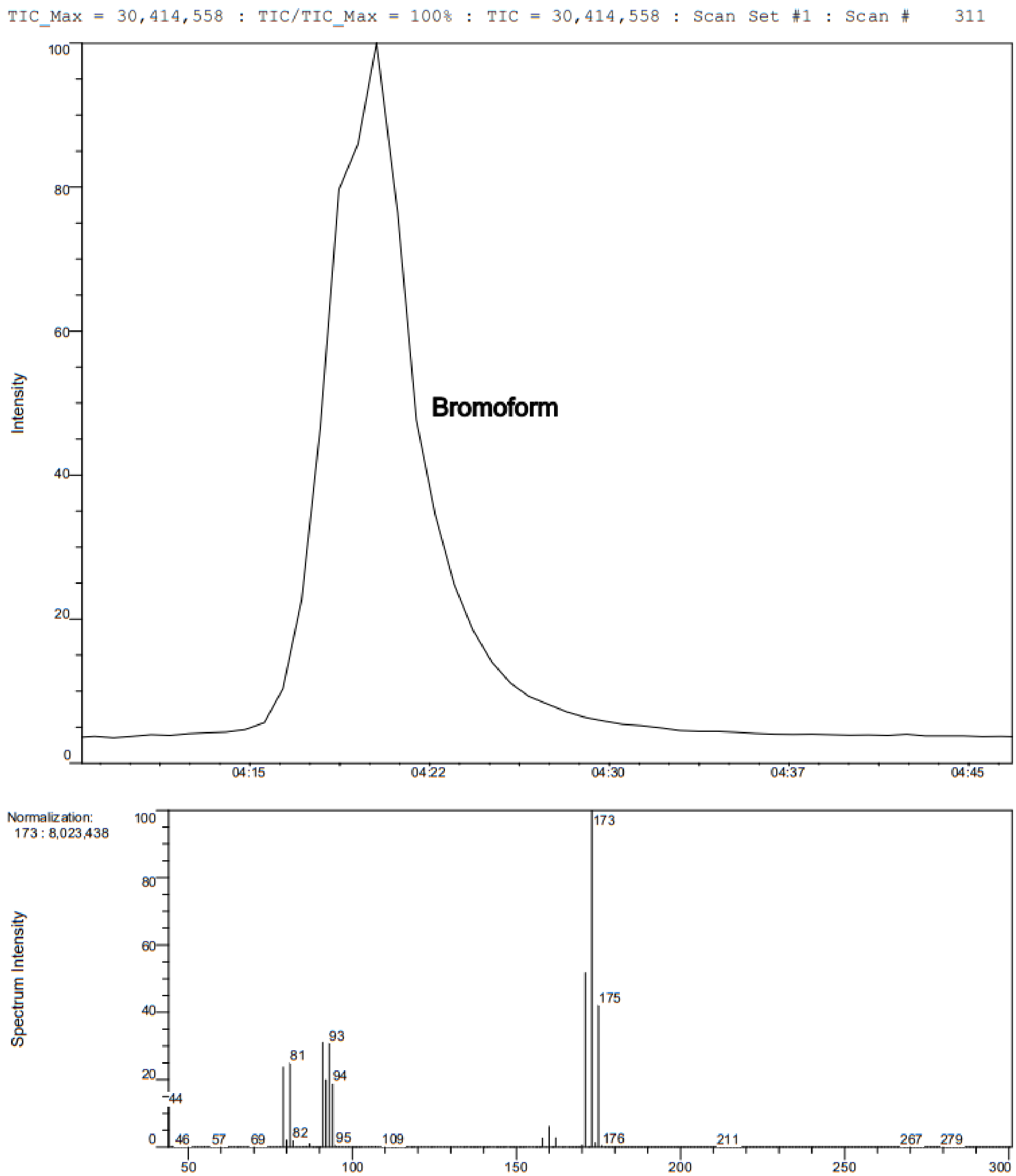


Figure 7.10: Mass Spectrum Obtained for Bromoform

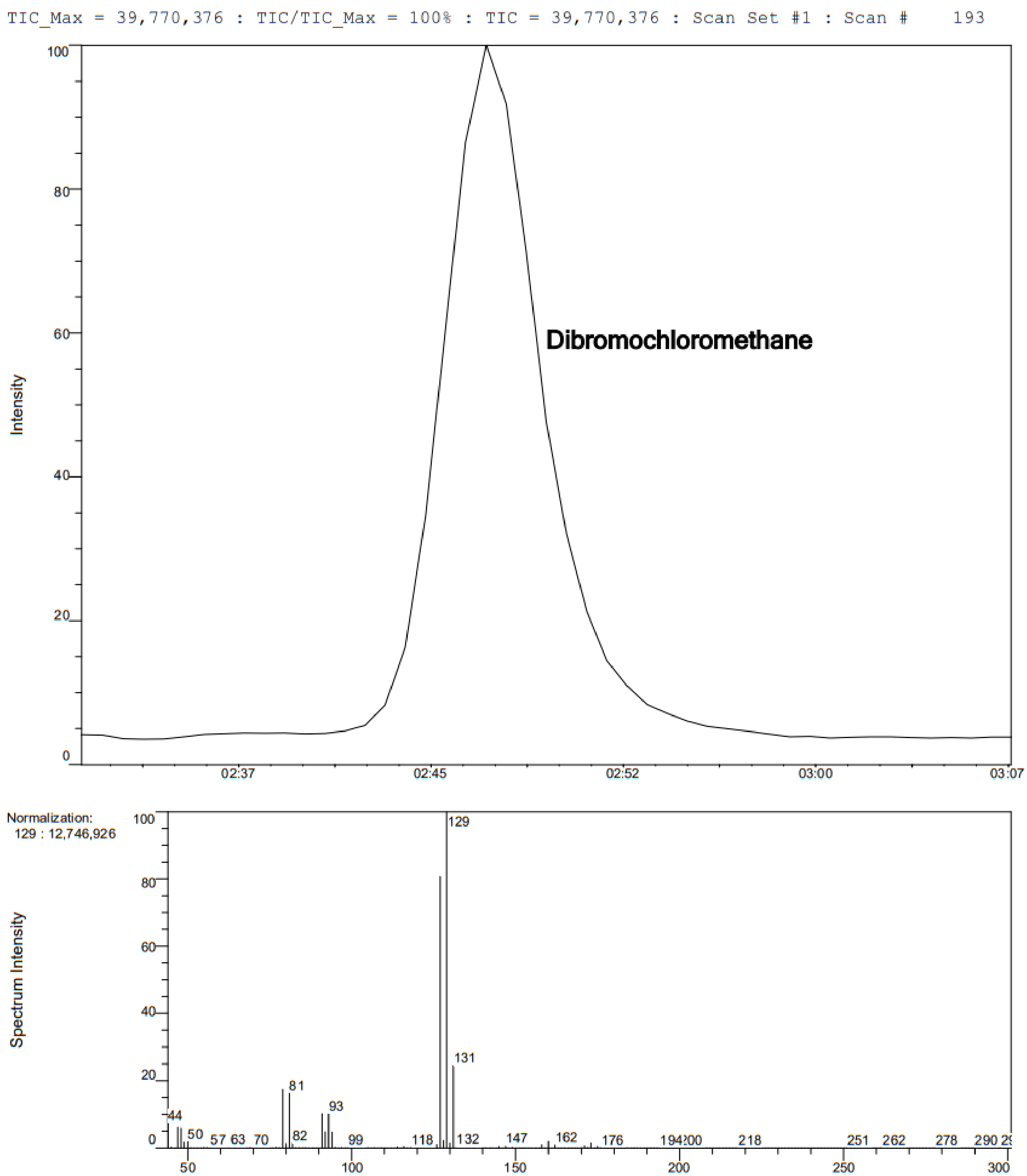
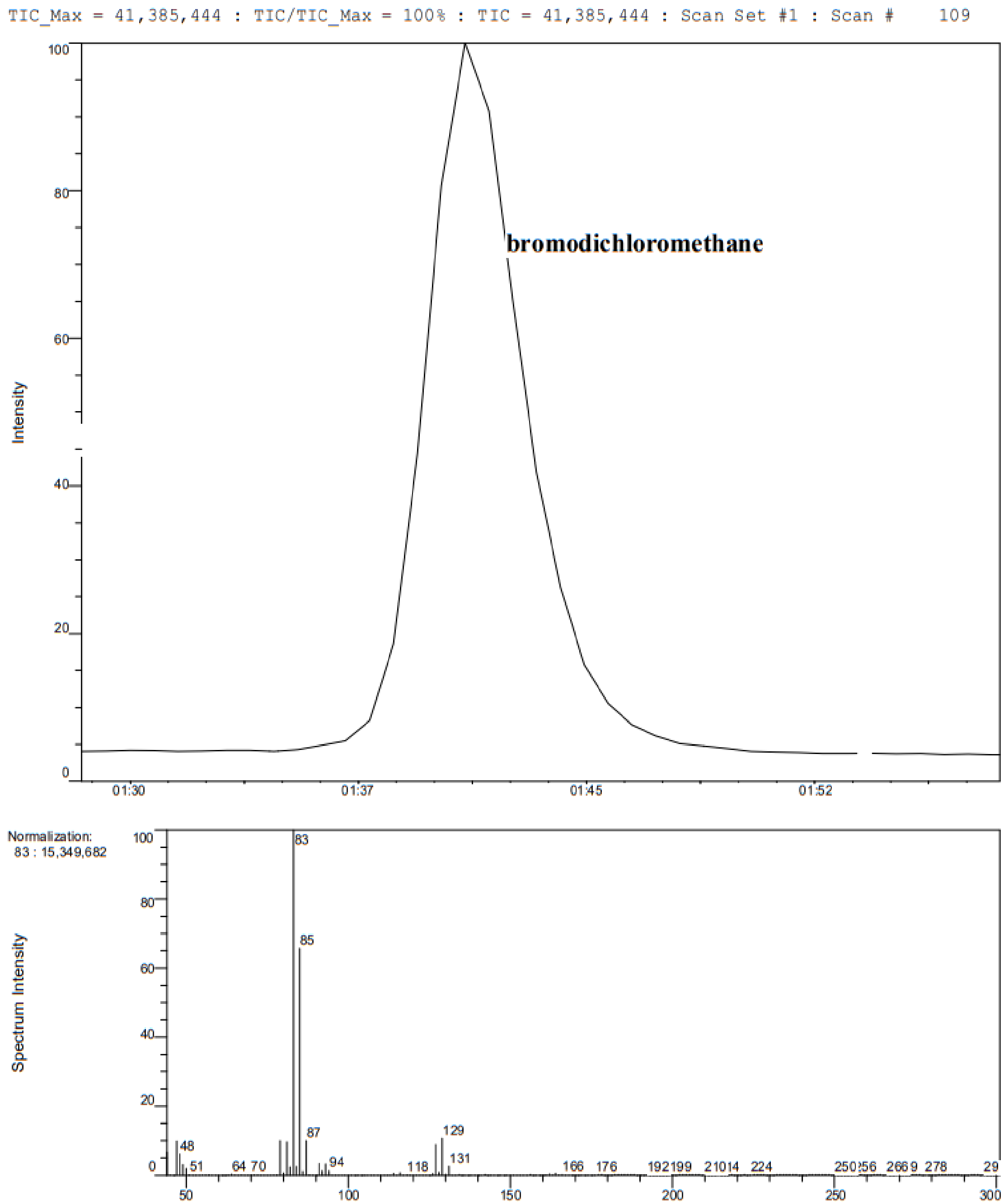


Figure 7.11: Mass Spectrum Obtained for Dibromochloromethane



igure 7.12: Mass Spectrum Obtained for Bromodichloromethane

Appendix C: Field and Laboratory Activities

Figure 7.13: Sampling along Ggaba Water Treatment Plant

Figure 7.14: Sampling from the Water Distribution System

Figure 7.15: Operating a HS Coupled with P& T GC-MS to Measure Trihalomethanes in Drinking Water.

Figure 7.16: Operating Total Organic Carbon Analyzer to Determine TOC in Drinking Water.

Figure 7.17: Operating the Cecil Spectrophotometer to Measure UV $_{254}$ in Drinking Water

Figure 7.18: Operating a Chlorine Meter to Measure Residual Chlorine

Figure 7.19: Operating a pH meter to Measure pH and Temperature in Drinking Water

Appendix D: Chromatograms for the Sampling Points

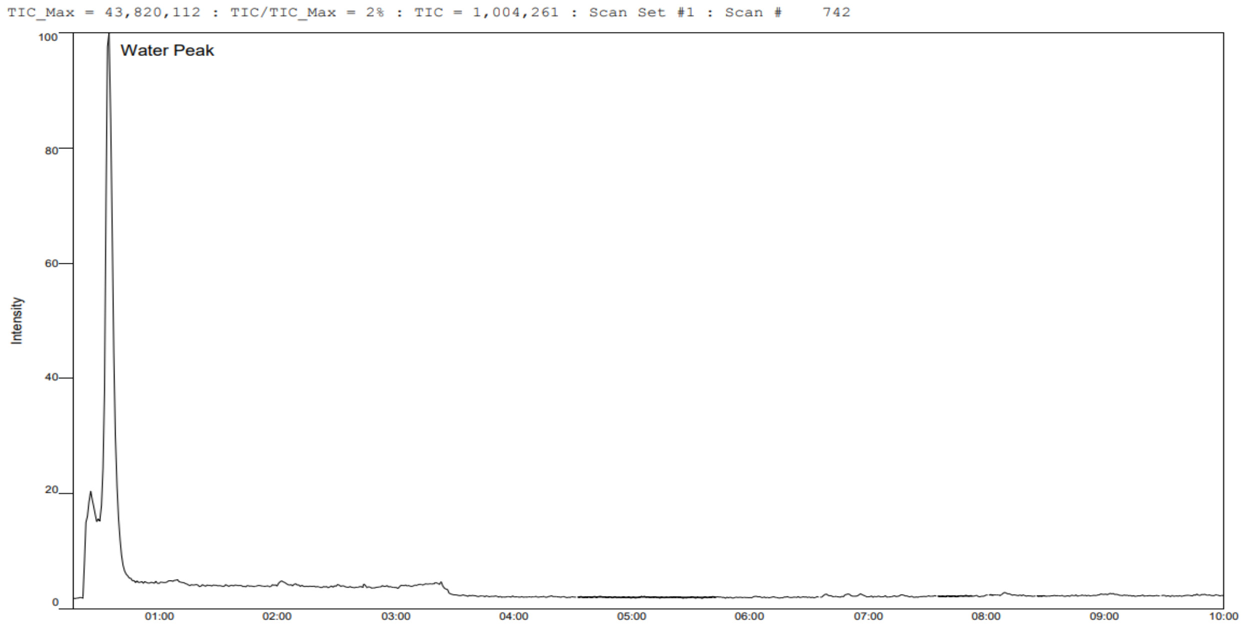


Figure 7.20: Chromatogram for Raw Water Sample at Ggaba Water Treatment Plant

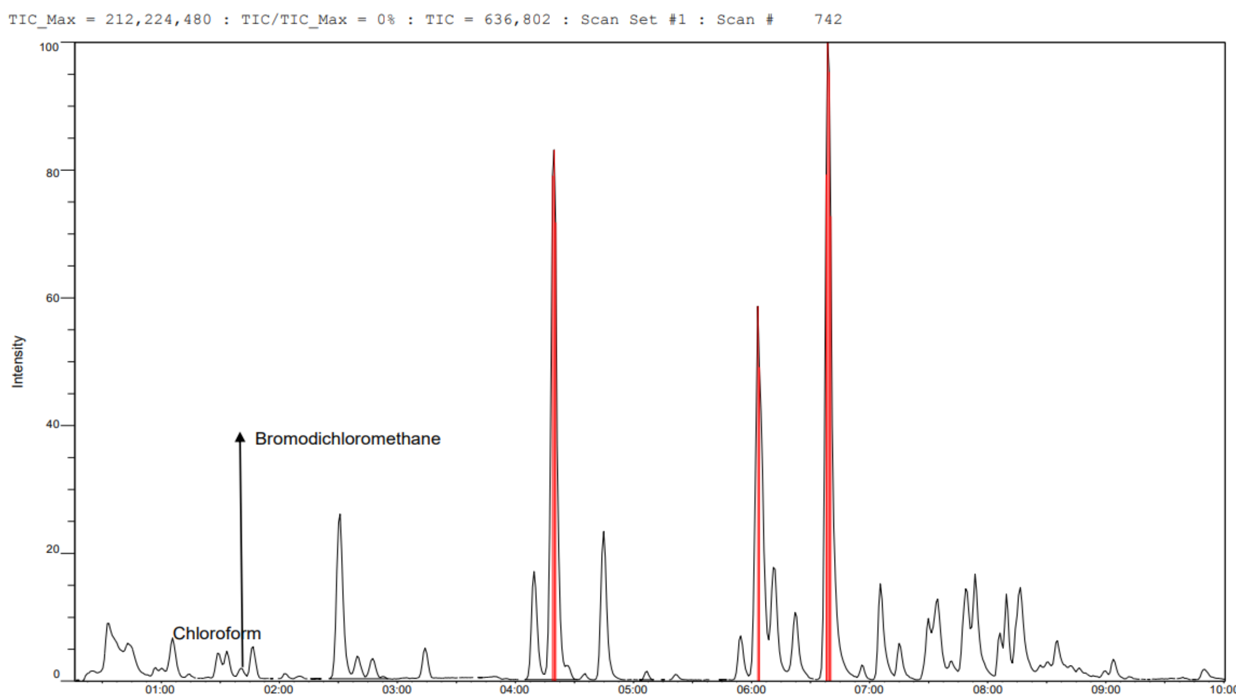


Figure 7.21: Chromatogram for Filtered Water Sample at Ggaba Water Treatment Plant

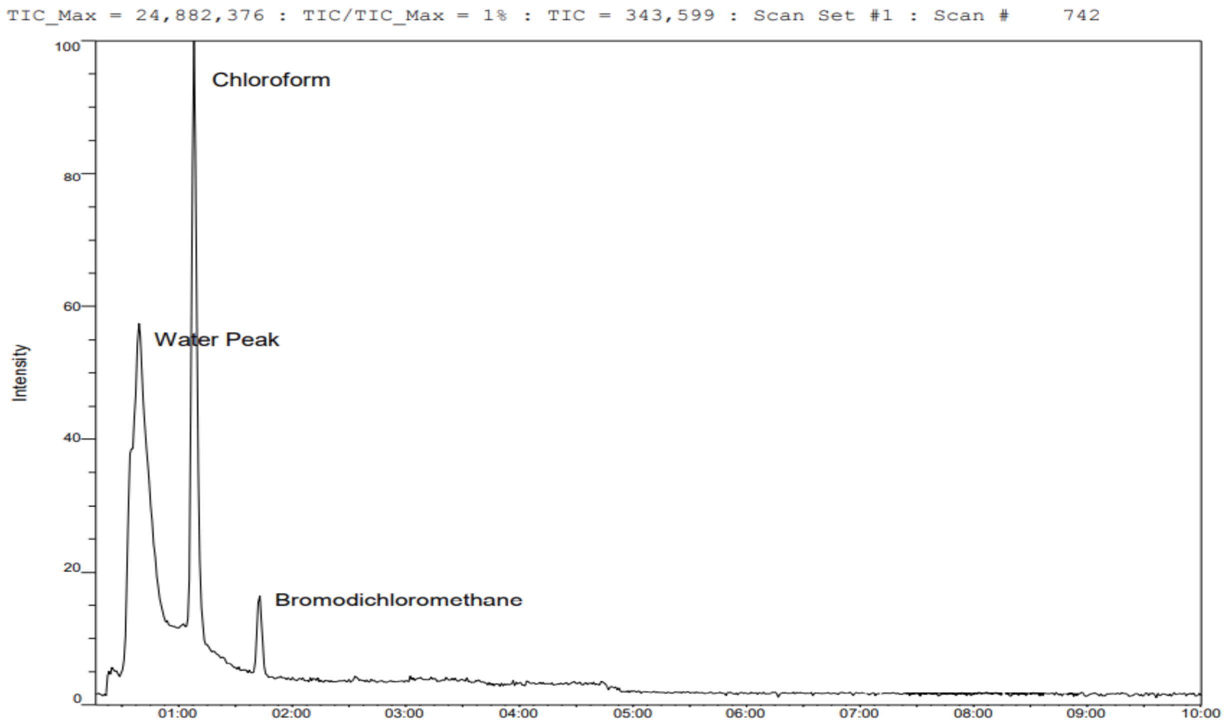


Figure 7.22: Chromatogram for the Final Water Sample at Ggaba Water Treatment Plant

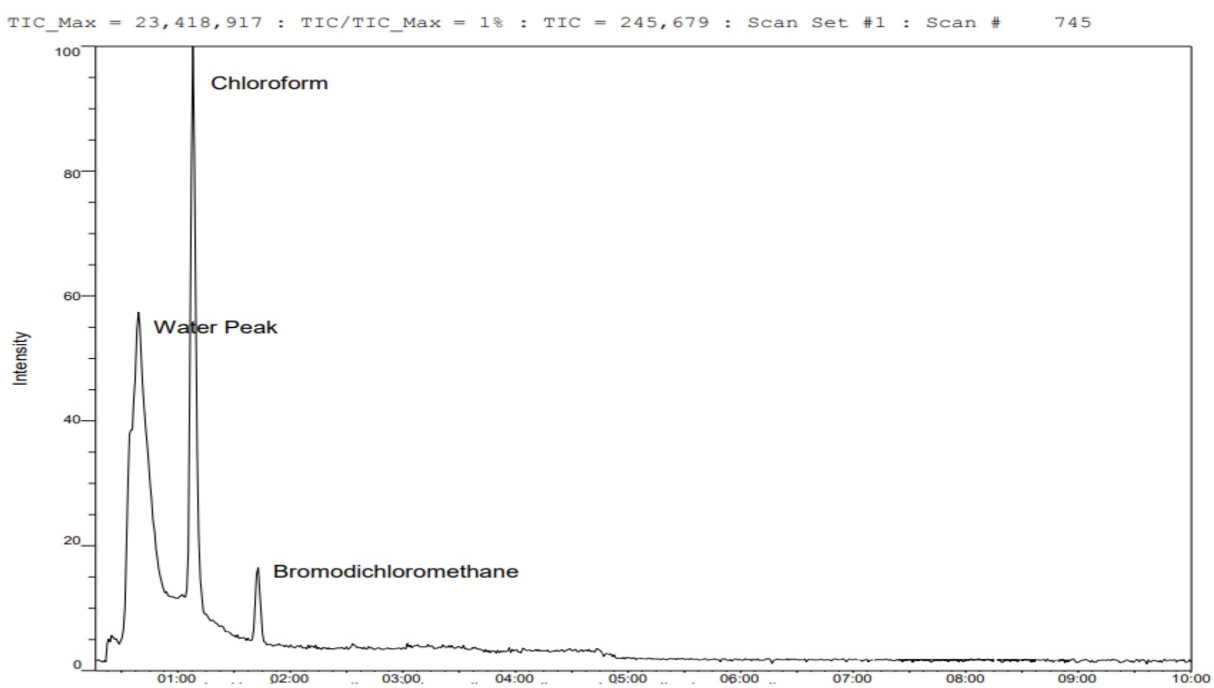


Figure 7.23: Chromatogram for Mawanga zone Sampling Point

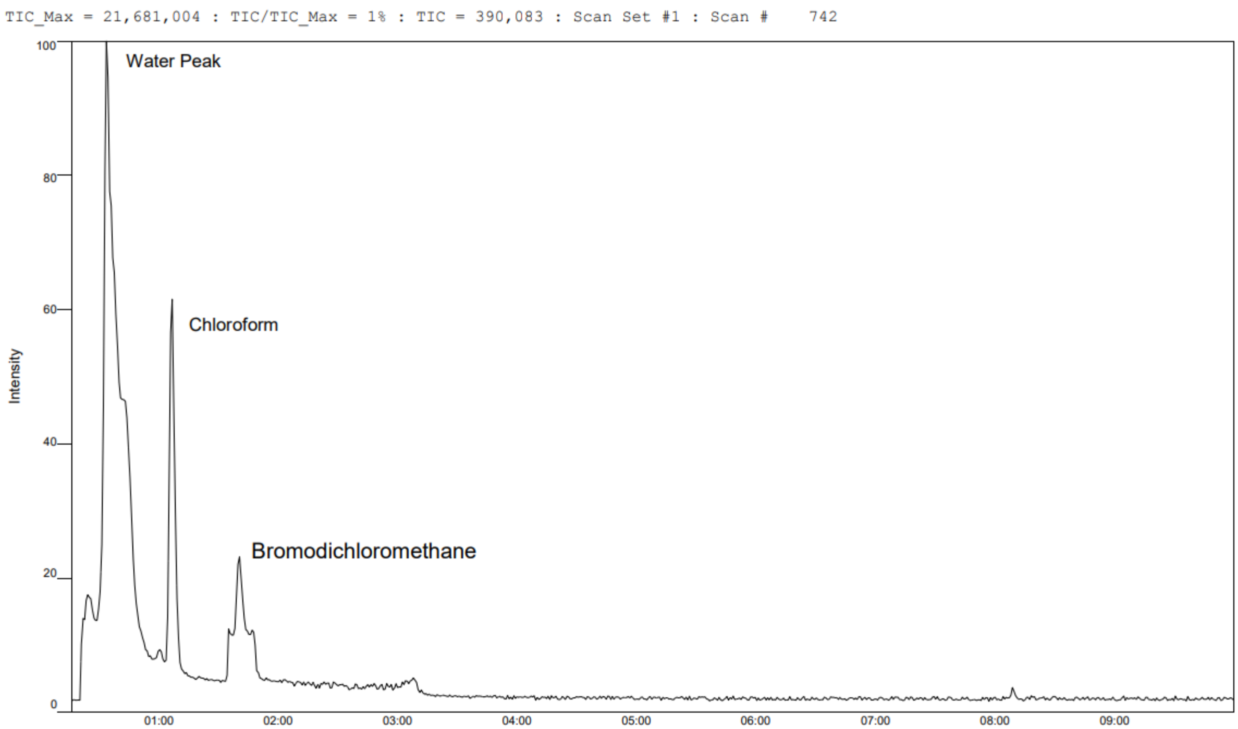


Figure 7.24: Chromatogram for Buziga Sampling Point

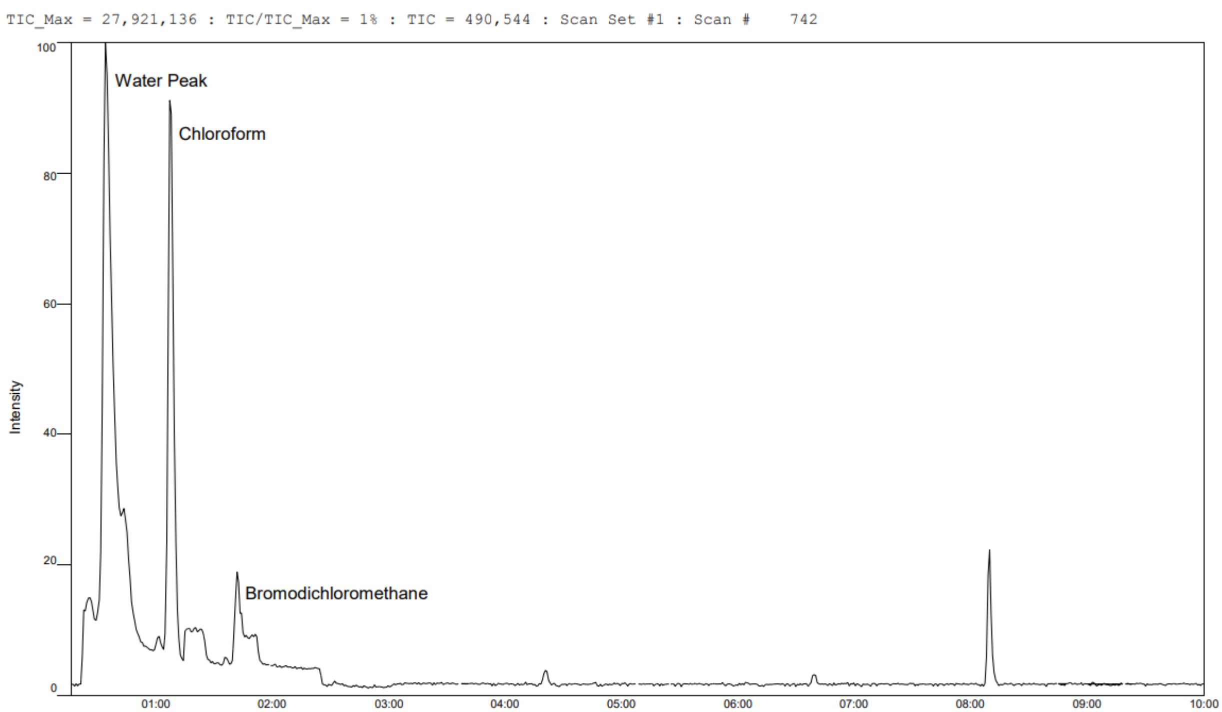


Figure 7.25: Chromatogram for Kansanga Market Sampling Point

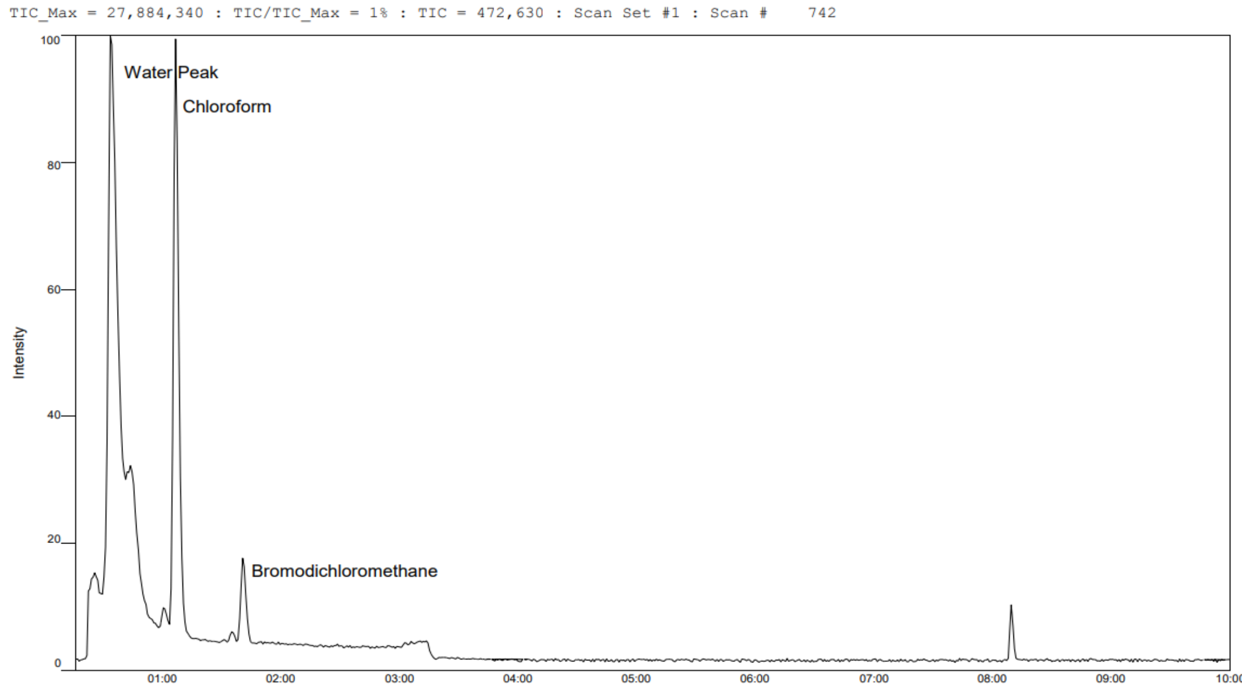


Figure 7.26: Chromatogram for Muyenga Sampling Point

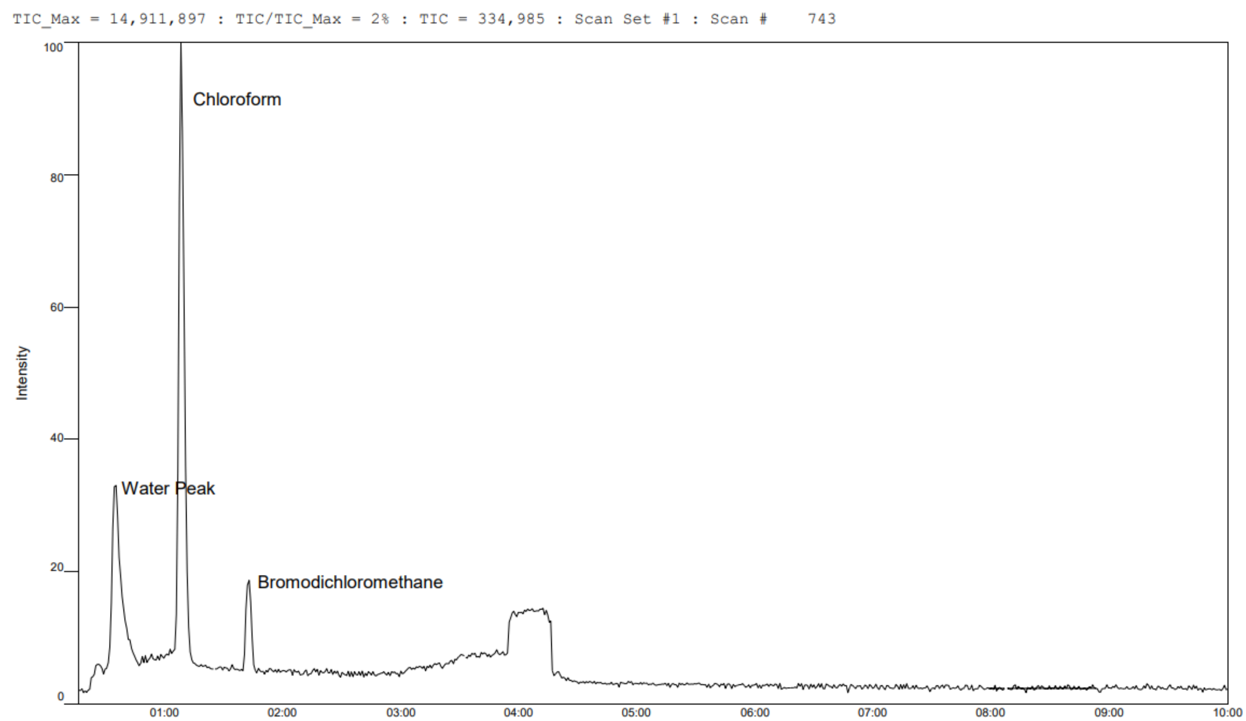


Figure 7.27: Chromatogram for Namuwongo Market Sampling Point

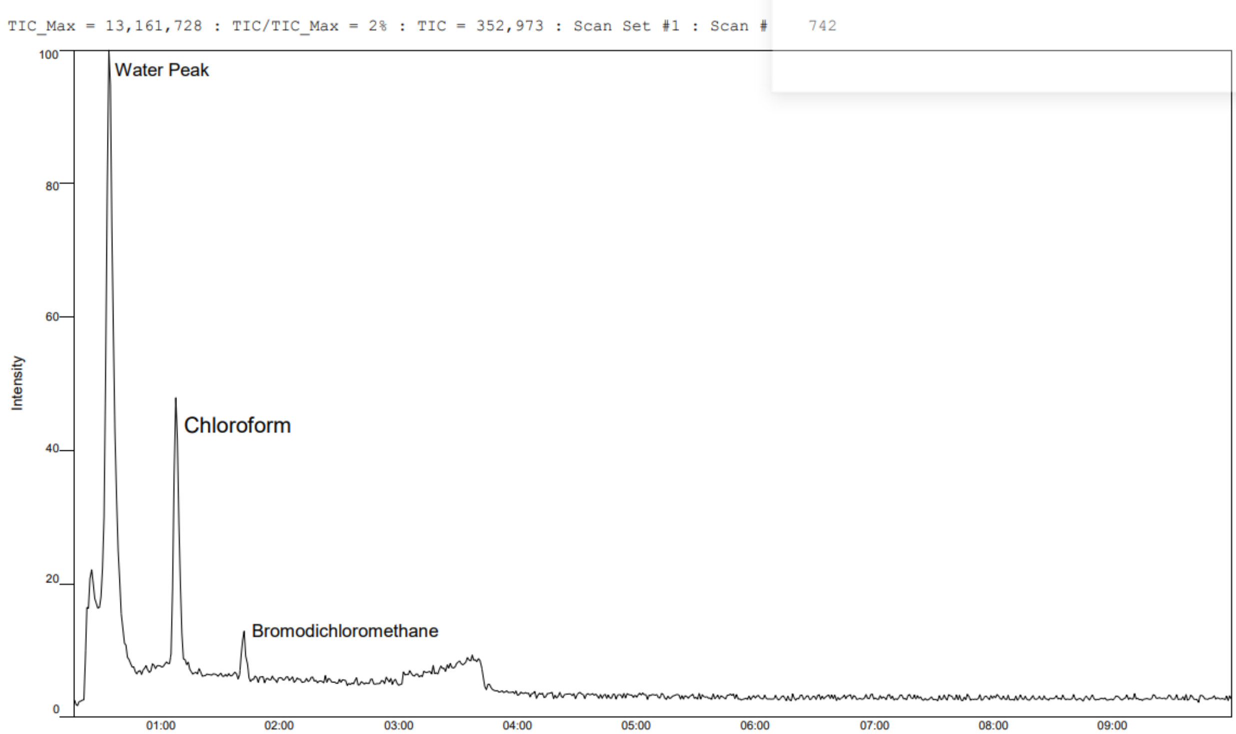


Figure 7.28: Chromatogram for Bugolobi Public Tap Sampling Point

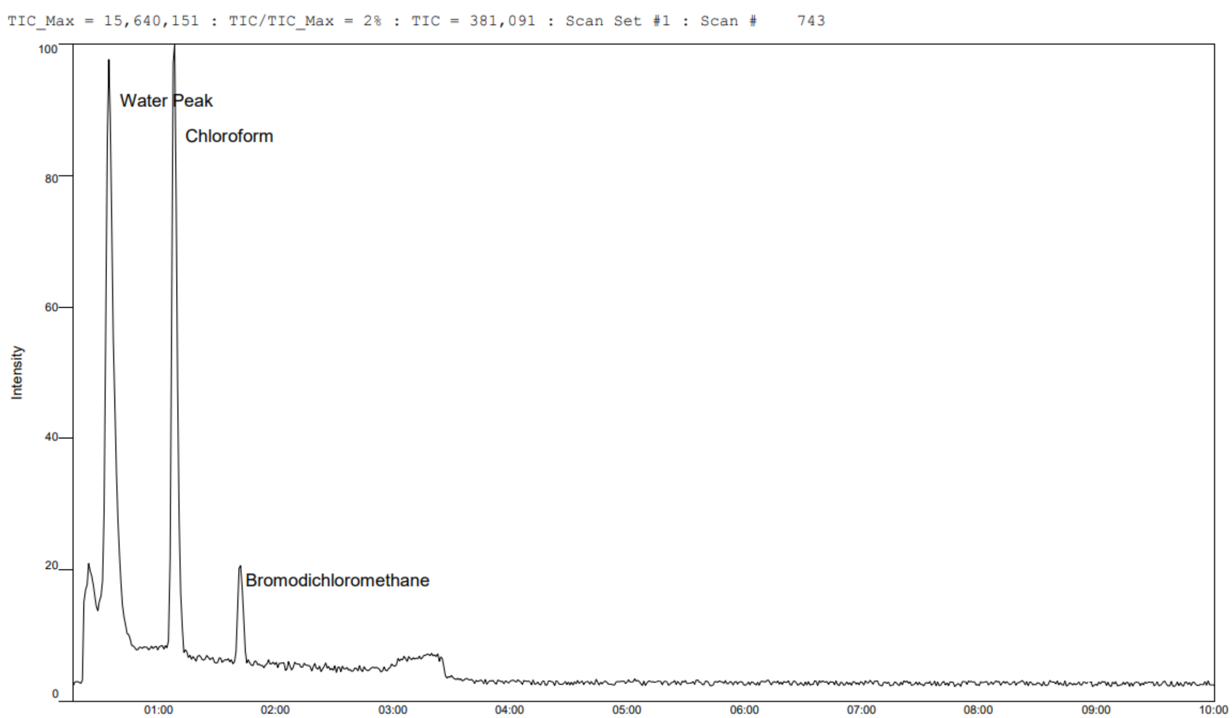


Figure 7.29: Chromatogram for Rubaga Sampling Point

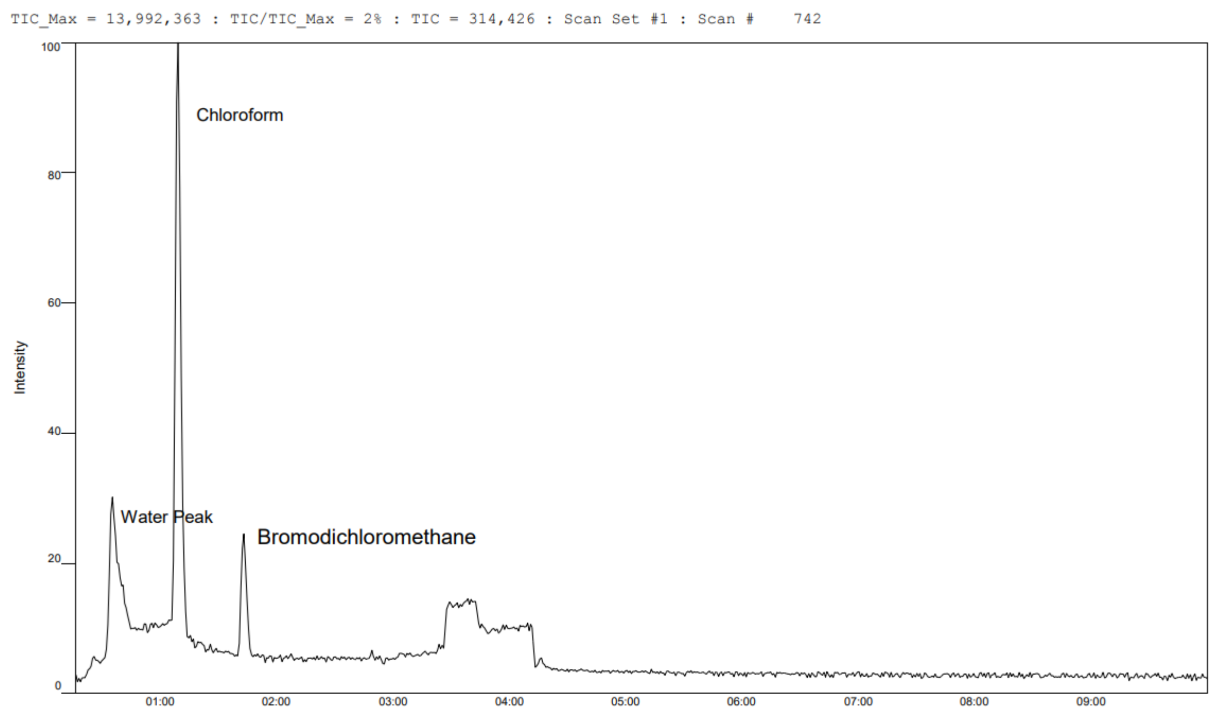


Figure 7.30: Chromatogram for Kabakanjagala Road Sampling Point