QATAR UNIVERSITY

Graduate Studies

College of Art & Sciences

DISINFECTION BY-PRODUCTS OF CHLORINE DIOXIDE (CHLORITE, CHLORATE, AND TRIHALOMETHANES): OCCURRENCE IN DRINKING WATER IN QATAR

A project in

Department of Biological &Environmental Sciences

By

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Submitted in Partial Fulfillment

Of the Requirements

For the Degree of

Master of Science

December 2014

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ABSTRACT

The occurrence of disinfection by-products (DBPs) of chlorine dioxide (ClO_2) in drinking water, namely: chlorite, chlorate, and THMs as well as the concentration of ClO_2 were investigated. Two hundred ninety four drinking water samples were collected during the time period from March to August 2014. The water samples were collected from seven desalination plants (DPs), four reservoirs and eight mosques distributed in South and North Qatar. The ClO_2 level was ranged from 0.38 to less than 0.02 mg/L, with mean value of 0.17, 0.12, and 0.04 mg/L in the desalination plants (DPs), the reservoirs (R), and the mosques (M), respectively. The chlorite level was varied from 12.78 – 436.36 ppb with median values varied from 12.78 to 230.76, from 77.43 to 325.25, and from 84.73 to 436.36 ppb in the DPs, the reservoirs, and the mosques, respectively. While chlorate was varied from 10.66 ppb to 282.71 ppb with mean values varied from 35.58 to 282.72 ppb, from 11.02 to 200.69, and from 10.66 to 150.38 ppb in the DPs, R, and M respectively. However, the average value of THMs was 4.90 ppb, while maximum value reached 76.97. Lower disinfectant residual was observed in few samples, however this could be attributed to the normal decomposition reaction of ClO_2 with organic and inorganic compounds, including biofilms, pipe materials, corrosion products, formation of slime or may due to the fact the water in distribution system experience water aging problem. Significant differences were observed in the concentration level of chlorite, chlorate and THMs between DPs, reservoirs and the mosques. However, the concentrations of all DBPs fell within the range of the regulatory limit set by GSO 149/2009, WHO and

KAHRAMAA (KM). It is recommended to slightly increase the average ClO_2 dosage at the DPs. Such slight increase would provide safer margin at the customer point of use in case of any microbial activities. Consideration must be given to the overall demand and should account for seasonal variations, temperature, and application points. As well as a monitoring approach is recommended for the drinking water safety assessment. Re-conducting the study to include other DPs of ClO_2 is recommended.

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List of Abbreviation Used in the Text

ANOVA	Analysis of Variance
AWWA	American Water Works Association
AP	Airport Reservoir
WB	West Bay Reservoir
CFL	Central Food Laboratory
$CHBr_3$	Bromoform
$CHCl_2Br$	Dichlorobromomethane
$CHCl_3$	Chloroform
ClO_2	Chlorine Dioxide
ClO_3^-	Chlorate
ClO_2^-	Chloriite
D	Duhail Reservoir
DBPs	Disinfection By-Products
D/DBP	Disinfectant/ Disinfection By-Product
DPs	Desalination Plants
EU	European Union
GAC	Granular Activated Carbon
GCC	Gulf Co-operation Countries
GC/MS	Gas Chromatography/ Mass Spectrometry
L/ca/d	Liter / Capita/ Day
HAAs	Halo- Acetic Acids
HANs	Haloacetonitriles
IARC	International Association of Cancer Registries
IC	Ion Chromatography

ICR	Information Collection Rule
IGPD	Imperial Gallons Per Day
KM	KAHRAMM
MCL	Maximum Contaminant Level
MED	Multi-Effect Distillation
MSFD	Multi-Stage Flash Distillation
MX	3-chloro-4-dichloromethyl-5-hydroxy-2(5H)-furanone
NCI	National Cancer Institute
NOM	Natural Organic matter
NS	New Salwa Reservoir
PAC	Powdered Activated Carbon
RLB,Q-Power	Ras Laffan Qatar-Power Desalination Plant
RAF A	Ras Abu-Fontas Desalination Plant A
RAF A1	Ras Abu-Fontas Desalination Plant A 1
RAF B	Ras Abu-Fontas Desalination Plant B
RAF B2	Ras Abu-Fontas Desalination Plant B 2
RLA	Ras Laffan A Desalination Plant
RLC, Ras-Girtas	Ras Laffan C (Ras-Girtas) Desalination Plant
SCH	Supreme Council of Health
STDV	Standard Deviation
THMs	Trihalomethanes
TOX	Total Organic Halide
USEPA	United State Environmental Protection Agency
WHO	World Health Organization

Acknowledgements

Honestly it is very difficult to find words to express my acknowledgement and appreciation. After completing three years of my master's program, wrapped up by writing and submitting this project, it was one of the most significant challenges in my life. I would not have reached this far without the full support and help of God.

My great thanks also for my children as well as my family for unconditional support, love and understanding to achieve my dream to get my master's degree. I also extend my deepest gratitude to my project supervisor, Dr. Mohammad Al-Ghouti, and to the committee members Dr. Talaat Youssef and Dr. Mohammad Ali from the Supreme Council of Health (SCH) for their unrelenting efforts, commitment, encouragement, guidance and support as well as providing great precise assistance towards my understanding and conducting the research.

Many thanks are also expressed to the staff and colleagues of the central food laboratories and KM for their help and support. Special thanks are expressed to Dr. Mohamad Al-Thani, director of Public Health and Mrs. Wassan Al-Baker, manager of Food Safety and Environmental Health. My thanks also extend to Dr. Tarek Ammar from KM, and my friend Zulfa al-Disi for their help and unlimited support.

Last but not least, I would like to deeply thank my country Qatar for providing such a great opportunity for all of us hard working Qatari ladies this master degree program, which will help all of us to achieve Qatar vision 2030. Thank you Qatar for believing in us.

1. Chapter 1. Introduction

Drinking water is essential to human life; therefore the water safety is one of the important public health issues. Qatar is located in Arabian Gulf, which is considered one of arid regions that suffers from water scarcity and limited resources of surface and fresh water. As a result, the essential source of drinking water (DW) in Qatar mainly comes from desalination of seawater (Kahramaa, KM, Statistical Report, 2012).

The demand on water have been increasing in the last decades due to expanding population and increasing infrastructure required to meet the huge socio-economic development since the 1970s, have most recently magnified the problem. Moreover, in 2012, KM reported that the water demand raised from 312.4 in 2008 to reach 437.1 million m^3/d. Therefore, the desalinated water is the only option for Qatar to meet the increased demand, as it represents (99.9%) of the water supply in the country (KM Statistical Report, 2012). The Qatar National Strategy (QNS) report for 2010–2016 stated that the average water consumption for Qatari citizens in 2009 was 1200 L/ca/d, while expatriates consumed 150 L/ca/d (Qatar General Secretariat for Development Planning, 2011). Desalination is a mature technology that has been providing a reliable supply of DW throughout the Gulf Co-operation Countries (GCC) for five decades. It provides water, which meets or exceeds the drinking water standards (KM, Statistical Year Book, 2010).

Qatar was among the early adopters of desalination, and its first major plant came online in 1953 with capacity of 150,000 imperial gallons per day (IGPD). Few years after creation the ministry of electricity and water in 1970, Ras Abu Fontas A (RAF A) desalination plant began operations in 1977 and was upgraded in stages to 1980.

Currently, there are seven desalination plants distributed as follows: three in Ras Laffan city namely: Ras Laffan; A (RLA), Q-Power and Ras Girtas. RLA started operation in May 2004, generating 151 million liters per day of desalinated water, Q-power the second largest water plant in the country, its operational since June 2008, this plant has capacity to produce 272,727 m^3/d and finally Ras Girtas which is the largest independent water and power facility in Qatar, and one of the biggest single-site producers of power and water in the world. This plant puts out 63 MIGD, this outputs account for 20% of the country's potable water. The four remaining plants are located in South of Qatar, in Ras AbuFontas city, namely: RAF A, RAF A1, RAF B and RAF B2. RAF A is comprised of two units with a combined production capacity of 204,545 m^3/d, which is equivalent to 10% of Qatar's national water production, it was originally constructed in 1970 and has been expanded several times. RAF B commissioned in the year 1995. The daily production is 150 m^3 and finally, RAF B2, which was completed, in late 2008, with design capacity of 131,818 m^3/d (Qatar Electricity and Water Company, 2014). The total water production in 2012 amounted to 437 million cubic meters. Production increased by 9 % in the year 2012 (KM, 2012).

A seawater desalination process separates saline seawater into two streams: a fresh water stream containing a low concentration of dissolved salts and a concentrated brine stream. This process requires some form of energy to desalinate, and utilizes several different technologies for separation. A variety of desalination technologies has been developed over the years on the basis of thermal distillation, membrane separation, freezing, etc. (Spiegler et al., 1980; Porteous et al., 1983; Bruggen, 2003). Commercially, the most important technologies are based on the multi-stage flash distillation (MSFD), multi-effect distillation (MED) and reverse osmosis (RO) processes. It is viewed that three processes will be dominant and competitive in the future. For instance, in 1999 approximately 78% of the world's seawater desalination capacity was made up of MSF plants while RO represented 10% (IDA, 1999). However, there has been a gradual increase in RO seawater desalination primarily due to its lower cost and simplicity.

In Qatar, mainly two desalination methods are used in the currently producing plants, MSFD and MED. The MSFD process primarily involves heating seawater in a vacuum evaporator to produce vapor. The vapor produced is then eventually condensed to produce fresh water. The process starts with heating the tubes in the distiller units brine heaters, which in turn heats the seawater intake. The heated seawater passes into the vacuum evaporator, where it boils rapidly and converts into steam.

The MED process is the oldest desalination method and is very efficient thermodynamically (Al-Shammiri et al., 1999). The MED process takes place in a series of evaporators called effects, and uses the principle of reducing the ambient pressure in the various effects. This process permits the seawater feed to undergo multiple boiling without supplying additional heat after the first effect. The seawater enters the first effect and is raised to the boiling point after being preheated in tubes. The seawater is sprayed onto the surface of evaporator tubes to promote rapid evaporation. The tubes are heated by externally supplied steam from a normally dual-purpose power plant. The steam is condensed on the opposite side of the tubes, and the steam condensate is recycled to the power plant for its boiler feed-water. The MED plant's steam economy is proportional to the number of effects. The total number of effects is limited by the total temperature range available and the minimum allowable temperature difference between one effect and the next effect.

Desalinated water produced from MSF plants is of high purity with a very small amount of dissolved salts and minerals. Therefore, the water is aggressive and corrosive to the materials commonly used in water distribution systems such as metals and concrete. In order to overcome the problems with aggressiveness and poor taste of the distillate, a number of potabilization processes (Kirby, 1989; WHO, 1979) have been practiced or proposed.

Besides chlorination in the presence or absence of aeration (Kirby, 1989), two typical treatment methods used are injection of CO_2 and hydrated lime (Kutty, 1991) and the passing of carbonated water through limestone bed filters (Al-Rqobal et al., 1989). Such treatment methods aid in establishing the calcium carbonate equilibrium and forming corrosion-inhibiting protective layers of calcium carbonate. As a source of the carbon dioxide, CO_2 gas from an MSF vent stream can be utilized (Dawoud, 2005).

Accordingly, a typical potabilization process consists of four unit operations liming, carbonation, chlorination, and aeration (Kutty, 1991). The water is remineralized by adding hydrate lime and CO_2 through the liming and carbonation steps, in order to raise hardness, alkalinity, pH, and dissolved mineral content. The chlorination is carried out by injecting chlorine gas, sodium or calcium hypochlorite to disinfect the water and eliminate bacterial growth. The aeration is done to replace oxygen driven out by the MSF distillation process, thereby improving the taste of the water.

The desalinated water produced from the seven plants supplies the potable water to 25 reservoirs to meet the demand for the entire country. The water is stored in these huge reservoirs to be distributed through distribution systems that are connected to the different areas in Qatar to deliver the municipal water to the final consumers (KM, 2012).

The process of providing public with safe water requires adding some chemical disinfectants, which is considered as a critical step to reduce the incidence of water-borne diseases and inhibit biofilm formation; this advancement has been one of the most important for public health (Agusa, 2009). For this purpose, water treatment industry uses a group of chemicals as water disinfectants.

The most common disinfectants are chlorine, chloramines, ozone and ClO_2 (WHO, 2004). These disinfectants are used frequently in water treatment to inactivate pathogenic microorganisms, inhibit biofilm formation and oxidize reduced inorganic solutes, such as sulfide and ferrous iron (MWH, 2005). However, each of the common disinfectants can produce disinfection by-products (DBPs) that pose threats to human health.

Chlorine and its compounds are the most commonly used disinfectants for the treatment of water and its popularity is due to higher oxidizing potential, which provides a minimum level of chlorine residual throughout the distribution system and protects against microbial recontamination (Sadiq et al., 2004). Disinfection by chlorination is the most important step in water treatment for public supply as chlorine remains in the water as long as it is not consumed. However, chlorine also reacts with the natural organic matter (NOM) present in the water and produces a number of by-products with harmful long-term effects. Use of chlorination reduces the risk of pathogenic infection but may pose chemical threat to human health due to disinfection residues and their byproducts. DBPs will be produced upon chlorination only if the water contains DBP precursors. During chlorination of water containing natural organic matter, a complex mixture of chlorine byproducts is formed and more than 300 different types of DBPs have been identified (Weinberg et al., 2002) The formation of these compounds in drinking water depends on several factors such as temperature, pH, dose, contact time, inorganic compounds and NOM that are present in the drinking water supply. The literature shows that these DBPs consist of trihalomethanes (THMs), halo- acetic acids (HAAs), haloacetonitriles (HANs), and others (Collivignarelli et el., 2004).

The term THMs typically refers to chloroform ($CHCl_3$), bromoform ($CHBr_3$), dichlorobromomethane ($CHCl_2Br$) and dibromochloromethane ($CHClBr_2$). Concerns associated with THMs in drinking water began after reports of the production of chloroform in chlorine- disinfected water in 1976. Following the discovery of chloroform in chlorinated water, scientists reported the formation of brominated THMs (Krasner et al., 1989). $CHCl_3$, $CHBr_3$ and $CHCl_2Br$ are classified as probable human carcinogens by the United States Environmental Protection Agency (USEPA, 1983). These THMs have been linked to induction of tumors in target organs (e.g., liver, kidney and bladder) of experimental animals (Coffin et al., 2000; Sittig, 1985; Yang et al., 1998).

THMs also have been shown to act as reproductive and developmental toxicants in several laboratory studies and have been linked to adverse reproductive effects in one epidemiological study (Waller et al., 1998; Klotz, 1999; Bove et al., 2002).

Ozone (O_3) use as a disinfection agent is becoming widespread due to its powerful oxidizing properties and effectiveness in the inactivation of microorganisms resistant to other disinfectants. Ozonation has not found practical implementation in pretreatment of seawater due to factors including potential oxidative damage to the RO membranes, high costs and excessive bromate ion (BrO_3^-) formation. In terms of by-product formation, ozonation typically minimizes the formation of conventional haloorganic DBPs like THMs and HAAs acids. Although halogenated organics are not formed at significant concentrations from ozonation of NOM, they are produced when subsequent chlorination and chloramination follows ozonation (Najm et al., 2001).

The major inorganic by-products of ozonation in aqueous systems include BrO_3^-, hypobromous acid/hypobromite ion ($HOBr/OBr^-$) and hydrogen peroxide (H_2O_2). $HOBr/OBr^-$ and H_2O_2 are generally unstable and may act as a residual disinfectant. Bromate, designated a Class 2B carcinogen (WHO, 2004), is the prominent stable by-product from ozonation of high-bromide water (Haag el al., 1983). Potassium bromate, administered via drinking water, caused renal cancer, mesotheliomas, and thyroid follicular cell tumors in rats (Kurokawa et al., 1983; IARC, 1986; Deangelo et al., 1998).

The WHO determined that an excess of 10^{-5} risk of renal carcinogenesis is present from lifetime consumption of 25 μg/L of BrO_3^- in drinking water (WHO, 2011). Currently, drinking water regulations in the United States and EU include a standard for BrO_3^- which is established at 10 μg/L. Bromate from the O_3 disinfection process is not considered a significant contaminant in surface waters because water treatment standard for this anion is much lower than the precautionary ecotoxicity safety value of 3.0 mg/L (Boorman et al., 1999).

Chloramines are used widely in water distribution systems when there are concerns about the formation of disinfection by-products. Chloramines also are attractive to operator of drinking water systems because they are more stable than free chlorine; making it easier to maintain a disinfectant residual within the distribution system. Chloramines usually are not used in distribution systems delivering only desalinated sea-water. However, in locations where desalinated water is blended with water from other sources, or in locations where chloramines are used in other parts of the distribution system, chloramines may be used. In such systems, the elevated concentrations of bromide, attributable to the desalinated water, and the NOM from the other water sources may result in the formation of bromamines and chloramine DBPs (Richardson et al., 2003).

ClO_2 is a widely employed oxidant in drinking water desalination plants (Richardson et al., 2000; Korn et al., 2002; Schmidt, 2004). It is generated ‘‘on site’’ (EPA, Alternative Disinfectants and Oxidants, 1999), mainly according to the following process with sodium chlorite as reagent:

$$2NaClO_2 + Cl_2 \leftrightarrows 2NaCl + 2ClO_2$$

or

$$5NaClO_2 + 4HCl \leftrightarrows 4ClO_2 + 5NaCl + 2H_2O$$

ClO_2 is a very strong oxidizing agent, having usually chloride (Cl^-) and chlorite

(ClO_2^-) ions as final products according to the following reactions:

$ClO_2 + 4H^+ + 5e^- \leftrightarrows Cl^- + 2H_2O$ (E° = 1.5 V)

$ClO_2 + e^- \leftrightarrows ClO_2^-$ (E° = 0.95 V)

In addition, ClO_2 is more powerful than chlorine (Cl_2) as a bactericide for water treatment due to its higher oxidation capacity (Pereira, 2008). ClO_2accepts five electrons when reduced to chloride ion. Based on its molecular weight and number of electrons transferred, ClO_2 has approximately 263% available chlorine, which is more than 2.5 times the oxidizing capacity of chlorine in HOCl or Cl_2 (Haas, 1990). Elevated water temperatures, disinfectant doses and longer contact times generally favor the inactivation of microorganisms by ClO_2 (Barbeau, 2005).

ClO_2 is a strong water disinfectant over a wide pH range. It has extensively been used as a primary drinking water disinfectant in Europe for decades (MWH, 2005). In North America, its use as disinfectant and pre-oxidant has been increasing (Singer, 1993). As a drinking water disinfectant, ClO_2 is especially effective on chlorine-resistant viruses and protozoan cysts. A smaller dosage and less reaction time are required for ClO_2 to produce the same disinfection effect. The major advantage of ClO_2 is that the disinfection process does not generate large quantities of halogenated by-products that are common with chlorination (USEPA, 1999; Volk et al., 2002). Another advantage is that ClO_2 significantly reduces odor and color (Aieta et al., 1986).

In addition to the above-mentioned advantages, ClO_2 also demonstrated promising behavior as a secondary disinfectant in full-scale distribution systems (Volk et al., 2002). The study of Volk et al., (2002) showed that the ClO_2 can be used as a secondary disinfectant in a full-scale distribution system, it is also shown that residuals can be maintained throughout these specific systems, without booster stations. ClO_2 decay in the distribution system is the result of auto-decomposition reactions and reactions with organic and inorganic compounds, including biofilms, pipe materials, and scales. ClO_2 is also subjected to photolytic decomposition (USEPA, 1998). Notable to say that ClO_2 does not react with bromides to form bromine, unlike ozone, chlorine, and hypochlorite (Singer, 1995).

ClO_2 produces low levels of organic by-products as compared to chlorine disinfection (Grubbs, 1995). Chlorite (ClO_2^-) and chlorate (ClO_3^-) are the disinfection by-products resulting from the use of ClO_2 as a disinfectant. The production of chlorite and chlorate varies depending on the NOM source in the raw water. Typically, up to 60% of the applied ClO_2 dose is reduced into chlorite ion and up to 10% is converted into chlorate ion (Collivignarelli et al., 1996).

ClO_2 typically does not react with NOM or humic substance (Lykins et al., 1986; Werdehoff et al., 1987; Lafrance et al., 1993 and Muttamara et al., 1995), but it rapidly decomposes into inorganic DBPs, namely chlorite and chlorate (Plewa et al., 2003). Therefore, the chief disadvantage of ClO_2 is the production of the potentially risky inorganic by-products, chlorate and chlorite ions. Despite its numerous advantages, ClO_2 may signify a potential cause of human health due to the production of these inorganic by-products.

Chlorite and chlorate induce hematological responses in subchronic and acute exposures resulting in oxidative damage to erythrocytes, methemoglobinanemia and hemolytic anemia (WHO, 2011). Reproductive, neurodevelopmental and endocrine toxicity of sodium chlorite also have been reported in laboratory animals (Gill et al., 2000). The water quality criteria (WQC) for acute ecotoxicity of chlorite is calculated to be between 25 to 135 μg/L, based on protection of the most sensitive family (the crustacean Daphnidae, LC_{50} = 270 μg/L) (Cantor, 2006). Acute and subchronic exposure to adult and larval rainbow trout determined that chlorine dioxide and chlorite ions are moderately toxic to fish, with maximum acceptable toxicant concentration of 0.21 mg/L and 3.3 mg/L, respectively (Dodds, 2001).

Due to the health effects accompanying with exposure to DBPs, the WHO and EPA have put regulations on adequate levels of DBPs in drinking water. In the United States, the USEPA established the federal drinking water threshold level of 0.8 mg/L for ClO_2 and 1.0 mg/L for chlorite ion (USEPA, 1998). More stringent regulations on chlorite ion are in place in parts of the EU and North America. For example, the maximum allowed concentration in drinking water in Italy was 200 μg/L in 2006 (Linder, et al., 2006). Despite the intensive work conducted on DBPs formation in disinfected water around the world, the potential hazards of DBPs and the scarcity of data in Qatar would make this type of research as essential.

As mentioned earlier, since the early 1950, Qatar uses chlorine as a major disinfectant. In view of the potential threat to human health caused by halogenated compounds, KM as a distributor company and the SCH as a monitoring authority have placed special emphasis on decreasing the amount of such compounds in drinking water. Moreover, as part of continuous improvement, KM has shifted from using chlorination for water disinfection to ClO_2. Accordingly, in 2009, KM started the pilot trials of using ClO_2 as a disinfectant of drinking water in the desalination plants. After 2013, all the desalination plants have utilized ClO_2 as single disinfectant (KM, 2012). Therefore, this project is part of the SCH's responsibility on monitoring drinking water quality and safety in collaboration with the KM.

1.1 Project Aims and Objectives

1. Aim:

The main aim of this project is to deeply investigate the occurrence of DBPs (chlorite, chlorate, and trihalomethanes) in drinking water as a result of using ClO_2 as a disinfectant from different locations of drinking water production and distribution. The concentration of ClO_2 residual in the collected water samples will also be investigated .The results will be compared with the international and local guidelines.

2. Objectives

In order to achieve the above-mentioned aim, the following specifics objectives were studied:

- Determine the concentration of chlorite, chlorate, and trihalomethanes in the collected water samples using ion chromatography technique (IC) (for chlorite and chlorate) and head space-gas chromatography (for trihalomethanes).
- Investigate the occurrence and the residual ClO_2 concentration in the collected samples, and
- Investigate the correlation using SPSS statistical analysis package.

2. Chapter 2. Literature Review

2.1 Background

The water disinfection process is considered as one of the most important public health developments (Ohanian, 1989). Disinfection is the last treatment action for drinking water treatment and is performed to sustain a residual trace disinfectant concentration in the water distribution system (Sabrina et al., 2014). Though, using chemicals in disinfection process has raised a public health issues (Kranser et al., 2006). These chemicals are very active in killing pathogens in water, and they are also excellent oxidant for many pollutants available in water. Chlorine, ClO_2, ozone, and chloramines are the common disinfectants. Each one of these creates its own group of DBPs in drinking water (Richardson, 1998).

Chlorine is considered as one of the excellent biocide for water disinfection because of its residual bactericidal effect and economical use (Rodriguez et al., 2001). However, chlorine reacts with organic compounds and generates carcinogenic and toxic DBPs, of which THMs is one of these DBPs (National Cancer Institute of Canada, 1998; Richardson et al., 2002; Waller et al., 1998; Villanueva et al., 2004; Xu and Weisel, 2005). Accordingly, there is a dire need for exploring for new treatment technologies and alternative disinfectants.

ClO_2 has recently been taken as an alternative to chlorine as it does not typically lead to the formation of toxic DBPs (Hofman, 1999), efficient in killing bacteria, and more powerful than chlorine over a wide pH range (Najm and Trussell, 1993, Pereira, et al., 2008, Haas, 1990). ClO_2, however, does not produce significant amounts of halogenated organic DBPs (Hua and Reckhow, 2007). Chlorite and chlorate are the primary products (Korn et al., 2002). DBPs formation during ClO_2 pretreatment has been studied (Linder et al., 2006; Lee et al., 2007; Yang et al., 2013). It has been shown that ClO_2 oxidation prior to chlorination can reduce the formation of THMs and total organic halogen (TOX) (Linder et al., 2006). A recent study has reported that ClO_2 pre-oxidation reduced THMs and other by-products (Yang et al., 2013).

Most developed countries have published guidelines or regulations to protect the public by controlling DBPs and diminish the exposure of consumers to hazardous chemicals while keeping the acceptable disinfection purposes. Furthermore, there is a necessity for better understanding of the disinfection processes and their related DBPs so as to have a greater understanding of the health risks concomitant with drinking water.

The first identification of DBPs ($CHCl_3$ and other THMs) in chlorinated drinking water was reported in 1974. EPA and the National Cancer Institute (NCI) also published in 1976, a survey showing that $CHCl_3$ and the other THMs were abundant in chlorinated drinking water.

Accordingly, substantial research efforts have been directed towards improving the understanding of DBPs formation, occurrence, and health impacts

(Richardson, 1998; IARC, 2004). However, this type of research was not conducted as needed in Gulf countries. Even though this type of research is critical is distinguishing features of water produced in such environment and conditions.

While more than 600 DBPs have been identified in the literature (Richardson, 1998; Boorman, 1999), only a few DBPs has been assessed for their occurrence or health impacts. The concentration of DBPs in drinking water are normally present at low concentrations in the ppb or ppm levels (Krasner et al, 1996, Stevens et al., 1989).

Richardson et al. (2007) studied many researches that address the carcinogenicity of regulated and unregulated DBPs by the U.S. Government. Richardson et al. (2007) provided an opening horizon in assessing various regulated and unregulated DBPs in drinking water.

2.2 Disinfectants and Their DBPs

Chlorination was first presented in 1902 in Middlekerke (Belgium), followed by the usage of ozone as a disinfectant in Nice (France) in 1906 (MWH, 2005). It was used in USA (Chicago and Jersey City) in 1908, and in Canada in 1916 (Peterborough) (Chlorine Chemistry Council, 2003; Peterborough Utilities Commission, 1998). Worldwide, chlorine has been used as the main fence to microbial contaminants in drinking water to protect the public health. The significant biocidal features of chlorine have fairly been balanced by the formation of DBPs.

Accordingly; other alternative chemical disinfectants are currently used such as ClO_2, O_3, and chloramines (Hua et al., 2007; Korn et al., 2002; Sabrina et al., 2014).

However, various factors may affect the formation of DBPs. This includes pH, disinfectant concentration, disinfectant dose, temperature, natural organic matter (NOM), and precursor properties (Yang et al., 2007). The chemical and physical properties of disinfectants and DBPs can affect their behaviors in drinking water (Yang et al., 2007, Richardson et al., 2000; Korn et al., 2002; Schmidt, 2004). However, when ClO_2 is used, it can react with both organic and inorganic compounds to form chlorite and chlorate, which can have adverse effects on human health. Oxidative stress causing changes in the red blood cells is the main and utmost consistent finding arizing from exposure to chlorite and chlorate is (WHO, 2011).

2.2.1 **Chemistry of ClO_2**

One of the few compounds that exist almost entirely as monomeric free radicals is ClO_2. ClO_2 does not hydrolyse in water to any considerable extent (WHO, 2000). It was discovered in 1811 (Aieta et al., 1986) and it is widely used in many industries including food processing, wastewater treatment, and wood pulp. It has been known as a management for odour produced by industrial wastes, such as phenols. However, ClO_2 can be employed in the treatment of any odor or taste problem that can be treated by an oxidizing material (Gates et al., 1998). ClO_2 shows an oxidation state (+4) intermediate between those of chlorate (+5) and chlorite (+3). No known acid or ions have the similar degree of oxidation. ClO_2 is a robust oxidizing agent that decompose into chlorite; in the presence of alkali and the absence of oxidizable substances, when dissolving in water, it decompose with the slow formation of chlorate and chlorite. ClO_2 disinfects by oxidation, not substitution as with chlorine. The molecule oxidizes other compounds forming the chlorite ion, which can consequently reduce to chlorate and chloride. ClO_2 is reduced to chlorite ion when it reacts with aqueous contaminants (Hagg and Hoigne, 1983).

ClO_2 is vulnerable to volatilization because it exists as a gas; it can be simply removed from water by aeration, and is destroyed by ultraviolet light when exposed to sunlight (U.S. EPA, 1999). In the absence of light, ClO_2 is stable in a closed container in dilute solution (U.S. EPA, 1999). One of the most important advantages of using ClO_2 over chlorine is the reduced formation of DBPs such as THMs, chlorite ion (ClO_2^-) and to a lesser extent chlorate ion (ClO_3^-) (Gate, 1998). In the 1940s, the USA implemented the use of ClO_2 as a controller for algal, taste and odor (Gates et al., 1998) and its biocidal effectiveness was equal to chlorine over a wide pH range (Aieta, 1989; White, 1992; Gates et al., 2009; Richardson, 2009; Rodriguez, 2007). Currently, ClO_2 is used for disinfection and the control of DBPs. In addition, it has also demonstrated good performance in a full-scale distribution systems (Volk et al., 2002). This study showed that the ClO_2 residuals can be preserved all over these systems, without booster stations. Another study has shown the opposite, being that residuals would vanish at the ends of the system without booster addition.

However, ClO_2 residuals would be affected by the water temperature and the size and complexity of the distribution system. Ammar et al., (2014) tackled the ClO_2 decay to provide an original mathematical equation for prediction of ClO_2 decay in desalinated water. The study was performed using five different doses of ClO_2; 1.4, 1.2, 1.0, 0.8 and 0.6 mg/L (to include the most regularly used doses “as primary disinfectant” within production facilities and/or “as secondary disinfectant” within the distribution system). Each concentration was tested at four different temperatures; 20°, 27°, 35°, and 45 °C. As a general conclusion, the study’s suggested a novel model/equation that illustrated reasonable levels of biocide strength. Furthermore, it covered the ClO_2 decline at a wide range of temperature profiles as well as a wide range of ClO_2 initial concentration dosages.

ClO_2 decay in the distribution system could be attributed to several factors such as auto-decomposition reactions, photolytic decomposition, and redox reactions with organic and inorganic compounds, including biofilms, pipe materials, and scales (USEPA, 1999, Karen et al., 1987). As a result, chlorite and chlorate ions would be formed as primary products. Under typical conditions in water treatment, approximately 50 to 70% of the ClO_2 is oxidized into chlorite (Karen et al., 1976, Rav-Acha et al., 1984). Ultraviolet light and even fluorescent lights can lead to photolysis (Griese et al., 1992; Zika et al., 1985). ClO2 is not known to react with humic substances to form THMs (Lafrance et al., 1993; Lykins, 1986; Muttamara et al., 1995; Singer, 1987).

2.2.1.1 ClO_2 Oxidation Potential

ClO_2 is a compound of chlorine with 5-oxidation state. It is highly energetic and volatile small molecule. It is a free radical even in dilute aqueous solution. It reacts aggressively with reducing agents at high concentration. However, it is stable in the diluted solution in closed container in the absences of light (AWWA, 1990, Hoehn et al., 1996). Below are the some key reactions for ClO_2 (CRC, 1990, Werdehoff and Singer, 1987):

$$\mathbf{ClO_{2(aq)} + e^- \leftrightarrows ClO_2^-} \qquad \mathbf{E° = 0.954V}$$

$$\mathbf{ClO_2^- + 2H_2O + 4e^- \leftrightarrows Cl^- + 4OH^-} \qquad \mathbf{E° = 0.76V}$$

$$\mathbf{ClO_3^- + H_2O + 2e- \leftrightarrows ClO_2^- + 2OH^-} \qquad \mathbf{E° = 0.33V}$$

$$\mathbf{ClO_3^- + 2H^+ + e^- \leftrightarrows ClO_2 + H_2O} \qquad \mathbf{E° = 1.152}$$

2.2.2 Production of ClO_2

ClO_2 is highly soluble in water, particularly in cold water. ClO_2 remains as dissolved gas in solution and do not hydrolyze to any appreciable extent, in contrast to the hydrolysis of chlorine gas in water (Weinberg, 1986; Gates, 1989). ClO_2 cannot be stored or compressed, since it is explosive under pressure. Therefore, it must be generated on-site (EPA, 1999).

The two most common ClO_2 generation methods are sodium chlorite-acid generation and sodium chlorite-chlorine generation in drinking water application; ClO_2 is generated from sodium chlorite solutions.

$$2NaClO_2 + Cl_2(g) \leftrightarrows 2ClO_2(g) + 2NaCl$$

$$2NaClO_2 + HOCl \leftrightarrows 2ClO_2(g) + NaCl + NaOH$$

$$5NaClO_2 + 4HCl \leftrightarrows 4ClO_2(g) + 5NaCl + 2H_2O$$

Table 2-1 presents information on some types of generators commercially used to generate the ClO_2.

Table 2-1: Commercial Chlorine Dioxide Generators.

Type	Principle Reactions Reactants, byproducts, main reaction	Particular Attribution
Acid-chlorite: **(direct addition for the acid)**	$4HCl + 5NaClO_2 \leftrightarrows 4ClO_2(aq) + ClO_3^-$ At low pH ClO_3^- possible formation Slow reaction rates	The pump that feed chemicals pump interlocks is required. Production limit ~ 25-30 lb/day. Highest yield at ~80% productivity.
Aqueous chlorine- chlorite: **(Cl_2 chemical pumps with gas ejectors for liquids or booster pump for ejector water).**	$Cl_2 + H_2O = [HOCl / HCl]$ $[HOCl/HCl] + NaClO_2 = ClO_2(g) + H/OCl^- + NaOH + ClO_3^-$ Low pH Production of ClO_3^- is possible Fairly slow reaction rates	Extra Cl_2 need to neutralize NaOH. Production rates reduced to ~ 1000 lb/day. High conversion but final yield only 80-92% in addition to corrosive effluent due to low pH (~2.8-3.5). 3 systems of chemical pump HCl, hypochlorite, chlorite, and dilution water to reaction chamber.
Gaseous chlorine- chlorite **(Gaseous Cl_2 and 25% solution of sodium chlorite; pulled by ejector into the reaction column.)**	$Cl_2(g) + NaClO_2(aq) \leftrightarrows ClO_2(aq)$ Neutral pH fast reaction could cause scaling in reactor under vacuum due to hardness of feedstock.	Production rates 5-120,000 lb/day. Ejector-based, with no pumps. Motive water is dilution water. Close to neutral pH effluent. No extra Cl_2. Turndown rated at 5-0X with production of 95-99%. Less than 2% excess Cl_2. Highly calibrated flow meters with min. line pressure ~ 40 psig required.
Gaseous chlorine- solids chlorite matrix **(Humidified Cl_2 gas is pulled or pumped through a stable matrix having solid sodium chlorite.)**	$Cl_2(g) + NaClO_2(s) = ClO_2(g) + NaCl$ Fast reaction rate Recent technology	Cl_2 gas diluted with N2 or filtered air to produce ~8% gaseous ClO_2 stream. Infinite turndown is possible with >99% production yield. Highest rate to ~1200 lb/day per column; ganged to >10,000 lb/day.
Electrochemical **(the generation is Continuous of ClO_2 from 25% ClO_2^- solution recycled through electrolyte cell)**	$NaClO_2(aq) \leftrightarrows ClO_2(aq) + e^-$ New technology	Counter-current cold water stream accepts gaseous ClO2 from production cell after it diffuses across the gas porous membrane. Small one-pass system requires exact flow for power needs (Coulombs law).
Acid/peroxide/chloride	$2NaClO_3 + H_2O_2 + H_2SO_4 = 2ClO_2 + O_2 + NaSO_4 + H_20$	Uses concentrated H_2O_2 and H_2SO_4. Downscaled version; Foam binding; at low pH.

Source: EPA, 1999.

2.2.3 **pH Effects on Chlorine Dioxide Production**

NaOH is one of the hypochlorous acid byproducts resulting from its reaction with $NaClO_2$ in solution. The pH of the mixture can be too high as NaOH is a common stabilizer of $NaClO_2$ feedstock. The high pH slows the production of ClO_2 and forces less effective chlorate-forming reactions. This is similar to the process in which ClO_2^- and hypochlorite ions react in drinking water to form ClO_3^-. This neutralizing effect of corrosive could be induced by unlike stabilities used in each of the forms and sources of $NaClO_2$, which are accepted for use in drinking water under AWWA Standard B303-95 (AWWA, 1995).

2.2.4 **Chlorate and Chlorite Byproduct Formation**

Chlorite and chlorate are the main ClO_2 by-products of concern (Haag and Hoigne, 1983). ClO_2 does not generate organochlorine compounds because it reacts only by oxidation, opposite to chlorine, which reacts by oxidation and electrophilic replacement. Furthermore, as evidenced by its minor disinfectant need compared to chlorine, ClO_2 is more selective in typical applications of water treatment. The chlorate ion is one of the greatest unwanted byproducts in generators. It can be formed as a result of reaction with the intermediate dimer, $\{Cl_2O_2\}$.

$$Cl_2 + ClO_2^- \leftrightarrows \{Cl\text{-}ClO_2\} + Cl^- \qquad [5]$$

The subsequent conditions may produce the chlorate ion (Hoehn et al., 1990):

- Existence of high concentrations of free chlorine at low pH in aqueous solutions.
- Extremely high ratios of Cl_2 gas: ClO_2^-.
- Base-catalyzed disproportionation of ClO_2 at pH >11.
- Dilute chlorite solutions held at low pH.
- Reaction mixtures are highly acidic (pH <3).
- (Independent of the quick formation of the {Cl_2O_2} intermediate), excess of hypochlorous acid oxidize chlorite ions to chlorate ions, but not to ClO_2)

2.3 Points of Application for ClO_2 and Primary Uses

2.3.1 In Disinfection Processes

When using ClO_2 for disinfection purposes, consideration must be given to the overall demand and should account for seasonal variations, temperature, and application points. Table 2-2 illustrates results for one sample of a market study completed on a surface water source (DeMers and Renner, 1992).

Table 2-2: Surface Water ClO_2 Demand Study Results.

Dose mg/l	Time (m)	ClO_2 (mg/l)	ClO_2^- (mg/l)	ClO_3^-(mg/l)
1.4	**3**	**0.47**	**0.76**	**0.05**
	10	**0.30**	**0.98**	**0.06**
	20	**0.23**	**1.08**	**0.07**
	40	**0.16**	**1.11**	**0.07**
	60	**0.11**	**1.11**	**0.07**

The maximum residual disinfectant level (MRDL) is 1.0 mg/L for chlorite per the D/DBP rule, for ClO_2 is 0.8 mg/L and the MCL ((Maximum Contaminant Level, is the maximum level of a contaminant that is allowable in drinking water and it is set as close to MCLG, which is the contaminant level in drinking water where there is no known or expected risk to health, (USEPA, 2010) as achievable using the best available treatment technology and with cost effective consideration MCLs are enforceable standards)). Which means that if the oxidant demand is higher than 1.4 mg/L, ClO_2 could be used as a disinfectant because the ClO_2^-/ClO_3^- ions byproduct might exceed the maximum level allowed, unless inorganic byproducts (e.g., chlorite) are then removed. However, the typical quantities of ClO_2 used in drinking water treatment as disinfectant is 0.07- 2.0 mg/L.

2.3.2 Taste and Odor Removal

The common application of ClO_2 in drinking water is to control odors and tastes associated with algae, decaying vegetation and from phenolic compounds. This depends on raw water quality, the nature of treatment plant and any other purposes for ClO_2 addition. It is, therefore, recommended to add ClO_2 close to the termination of conventional treatment plants. If the turbidity of the water is low (less than 10 NTU), then it can be added at the opening of the plant. This would control the growth of algae (DeMers and Renner, 1992).

2.3.3 Oxidation of Fe and Mn

ClO_2 reacts with Fe and Mn to form precipitates that can be removed through sedimentation and filtration. In this reaction, ClO_2 reduces to chlorite ion.

2.3.3.1 The Environmental Effect on ClO2 Efficiency

Studies have been conducted to establish the effect of pH, temperature, and suspended matter on the disinfection efficiency of ClO_2. Next is a summary of the effects these parameters have on pathogen inactivation.

2.3.3.1.1 Effect of pH

Several investigations have shown that pH has much less influence on pathogen inactivation for viruses and cysts with ClO_2 than with chlorine in the pH range of 6 to 8.5 (Liyanage et al., 1997). More investigations are also required to elucidate further how pH impacts on ClO_2 effectiveness.

2.3.3.1.2 Temperature Effect

The disinfection effectiveness of ClO_2 decreases as temperature decreases (Chen et al., 1984). LeChevallier et al. (1997) showed that decreasing temperature from 20°C to 10°C led to a reduction in the disinfection efficiency of ClO_2 on *Cryptosporidium* by 40 percent, which is same as former results for *Giardia* and viruses.

2.4 Efficacy of ClO_2 as a Disinfectant

Many studies have been conducted to investigate the germicidal efficiency of ClO_2 (EPA, 1999). It was shown that ClO_2 is a more active disinfectant than chlorine but is less active than ozone.

2.5 Disinfection By-Products of ClO_2

The chief DBPs of ClO_2 are chlorite and chlorate ions (WHO, 2004). The main features affecting the formation of chlorite, and chlorate in drinking water would include (Aieta et al., 1984):

- The applied dose/oxidant ratio.
- The mixing ratios of sodium chlorite and chlorine throughout the ClO_2 production method.
- Exposure to sunlight.
- Reactions between chlorine and ClO_2^- and chlorine in case of using free chlorine in distribution system as residual maintenance.
- Concentrations of chlorate in sodium chlorite feedstock.

2.5.1 **Organic By-Products Produced By ClO_2**

ClO_2 usually produces small amount of organic DBPs such as total organic halide (TOX) (Werdehoff and Singer, 1987, Singer (1992). Many were not found after ClO_2 was added to the water; however, THMs did show up following chlorination. Other reaction by-products of ClO_2 with organics in drinking- water have not been well described but include aldehydes, carboxylic acids, haloacids, chlorophenols, quinones and benzoquinone (Bull and Kopfler, 1991). In a recent article pilot plant in Indiana a identified more than 40 organic disinfection by-products when ClO_2 was used as a primary disinfectant (Hoehn et al., 2003). The toxicity of these by-products is mostly unknown (Richardson et al. 1994). In desalination, the production of THMs systems has been studied at several full-scale plants. In general, the operators of desalination plants employ distillation and were not concerned of THMs formation because these compounds volatilize during distillation: less than 10% of the THMs in the seawater are carried over into the final product water (Amy et al., 1987)

2.6 **Controlling Strategies of DBPs Formation**

USEPA in 1983 recommended that the total ClO_2 concentration, chlorite, and chlorate should be less than 1.0 mg/L. Furthermore, ClO_2 concentration with greater than 0.4 to 0.5 mg/L led to taste and odor problems. Accordingly, the use of ClO_2 would be slightly limited in moderate to high TOC water. No well-known method is available for eliminating chlorate once it is formed. However, the following approaches have demonstrated their effectiveness for chlorite removal (Gallagher et al., 1994):

- Adding reduced iron salts, such as ferrous sulfate.
- Applying either powdered activated carbon (PAC) or granular activated carbon (GAC).
- Adding reduced-sulfur compounds such as sulfur dioxide.

2.7 Overview of Disinfection By-Products Regulation

In 1979, the U.S. EPA published a regulation to control total THMs at an annual average of 100 mg/L (ppb) in drinking water; THMs defined as $CHCl_3$, $CHCl_2Br$, and CHClBr2. In 1998, the U.S. EPA released the Stage 1 Disinfectants (D)/DBP Rule, which lowered permitted levels of total THMs to 80 mg/L and regulated for bromate (10 mg/L), and chlorite (1000 mg/L) (Table 2-3) (USEPA, 1998). Stage 1 regulations obligatory monitoring based on running annual averages, which represented averages of all samples collected in a utility's distribution system. In one-year period, on January 2002, this Rule became active (McGuire, 2002). The Stage 2 D/DBP Rule which published in January 2006, provided the Stage 1 Rule maximum contaminant levels (MCLs) for THMs and required that MCLs be based on locational running annual averages; that is, each location in the distribution system needs to comply on a running annual average basis (USEPA, 2006).

This modification was that the running annual averages (used with the Stage 1 D/DBP Rule) allowable for some locations within a water distribution system to exceed the MCLs as long as the average of all sampling points did not exceed the MCLs. Thus, consumers served by a specific section of the distribution system could receive water that regularly exceeded the MCLs. The Stage 2 D/DBP Rule keeps the MCLs for bromate and chlorite; though, the U.S. EPA plans to review the bromate MCL as part of their 6-year review process. A slightly less strict standard for total THMs established by the European Union (EU) has been transferred into national drinking water standards in most EU-member countries (Linder, 2005).

The World Health Organization (WHO) has set provisional guidelines for each THM species that are generally much higher than the USEPA and EU standards (WHO, 2011). The standards in Qatar mainly drew from WHO guidelines but KM also set Water Quality Requirement, Table 2-3 (KM, 2012).

As a result of new regulations, many drinking-water utilities have changed their disinfection practices to meet the new regulations. Regularly, the primary disinfectant is changed from chlorine to alternative disinfectants, including ozone, ClO_2, and chloramines. In Qatar, the shifting from chlorine to ClO_2 as a disinfectant was started in 2009. In some cases, chlorine is used as a secondary disinfectant following primary treatment with an alternative disinfectant, particularly for ozone and ClO_2. However, new problems can result with changes in disinfection practice. For example, the use of ozone can significantly reduce or eliminate the formation of

THMs and HAAs, but it can result in the formation of bromate, particularly when higher levels of bromide exist in the source waters.

The higher concentrations of bromoform in the Middle Eastern desalination plants, could be attributed to the higher concentrations of dissolved organic matter at the sites of Arabian Gulf desalination plants e.g., typical dissolved organic concentrations at desalination plants in UAE and Kuwait were 2.5 mg C/L compared to around 1 mg C/L in the US and Europe where DBP formation was measured (Aieta et al., 1984).

Otherwise, the higher levels of $CHBr_3$ could be linked to hydrocarbon pollution, as shown by a study in which an oil spill resulted in $CHBr_3$ concentrations of around 225 μg/L in water that had passed through a chlorinated seawater intake (Gallard et al., 2002). $CHBr_3$ will be the predominant THM formed when chlorine is used for seawater pre-treatment or disinfection of desalinated water. $CHBr_3$ production in water distribution systems will only approach regulatory guidelines when the desalinated water is blended with waters that contain high concentrations of THM precursors.

Table 2-3: Regulations and Guidelines for DBPS and ClO2.

DBP	
U.S. EPA regulations	**MLC (mg/L)**
Total THMs	0.080
Bromate	0.010
Chlorite	1.0
World Health Organization (WHO) guidelines	
DPB	**Guidelines value (mg/L)**
Chloroform	0.2
Bromodichloromethame	0.06
Chlorodibromomethane	0.1
Bromoform	0.1
Bromate	0.01
Chlorite	0.7
European Union Standards	
DBP	**Standard value (mg/L)**
Total THMs	0.1
Bromate	0.01
Kahramaa (KM) Water Quality Requirements	**Guidelines value (mg/L)**
Chloroform	0.15
Bromodichloromethame	0.06
Chlorodibromomethane	0.08
Bromoform	0.01
Bromate	0.01
Chlorite	0.07
Chlorate	0.07
Total THM	0.080
ClO2	
World Health Organization (WHO) guidelines	
WHO did not set a guideline value for CLO2, but the threshold level for taste and odour was determine at 0.4 threshold. WHO consider residual of a few tenths from ClO_2 in mg/l is normal practice to supply water to act as a preservative	
EPA set 0.8 mg/L as the maximum residual disinfectant level for ClO2.	
Kahramaa (KM) Water Quality Requirements	
The maximum and minimum level set for producing companies and distribution system. The Max value should not exceed 0.7 mg/L and the Min value should not be less than 0.05 mg/L	

2.8 Summary of Epidemiology Studies of Cancer and Drinking Water

Some epidemiologic studies have shown that a life- time exposure to chlorinated water is linked with an increased risk for cancer, especially of the urinary bladder and colorectum (IARC, 1995 and 2004). The bladder cancer risk has usually been linked with THM levels (Cantor, 1997; Villanueva, 2007). One study showed that both bladder and kidney cancer risks were related with the mutagenicity of the water, which may be correlated to levels of the chlorinated furanone, MX which is one of disinfectant by-products from chlorination, (Koivusalo, 1994) or possibly other mutagenic DBPs. Risk for rectal cancer has recently been shown to be linked specially with levels of the THM bromoform (Bove et al., 2007).

The only and first epidemiologic study to stratify risk by route of exposure has found that much of the bladder cancer risk linked to with chlorinated water seems to be due to swimming, bathing and showering rather than to drinking the water (Villanueva et al., 2007) and that the risk could be highest for people having the GSTT1-1 gene (Cantor et al., 2006). The previous observations suggest that genetic susceptibility may play a role in the cancer risk and that the risk may be specially related to inhalation and dermal exposure (Sassvilled et al., 1999). If we try to correlate this observation with the amount of water that is used every day by Qatari individual (1200 L/cap/day) and take in to consideration other routes of exposure, so the scenario will be more worse and need more investigation. Especially in light of the epidemiologic study that stratify risk by route of exposure has found that much of the bladder cancer risk linked to with chlorinated water seems to be due to swimming, bathing and showering rather than to drinking the water (Villanueva et al., 2007).

One study has shown that the risk for bladder cancer decreased as the duration of exposure to ozonated water increased (Chevrier et al., 2004), this observation supports the shift from chlorination to other disinfectant such as ozonation. Previous studies had found that organic extracts of ozonated water were far less mutagenic than those of chlorinated water (DeMarinir et al., 1995; Patterson et al., 1995; Noot et al., 1989). This has been newly established for organic concentrates of ozonated water (Claxton et al., in press). Though, studies of water treated with alternative disinfectants are incomplete, and there has not been a systematic analysis carried out on drinking water prepared from various types of source waters, including high-bromide/iodide source waters.

Most of the DBPs tested for carcinogenicity in rodents cause primarily liver cancer rather than bladder or colorectal cancer (IARC, 1995, 2004). The exclusions include renal tumors induced by $CHCl_2Br$, $CHCl_3$, and bromate; intestinal tumors induced by $CHCl_2Br$ and $CHBr_3$; and thyroid tumors stimulated by bromate. The most striking exception is the variation of organ sites at which MX induced tumors in the rat, as well as the low doses at which these tumors were stimulated.

This general deficiency of association between site of tumors in animal cancer studies for individual DBPs and human epidemiological studies for drinking water has not yet been clarified. Nevertheless, in addressing the potential for animal carcinogens to be hazardous to humans, most regulatory agencies do not believe that there is tumor site concordance between rodents and humans. Possible areas for exploration involve route of exposure. Most of the carcinogenicity studies of DBPs have involved administration of the DBP in the drinking water (oral exposures). However, the recent route-of-exposure study, Villanueva et al (2007) showed that the influence abundant of the bladder cancer linked to chlorinated water may be due to showering, bathing, and swimming (dermal and inhalation exposures) rather than oral exposures.

2.10 Occurrence of Disinfectant and the DBPs Addressed in This Project

2.10.1.Disinfectants

ClO_2, chlorine gas and chloramine are considered as some of the strongest respiratory irritants. Few assessments have been conducted to evaluate of the toxicity effects in experimental animals or humans. The results from animal and human studies propose that chlorine, chloramine and ClO_2 do not participate in the development of toxic effects or cancer.

2.10.2.Trihalomethanes (THMs)

From this group, 600 DBPs in drinking water have been identified. THMs are one group from halomethanes that consist of ($CHCl_2Br$, $CHCl_3$, $CHBr_3$ and $CHCl_2Br$), which are regulated by the U.S. EPA at a level of 80 mg/L (USEPA, 2006). THMs and HAAs are the almost the predominant classes of DBPs formed in chlorinated drinking water and account for almost 25% of the halogenated DBPs (Krasner et al., 2006; Weinberg, 2002). They are also formed at lower levels in drinking water treated with chlorination ,bromoform can be formed in high-bromide source waters treated with ozone (Richardson, 1998; Glaze, 1993). Using ClO_2 in disinfection process does not form THMs; yet, low THM levels can be present due to chlorine impurities in ClO_2.

The U.S. EPA Information Collection Rule (ICR) that involved 500 large drinking-water plants in assessment process found that the level for THMs in the distribution system was 38 mg/L (McGuire, 2003). Chloroform was measured, and it had the concentration of 23 mg/L. Natural bromide in source waters can increase the formation of brominated THMs ($CHCl_2Br$, $CHBr_3$ and $CHCl_2Br$) (McGuire, 2003).

2.10.3.Chlorite

Chlorite is a main DBPs formed with ClO_2 treatment, now its regulated at 1.0 mg/L in the United States (USEPA, 1998 and 2006). However WHO and Qatar have regulated chlorite at 0.07 mg/L. Under low or zero oxidant-demand conditions dilute solutions of ClO_2 are stable, but when ClO_2 is in contact with organic and inorganic matter, ClO_2 quickly degrades to chlorite (ClO_2^-), chlorate (ClO_3^-), and chloride (Cl^-) (Werdehoff, 1987). Chlorite levels are found from 30 to 70% of the ClO_2 dose, depending on some factors such as on oxidant demand, temperature, competitive side reactions with other chemicals or processes, and generator efficiency (Werdehoff et al., 1987; Gates, 1998).

The median level of chlorite comes from the ICR was 0.29 mg/L at water treatment plants using ClO_2 for disinfection. New measurements of chlorite included a study of full-scale treatment plants was 0.58 mg/L (Richardson et al., 2003), another in Virginia found chlorite at a median level of 0.29 mg/L (Hoehn, 2003) however in Quebec, the maximum level of chlorite was found at 1.1 mg/ L (Baribeau, 2002; Korn et al. 2002).

2.10.4.Chlorate

Chlorate is a second significant DBP from ClO_2 treatment, however it can also present as a contaminant from chlorination treatment (Baribea et al., 2002). The decomposition product of ClO_2 is a Chlorate, the level of chlorate can hit at about 20% of the original ClO_2 dose (Thompson, 1992). In the U.S. EPA's ICR, that represents the most extensive data for DBPs, found the median level of chlorate at 0.12 mg/L at plants using ClO_2 for disinfection (McGuire, 2002; USEPA, 2000). New measurements of chlorate was done by Richardson (2003) and the level of chlorate was found at 0.052 mg/ L; however in a treatment plant in Virginia the chlorate median level was found at 0.014 mg/L (Hoehn et al., 2003); while in Quebec the maximum level hit 0.19 mg/L (Baribeau et al., 2002).

2.11. The DBPs from Anthropogenic Contaminants

Most of DBPs studies were investigated and evaluated in source water and drinking water. But other source of contamination that could affect the source water was not taken in to consideration such as industrial emissions that may impact the source water (Kolpin et al., 2002). Current studies have shown that some of these water contaminants can also react with disinfectants used in drinking-water treatment to form their own by-products (Zwiener et al., 2007; Zwiener et al., 2003). Furthermore these disinfectant reactions have been conducted in controlled laboratory studies and have not been identified in finished drinking water, but the potential is there for their formation in drinking-water treatment. Still, the toxicology and occurrence of DBPs formed from anthropogenic contaminants have not been investigated probably and not much is known about the genotoxicity or carcinogenicity of the contaminant by-products formed.

2.12. Risk Assessment of DBPs

Even with the huge number of research that have been conducted on DBPs, there are many scientific questions that need clear and specific answers (Richardson, 2007). Some of these questions are on the types of data and evaluations needed to validate that DBPs are controlled at a safe level while providing the acceptable level of protection needed against microbial contamination to protect the public health to respond to this need, the U.S. EPA and other groups have used the tools of risk assessment in their analysis of potential health effects of DBPs. The regulated DBPs have all been assessed several times using these created tools as well as to be prepared for the proposal and declaration of the Stage 2 D/DBP Rule. That set of risk assessments tools reflected the concerns that are growing for reproductive and developmental effects that may be associated with DBP exposure. These assessment tools also combined novel methods to estimating cancer risk. These newer methods highlight maximum use of suitable data rather than trusting and depending only on default measures. The Cancer guidelines that are set by EPA categorize the method of action as the critical information required to determine if data are applicable to humans and how to approach dose–response assessment.

2.13. Demand for This Study in Qatar

Other than chlorine DBPs, there are very few data on the occurrence of ClO_2 DBPs in finished water and distribution systems as well as on a full-scale study. Most of these studies and research are based on laboratory databases and not on real measurements collected from the field after the drinking water quality impacted by significant changes and the different behaviors of DBPs; these have been that may affected by many factors in water storage area and distribution system. The proposed empirical models from different studies have been developed to predict the concentrations of DBPs, these models can be used to conduct a assessment to predict the impact of treatment changes and in exposure assessment to simulate missing or past data but still there is a need to measure the DBPs in finished water and distribution system, which makes this study distinguishable from others. The current study follows the occurrence of main DBPs of ClO_2 as well the residual ClO_2 as main disinfectant used in water treatment. These levels followed from the place of production at desalination plants through storage area where the water aging may be a concern and finally at the end consumption points where the behaviors of these compounds could be highly affected by many factors that may significantly affect the water quality and safety. Despite the intensive work conducted on DBPs formation in disinfected water worldwide, the potential hazards of DBPs and the scarcity of data in Qatar and GCC make this type of study potential useful and essential.

3. Chapter 3. Materials and Methods

3.1 Sample Collection

In order to properly investigate the DBPs throughout the entire distribution system, the sampling regime covered three major categories; representing drinking water production facilities, reservoirs and customer point of use. The first category of the water samples were collected from seven desalination plants outlets either at the northern side of Qatar (RLC, Q-power and Ras-Girtas) or at the Southerned of Qatar (RAF A, RAF A1, RAF B and RAF B2). Such samples represented the feed water (water source) to the distribution system where the measured DPB levels represent out the influence of desalination and treatment process on DBPs formation. See Appendix D for different images of collection points.

The second category of the water samples was collected from the KM reservoirs (New Salwa (NS), Airport, Duhail (D) and West Bay (WB)). These reservoirs represented key points within the distribution system as they supply DW to bulk number of customers, and the water aging inside the reservoir may influence the DBPs formation. These reservoirs are located in Abu-Hammor, Um-Goulina, Al-Kheesa and Al-Markhiya area, respectively. Each reservoir has different capacity and they are built in different years. Please refer to Table 3-1 which present the capacity, installation yea and name of feeding desalination plant. The Airport and New Salwa reservoirs are feed by Rass- Abu-Fontas desalination plants while Duhail reservoir is feed from RLA and RLB respectively which consider two different desalination plant and they are using different technology to distillate the water. There is a little bit different in feeding process for West Bay reservoir because his water is mixed from Ras Laffan and Ras Abu-Fontas DPs, where it feed by RLA, RLB, RAF A and RAF A1 respectively. The reservoirs' selection criteria were carefully chosen to cover different areas in Qatar, different capacities and different population intensity (i.e.: different water aging). The water samples were, however, collected from the outlets of each reservoir.

The third category of the samples was collected from the customer point of use. These samples represented the final water that will be used for drinking purposes where ablution areas at mosques were selected for sampling purposes to reflect high number of customers. For each of the aforementioned reservoirs, two mosques were selected. Thus, the water samples were collected from eight mosques (namely; mosque number: 82, 266, 141, 600, 1077, 1146, 1164, 1066). The details and the location of the sampling points are shown in Table 3-2 and Figure 3-1. Two hundred ninety four (294) water samples were collected; 98 from the DPs, 64 from the reservoirs and 132 from the mosques. The sampling time took place in the morning from 6-10 a.m unless there were an out of control situation. The period of collecting the water samples were from the first three weeks of the whole five months. In each location, the sample is collected in two types of containers. One is amber glass with Teflon screw cap with a capacity of 100 mL and the second is plastic opaque with a capacity of 250 mL. All glass bottles were thoroughly cleaned with water and rinsed several times with deionized water. Vials (without caps) were dried in an oven at 140

°C and the same procedures were used to clean plastic containers but they were dried at 70°C instead.

Table 3-1: Reservoir Name, Capacity, Installation Year and Inlets from DP Name

Reservoir Name	**Capacity (MIG)**	**Installation Year**	**Inlet from (DP Name)**
Airport	28.1	1981	RAF A & RAF A1/ RAF B
New Salwa	29.6	1993	RAF A & RAF A1 / RAF B
Duhail	134.3	2013	RLC(Ras-Girtas)/ RLB (Q-Power)
West Bay	45.5	2004	RLA/ RLB/ RAF A & RAF A1

All water samples were collected according to the international protocol and practices for collection and handling of drinking water samples (U.S. EPA, Guide to Drinking Water Sample Collection, 2005). The water is flushing at each point of collection for 4 minutes and until the water temperature is stable. All samples were taken with special care to avoid inadvertent contamination, and filled slowly to eliminate bubble formation and to prevent overflowing, as the preservative was pre-charged to the containers according to the sampling protocol. Sodium thiosulfate was added to the first vial and ethylene diamine (EDA) was added to the vial used to analyze chlorite, and chlorate. The second water sample was sparged with nitrogen gas for five minutes. After collection, all vials were labeled and stored in icebox with ice package and maintained at 10- 12°C and kept away from light until delivers to the central food laboratory/Qatar where the samples were analyzed. Please refer to appendix E in appendices section where the photos show the procedures for collection, labeling and preparation.

Table 3-2: Details of Sampling Collection Points.

Location	Sampling Point
Abu-Fontas, Al Wakra	
1	Ras Abu Fontas Desalination Plant (DP) - (RAF A)
2	Ras Abu Fontas Desalination Plant (DP) - (RAF A1)
3	Ras Abu Fontas Desalination Plant (DP) - (RAF B)
4	Ras Abu Fontas Desalination Plant (DP) - (RAF B2)
Ras Laffan Industrial City	
5	Ras Laffan Desalination Plant (DP) - (RLPC) (RLA)
6	Ras Laffan Desalination Plant (DP) - (Q.power) (RLB)
7	Ras Laffan Desalination Plant (DP) - (Ras Girtas) (RLC)
Abu Hamour, Doha	
8	New Salwa Reservoir
9	Mosque No. 82
10	Mosque No. 266
Umm Ghuwailina, Doha	
11	Airport Reservoir
12	Mosque No. 141
13	Mosque No. 600
Al-Kheesa, Doha	
14	Duhail Reservoir
15	Mosque No. 1146
Al-Eeb, Doha	
16	Mosque No. 1077
Al-Markhiya, Doha	
17	West Bay Reservoir
18	Mosque No. 1164
19	Mosque No. 1066

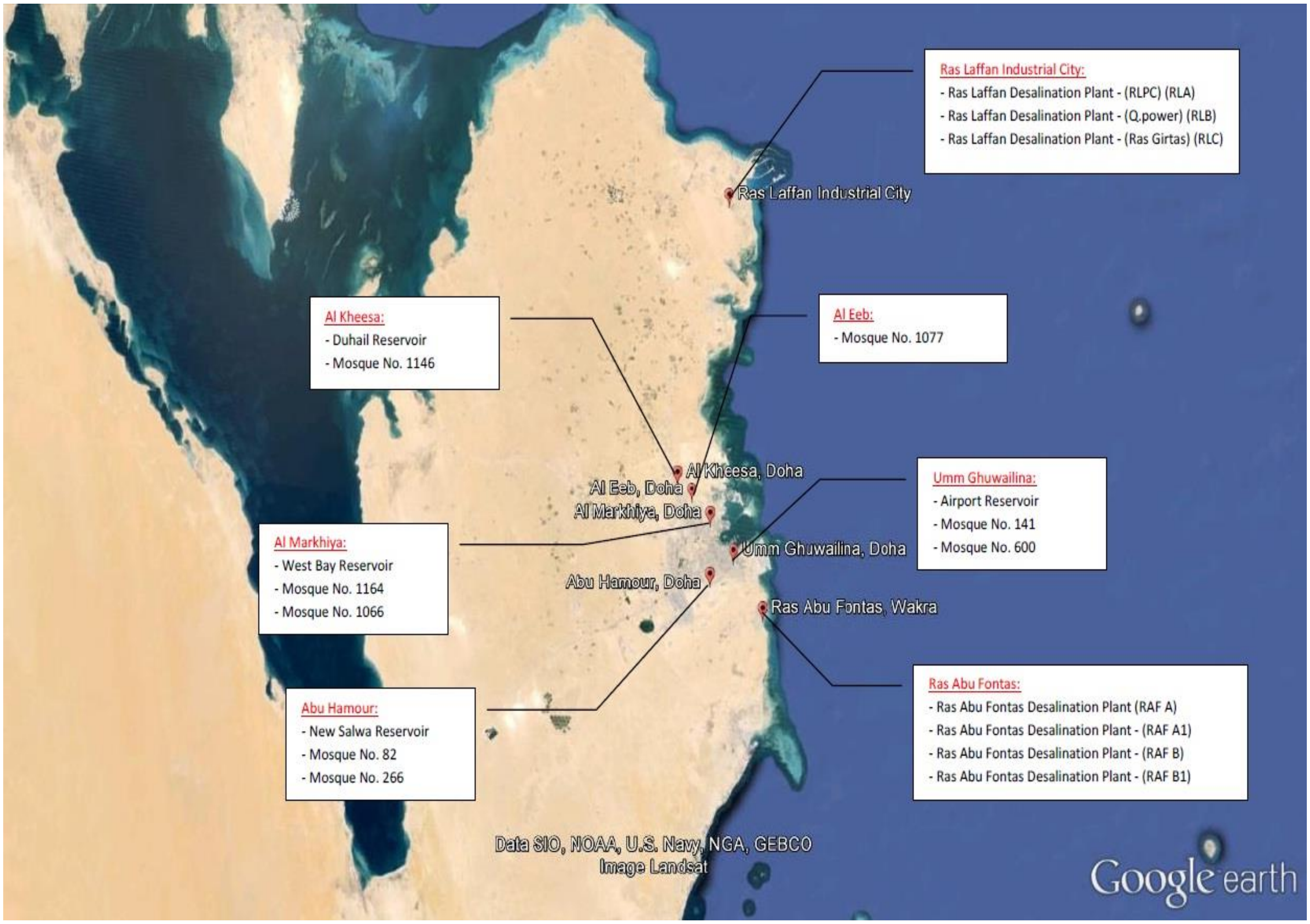


Figure 3-1: Qatar Map Showing The Location of Sampling Points.

3.2 Measurement on Site

All water samples were subjected to onsite measurements to measure some physical and chemical parameters; namely: temperature, pH, conductivity, turbidity, and ClO_2. Such parameters were measured using portable devices.

3.2.1 On-site Measuring Instruments

Various portable devices were used for the measurements. These devices were built to meet the demands of multiple user laboratory or plant environments. These devices are microprocessor controlled, which aids in the delivery of accurate and precise measurements. All portable instruments were subjected to calibration and verification. Verification process was carried out at the laboratory before moving to the site and after the last sample. Please refer to Appendix C for images of those instruments and equipment used. The devices used were as follows:

- Orion Star and Star Plus Meter from Thermo scientific: this device was used to measure the temperature, pH and conductivity. The relative accuracy for the pH meters is ± 0.002 and the range was from -2 to + 19.999. The range for conductivity meter is from 0.000 to 3000 μs/cm and the relative accuracy is ± 0.01. The temperature electrode range is from -5 to 105 °C.

- 2020wi Tc- 300wi LTC- 3000wi, Turbidimeter (LaMotte) portable device was used to measure the turbidity. The device was calibrated using three turbidity standards 0.0, 1, 0 and 10 FNU.

- Thermo Scientific ChlordioXense, Palintest was used to measure ClO_2. This device is a precise instrument used with unique pre-calibrated disposable sensors. It offers a simple and rapid, technique with reagent-free method of analyzing water for ClO_2. The sensor is designed for single use only. The surface of the sensor is highly sensitive and is handled with care through the foil packaging only. The sensor response compensates for the sample temperature in the range from 2 to 25°C, since the temperature for some locations exceeded this range; therefore all water samples were pre-cooled before measuring ClO_2. The nitrogen gas cylinder with capacity of 50L and pressure of 5 psi was used for purging all water samples; in order to prepare it for chlorite and chlorate test for four minutes.

3.3 Sample Analysis

All samples were fully analyzed in the central food laboratory (CFL) using ion chromatography for chlorate, and chlorite. These oxyhalides were determined by ion chromatography according to EPA Method 300.1: " Determination of inorganic anions in drinking water by ion chromatography'. The instrument used for chlorite and chlorate was Dionex ICS 5000. Ion Chromatography is a method for separating chemical substances that relies on differences in partitioning behavior between a mobile phase and a stationary phase to separate the components in a mixture. Due to the simplicity, sensitivity, and effectiveness in separating components of mixtures, this technique is considered as one of the most important tools in chemistry. The summary of the method is; a small volume of sample is introduced into an ion chromatograph. The anions of interest are separated and measured, using a system comprised of a guard column, suppressor device, analytical column and conductivity detector (John D. Pfaff (USEPA, ORD, NERL) - Method 300.0, (1993)). Water sample was analyzed with out sample preparation other than filtering through 0.2-micron before injection. The vials are failed with 10 ml of water and the septum is pushed fully into the cap and the cap is securely tightened. The vials were loaded into the sample tray. See Appendix E for sampling procedures and analysis.

With these experimental conditions: the water sample was injected into a stream of eluent and passed through a series of ion exchangers. The anions of interest are separated according to their relative affinities for a low capacity, strongly basic anion exchanger. The separated anions are directed through a suppressor device that provides continuous suppression of eluent conductivity and enhances analyte response. In the suppressor devices, the separated anions are converted to their highly conductive acid forms while the eluent's conductivity is greatly decreased. The separated anions in their acid forms are measured by conductivity. The identification of the anions of interest is based on the retention time as compared to the standards. Quantitation is by measurement of peak area or peak height.

Method 8260B is approved by EPA to quantitate the volatile organic compounds that have boiling points of less than 200 ^{o}C by gas chromatography/

mass spectrometry (GC/MS). This method was used to measure THMs using Headspace-Gas Chromatography/ Mass Spectrometry (GC/MS). The summary of the method is; the volatile compounds are introduced into the gas chromatograph by the purge-and-trap method. The analytes are introduced directly to a wide-bore capillary column or cryofocussed on a capillary pre-column before being flash evaporated to a narrow-bore capillary for analysis. The column is temperature-programmed to separate the analytes, which are then detected with a mass spectrometer (MS) interfaced to the gas chromatograph (GC). The analytes eluted from the capillary column are introduced into the mass spectrometer via a jet separator or a direct connection. Identification of target analytes is accomplished by comparing their mass spectra with the electron impact (or electron impact-like) spectra of authentic standards. Quantitation is accomplished by comparing the response of a major (quantitation) ion relative to an internal standard using a five-point calibration curve. The gas chromatography/mass spectrometry (GC-MS) method is based on the same principle as the GC method, using a mass spectrometer as the detector. As the gas emerges from the end of the GC column opening, it flows through a capillary column interface into the MS. The sample then enters the ionization chamber, where a collimated beam of electrons impacts the sample molecules, causing ionization and fragmentation (Kanjino et al., 1981). The Perkin Elmer GC-MS Clarus 600 was used to quantitate the THMs in CFL.

3.3.1 Preparation of Solutions and Reagents

3.3.1.1 Stock Standard Solutions

1000 mg/L standard solutions of chlorite and chlorate were prepared by dissolving the appropriate amounts of the required analyte in 100 mL of deionized water. Stock standards for most anions are stable for at least 6 months when stored at 4 °C. The chlorite standard is only stable for two weeks when stored protected from light at 4 °C.

3.3.2 Equipment

Thermo Scientific Dionex ICS-5000 Reagent-Free Ion Chromatography (RFIC™) System was used in this work. The Dionex ICS-5000 is an integrated ion chromatograph and consists of:

- Eluent Generator
- Column Heater
- Pump with Degasser
- Thermo Scientific Dionex EluGen™ EGC II KOH
- Cartridge (P/N 058900)
- Thermo Scientific Dionex CR-ATC Continuously Regenerated Anion Trap Column (P/N 060477)

3.3.3 Reagents and Standards

- Deionized water.
- Sodium and Potassium salts, A.C.S. reagent grade or better, for preparing anion standards (VWR or other)

- Fluoride standard 1000 mg/L, 100 mL (P/N 037158)
- Chloride standard 1000 mg/L, 100 mL (P/N 037159)
- Sulfate standard 1000 mg/L, 100 mL (P/N 037160)
- Bromide standard 1000 mg/L, 100 mL (Ultra Scientific, VWR P/N ICC-001)
- Sodium Chlorite, 80% (Fluka Chemical Co.)
- Sodium Bromate (EM Science, VWR P/N EM SX0385-1)
- Ethylenediamine, 99% (Sigma-Aldrich)

Table 3-3: Specification of Equipment Used in Samples Analysis.

Condition	
Columns	Dionex IonPac AS19 Analytical, 4 × 250 mm (P/N 062885) Dionex IonPac AG19 Guard, 4 × 50 mm (P/N 062887)
Eluent	10 mM KOH from 0 to 10 min, 10–45 mM from 10 to 25 min*
Eluent Source	Dionex ICS-5000 EG with Dionex CR-ATC
Temperature	30 °C
Flow Rate	1.0 mL/min
Injection	250 µL
Detection	Suppressed conductivity, Thermo Scientific Dionex ASRS™ ULTRA II Suppressor, 4 mm (P/N 061561) auto-suppression, recycle mode, 130 mA current
Background Conductance:	<1 µS
System Backpressure:	~2200 psi
Run Time	30 min

*Method returns to 10 mM KOH for 3 min prior to injection.

3.3.4 Reagents for Perkin Elmer GC-MS Clarus 600

- A reagent grade inorganic chemical was used in all tests.
- Organic free reagent water.
- Methanol.
- Reagent hexadecane
- Polyethylene glycol
- Hydrochloric acid (1:1 v/v), HCl
- Stock solutions
- Secondary dilution standards
- Surrogate standards
- Internal standards, calibration standards, initial calibration standards and calibration verification standards
- Matrix spiking and laboratory control sample

Table 3-4 : Specification of Equipment Used in Samples Analysis for THMs

GC Conditions	
Gas:	Helium, He 99.9995%
Gas Flow:	1 ml/min
Injection volume	1 µl
Split ratio:	20ml/min (Split flow)
Inlet temperature:	255°C
Column:	Elite Volatile capillary column (30 m, 0.25mm ID, 1.4 µm DF)

Oven Temperature:	40° C for 2 min 10° C/min to 100° C hold for 0 min 30° C/min to 240° C hold for 5 min
Aux Temperature (Transfer line) :	200° C
GC Run Time:	17.67 min

Scan Mode:	**MS Scan**
Scan Range:	35 – 300 m/z
Ion source Temperature	200° C
Ionization:	Electron Impact. (EI+)
Electron Energy:	70 eV
Method File Name :	SCH VOC ELITE VOLATILE

HS TRAP Conditions	
Temperatures: (°C)	
Vial Oven	80
Transfer line	120
Needle	90
Trap Hi	280
Trap Lo	40
Pneumatics (psi):	
Column pressure	25.0
Vial pressure	35.0
Desorb pressure	10.0

Times (min):	80
Thermostatting	30.0
Pressurize	1.0
Withdraw	0.2
Inject (ml)	0.04
Trap Hold	6.0
Dry purge	5.0
Desorb	0.5

3.4. Statistical Analysis and Relationships

More than one software and statistical analysis programs were run to analyze the results in order to correlate and determine the different relationships. Excel Microsoft Office and statistical package for the social sciences (SPSS) package were used. The SPSS version 22 (IBM, Armonk, NY) was used for the data analysis. Basic descriptive statistics were calculated for each variable. Bivariate regression was run between the ClO_2 concentration and other parameters. Calculating Pearson's correlation coefficients assessed the relationship between ClO_2 concentration and chlorite formation and other applicable association. Tool package in Excel and SPSS were run to answer the following questions:

- Is there any relationship between the concentration of ClO_2 and it's by products? (Chlorite, chlorate, and THMs)?
- Is there any relationship between the pH and chlorite formation?

- Is there any significant difference between the DPs, reservoirs and the mosques in terms of ClO_2 residual, chlorite, chlorate and THMs concentration?

4. Chapter 4. Result and Discussion

The following sections give the detailed investigation on ClO_2 residual and its by-products in drinking water as an indicator of drinking water quality and their compliance with the regulatory limit. 294 water samples were collected from seven desalination plants, four reservoirs and eight mosques distributed from north and south Qatar. The determination of the concentrations of DBPs and ClO_2 residual are considered one of the methods that have been used to assess the quality and safety of the drinkable water in the country.

Due to the health effects as a result of exposure to DBPs, the WHO and EPA have put regulations on adequate levels of DBPs in drinking water. These regulations were published to protect the public by controlling DBPs and minimize consumers' exposure to potentially hazardous chemicals while maintaining adequate disinfection and control of targeted pathogens. This would provide warning signals, diagnose, and formulate adequate solutions on the causes of any noncompliance or contamination of drinking water with those by-products or an indication of insufficient disinfection process. However, there are several factors that may influence disinfection processes and the formation of harmful DBPs. These factors must be carefully studied, understood and evaluated in order to minimize their impact on health.

Statistical analysis was employed using SPSS version 22. Basic descriptive statistics were calculated for each variable. Bivariate regression was run between the

ClO_2 concentration and the physical and chemical parameters as well as the DBPs. Analysis of variance (ANOVA), Spearman's or Pearson's correlation were used to assesse the relationship between ClO_2, if any, with chlorite, chlorate and THMs. The data was also represented by a histogram or columns in order to show the spread of the values observed. The minimum, maximum, and the average were also calculated. Moreover, the values obtained were compared with the international and local guidelines with its designated contaminant criteria.

This chapter consists of two sub-sections namely: physical and chemical characteristics of the collected waters, statistical analysis and coloration. The discussion part mainly focuses on the DBPs formation and the ClO_2 residual.

4.1 Physical and Chemical Parameters of The Collected Water Samples

4.1.1 Water Temperature

The median, max, mini and standard deviation of water temperature of the collected samples are summarized in Table 4-1 and illustrated in Figure 4-1. Figure 4-1 shows that the over all median water temperature was 38.5°C while the maximum and minimum measured values reached 46.0 and 18.7°C respectively. This difference in water temperature between DPs and reservoirs compared to the mosques could be attributed to using the mosques a method to cool the water for the users in ablution areas. KM declared that the acceptable limits for water temperature is 45°C (KM, Water Quality Requirements, 2012) while WHO does not specify any temperature limits. Accordingly, temperature of water samples lies within the acceptable range. The seasonal variation in water temperature should be taken in consideration when calculation the required disinfectant dose from chlorine dioxide.

Table 4-1: Max, Min, Median, STDV and Accepted Limit of Water Temperature (°C) at Different Water Sources.

Water Source	Median	Max	Min.	STDV	Limits
Desalination Plant	41.20	45.9	31.3	2.85	45
Reservoir	38.55	45.6	30.2	3.48	45
Distribution System(Mosques)	35.68	46.0	18.7	5.36	45
Overall Water	**38.50**	**46.0**	**18.7**	**3.89**	**45**

N= 294, where N is the total number of samples.

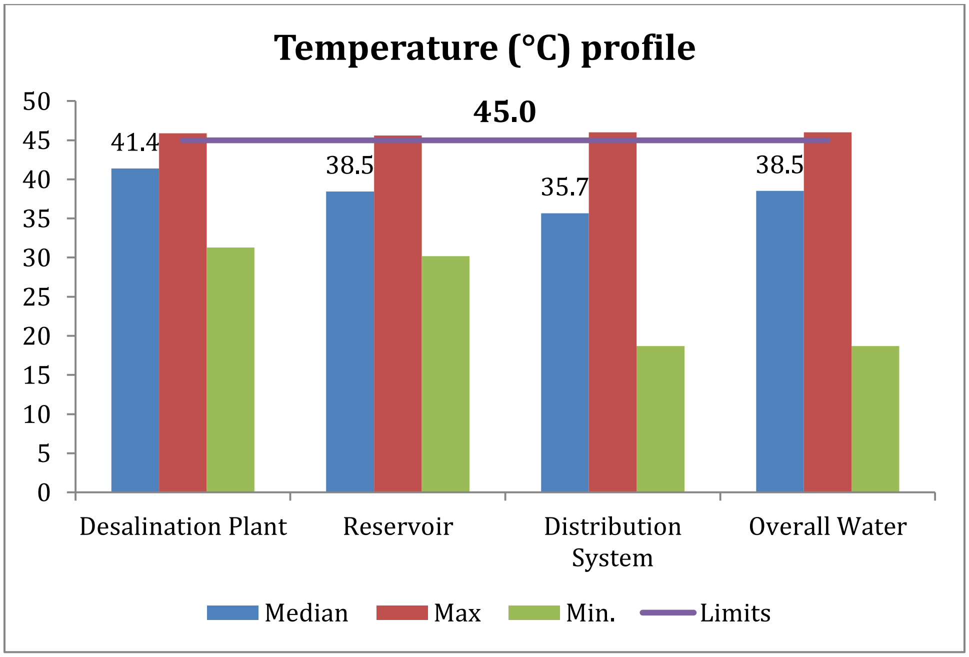


Figure 4-1: Max, Min, Median and Accepted Limit of Water Temperature (°C) at Different Water Sources.

4.1.2 pH

The median, max, mini and standard deviation of water pH values of the collected samples summarized in Table 4-2 and illustrated in Figure 4-2. Figure 4-2 shows that the over all median pH value was 7.9 while the maximum and minimum measured values reached 8.5 and 7.2, respectively. However, KM (KM, Water Quality Requirements, 2012) as well as WHO guidelines declared that the pH's acceptable operational range for drinking water is 6.5-8.5. Accordingly; all the pH of collected samples lie within the acceptable range.

Table 4-2. Max, Min, Median, STDV and Accepted Limit of pH Value at Different Water Sources.

Water Source	**Median**	**Max.**	**Min.**	**Lower Limit**	**Upper Limit**	**STDV**
Desalination Plant	7.7	8.4	7.3	6.5	8.5	0.20
Reservoir	7.8	8.2	7.2	6.5	8.5	0.18
Distribution System (Mosques)	8.0	8.5	7.2	6.5	8.5	0.26
Overall Water	**7.9**	**8.5**	**7.2**	**6.5**	**8.5**	**0.21**

N= 294, where N is the total number of samples.

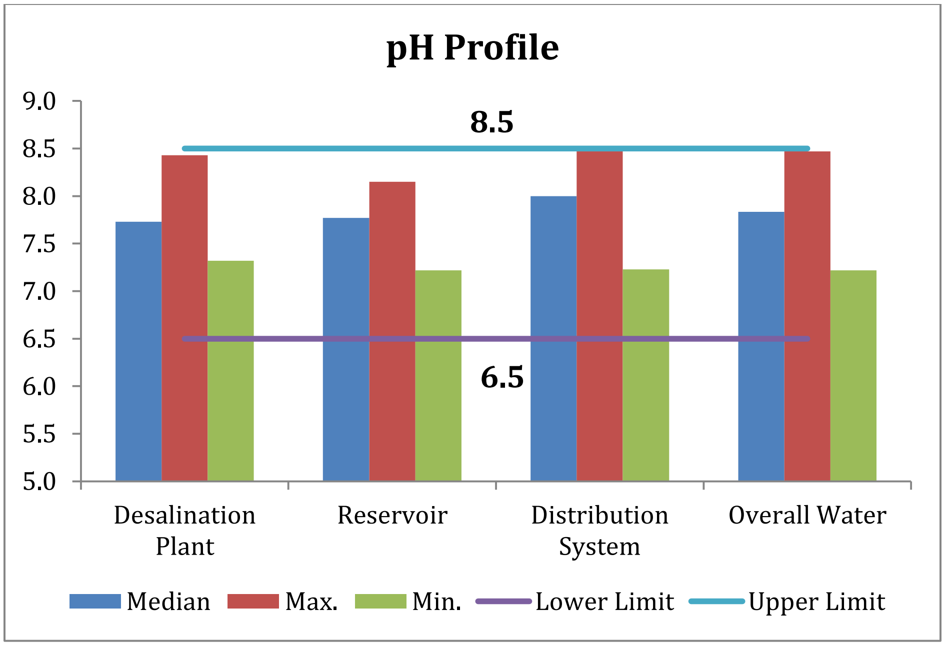


Figure 4-2: Max, Min, Median and Accepted Limits of pH Values at Different Water Sources.

4.1.3 Turbidity

The median, max, mini and standard deviation of water turbidity of the collected samples are summarized in Table 4-3 and illustrated in Figure 4-3. Figure 4-3 shows that the over all median turbidity value was 0.18 NFU while the maximum and minimum measured values reached 2.7 and 0.01 NFU, respectively. However, KM (KM, Water Quality Requirements, 2012) declared that the value less than 4 however, WHO declared that the value less than 5.0 NFU would be the acceptable level for turbidity. Accordingly, all the collected samples lie within the acceptable range for both WHO and KM.

Table 4-3: Max, Min, Median and Accepted Limit of Turbidity (FNU) Value at Different Water Sources.

Water Source	**Median**	**Max**	**Min**	**WHO Guidelines**	**KM Requirements**	**STDV**
Desalination Plant	0.17	1.96	0.01	5.00	4.00	0.30
Reservoir	0.18	0.78	0.01	5.00	4.00	0.19
Distribution System (Mosques)	0.19	2.70	0.01	5.00	4.00	0.34
Overall Water	**0.18**	**2.70**	**0.01**	**5.00**	**4.00**	**0.28**

N= 293, where N is the total number of samples. Outlier = one sample.

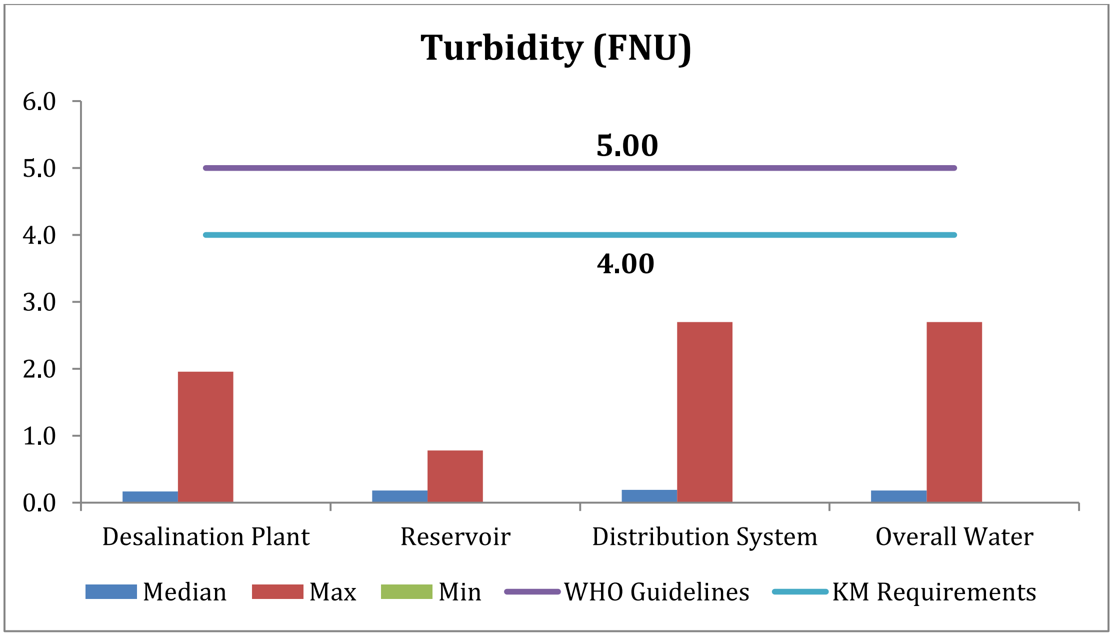


Figure 4-3: Max, Min, Median and Accepted Limit of Turbidity (FNU) Value at Different Water Sources.

4.1.4 Conductivity

The median, max, mini and standard deviation of water conductivity values of the collected samples are summarized in Table 4-4 and illustrated in Figure 4-4. Figure 4-4 shows that the over all median conductivity value was 170.2 (µs/cm) while the maximum and minimum measured values reached 384 and 95.3 µs/cm, respectively. However, KM (KM, Water Quality Requirements, 2012) as well as WHO declared that the acceptable limit for conductivity should be less than 500 µs/cm. Accordingly, all samples lie within the acceptable limit.

Table 4-4: Max, Min, Median, STDV and Accepted Limit of Conductivity µs/cm at Different Water Sources.

Water Source	**Median**	**Max.**	**Min.**	**Lower Limit**	**Upper Limit**	**STDV**
Desalination Plant	155.4	338	95.3	150	500	22.14
Reservoir	174.7	384	146.1	150	500	28.19
Distribution System (Mosques)	180.4	368	145.6	150	500	32.92
Overall Water	**170.2**	**384**	**95.3**	**150**	**500**	**27.75**

N= 292, where N is the total number of samples. Outliers = 2.

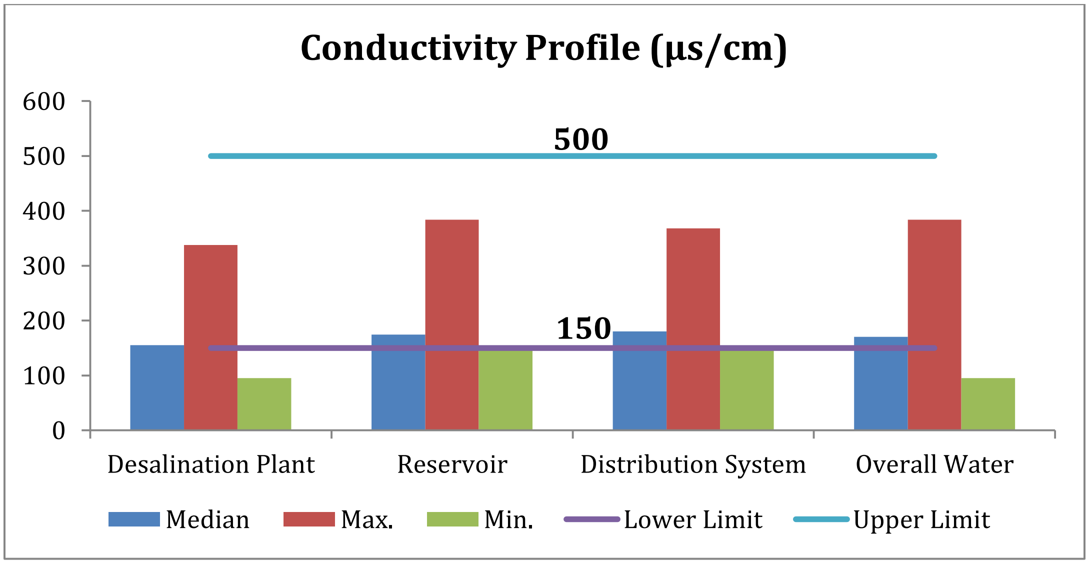


Figure 4-4: Max, Min, Median and Accepted Limit of Conductivity µs/cm at Different Water Sources.

4.1.5 ClO_2 Residual

The median, max, mini and standard deviation of water residual ClO_2 concentrations are presented in Table 4-5 and illustrated in Figure 4-5. It is observed that the concentration of ClO_2 was decayed by one order of magnitude, which was smaller than in the mosques compared to its concentration in the reservoirs and desalinated plants, as shown in Figure 4-6 and Figure 4-7.

The medians of ClO_2 were 0.17, 0.12, and 0.04 mg/L in the desalination plants, the reservoirs and the mosques, respectively. The highest ClO_2 concentration was recorded in Ras-Girtas DP, which was 0.38 mg/L, and the lowest value was recorded in RAF B and B2 that was 0.02 mg/L. While in the reservoirs, the highest value was recorded in West Bay that reached 0.24 mg/L and the lowest value was recorded in New Salwa that was 0.02 mg/L. While in the mosques the highest value was recorded in the mosques number 1066 WB that was 0.13 mg/L.

Table 4-5: ClO_2 Concentration (mg/L) Range and Average in The Collected Drinking Water Samples.

Collection Source	**Collection points**	**Chlorine dioxide concentration (mg/L)**			**STDV**
		MIN	**MAX**	**Median**	**0.06**
Desalination Plants	**Q-power**	0.060	0.240	0.15	0.04
	RLA	0.130	0.270	0.20	0.11
	Ras-Girtas	0.070	0.380	0.20	0.07
	RAF A1	0.020	0.230	0.19	0.07
	RAF A	0.060	0.350	0.19	0.05
	RAF B2	0.020	0.170	0.11	0.09
	RAF B	0.020	0.240	0.16	0.04
Reservoirs	**AP**	0.030	0.180	0.10	0.04
	NS	0.020	0.150	0.08	0.04

	D	0.060	0.190	0.13	0.04
	WB	0.100	0.240	0.17	0.04
Mosques	**141 AP**	0.020	0.090	0.02	0.02
	600 AP	0.020	0.120	0.03	0.03
	82 NS	0.020	0.020	0.02	00
	266 NS	0.020	0.020	0.02	00
	1077 D	0.020	0.090	0.02	0.02
	1146 D	0.020	0.080	0.03	0.02
	1164 WB	0.020	0.060	0.05	0.02
	1066 WB	0.020	0.130	0.10	0.04

Table 4-6: Max, Min, Median, STDV and Accepted Limit of ClO_2 (mg/L) at Different Water Sources.

Water Source	Median	Max	Min	Lower Limit	Upper Limit	STDV
Desalination Plant	0.17	0.38	0.02	0.05	0.7	0.07
Reservoir	0.12	0.24	0.02	0.05	0.7	0.04
Distribution System (Mosques)	0.04	0.13	0.02	0.05	0.7	0.02
Overall Water	**0.11**	**0.38**	**0.02**	**0.05**	**0.7**	**0.04**

N= 294, where N is the total number of samples

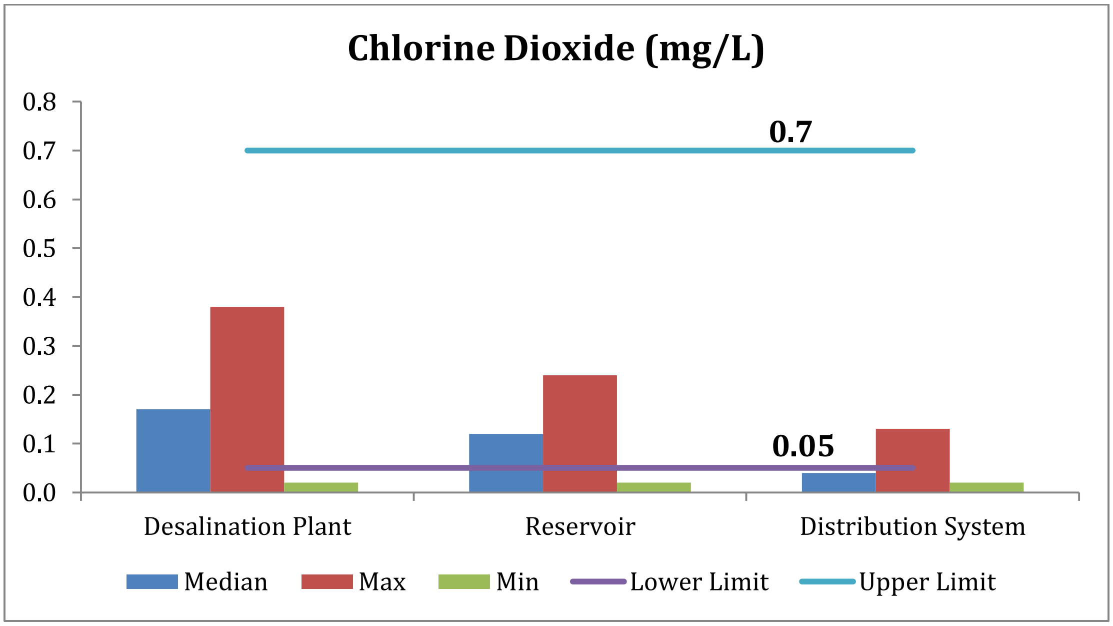


Figure 4-5: Max, Min, Median and Accepted Limit of Chlorine Dioxide (mg/L) at Different Water Sources.

It is noticed that few samples have less residual ClO_2 concentration than the recommended value that is set by the KM that is 0.05-0.7 mg/L. However, the lower ClO_2 level was measured at the entry of two different distribution systems that would be completely dissipated at the end of these systems (Gatel et al. 1995). ClO_2 disappearance was also reported at high temperatures and organic matter concentrations. In another distribution network (Laval, Qué.), plant effluent residuals of ClO_2 was varied with temperature and TOC levels and ranged between 0.02 and 0.41 mg/L (Lafrance et al. 1992).

This also could be attributed to normal decay process as a result of auto-decomposition reactions and reactions with organic and inorganic compounds, including biofilms, pipe materials, corrosion products, formation of slime, which gives a bio-film, produced by the living cells and their metabolic by-products and scales. ClO_2 is also subjected to photolytic decomposition (USEPA, 1999).

In addition, the decrease in ClO_2 level in the distribution system (mosques) may be due to that the water in distribution system experience both water aging and mixing problems. The latter can lead to stratification or large stagnant zones within the water volume and can lead to a deterioration of water quality. The system of pipes that carry water from the source for long period of time and the biofilms that are attached to pipe walls can result in significant loss of disinfectant residual, thereby adversely affecting water quality (Geter, 2004). These unwanted changes may occur due to various reasons including failures at the treatment barrier, transformations in the bulk phase, corrosion and leaching of pipe material, biofilm formation, and mixing between different sources of water. Few researchers have investigated the factors that influence water quality deterioration once it enters the distribution system (Geter, 2004). In pipes, it has been found that ClO_2 can be lost through both the interaction with NOM in the bulk phase and with pipe walls themselves in transporting finished water .The pipe wall demand, possibly due to biofilm. Maintaining adequate levels of disinfectant residual may require routine cleaning/ replacement of pipes and intensive treatment. Volk et al (2002) showed that the ClO_2 residuals could be maintained throughout specific distribution systems, without booster stations. Other study has demonstrated the opposite, being that residuals disappear at the ends of the system without booster addition; this is considered to be in good agreement with the current study finding, where the ClO_2 level was less than 0.02 mg/L at the end points of the distribution.

4.1.5.1 **ClO_2 Decay**

Figure 4-6 displays the overall decay of ClO_2. The ClO_2 decay within the distribution system was quite reasonable (Ammar, 2014). The average dosage at desalination plant was 0.17 mg/L and it decreased with 30 % to touch 0.12 mg/L at the outlet of the reservoirs. 36 % decrease was observed from the reservoir outlet to the customer point of use (mosques) to hit 0.04 mg/L. As an overall conclusion, 76% decrease in ClO_2 level was observed within the entire distribution systems, Figure 4-7. Although the ClO_2 levels at few customer points of use are compliant with the KM requirements, it would be an added value to slightly increase the average ClO_2 dosage at the desalination plants. Such slight increase (suggested to be around 0.2 mg/L) would provide safer margin at the customer points of use in case of any microbial activities. However, deep investigation of the factors that led to low disinfectant residual at the end of network should be conduct.

Volk et al., 2002 found that the total disinfectant residual average was 0.27 mg/L in the distribution network (when ClO_2 was used at a disinfectant) and 0.20 mg/l at the end of the system. The ClO_2 average consumption in the same study was 50% (for water temperature of 16.1^{o}C). As a comparison with other studies, lower ClO_2 concentration was measured at the point of entry of two different distribution systems (Gatel et al., 1995). However, ClO_2 was reported to be completely dissipated at the end of the system. ClO_2 disappearance was also reported to be greater at higher temperature and organic matter concentration. In another distribution network (Laval, city in Italy), plant effluent residual of ClO_2 varied with temperature and TOC levels and ranged between 0.02 and 0.41 mg/l (Gallard, 2002). As observed in the study by Gatel et al. (1995), the disinfectant residual disappeared within the network.

In the current study, the consumption of ClO_2 at the distribution system was 76% (Figure 4-7) at the median temperature of 38.5oC (Table- 4-1). The measured disinfectant residual at the end of the distribution system (mosques) was less than 0.02 mg/L, which could be reasonable and acceptable especially if we took the effect of high temperature into consideration. However water aging and retention time in the distribution system shall also be taken into account for our further investigations, so as to collect the water samples at different intervals and to make a proper judgment on the relationship between the water temperature and ClO_2 decay.

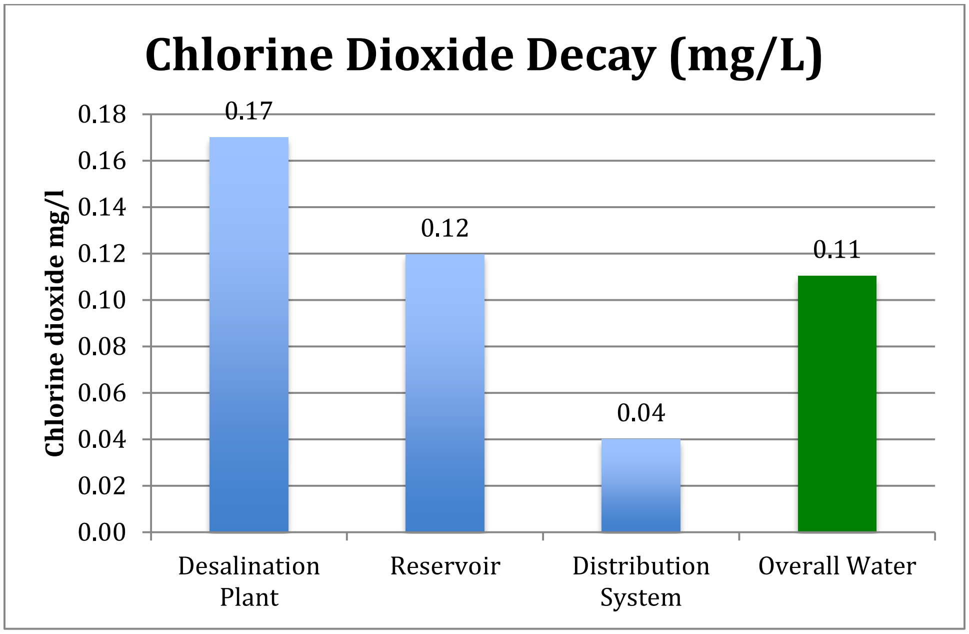


Figure 4-6 : The Overall Decay in ClO_2 (mg/L).

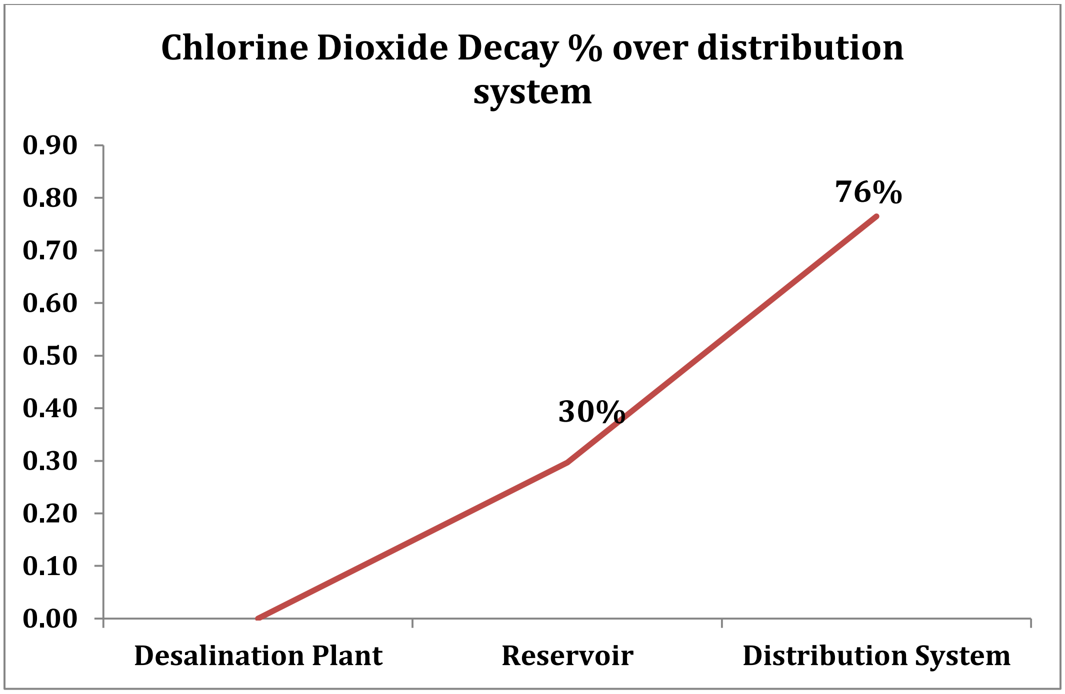


Figure 4-7: The Percentage of Decay of ClO_2 In the Entire System.

4.1.6 Chlorate

The median, max, mini and standard deviation of chlorate in the collected drinking water are illustrated in Figure 4-8 and presented in Table 4-7. The concentrations of chlorate in the collected water samples that varied from 10.66 ppb to 282.72 ppb with mean values varied from 35.58 to 282.72, from 11.02 to 200.69, and from 10.66 to 150.38 ppb in the desalinated plants, the reservoirs, and the mosques, respectively. However, the concentrations of chlorate in the collected water mosques samples were lower than the concentrations of chlorate in the desalinated plants and the reservoirs, as shown in Figure 4-16. This could be attributed to the reaction of chlorate with organic matter that could be carried with the water from DPs until the network, this type of reaction led to the deceasing the concentration of chlorate. The concentrations of chlorate in all water samples were less than 700 ppb which are the maximum values regulated by the US-EPA (USEPA, 1998 and 2006), WHO (WHO, 2003) and KM (KM, 2012).

Table 4-7: The Chlorate Concentration (ppb) Range, Median and STDV in the Collected Drinking Water Samples.

Collection Source	**Collection points**	**MIN**	**MAX**	**Median**	**STDV**
Desalination Plants	**Q-power**	39.22	177.54	118.39	46.23
	RLA	36.69	157.67	57.91	37.04
	RasGirtas	75.63	692.90	147.26	62.17
	RAF A1	44.07	348.73	135.28	52.10
	RAF A	52.36	199.45	119.44	48.86
	RAF B2	59.20	188.16	111.66	38.51
	RAF B	35.58	201.00	90.18	49.93
Reservoirs	**AP**	11.02	120.29	62.87	30.03
	NS	53.88	147.65	112.63	31.11

	D	6.52	200.69	98.79	49.64
	WB	37.79	108.90	63.86	21.05
Mosques	**141 AP**	4.05	310.86	57.14	33.85
	600 AP	45.93	327.00	68.66	30.10
	82 NS	2.33	110.24	50.60	25.23
	266 NS	25.10	141.21	53.33	31.33
	1077 D	1.71	364.59	29.77	14.52
	1146 D	1.03	208.17	47.77	14.44
	1164 WB	1.86	83.69	46.49	20.68
	1066 WB	12.86	107.98	42.28	28.09

N= 250, where N is the total number of samples. Outliers = 44.

Table 4-8: Max, Min, Median, STDV and Accepted Limit of Chlorate (ppb) at Different Water Sources.

Water Source	**Median**	**Max.**	**Min.**	**Limit**	**STDV**
Desalination Plant	118.39	282.72	35.58	700.0	47.69
Reservoir	84.31	200.69	11.02	700.0	32.95
Distribution System (Mosques)	49.47	150.38	10.66	700.0	24.78
Overall Water	**83.94**	**282.72**	**10.66**	**700.0**	**35.14**

N= 250, where N is the total number of samples. Outliers = 44.

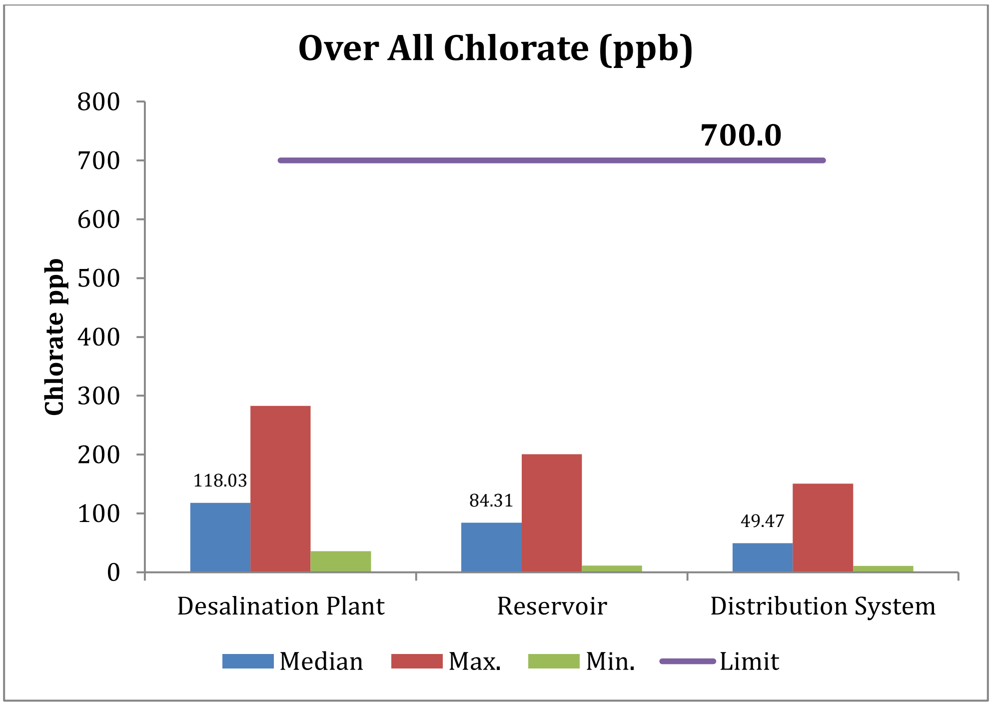


Figure 4-8: Max, Min, Median and Accepted Limit of Chlorate (ppb) at Different Water Sources.

4.1.7 Chlorite

The median, max, mini and standard deviation of chlorite in the collected drinking water are given in Table 4-9. The concentrations of chlorite in the samples varying from 12.78 – 436.36 ppb with mean values vary from 12.78 to 230.76, from 77.43 to 325.25, and from 84.73 to 436.36 ppb in the desalination plants, the reservoirs, and the mosques, respectively. However, the concentrations of chlorite in the collected water samples from the mosques were higher than the concentrations of chlorite in the desalination plants and the reservoirs, as shown in Figure 4-15. The concentrations of chlorite in all samples were less than 1000 and 700 which are the maximum values regulated by the USEPA (1998 and updated in

2006), WHO (WHO, 2003, GSO 149/2009 and KM (KM, 2012), respectively.

Table 4-9: The Chlorite Concentration (ppb) Range, STDV and Median in The Collected Drinking Water Samples.

Water Source	Collection points	MIN	MAX	Median	STDV
Desalination Plants	**Q-power**	31.66	205.47	87.86	47.66
	RLA	29.28	170.76	97.68	39.71
	RasGirtas	6.03	230.76	80.44	59.53
	RAF A1	36.89	211.99	62.85	42.09
	RAF A	27.01	143.87	78.67	31.27
	RAF B2	35.29	429.92	53.67	25.09
	RAF B	37.34	634.08	94.47	43.49
Reservoirs	**AP**	134.60	227.13	172.02	28.61
	NS	77.43	238.90	122.16	42.54
	D	149.76	256.34	178.22	33.27
	WB	125.69	325.25	183.08	66.64
Mosques	**141 AP**	100.27	264.98	234.91	39.35
	600 AP	84.73	250.00	194.71	41.18
	82 NS	119.82	302.18	233.46	45.10
	266 NS	118.49	252.40	218.55	36.23
	1077 D	169.63	436.36	295.26	74.38
	1146 D	176.95	361.92	285.89	62.23
	1164 WB	192.35	368.08	294.26	53.53
	1066 WB	162.74	390.13	259.10	71.72

N= 286, where N is the total number of samples. Outliers = 8.

If we compare the guidelines of the KM and WHO with the EU guidelines, we notice that latter is more stringent since the maximum allowable concentration of chlorite ion in drinking water in Italy was 200 μg/L (Linder el at., 2006).

Table 4-10: Max, Min, Median, STDV and Accepted Limit of Chlorite (ppb) at Different Water Sources.

Water Source	Median	Max.	Min.	Limit	STDV
Desalination Plant	79.31	230.76	12.78	700	41.12
Reservoir	163.86	325.25	77.43	700	42.76
Distribution System (Mosques)	252.02	436.36	84.73	700	52.96
Overall Water	**165.06**	**436.36**	**12.78**	**700**	**45.61**

N= 286, where N is the total number of samples. Outliers = 8.

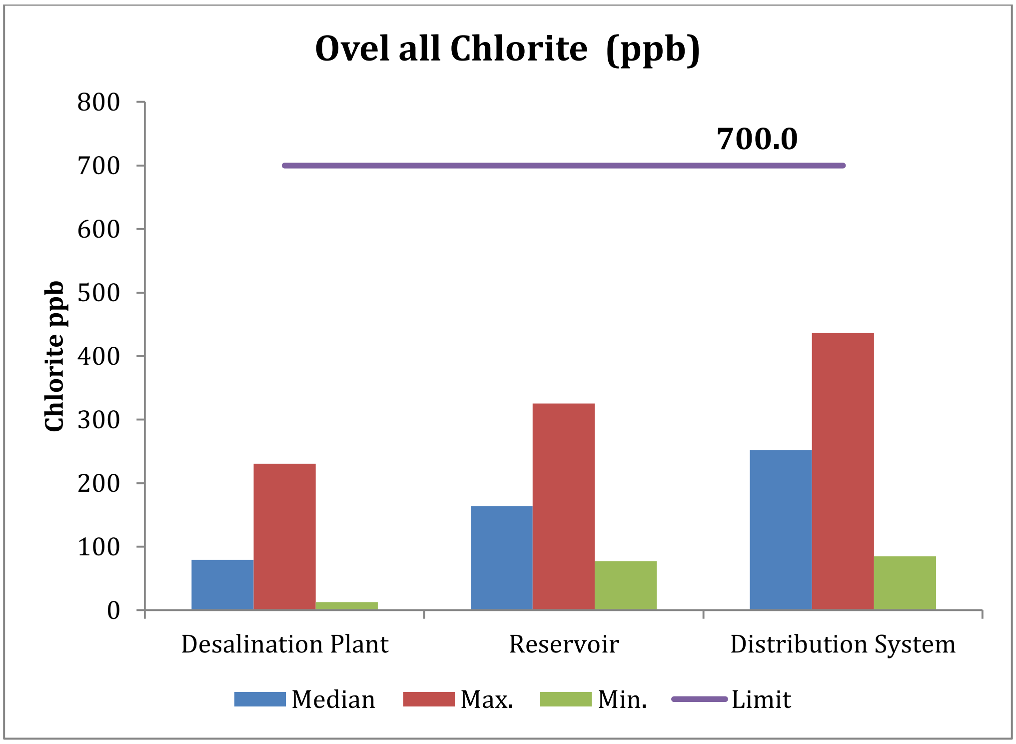


Figure 4-9: Max, Min, Median and Accepted Limit of Chlorite (ppb) at Different Water Sources.

When ClO_2 reacts and decays, chlorite and chlorate are formed (Yang, 2013). Previous studies have shown that approximately 60% of the applied ClO_2 will eventually form chlorite, while about 8 % will form chlorate (Yang, 2013). Volk et al., (2002) showed that the median chlorite levels were 0.68 and 0.69 mg/L in the plant effluent and the distribution system, respectively. The chlorite levels were below the recommended levels, which is of 1.0 mg/L in the United States (USEPA 1998). The Volk's study showed that the maximum daily average of chlorite concentration measured in the distribution system was approximately 0.9 mg/L, with a highest overall measurement of 1.0 mg/L at the water treatment plant, this level is consider noncompliant with the regulation set by WHO and KM.

It should be noted that, during the study period, the highest ClO_2 residual concentration was 0.38 mg/L in Ras Girtas DPs. It is anticipated that this value could be trimmed over time, and the associated chlorite concentration also lowered. This observation could be related to the fact that the distribution system was too large which could lead to drastic changes in the disinfectant residual. The same trend was observed for a larger system, in Laval (city in North Italy), where ClO_2 disappeared rapidly in the distribution network. This is in good agreement with the findings of the current study; and only residual chlorite was found at the extremities of the system. In that study, the chlorite disappeared entirely in the dead end points (small pipes with low flows) (Lafrance et al., 1992), but in our study, the average of chlorite level in the end points was 250.31 ppb.

Past surveys of water treated with ClO_2 often showed high chlorate concentrations (Gordon and Bubnis, 1995). High chlorate concentrations were not related to ClO_2 reaction and decay but to inefficient ClO_2 production.

Figure 4-10 illustrates the increase in chlorite levels within the distribution system as a result of ClO_2 decay. The median level detected at the desalination plant was almost 79 ppb and it was increased to hit (163.86 ppb) at the outlet of the reservoirs. Another increase in the chlorite level was observed at the customer points of use (mosques) to hit levels closer to 252 ppb. As an overall conclusion, 218 % increase in chlorite level was observed within the entire distribution system., Figure 4-11. The levels detected at the customer points of use were varied far from the maximum value required by both WHO and the KM (700 ppb). It should also be noted that, if the ClO_2 dosage was increased at the desalination plants to levels closer to 0.2 mg/L (as recommended in ClO_2 charts), the chlorite levels will still be compliant.

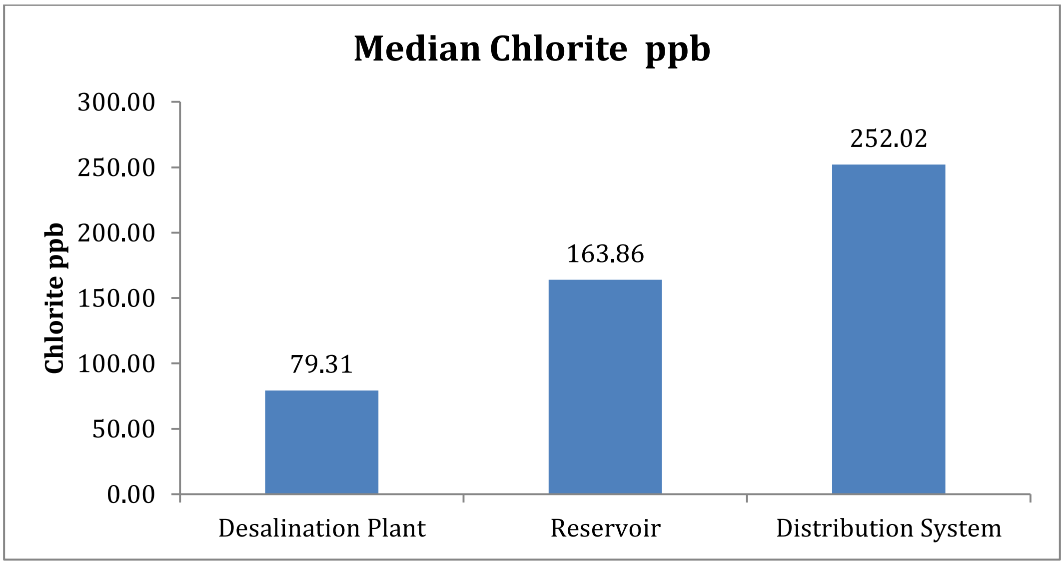


Figure 4-10: Median Chlorite Increasing (ppb) at Different Water Sources.

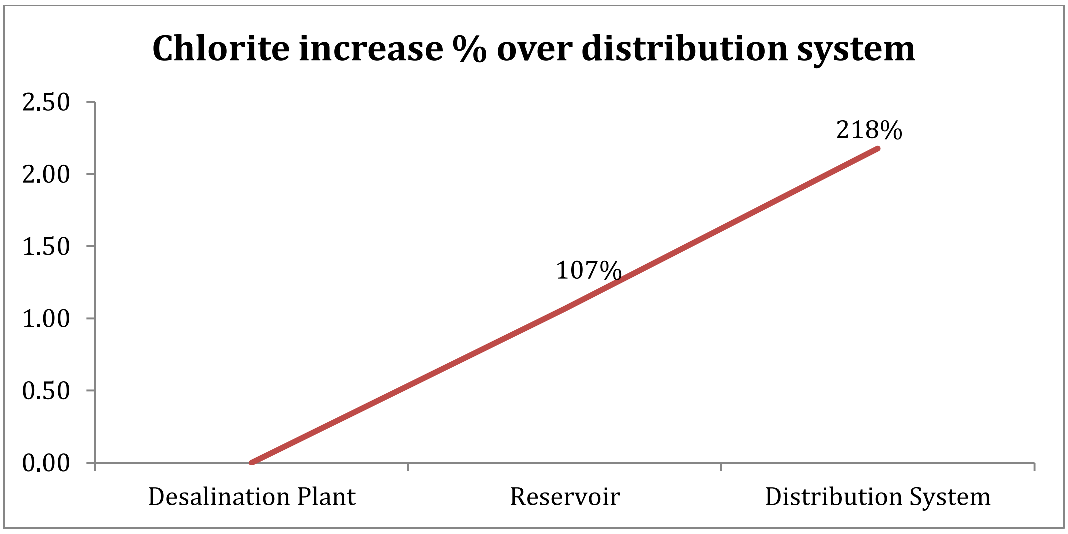


Figure 4-11: Chlorite Increasing % at Different Water Sources.

4.1.8 THMs

The concentrations of THMs are summarized in Table 4-11 and illustrated in Figure 4-12. Table 4-11 shows that the formation potentials of 294 water samples for all sampling points showed an average value of 4.90 ppb, while the maximum and minimum measured values reached 76.97 and 0.00 ppb, respectively. All species of THMs ($CHBr_3$, $CHCl_3$, $CHCl_2Br$, and $CHClBr_2$) were detected in the current study, however the bromoform was the most abundant compound. This result could be explained using the same findings of Wen et al., in (1996). They revealed that the $CHBr_3$ was formed in water containing bromide ion because ClO_2 could oxidize bromide ions to hypobromous acid, which subsequently reacted with humic acid. This study also detected all four species of THMs when ClO_2 was employed in the presence of bromide; ClO_2 reacted with humic acid to render them unreactive or unavailable for THMs production. In the current study, all water samples showed values within the acceptable range and the THMs. The replacement of chlorine by ClO_2 in the distribution system could be corresponding to 81% reduction in THMs concentrations (Volk et al., 2002).

Table 4-11: Max, Min, and Average of THMs (ppb) at Different Water Sources.

THMs	Source	Average	Max.	Min.
Bromoform	DPs	20.89	72.95	3.99
	R	15.11	72.97	1.65
	M	14.60	55.97	1.44
Chloroform	DPs	0.06	4.96	0.01
	R	0.80	4.55	0.01
	M	0.82	4.58	0.00
Bromodichloromethane	DPs	0.21	2.66	0.01
	R	1.27	5.30	0.01
	M	2.59	26.24	0.01
Dichlorobromomethane	DPs	0.52	2.74	0.01
	R	0.89	2.21	0.01
	M	1.04	2.43	0.01
Overall (ppb)		4.90	72.97	0.00

N= 294, where N is the total number of samples.

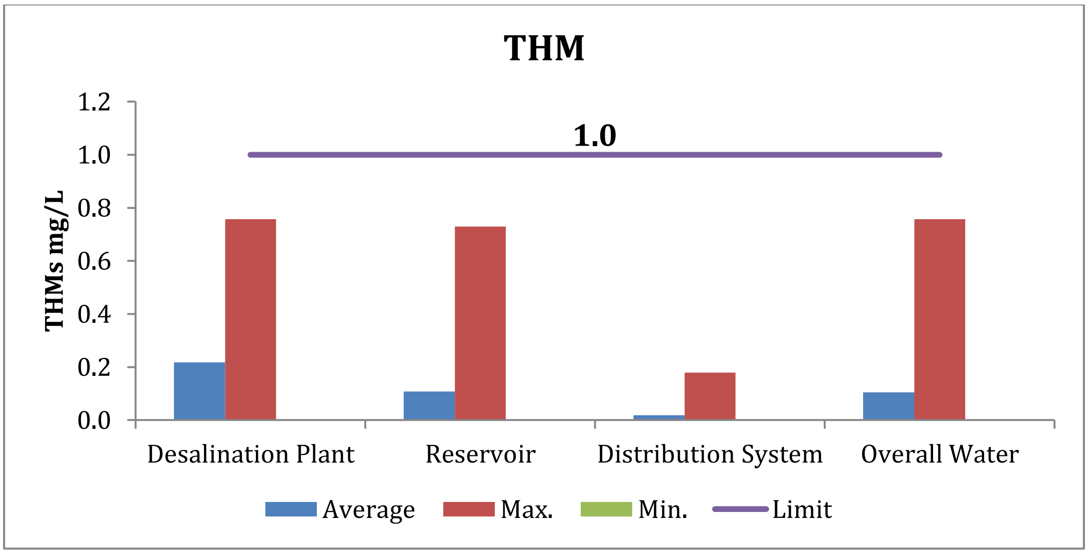


Figure 4-12: Max, Min, Average and Accepted Limit of THMs at Different Water Sources.

4.1.9 Bromoform

The median distribution for bromoform in the collected water samples are illustrated in Figure 4-13 and presented in Table 4-12. The concentrations of bromoform in the collected water samples varied from 1.44 to 72.97 ppb with range varying from 3.44 to 72.95, from 1.65 to 72.97, and from 1.44 to 55.97 ppb in the desalination plants, the reservoirs, and the mosques, respectively. From Table 4-12 and Figure 4-17, we clearly notice that the concentration of bromoform were low in both Duhail and West Bay reservoirs, this low concentration was clearly reflect on the concentration of $CHBr_3$ that measured in both mosques 1077 D and 1146D.This variation in mentioned mosques could be explained by that the feeding water for both mosques was from Duhail Reservoir, this reservoir is feed from Ras-Girtas DPs, this plant consider the only desalination plant that use different technology to distal the drinking water. This plant use MSFD to produce the drinking water, while the other plants use MED technology. All the concentrations of bromoform in all samples are less than 100 ppb, which is the maximum value regulated by the US-EPA (USEPA, 1998 and 2006), WHO (WHO, 2003), GSO 149/2009 and KM (KM, 2012).

Table 4-12: The Bromoform Concentration Range and median in the Collected Drinking Water Samples.

Water Source	Collection points	MIN	MAX	Median	SD
Desalination Plants	**Q-power**	12.16	49.62	17.58	13.68
	RLA	19.49	48.54	24.10	10.20
	RasGirtas	3.99	4.79	4.22	0.26
	RAF A1	23.93	72.95	40.55	15.67
	RAF A	7.93	16.01	9.94	2.23
	RAF B2	6.72	32.02	19.51	9.17
	RAF B	8.39	38.67	19.90	9.31
Reservoirs	**AP**	11.95	72.97	21.52	15.20
	NS	9.94	37.61	18.62	8.14
	D	1.65	5.94	4.21	1.79
	WB	6.1	20.35	4.91	4.10
Mosques	**141 AP**	18.22	55.26	27.20	10.38
	600 AP	19.06	55.97	26.95	10.86
	82 NS	9.72	37.17	15.67	8.14
	266 NS	3.25	19.75	9.41	4.91
	1077 D	3.96	8.07	4.24	1.11
	1146 D	1.44	5.52	4.16	1.17
	1164 WB	2.83	35.67	6.73	7.94
	1066 WB	5.43	17.93	7.06	4.41

N= 276 , where N is the total number of samples. Outliers = 18.

The median, max, mini and standard deviation of bromoform are summarized in Table 4-13 and illustrated in Figure 4-17. It showed that the overall median value of bromoform was 15.22 ppb, while the maximum and minimum measured values reached 72.97 and 1.44 ppb, respectively. Given that KM (KM, Water Quality Requirements, 2012) as well as WHO requirements have declared that 100 ppb as bromoform’s acceptable level for drinking water, all the collected samples were found within the acceptable range.

Table 4-13: Max, Min, Median, STDV and Accepted Limit of Bromoform (ppb) at Different Water Sources.

Water Source	Median	Max.	Min.	Limit	STDV
Desalination Plant	19.40	72.95	3.99	100.0	8.64
Reservoir	13.57	72.97	1.65	100.0	7.31
DistributionSystem (Mosques)	12.68	55.97	1.44	100.0	6.11
Overall Water	**15.22**	**72.97**	**1.44**	**100.0**	**7.35**

N= 276, where N is the total number of samples. Outliers = 18.

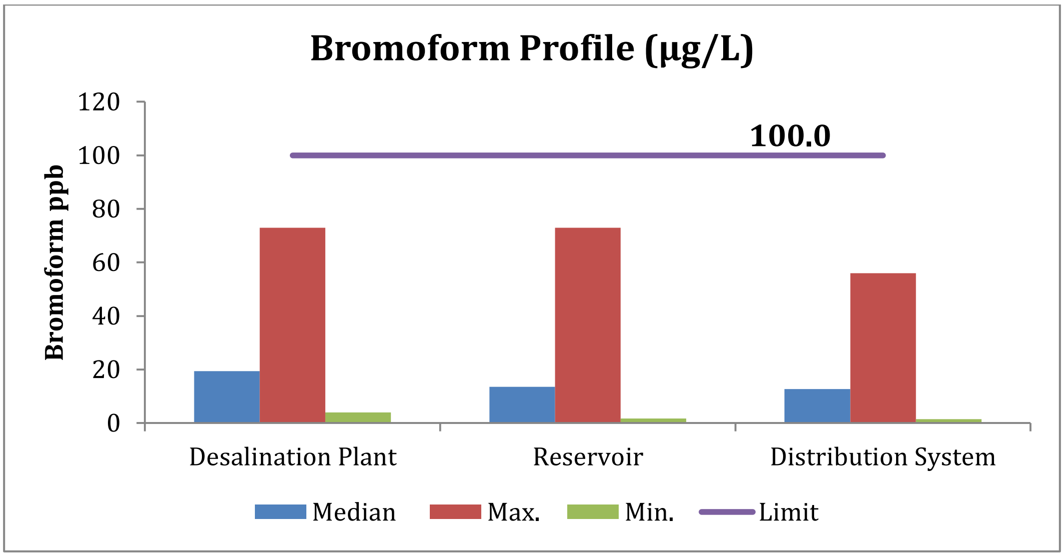


Figure 4-13: Max, Min, Median and Accepted Limit of Bromoform (ppb) at Different Water Sources.

4.1.10 **Effect of ClO_2 on by-Product Formation**

4.1.10.1 **THMs**

The formation of THMs is affected by the ClO_2 concentration in the water; the low concentration of ClO_2 led to decrease in the THMs concentration as shown in Table 4-11 and Figure 4-14. The average concentration of ClO_2 decreased from 0.17 in the DPs to 0.04 mg/L in the mosques; this decrease was accompanied by a decrease in the THMs level from 0.22 in the DPs to 0.02 mg/L in the mosques. This is due to the fact that an elevated ClO_2 level might increase the chance of interaction with active radicals ($^{\cdot}$OH and OCH3) on humic acid and it habited the halo-organic DBPs formation. This observation has good agreement with the finding by Lykins and Griese (1986). The other possibility that the oxidation reaction favored to proceed directly under the higher ClO_2 dosage condition rather than substitution reaction. A recent study has reported that ClO_2 pre-oxidation reduced THM and other by-products (Yang et al., 2013). Lafrance et al. (1992) found that THMs and other chlorinated products were below the detection level (<2 μg/L) with ClO_2, while the THM formation potential was 100–200 μg/L with chlorine. These repeated findings are in agreement with results of the current study.

Figure 4-17 shows the median concentration of bromoform as dominant species of THMs at the desalination plants, the reservoirs, and the mosques. It was shown that bromoform is the most abundant THMs species that be detected in this study; other species were detected in very low concentration and this is in agreement with the finding of Wen et al., 1996 where the bromoform was the most dominant species of THMs when ClO_2 was employed as a disinfectant.

4.1.10.2 **Chlorite and Chlorate formation**

The formation of chlorite and chlorate ions can be explained by the numerous inorganic and biological materials found in raw water that may react with ClO_2 (Noack and Doerr, 1977). Chlorite (ClO_2^-) ions are the dominant degradation species arising from ClO_2 reactions, although chlorate (ClO_3-) can appear for a variety of reasons when ClO_2 is used (Gordon et al., 1990; Werdehoff and Singer, 1987). The immediate redox reactions with natural organic matter play the dominant role in the decay of ClO_2 into chlorite in drinking water (Werdehoff and Singer, 1987). Chlorite ion is generally the primary product of ClO_2 reduction. Chlorite is relatively stable in the presence of organic material but can be oxidized to chlorate by free chlorine if added as a secondary disinfectant (Singer and O'Neil, 1987). Chlorate is therefore produced through the reaction of residual chlorite and free chlorine during secondary disinfection. The occurrence of photochemical decomposition of ClO_2 can affect the ultimate concentrations of ClO_2, chlorite, and chlorate in water treated with ClO_2.

The primary factors affecting the concentrations of ClO_2, chlorite, and chlorate in finished drinking water involve: dosage applied/oxidant demand ratio, blending ratios of sodium chlorite and chlorine during generation process, exposure to sunlight, incomplete reaction of the sodium chlorite and chlorine reactants can result in unreacted chlorite. The quantity of chlorate produced during the ClO_2 generation process is greater with excess chlorine addition. Likewise, a low or high pH can increase the quantity of chlorate during the ClO_2 generation process. The distribution of chlorite and chlorate is influenced by pH and sunlight. Approximately 50 to 70 % of the ClO_2 consumed by oxidation reactions is converted to chlorite under conditions typical in water treatment (Werdehoff and Singer, 1987).

Figures 4-14, 4-15 and 4-16 summaries the over all median of ClO_2, chlorite and chlorate, respectively, the error bar is shown in the figures to represent the variability of data and to indicate to uncertainty in the data. From the figures, we can notice that the chlorite increasing from the DPs to the mosques as a result of decaying process of ClO_2. However the chlorate decreasing from the DPs to the network, this is could be explained by reacting of chlorate with organic material that could be found in water.

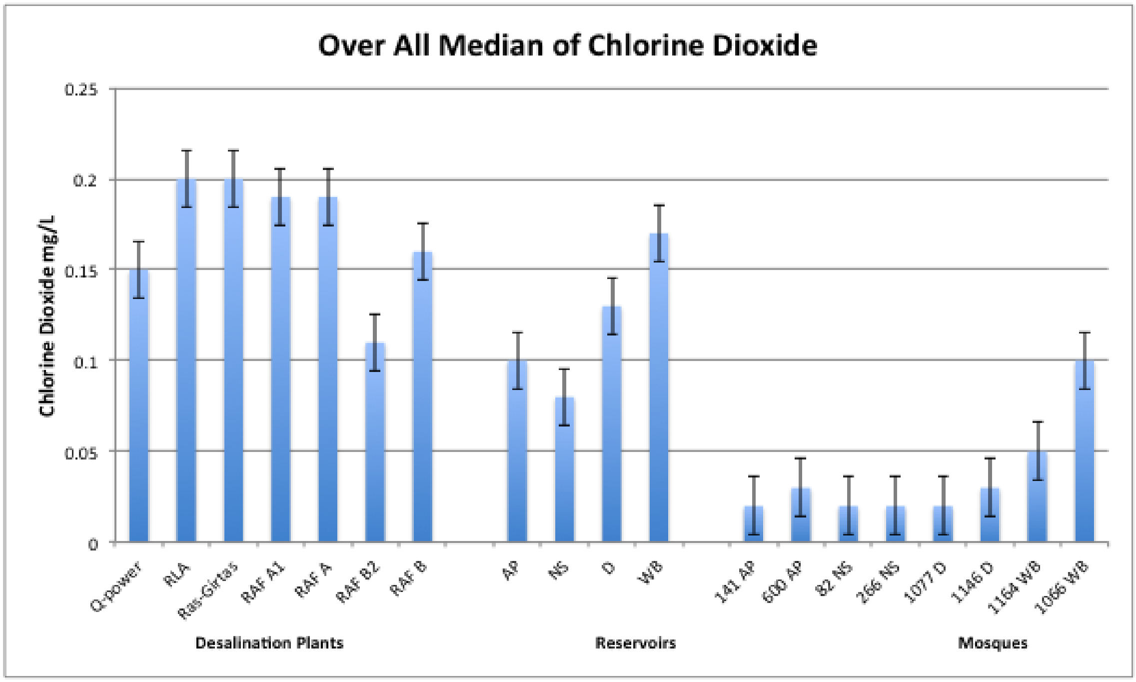


Figure 4-14: The Over All Median of ClO_2 at The Desalination Plants, Reservoirs, and Mosques. N= 294, where N is the total number of sample.

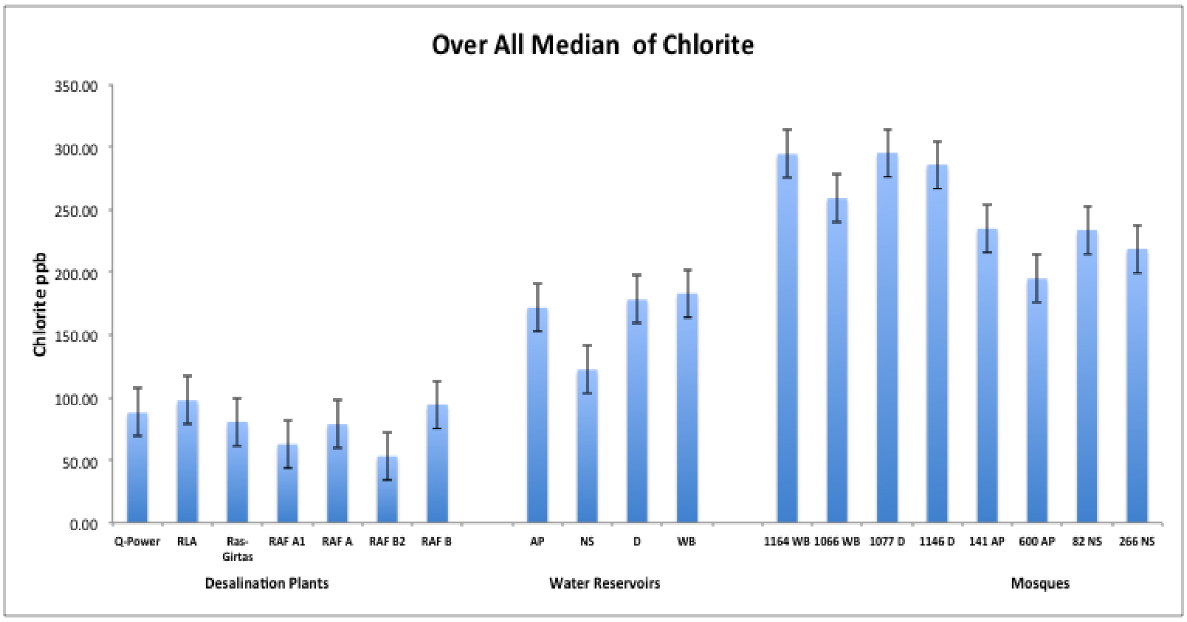


Figure 4-15: The Over All Median of Chlorite at Desalination Plants, Reservoirs, and Mosques. N= 284, where N is the total number of samples.

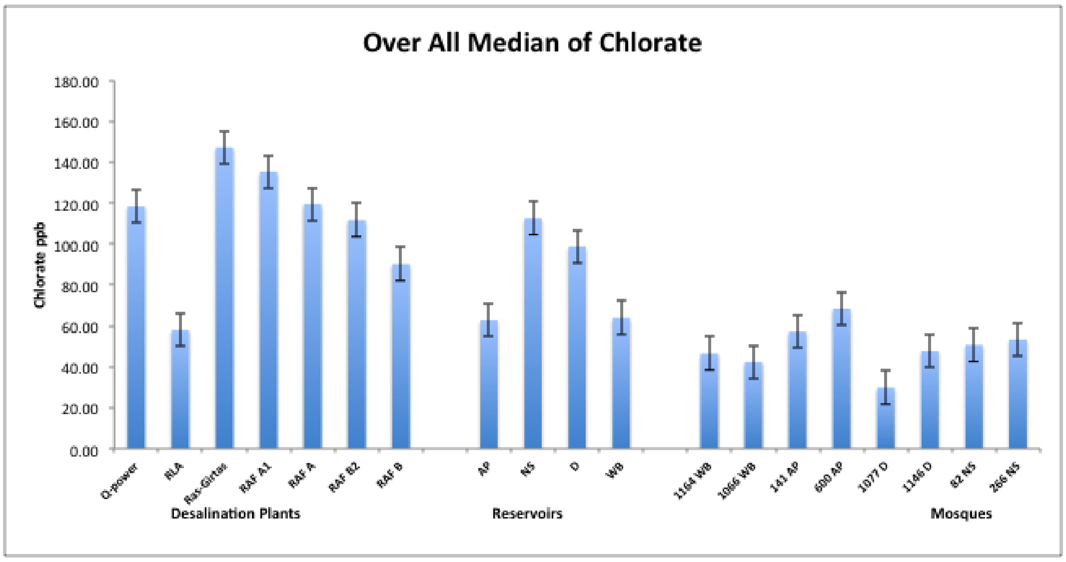


Figure 4-16: The Overall Median of Chlorate at Desalination Plants, Reservoirs, and Mosques.

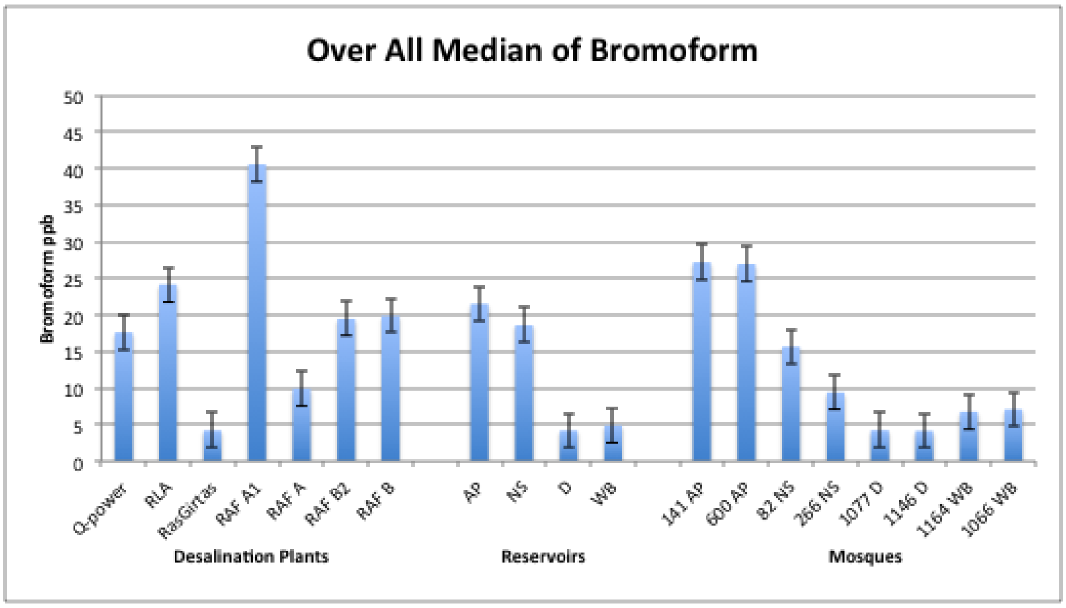


Figure 4-17: The Over All Median of Bromoform as The Dominate Species of THMs at Desalination Plants, Reservoirs, and Mosques.

4.1.11 **Comparison to WHO, KM and Other International Guidelines and Studies**

Various international and local regulation and guidelines were used to identify the potential of existing DBPs in the collected samples. The comparison with the GCC countries was not performed as the KM guidelines were drawn from GCC guidelines.

The international and local guidelines with its designated contaminant criteria include:

1. Disinfection and disinfection by-products, WHO, Geneva.
2. Guidelines for Drinking-Water Quality. Fourth Edition, 2011.
3. EPA Office of Water, 1999. Alternative Disinfectants and Oxidants Guidance Manual. (EPA 815-R-99-014). Washington, D.C, updated in 2006.
4. GSO 149/2009 Standard For Un-Bottled Water.
5. Kahramaa Drinking Water Quality Requirements, 2012.

Several studies have been published for water chlorination by-products over the world, but very few articles addressed the by-products of ClO_2. Even though, all the studies were carried out in the lab scale and their concern was to find a method to reduce the by-product formation or to predict the module of decaying of ClO_2 and its by-products.

In a survey conducted in the USEPA (1998), the typical dosages of ClO_2 used as a disinfectant in drinking water treatment ranged from 0.07 to

2.0 mg/L, compared to the KM level which ranged from 0.05- 0.7 mg/L. We notice that the level set by EPA is higher than the level set by KM. Again, the limit was measured in our study was lower than the corresponding in the US. However, the level set for chlorite in EU, which is 200 ppb is more stringent than the USEPA and the KM. Other studies reported that the chlorite level in water ranged from 3.2 to 7.0 mg/L (Michael et al., 1981) and this occurs in drinking water when ClO_2 is used for purification purposes. Comparing the current study finding for the rest of other by-products such as THMs was difficult as there are no available studies in the literature where THMs were investigated in drinking water.

According to my knowledge, this is the first study that investigates the DBPs formation in the entire drinking water system in Qatar as well as the ClO_2 disinfection residual. The current study has tried to filling the gap due to missing part of information that quantifies the real amount of residual disinfectant of ClO_2 and associated DBPs in entire drinking water system, from the production till to the end consumers. Accordingly, this study is a novel approach to quantify the real amount of DBPs in drinking water.

4.2 Statistical Analysis and Correlation

In the present study the Statistical Package for the Social Sciences (SPSS) version 22 (IBM, Armonk, NY) was used in the data analysis and Excel used in data illustration. The level of statistical significance for all statistical tests was set at p =0.01. Basic descriptive statistics were calculated for each variable. Bivariate regression was run between the various variables that can influence ClO2 and by-products formation as well as the relationships between different variables.

One way Analysis of Variance (ANOVA) test presented in Table 4-14 showed that water temperature, pH, conductivity, chlorine dioxide, chlorate, chlorite and bromoform, have significant differences with p-values < 0.01, 0.01, 0.01, 0.01, 0.01 and 0.01 respectively. However, the conductivity and turbidity did not show significant differences where p- values were 0.049 and 0.315 respectively.

The different types of applicable correlation were investigated using Pearson’s correlation coefficients and summarized in Table 4-15. Based on the obtained results, the following relationship under the investigation can be elaborated as the following:

- Negative relationship was observed between ClO_2 and chlorite, this relation is statistically significant where the correlation coefficient was -0.360 with p- value of <0.01. This could be attributed to auto-decomposition of chlorine dioxide to form chlorite. The deceasing of chlorine dioxide means the formation of chlorite, because 76% of chlorine dioxide will form chlorite according to the reviewer articles. This relation is illustrated in Figures 4-18 and 4-19 and to some extent illustrate a good agreement with the finding by other study where they stated that the ClO_2 consumed by oxidation reaction to be converted to chlorite by 50% where our study showed that the percentage of chlorite formed is almost 40%.

- Positive relationship was found between $CHBr_3$ and Bromide ion, where the correlation coefficient was 0.253. This relation is statistically significant where p- value <0.01. This could be explained by the water source is seawater that normally contain high concentration of bromide ions. The relation is illustrated in Figures 4-20 and 4-21.
- Positive weak correlation was observed between pH and chlorite ion, where the correlation coefficient was 0.273, but again it is statistically significant where p- value <0.01.
- One more significant positive relationship was found between ClO_2 and chlorate ion, where the correlation coefficient was 0.165 with p- value was 0.005. The relation is illustrated in Figures 4-22 and 4-23. This could be attributed to normal decay process of chlorine dioxide, according to the articles 10-20% of chlorine dioxide will reduced to chlorate.
- The correlation between $CHBr_3$ and THMs was positive and highly significant where the correlation coefficient was 0.988 where p- value < 0.01. This result is highly supporting our finding, where the $CHBr_3$ was the most prominent species of THMs that was detected in the current study. Figures 4-24 and 4-25 show the relationship between the two variables.

- The correlation between ClO_2 and water temperature was positively significant, where the correlation coefficient was 0.252 with p- value was <0.01, this could be explained by that the decaying of chlorine dioxide is affected positively with increasing of water temperature.
- The only negative relationship was obtained between ClO_2 and pH, where the correlation coefficient was -0.342 and is statistically significant where p- value < 0.01.

Table 4-14: Analysis of Variance for The Measured Variables.

S.O.V.	D.F.	Means of squares							
		Water Temp	**pH**	**Turbidity NFU**	**Conductivity. µ s/cm**	**ClO_2 mg/L**	**Chlorate ppb**	**Chlorite ppb**	**Bromoform $CHBr_3$ ppb**
Between Groups	2	873.9**	1.49**	0.137^{ns}	6985.359^{ns}	.416**	140182.145**	658224.310**	1450.939**
Within Groups	291	21.004	.060	0.118	2292.717	.003	4202.225	5297.061	179.965
Total	293								

**; Significant differences at 0.01, ns; not significant.

Table 4-15: Different Types of Correlations Between Different Variables.

Factors		**Water Temp. C**	**pH**	**Br- ppb**	**ClO_2 mg/L**	**Chlorate ppb**	**$CHBr_3$ ppb**	**THMs**	**Chlorite ppb**
Water Temperature C	**Pearson Correlation**	1	.073	.244**	.252**	.226**	.103	.105	-.262**
	Sig. (2-tailed)		.210	.000	.000	.000	.079	.072	.000
	N	294	294	293	294	294	294	294	294
pH	**Pearson Correlation**	.073	1	-.073	-.342**	-.156**	-.079	-.070	.273**
	Sig. (2-tailed)	.210		.213	.000	.007	.177	.233	.000
	N	294	294	293	294	294	294	294	294
bromide mg/l	**Pearson Correlation**	.244**	-.073	1	.372**	.298**	.253**	.238**	-.509**
	Sig. (2-tailed)	.000	.213		.000	.000	.000	.000	.000

	N	293	293	293	293	293	293	293	293
Chlorine dioxide mg/L	**Pearson Correlation**	.252**	-.342**	.372**	1	.221**	-.024	-.049	-.399**
	Sig. (2-tailed)	.000	.000	.000		.005	.678	.399	.000
	N	294	294	293	294	294	294	294	294
Chlorate ppb	**Pearson Correlation**	.226**	-.156**	.298**	.221**	1	.127*	.144*	-.564**
	Sig. (2-tailed)	.000	.007	.000	.005		.030	.014	.000
	N	294	294	293	294	294	294	294	294
Bromoform CHBr3 ppb	**Pearson Correlation**	.103	-.079	.253**	-.024	.127*	1	.988**	-.353**
	Sig. (2-tailed)	.079	.177	.000	.678	.030		.000	.000
	N	294	294	293	294	294	294	294	294
THMs	**Pearson Correlation**	.105	-.070	.238**	-.049	.144*	.988**	1	-.350**
	Sig. (2-tailed)	.072	.233	.000	.399	.014	.000		.000
	N	294	294	293	294	294	294	294	294
Chlorite ppb	**Pearson Correlation**	-.262**	.273**	-.509**	-.399**	-.564**	-.353**	-.350**	1
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	
	N	294	294	293	294	294	294	294	294

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.01.

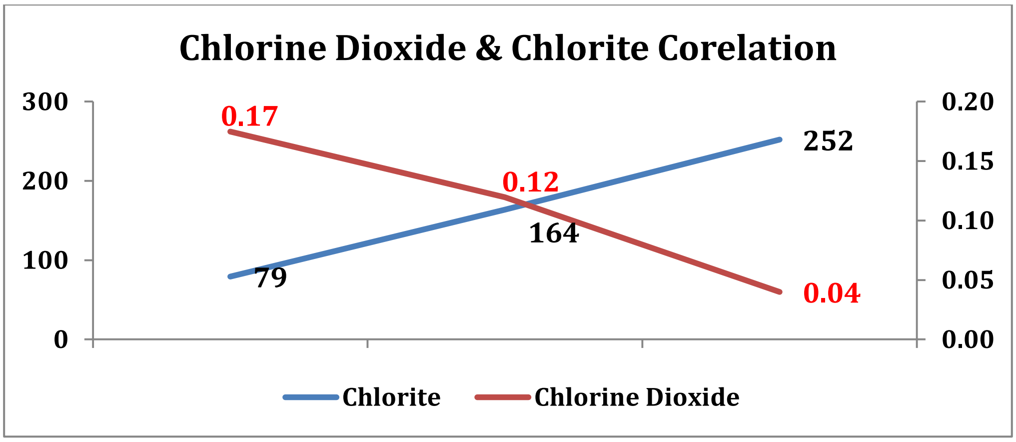


Figure 4-18: Average of Chlorine Dioxide and Average Chlorite Correlation.

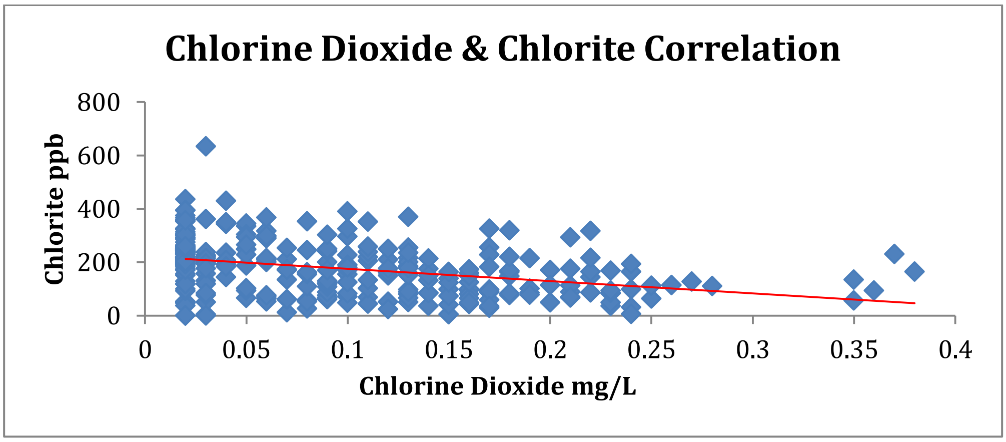


Figure 4-19: Chlorine Dioxide Vs. Chlorite Correlation.

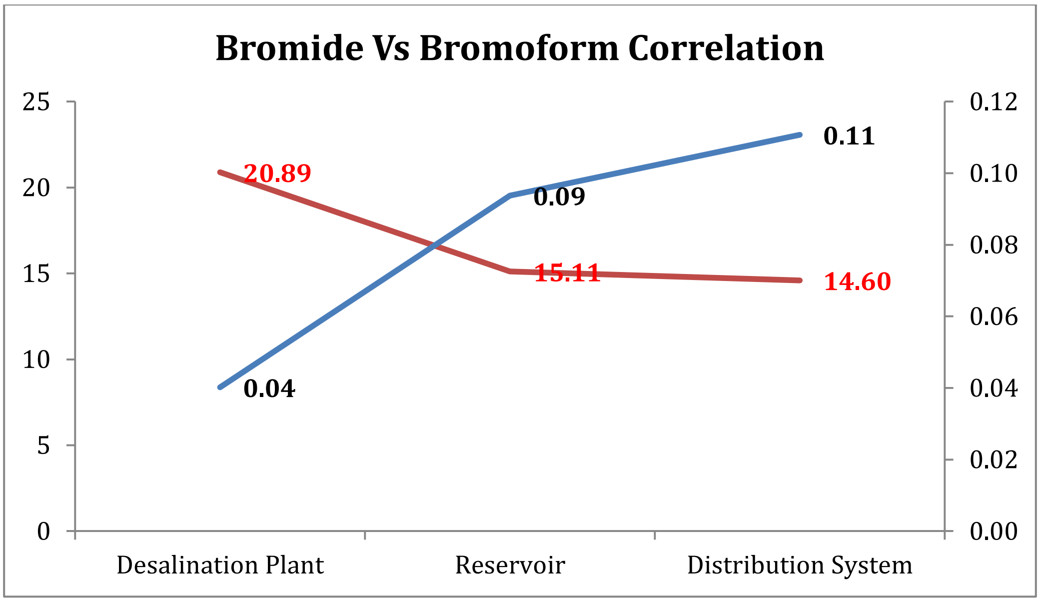


Figure 4-20: Average of Bormoform and Average Bromide Correlation.

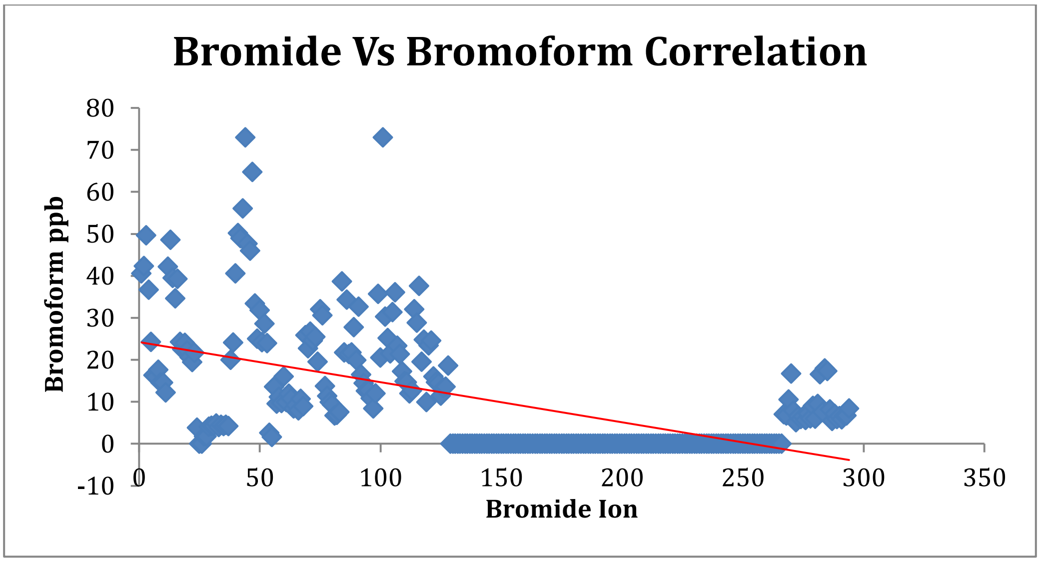


Figure 4-21: Bormoform Vs. Bromide Correlation.

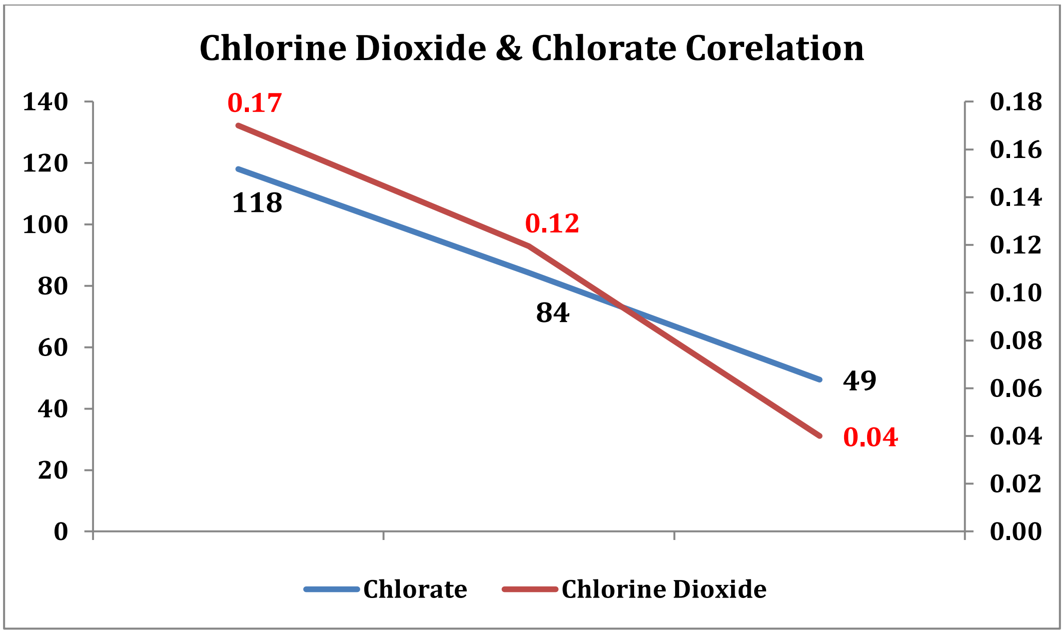


Figure 4-22: Average of Chlorine Dioxide and Average Chlorate Correlation.

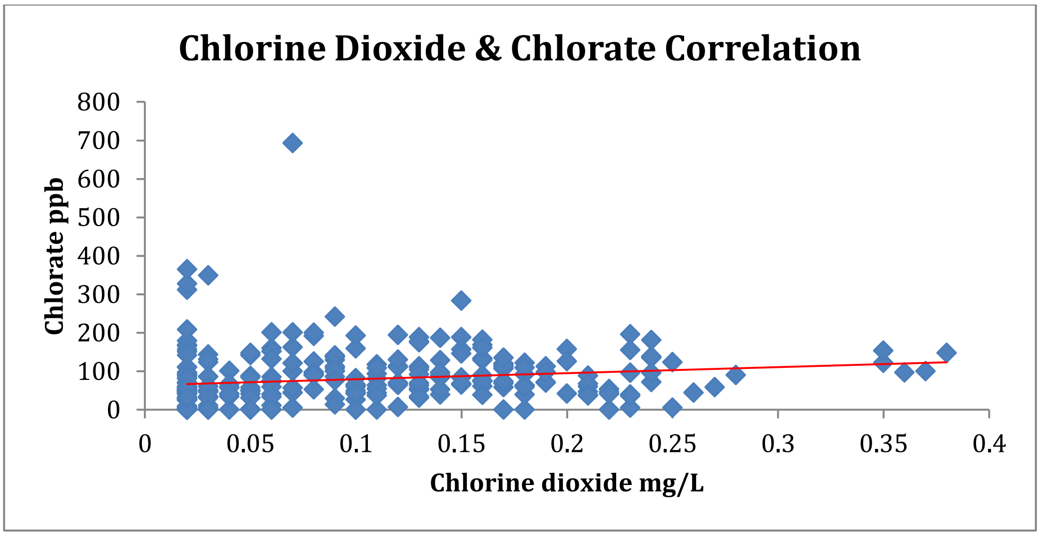


Figure 4-23: Chlorine Dioxide Vs. Chlorate Correlation.

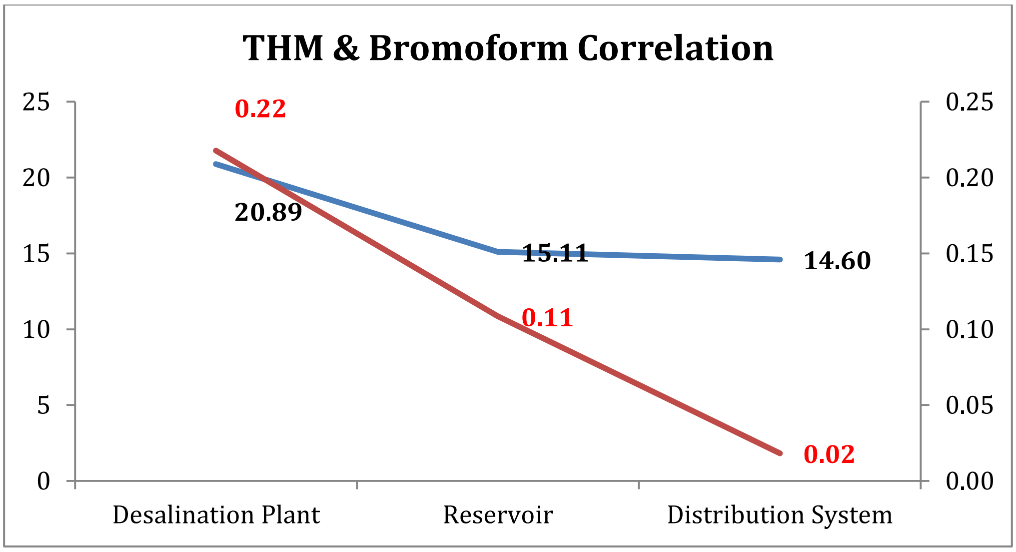


Figure 4-24: Average of Bromoform and Average THMs Correlation.

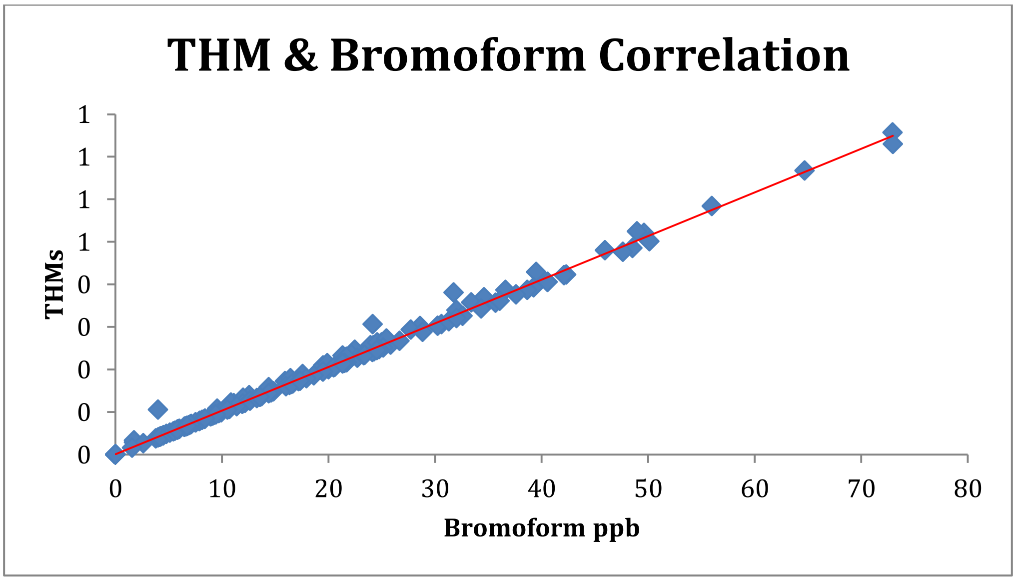


Figure 4-25: Bromoform Vs. THMs Correlation

5. Chapter 5: Conclusion and Recommendation

Chemical disinfectants are added into drinking water for disinfection purposes. This would reduce the microbial contamination and protect the public health. However, using chemical in disinfection process has also raised public health issues; the potential for cancer of some organs and reproductive/ developmental effects associated with chemical disinfection by-products (DBPs). The quantification is needed to demonstrate that DBPs are controlled to an acceptable level while maintaining the needed degree of protection against microbial disease that water disinfection provides.

The current study investigated at field scale the occurrences of disinfection by-products for ClO_2 as well as the ClO_2 residual in seven desalination plants, four reservoirs and eight mosques in drinking water in Qatar. The study also attempt to compare the real measured amounts with the guidelines set by WHO and the KM.

For the physical and chemical parameters that were measured on-site, the following conclusions could be drawn:

- The median water temperature was of 38.5°C while the maximum and minimum measured values reached 46.0 and 18.7°C, respectively.
- The median pH value was 7.8 while the maximum and minimum measured values reached 8.5 and 7.2, respectively.

- The median turbidity value was 0.18 NFU while the maximum and minimum measured values reached 2.7 and 0.01 NFU, respectively.
- The median conductivity value was 170 (µs/cm) while the maximum and minimum measured values reached 384 and 95.3 µs/cm, respectively.

For disinfectant residual and the by-products formation, the following conclusions could be drawn:

- The ClO_2 level was ranged from 0.38 to less than 0.02 mg/L. It is observed that the concentration of ClO_2 was decayed by one order of magnitude, which was smaller in the mosques compared to its concentration in the reservoirs and desalinated plants. The median of ClO_2 was 0.17, 0.12, and 0.04 mg/L in the desalination plants, the reservoirs and the mosques, respectively. The highest ClO_2 concentration was recorded in Ras-Girtas DP, which was 0.38 mg/L while the lowest was in RAF B and B2, which was 0.02 mg/L. In the reservoirs, the highest value was recorded in West Bay, which reached 0.24 mg/L, and the lowest value was recorded in New Salwa which was 0.02 mg/L. While in the mosques, the highest value was recorded in the mosques number 1066 WB which was 0.13 mg/L. It is noticed that few samples have less ClO_2 concentration than the recommended value that is set by the KM, which is 0.05-0.7 mg/L. This could be attributed to normal decay process of ClO_2 as a result of auto-decomposition reactions and reactions with organic and inorganic compounds, including biofilms, pipe materials, corrosion products, formation of slime or may due to the fact the water in distribution system experience water aging problem.

- The chlorite was the highest concentration of ClO_2 DBPs measured in this study. The concentrations of chlorite in the collected water samples varied from 12.78 to 436.36 ppb with mean values varied from 12.78 to 230.76, from 77.43 to 325.25, and from 84.73 to 436.36 ppb in the desalination plants, the reservoirs, and the mosques, respectively. However, the concentrations of chlorite in the collected water samples from mosques were higher than the concentrations of chlorite in the desalination plants and the reservoirs.
- The concentrations of chlorate in the collected water samples varied from 10.66 to 282.72 ppb with mean values varied from 35.58 to 282.72, from 11.02 to 200.69, and from 10.66 to 150.38 ppb in the desalination plants, reservoirs, and the mosques, respectively. However, the concentrations of chlorate in the collected water mosques samples were lower than the concentrations of chlorate in the desalination plants and the reservoirs
- For the THMs, the median value of 4.90 ppb, while the maximum and minimum measured values reached 76.97 and 0.00 ppb respectively. All species of THMs ($CHBr_3$, $CHCl_3$, $CHCl_2Br$, and $CHClBr_2$) were detected in the current study, however the $CHBr_3$ was the most abundant compound.

- ANOVA test was used to figure the significances between the different parameters, and the result showed that the pH, ClO_2, chlorate, chlorite and bromoform, have p-value < 0.01, 0.01, 0.01, 0.01 and 0.01 respectively. Except the conductivity and turbidity was not significant, p- value = 0.049 and 0.315, respectively. In addition different types of applicable correlations were investigated using Pearson’s correlation coefficients, and the results showed a positive relationship between ClO_2 and chlorate, bromoform with bromide, pH with chlorite, chlorite with water source and finally bromoform with THMs; and all of these relations were statistically significant, $p < 0.01$. While negative relationship were found between ClO_2 with chlorite, ClO_2 with water source, ClO_2 with pH and also all of those relation were statistically significant, $p < 0.01$.
- All the concentration of DBPs in the current study were within the regulation limit set by GSO 149/2009, WHO and KM and even with the maximum value reached, all values still far from the limit.

According to the findings, the followings are recommended:

1. Consideration must be given to the overall demand and should account for seasonal variations, temperature, and application points.
2. Re-conducting the study to include the seasonal variation in temperatures, disinfectants demands and biological factors and total organic carbon (TOC).

3. Slightly increase the ClO_2 dosage at the desalination plants, such slight increase would provide safer margin at the customer points of use in case of any microbial activities; or installing a number of boosting stations to keep the proper residual disinfectant level within the distribution systems.
4. Deep investigation of the factors that led to low disinfectant residual at the end of network and the increasing level of chlorite
5. Maintaining adequate level of disinfectant residual in network may require routine cleaning/ replacement of pipes and intensive treatment
6. Effective use of boosting stations at KM reservoirs to maintain proper residual disinfectant level.
7. Routine monitoring studies to investigate the residual disinfectants and by-products formation.
8. Investigate ClO_2 organic by-products such as haloacetic acids HAAs, aldehydes, ketones, halonitriles and cyanogen's. Since some reviews identified more that 40 by-product.
9. Minimization of chlorite and chlorate formation and reduction of ClO_2 demand can be achieved by using aluminum sulfate or activated carbon which reduced

the demand by 50% and DPs formation by 20-40% (Sabrina, 2014).

10. Other route of exposure such as showering, bathing should be investigated. (Villanueva et al., 2007)
11. Adequate investigation of waterborne disease associated with insufficient residual disinfection in drinking water.
12. Epidemiology investigation studies that specifically target the distribution system component of waterborne disease are needed.
13. Routine monitoring studies to investigate the residual disinfectants and by-products formation.

6. REFERENCES

1. Aieta, E.M., Berg, J.D., 1986. A review of ClO2 in drinking water treatment. J. Am. Water Works Assoc. 78 (6), 62–72.
2. Aieta, E.M., P.V. Roberts, and M. Hernandez. 1984. Determination of ClO2, Chlorine and Chlorate in Water. J. AWWA. 76(1):64-70.
3. Agusa, E. Eva, A. N., Nikolay, and V. David. 2007. "`Disinfection by-products and their potential impact on the quality of water produced by desalination system. Desalination 237 .2009. 214-237.
4. Al-Rqobal H. and Al-Munayyis, A. 1989. A recarbonation process for treatment of distilled water by MSF plants in Kuwait, Desalination, (73) 295–312.
5. Al-Shammiri, M., and M. Safar. 1999. Multi-effect distillation plants: state of the art. Desalination. 126:45-59.
6. Ammar , T.A., Abid , K.Y., El-Bindary, A.A., El-Sonbati, A.Z. (2014) ClO2 bulk decay prediction in desalinated drinking water. Desalination 352 45–51
7. Amy, G.L., Minear, R.A., Cooper, W.J. (1987). Testing and validation of a multiple nonlinear regression model for predicting trihalomethane format ion potential, Water Res. 21 (6) 649–659.
8. AWWA (American Water Works Association). Water Quality and Treatment, fourth edition. McGraw-Hill, Inc., New York, NY 1990.
9. AWWA (American Water Works Association). Disinfection Systems survey committee report, water quality division. J Am Water Works Assoc 2000;9:24–43.
10. AWWA : AWWA Standard B303-95: Sodium Chlorite, 1995.
11. AWWA: Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources, 1991.
12. Barbeau H. and Son, M. 2005. Prevost, Impacts of water quality on chlorine and ClO2 efficacy in natural waters, Water Res. 39 2024–2033.

13. Baribeau, H., Prevost, M., Desjardins, R., Lafrance, P., Gates, D.J. 2002. Chlorite and chlorate ion variability in distribution systems, J. Am. Water Works Assoc. (94) 96–105.
14. Becher, G. .1999. Drinking water chlorination and health. Acta Hydrochem. Hydrobiol, (27) 100–102.
15. Boorman, G.A., Dellarco, V., Dunnick, J.K., Chapin, R.E., Hunter, S., Hauchman, F. Gardner, H., Cox, M., Sills, R.C. (1999) Drinking water disinfection byproducts: review and approach to toxicity evaluation, Environ. Health Perspect. (107) 207–217.
16. Bove Jr., G.E., Rogerson, P.A., Vena, J.E. (2007). Case control study of thegeographic variability of exposure to disinfectant byproducts and risk for rectal cancer, Int. J. Health Geogr. (6) 18.
17. Bove, F.J., Fulcomer, M.C., Klotz, J.B., Esmart, J., Dufficy, E.M., Savrin, J.E. (1995). Public drinking water contamination and birth outcomes, Am. J. Epidemiology study. 141 850–862.

18. Bull, R.J., Krasner, S.W., Daniel, P.A., Bull, R.D. 2001. Health Effects and Occurrence of Disinfection By-products, AWWA Research Foundation, Denver, CO.
19. Cantor, K.P., Drinking water and cancer, Cancer Causes Control 8 .1997. 292–308.
20. Cantor, K.P., Villanueva, C., Garcia-Closas, M., Silverman, D. Real, F.X., Dosemeci, M., Malats, N., Yeager, M., Welch, R., Chanock, S. 2006. Bladder cancer, disinfection byproducts, and markers of genetic susceptibility in a case–control study from Spain,Epidemiology 17 S150.
21. Chen WJ, Weisel CP. Halogenated DBP concentrations in a distribution system. J Am.
22. Chen, C., Zhang, X., He, W., Lu, W., Han, H., 2007. Comparison of seven kinds of drinking water treatment processes to enhance organic material removal: a pilot test. Sci. Total Environ. 382, 93-102.
23. Chen, Y.S.R., O.J. Sproul, and A.J. Rubin. 1984. “Inactivation of Naegleria Gruberi cysts by ClO2.” EPA Grant R808150-02-0, Department

of Civil Engineering, Ohio State University.

24. Chen, Y.S.R., O.J. Sproul, and A.J. Rubin. 1985. "Inactivation of Naegleria gruberi Cysts by ClO2." Water Res. 19(6):783
25. Coffin, J. C., Ge, R., Yang, S., Kramer, P. M., Tao, L., and Pereira, M. A., (2000). Effect of trihalomethanes on cell proliferation and DNA methylation in female B6C3F1 mouse liver. Toxicol. Sci., 58, 243–252.
26. Collivignarelli, C., Sorlini, S., 2004. Trihalomethane, chlorite and bromate formation in drinking water oxidation of Italian surface waters. J. Water Supply: Res. Technol.-Aqua 53, 159-168.
27. Dawoud, M. A., 2005. The role of desalination in augmentation of water supply in GCC countries, Desalination 186 (1-3) .2005. 187-198.
28. DeAngelo, A. B., George, M. H., Kilburn, S. R., Moore, T. M., Wolf, D. C. 1998. Carcinogenicity of potassium bromate administered in the drinking water to male B6C3F1 mice and F344/N rats, Toxicol. Pathol. 26 587–594.
29. DeAngelo, A. B., Geter, D. R., Rosenberg, D.W., Crary, C. K., George, M.H. (2002). The induction of aberrant crypt foci (CF) in the colons of rats by trihalomethanes administered in the drinking water. Cancer Letters.
30. Demers, L.D., and R. Renner. 1992. Alternative Disinfectant Technologies for Small Drinking Water Systems. AWWARF, Denver, CO.
31. Dodds, L., King, W., Woolcott, C., Pole, J. 1999. Trihalomethanes in public water supplies and adverse birth outcomes, Epidemiology 10 233–237.
32. Dodds, L., King, W.D. (2001). Relation between trihalomethane compounds and birth defects, Occup. Environ. Med. 58 443–446.
33. EPA Office of Research and Development, 2001. Controlling Disinfection By-Products and Microbial Contaminants in Drinking Water. (EPA/600/R-01/110). Washington, D.C.

34. EPA Office of Water, 1999. Alternative Disinfectants and Oxidants Guidance Manual. (EPA 815-R-99-014). Washington, D.C.

35. EPA-530-D-98-001A. USA: USEPA Office of Solid Waste; 1998a. USEPA (US Environmental Protection Agency). National primary drinking water regulations: disinfectants and disinfection byproducts notice of data availability. Fed Regist 1998b;63(61):15673–92. USEPA (US Environmental Protection Agency). National primary drinking water standards.
36. Gallagher DL, Hoehn RC, Dietrich AM. Sources, occurrence and control of ClO2 by-product residuals in drinking water. Denver, CO: AWWA Research Foundation, 1994. 184pp.
37. Gallagher, M.D., Nuckols, J.R., Stallones, L., Savitz, D.A. (1998). Exposure to trihalomethanes and adverse pregnancy outcomes, Epidemiology 9 484–489.
38. Gate, DJ., Dernat, M., and Bazer-Bachi, A. 1995. Drinking water use of ClO2: a case study in France. Proceedings of the Third International Symposium on ClO2. 14–25 September, New Orleans, La. CMA, AWWARF and USEPA.
39. Gates, D.J. 1989. “ClO2 Generation Technology and Mythology.” Conference proceedings, Advances in Water Analysis and Treatment, AWWA, Philadelphia, PA.
40. Gates, D.J. 1998. The ClO2 Handbook; Water Disinfection Series. AWWA Publishing, Denver, CO.
41. Gates, D.J. The ClO2 Handbook; Water Disinfection Series, American Water Works Association, Denver, CO, 1998.
42. Geter, D.R., George, M.H., Moore, T.M., Kilburn, S., Allen, J.W., Nelson, G.M., Winkfield, E., DeAngelo, A.B. 2005. Tribromo- methane exposure and dietary folate deficiency in the formation of aberrant crypt foci in the colons of F344/N rats, Food Chem. Toxicol. 43 1405–1412.
43. Geter, D.R., George, M.H., Moore, T.M., Kilburn, S., Huggins-Clark, G., DeAngelo, A.B. (2004). Vehicle and mode of administration effects on the induction of aberrant crypt foci in the colons of male F344/N rats exposed to bromodichloromethane, J. Toxicol. Environ. Health A 67 23–29.
44. Geter, D.R., George, M.H., Moore, T.M., Kilburn, S., Huggins-Clark, G.,

DeAngelo, A.B. (2004). The effects of a high animal fat diet on the induction of aberrant crypt foci in the colons of male F344/N rats exposed to trihalomethanes in the drinking water, Toxicol. Lett. 147 (2004) 245–252.

45. Gill, T. I. Smith, G. J. Wissler, R. W. and Kunz, H. W.(1989). The rat as experimental animal, Sciece 254, 269-276. Gold, R., Hartung, H. P., and Tokya, K. V. (2000). Animal models for autoimmune demyelinating disorders.
46. Glaze, W., Weinberg, H. 1993. Identification and Occurrence of Ozonation By-products in Drinking Water, AWWA Research Foundation, Denver, CO.
47. Gordon, G., and Bubnis, B. 1995. ClO2: chemistry is- sues. Proceedings of the Third International Symposium on ClO2. 14–25 September, New Orleans, La. CMA, AWWARF and USEPA.
48. Gordon, G., et al. 1990. “Minimizing Chlorite Ion and Chlorate Ion in Water Treated with ClO2.” J. AWWA. 82(4): 160-165.

49. Gordon, G., G.L. Emmert, and B. Bubnis. 1995. “Bromate Ion Formation in Water When ClO2 is Photolyzed in the Presence of Bromide Ion.” Conference proceedings, AWWA Water Quality Technology Conference, New Orleans, LA.
50. Gordon, G., Slootmaekers, B., Tachiyashiki, S., Wood, D.W. (1990). Minimizing chlorite ion and chlorate ion in water treated with ClO2, J. Am. Water Works Assoc. 82 160–165.
51. Gordon, G., W.J. Cooper, R.G. Rice, and G.E. Pacey. 1987. Disinfectant Residual Measurement Methods, AWWARF, Denver, CO.

52. Griese, M.H. et al. (1992). Combining methods for reduction of oxychlorine compounds in drinking water, J. AWWA 84 69–77.
53. Haag WR, Hoigné J (1983) Ozonation of bromide-containing water: kinetics of formation of hypobromous acid and bromate. Environmental Science and Technology, 17:261–267.

54. Health Canada. Guidelines for Canadian drinking water quality; 2007.
55. Hoehn, R.C., Ellenberger, C.S., Gallagher, D.L., Wiseman, E.V., Benninger, R.W., Rosenblatt, A. 2003. ClO_2 and by-product persis- tence in a drinking water system, J. Am. Water Works Assoc. 95 141–150.
56. Hofman, R., R.C. Andrews, and Q. Ye. 1997. “Chlorite Formation When Disinfecting Drinking Water to Giardia Inactivation Requirements Using ClO_2.” Conference proceedings, ASCE/CSCE Conference, Edmonton, Alberta, July.
57. Hua, G., Reckhow, D.A., 2007. Comparison of disinfection byproduct formation from chlorine and alternative disinfectants. Water Research 41, 1667-1678.

58. IARC .1986. Some naturally occurring and synthetic food components, furocoumarins and ultraviolet radiation. Lyon, International Agency for Research on Cancer, pp. 207–220 (IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 40.
59. IARC, Monographs on the Evaluation of Carcinogenic Risks to Humans. Coffee, Tea, Mate, Methylxanthines and Methyl- glyoxal, vol. 51, International Agency for Research on Cancer, Lyon, France, 1991.
60. IARC, Monographs on the Evaluation of Carcinogenic Risks to Humans. Dry Cleaning, Some Chlorinated Solvents and Other Industrial Chemicals, vol. 63, International Agency for Research on Cancer, Lyon, France, 1995.
61. IARC, Monographs on the Evaluation of Carcinogenic Risks to Humans. Some Drinking-water Disinfectants and Contaminants, Including Arsenic, vol. 84, International Agency for Research on Cancer, Lyon, France, 2004.
62. IARC, Re-evaluation of Some Organic Chemicals, Hydrazine and Hydrogen Peroxide, vol. 71, International Agency for Research on Cancer, Lyon, France, 1999.
63. IDA desalination yearbook 2011-2012. Oxford: Media Analytics Ltd; 2012.
64. IRIS (Integrated Risk Information System). The Integrated Risk Information System online database. Washington DC: US Environmental

Protection Agency; 2006. Website: http://www.epa.gov/iris/subst/index.html.

65. Karen S. Werdehoff, Philip C. Singer, ClO2 effects on THMFP, TOXFP and the formation of inorganic by-products, J. AWWA 79 (9) (1987) 107–113.
66. Khawaji, A.D. and Wie, J.M. (1994), "Potabilization of desalinated water at Madinat Yanbu Al-Sinaiyah", Desalination, Vol. 98, pp. 135–146.
67. Klotz, J.B., Pyrch, L.A. (1999). Neural tube defects and drinking water disinfection by-products, Epidemiology 10 383–390.
68. Koivusalo, M., Jaakkola, J.J., Vartiainen, T, T. Hakulinen., Karjalainen, S., Pukkala, E. Tuomisto, J. (1994). Drinking water muta- genicity and gastrointestinal and urinary tract cancers: anecological study in Finland, Am. J. Public Health 84 1223–1228, 1981.
69. Kolpin, D.W., Furlong, E.T., Meyer, M.T., Thurman, E.M., Zaugg, S.D., Barber, L.B., Buxton, H.T. (2002). Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999–2000: a national reconnaissance, Environ. Sci. Technol. 36 1202–121.
70. Korn, C. 1998. M.A.Sc. thesis. Department of Civil Engineering, University of Toronto, Toronto, Ont.
71. Korn, C., Andrews, R.C., Escobar, M.D., 2002. Development of ClO2-related by-product models for drinking water treatment. Water Research 36, 330-342.
72. Krasner, S.W., Coffey, B.M., Hacker, P.A., Hwang, C.J., Kuo, C., Mofidi, A.A., Sclimenti, M.J. (1996). International working group on biodegradable organic matter in drinking water, in: Proceedings of the Fourth International BOM Conference, Waterloo, Canada.
73. Krasner, S.W., Weinberg, H.S., Richardson, S.D., Pastor,.J., Chinn,,R. Sclimenti, M.J., Onstad, G.D., Thruston Jr., A.D. (2006). Occurrence of a new generation of disinfection byproducts, Environ. Sci. Technol. 40 7175–7185.
74. Kurokawa, Y et al. (1983). Carcinogenicity of potassium bromate administered orally to F344 rats. Journal of the National Cancer Institute,

71:965–972.

75. Kurokawa, Y., Aoki, S., Matsushima, Y., Takamura, N., Ima- zawa, T., Hayashi, Y. (1986). Dose–response studies on the carcinogeni- city of potassium bromate in F344 rats after long-term oral administration, J. Natl. Cancer Inst. 77 977–982.
76. Kurokawa, Y., Takayama, S., Konishi, Y., Hiasa, Y., Asahina, S., Takahashi, M., Maekawa, A., Hayashi, Y. (1986). Long-term in vivo carcinogenicity tests of potassium bromate, sodium hypochlorite, and sodium chlorite conducted in Japan, Environ. Health Perspect. 69 221–235.
77. Lafrance, P., Duschene, P., Arcouette, N., and Prevost, M. 1992. The use of ClO2: case study of Laval. Proceedings of the Second Inter- national Symposium on ClO2. 7–8 May, Houston, Tex. CMA, AWWARF and USEPA.
78. LeChevallier, M.W., et al. 1997. "ClO2 for Control of Cryptosporidium and Disinfection Byproducts." Conference proceedings, 1996 AWWA Water Quality Technology Conference Part II, Boston, Massachusetts.
79. Lee, C., Schmidt, C., Yoon, J., von Gunten, U., 2007. Oxidation of N-nitrosodimethylamine (NDMA) precursors with ozone and ClO2: kinetics and effect on NDMA formation potential. Environmental Science & Technology 41, 2056-2063.
80. Linder, K., Lew, J., Carter, B., Brauer, R., 2006. Avoiding chlorite: chlorine and ClO2 together form fewer DBPs (Disinfection by- products). Opflow 32, 24-26.
81. Liyanage, L.R.J, et al. 1997. "Effects of Aqueous Chlorine and Oxychlorine Compounds on Cryptosporidium Parvum Oocysts." Environ. Sci. & Tech. 31(7): 1992-1994.
82. Lykins Jr BW, Griese MH. Using ClO2 for trihalomethane control. J Am. Water Works Assoc 1986;78(6):88–93.
83. McGuire, M.J., McLain, J.L., Obolensky, A. (2002).Information Collection Rule Data Analysis, AWWA Foundation and AWWA, Denver, CO.

84. Michael GE et al. (1981) ClO2 water disinfection: a prospective epidemiology study. Archives of Environmental Health, 36:20–27.
85. MOE (Ministry of Environment, Ontario, Canada), 2006. Drinking Water Surveillance Program (DWSP) monitoring data for 2000–2004 on 179 municipal water supply systems (MWSS) in Ontario.
86. Muttamara S, Sales CI, Gazali Z. (1995).The formation of trihalomethane from chemical disinfectants and humic substances in drinking water. Water Supply;13(2):105–17.
87. MWH (Montgomery Watson Harza). Water treatment: principles and design. NJ, USA: John Wiley & Sons; 2005.
88. Nada, N.A., Zahrani A., Ericsson, and B. (1987). Experience on pre- and post-treatment from sea water desalination plants in Saudi Arabia, Desalination, 66 365–383.
89. Najm, I. & Trussell, R.R., 2001. NDMA Formation in Water and Wastewater. Journal American 505 Water Works Association, 93:2:92.
90. National Cancer Institute of Canada. Canadian cancer statistics; 1998. Web Address: http://www.cancer.ca/stats.
91. National Cancer Institute, Report on the carcinogenesis bioas- say of chloroform (CAS no. 67-66-3), National Cancer Insti- tute, TR-000 NTIS Rpt No. PB264018, Bethesda, MD, 1976.
92. National Toxicology Program, Toxicology and carcinogenesis studies of sodium chlorate (CAS no. 7775-09-9) in F344/N rats and B6C3F1 mice (drinking water studies), Natl. Toxicol. Program Tech. Rep. Ser. 517 (2005) 1–255.
93. Ohanian,E.V., Mullin, C.S., Orme, J. (1989). Health effects of disinfectants and disinfection by-products: a regulatory perspective, Water Chlorination: Chem. Environ. Impact Health Effects 6.
94. Pereira MA. Carcinogenic activity of dichloroacetic acid and trichloroacetic acid in the liver of female B6C3F1 mice. Fundam Appl Toxicol 1996;31:192–9.
95. Pereira T., Pereira, A.O. Costa, J.T., Silva, M.B.O., Schuchard, W., Osaki, S.C., Castro, E.A., Paulino, R.C., Soccol, V.T. (2008). Comparing the

efficacy of chlorine, ClO2, and ozone in the inactivation of Cryptosporidium Parvum in water from Parana State, Southern Brazil, Appl. Biochem. Biotech. 151 464–473.

96. Plewa, M.J., Kargalioglu, Y., Vankerk, D., Minear, R.A., Wagner, E.D. (2002) .Mammalian cell cytotoxicity and genotoxicity analysis of drinking water disinfection by-products, Environ. Mol. Mutagen. 40 134–142.
97. Plewa, M.J., Wagner, E.D., Jazwierska, P., Richardson, S.D., Chen, P.H., McKague, A.B. (2004). Halonitromethane drinking water disinfection byproducts: chemical characterization and mammalian cell cytotoxicity and genotoxicity, Environ. Sci. Technol. 38 62–68.
98. Plewa, M.J., Wagner, E.D., Muellner, M.G., Hsu, K.M., Richardson, S.D. Comparative mammalian cell toxicity of N-DBPs and C-DBPs, in: T. Karanfil, S.W. Krasner, P. Westerhoff, Y. Xie (Eds.), Occurrence, Formation, Health Effects and Control of Disinfection By-products in Drinking Water, American Chemical Society, Washington, DC, in press.
99. Plewa, M.J., Wagner, E.D., Richardson, S.D., Thruston Jr., A.D. Woo, Y.T., McKague, A.B. (2004). Chemical and biological characterization of newly discovered iodoacid drinking water disinfection byproducts, Environ. Sci. Technol. 38 4713–4722.
100. Qatar General Electricity & Water Corporation KAHRAMAA, Statistical Year Book, KAHRAMA Publications, September 2012.
101. Rav-Acha, C., A. Serri, E. Choshen, B. Limoni. 1984. “Disinfection of Drinking Water Rich in Bromide with Chlorine and Chlorine Dioxide, While Minimizing the Formation of Undesirable Byproducts.” Wat. Sci. Technol. 17:611.
102. Reckhow, D.A., Singer, P.C., 1984. The removal of organic halide precursors by preozonation and alum coagulation. J. Am. Water Works Assoc. 76 (4), 151–157.
103. Richardson SD, Thruston Jr AD, Krasner SW, Weinberg HS, Miltner RJ, Schenck KM, et al. Integrated disinfection by-products mixtures research: comprehensive characterization of water concentrates prepared from chlorinated and ozonated/postchlori- nated drinking water. J Toxicol

Environ Health, Part A 2008;71(17):1165–86.

104. Richardson, S.D. (1998). Drinking water disinfection by-products, Encyclopedia Environ. Anal. Remed. 3 1398–1421.

105. Richardson, S.D. (2003). Disinfection by-products and other emerging contaminants in drinking water, Trends Anal. Chem. 22 666–684.

106. Richardson, S.D., Simmons, J.E., Rice, G. (2002). Disinfection byproducts: the next generation, Environ. Sci. Technol. 36 198A–205A.

107. Richardson, S.D., Thruston Jr., A.D., Caughran, T.V., Chen, P.H., Collette, T.W., Floyd, T.L., Schenck, K.M., Lykins Jr., B.W., Sun, G., Majetich, G. (1999). Identification of new drinking water disin- fection byproducts formed in the presence of bromide, Environ. Sci. Technol. 33 3378–3383.

108. Richardson, S.D., Thruston, A.D., Caughran, T.V., Chen, P.H., Collette, T.W., Schenck, K.M., Lykins Jr., B.W., Rav-Acha, C., Glezer, V., 2000. Identification of new drinking water disinfection by-products from ozone, ClO2, chloramine, and chlorine. Water Air Soil Pollut. 123, 95-102.

109. Richardson, S.D., ThrustonJr.,A.D., Rav-Acha, C., Groisman, L. Popilevsky, I., Juraev, O., Glezer, V., McKague, A.B., Plewa, M.J., Wagner, E.D. (2003) Tribromopyrrole, brominated acids, and other disinfection byproducts produced by disinfection of drinking water rich in bromide, Environ. Sci. Technol. 37 3782– 3793.

110. Rodriguez, M.J., Srodes, J.B. (2001). Spatial and temporal evolution of trihalomethanes in three water distribution systems, Water Res. 35 (6) 1572– 1586.

111. Sabrina, S. Francesca, G., Michela B, Carlo C. Influence of drinking water treatments on chlorine dioxide consumption and chlorite/chlorate formation. Water research 54 (2014) 44 -52.

112. Sadiq R, Rodriguez M. (2004) Disinfection byproducts (DBPs) in drinking water and predictive models for their occurrences: a review. Sci Total Environ 2004; 321:21–46.

113. Schmidt, W., 2004. Using ClO2 for drinking water disinfection by the application of the chlorine/chlorite process. Acta Hydrochim. Hydrobiol.

32, 48-60.

114. Singer PC, Obolensky A, Greiner A. 1995. DBPs in chlorinated North Carolina drinking water. Am Water Works Assoc; 87(10): 83–92.

115. Singer PC. 1994. Control of disinfection by-products in drinking water. J Environ Eng 120 (4):727–37.

116. Singer, P.C. 1992. “Formation and Characterization of Disinfection Byproducts.” Presented at the First International Conference on the Safety of Water Disinfection: Balancing Chemical and Microbial Risks. .

117. Singer, P.C., 1994. Control of disinfection by-products in drinking water. J. Environ. Eng.—ASCE 120 (4), 727–744.

118. Singer, P.C., and W.K. O’Neil. 1987. “Technical Note: The Formation of Chlorate from the Reaction of Chlorine and Chlorite in Dilute Aqueous Solution.” J. AWWA. 79 (11):75.

119. Singer, P.C., Obolensky, A., Greiner, A., 1995. DBPs in chlorinated North Carolina drinking waters. J. Am. Water Works Assoc. 87 (10), 83–92.

120. Sittig, M. 1985a. Bromoform. In: Handbook of toxic and hazardous chemicals and compounds. Park Ridge, NJ: Noyes Publications, 149-150.

121. Stevens, A. A., Moore, L. A., Slocum, C. J., Smith, B. L., Seeger. D. R., Ireland, and J.C. (1989). Disinfection By-products: Current Perspectives. American Water Works Association (AWWA), Denver, CO.

122. Towards Qatar National Vision (2030), Qatar National Development Strategy, 2011–2016, Qatar General Secretariat for Development Planning, 2011. First Published March.

123. U.S. Environmental Protection Agency (EPA), Registration Division Office of Pesticide Program, Criteria and Standards Division Office of Drinking Water, 1987. Guide Standard and Protocol for Testing Microbiological Water Purifiers. Washington, D.C

124. U.S. Environmental Protection Agency, ICR Auxiliary 1 Data- base: Version 5.0, Query Tool—Version 2.0, Office of Water, Washington, DC, 2000.

125. U.S. Environmental Protection Agency, IRIS—Integrated Risk

Information System, http://www.epa.gov/iriswebp/iris/index/ html, 2003

126. U.S. Environmental Protection Agency, National interim primary drinking water regulations: control of trihalomethanes in drinking water: final rules, Fed. Reg. 44 (1979) 68624–68705.
127. U.S. Environmental Protection Agency, National primary drinking water regulations: disinfectants and disinfection byproducts; final rule, Fed. Reg. 63 (1998) 69390–69476.
128. U.S. Environmental Protection Agency, National primary drinking water regulations: stage 2 disinfectants and disinfec- tion byproducts rule, Fed. Reg. 71 (2006) 387–493.
129. UK Water supply (water quality), 2000. Regulations for England and Wales. Web site address: www.dwi.detr.gov.ukyregsysi3184y3184.htm.
130. USEPA (U.S. Environmental Protection Agency). 1983. “Trihalomethanes in Drinking Water: Sampling, Analysis, Monitoring, and Compliance.” EPA 570/9-83-002, August.
131. USEPA, 2006. Stage 2 Disinfectants and Disinfection Byproducts Rule. EPA-HQ-OW-2002-0043.
132. USEPA, Alternative Disinfectants and Oxidants Guidance Manual, US Environmental Protection Agency, 1999.
133. USEPA; 2001a. 816-F-01-007. USEPA (US Environmental Protection Agency). Controlling disinfection by-products and microbial contaminants in drinking water. USEPA; 2001b. 600-R-01-110. USEPA (US Environmental Protection Agency). National primary drinking water regulations: stage 2 disinfectants and disinfection by products rule: final rule. Fed Regist 2006; 71(2).
134. Villanueva CM, Cantor KP, Cordier S, Jaakkola JJK, King WD, Lynch CF, et al. (2004). Disinfection byproducts and bladder cancer: a pooled analysis. Epidemiology 15(3): 357–67.
135. Villanueva, C.M., Cantor, K.P., Grimalt, J.O., Malats, N., Silverman, D., Tardon, A. Garcia-Closas, R., Serra, C., Carrato, A., Castano-Vinyals, G., Marcos, R., Rothman, N., Real, F.X., Dosemeci, M., Kogevinas, M. (2007) Bladder cancer and exposure to water disinfection by-products

through ingestion, bathing, showering and swimming in pools, Am. J. Epidemiol. 165 148–156.

136. Volk, C.J. et al. (2002) Implementation of ClO2 disinfection: effects of the treatment change on drinking water quality in a full-scale distribution system, J. Environ. Eng. Sci. 1 (5) 323–330.

137. Waller K., Swan S. H., DeLornze G., Hopkins B. (1998). Trihalomethanes in drinking water and spontaneous abortion. Epidemiology 9: 134-140.

138. Waller, K., Swan, S.H., DeLorenze, G., Hopkins, B. (1998). Trihalomethanes in drinking water and spontaneous abortion, Epidemiology 9 134–140.

139. Waller, K., Swan, S.H., Windham, G.C., Fenster, L. (2001). Influence of exposure assessment methods on risk estimates in an epidemio- logic study of total trihalomethane exposure and spontaneous abortion, J. Exp. Anal. Environ. Epidemiol. 11 522–531.

140. Water Treatment Plant Design, AWWA, 4th Edition, 2005 2 EPA Guidance Manual, Alternative Disinfectants and Oxidants – Chapter 4: ClO2, April 1999.

141. Water Works Assoc 1998;90(4):151–63. Chlorine Chemistry Council. Drinking water chlorination: a review of disinfection practices and issues.

142. Weinberg, H.S., Krasner, S.W., Richardson, S.D., Thruston Jr., A.D. (2002). The occurrence of disinfection by-products (DBPs) of health concern in drinking water: results of a nationwide DBP occurrence study, EPA/600/R02/068.

143. Wen Jun Li, Zuobin Yu, Xinpei Cal, Ming Gao and Fuhuan. (1996).Trihalomethane Formation in Water Treated with ClO2. Institute of Hygiene and Environmental Medicine China, Vol. 30,, No, 10 pp. 2371-2376.

144. Werdehoff KS, Singer PC. 1987. ClO2 effects on THMPF, TOXFP, and the formation of inorganic by- products. J Am Water Works Asso 79(9):107–13.

145. White DM, Garland DS, Narr J, Woolard CR. 2003. Natural organic

matter and DBP formation potential in Alaskan water supplies. Water Res 37:939–47.

146. White, P.A., Rasmussen, J.B. (1998). The genotoxic hazards of domestic wastes in surface waters, Mutat. Res. 410 223–236.

147. WHO (World Health Organization). Guidelines for drinking-water quality. Recommen-dations, 3rd eds.Geneva; 2004. Wigle DT. Safe drinking water: a public health challenge. Chronic Dis Can 1998; 19(3): 103–7.

148. WHO (World Health Organization). Guidelines for drinking-water quality. Recommen-dations, 4th eds.Geneva; 2011.

149. World Health Organization (1979), Health effects of the removal of substances occurring naturally in drinking-water with special reference to demineralized and desalinated water, EURO Reports and Studies, Vol. 16, pp. 1-24. http://docs.watsan.net/Scanned_PDF_Files/Class_Code_2_Water/250-79HE-5721.pdf.

150. World Health Organization, Guidelines for Drinking-water Quality, Fourth edition WHO Press, Geneva, 2011.

151. Xu X, Weisel CP. 2005. Human respiratory uptake of chloroform and haloketones during showering. J Expo Anal Environ Epidemiol 15:6-16.

152. Yang Ch. Y. (1998) Calcium and magnesium in drinking water and risk of death from cerebrovascular disease. Stroke 29, 411-414.

153. Yang, X., Guo, W., Lee, W., 2013. Formation of disinfection byproducts upon ClO2 preoxidation followed by chlorination or chloramination of natural organic matter.

154. Zika, R.G. et al. (1985). Sunlight-induced photodecomposition of ClO2, water chlorination: chemistry, Environ. Impact Health Eff. J. 5 1041–1053.

155. Zwiener, C., Glauner, T., Frimmel, F.H. (2003) Abstracts of the Workshop on Pool Water Chemistry and Health, University of Karlsruhe, Germany, http://www.wasserchemie.uni- karlsruhe.de.

156. Zwiener, C., Richardson, S.D., DeMarini, D.M., Grummt, T., Glauner, T., Frimmel, F.H. (2007) Drowning in disinfection byproducts? Assessing swimming pool water, Environ. Sci. Te.

7. APPENDIX A: RESULT OF BY-PRODUCTS AND CHLORINE DIOXIDE

Table 7-1: On - site Measurement of ClO2 (mg/L) at Desalination Plants, Reservoirs and Mosques.

	Desalination Plants							**Reservoirs**				**Mosques**							
	Q-power	**RLA**	**Ras-Girtas**	**RAF A1**	**RAF A**	**RAF B2**	**RAF B**	**AP**	**NS**	**D**	**WB**	**141 AP**	**600 AP**	**82 NS**	**266 NS**	**1077 D**	**1146 D**	**1164 WB**	**1066 WB**
	0.240	0.220	0.240	0.230	0.160	0.160	0.160	0.120	0.150	0.100	0.140	0.040	0.120	0.020	0.020	0.020	0.030	0.040	0.040
	0.120	0.170	0.160	0.070	0.210	0.020	0.020	0.030	0.030	0.130	0.100	0.090	ND	ND	0.020	ND	0.050	0.020	0.020
	0.160	0.130	0.160	0.170	0.140	0.080	0.020	0.180	0.090	0.130	0.160	0.050	0.060	ND	ND	ND	0.060	0.060	ND
	0.240	0.170	0.120	0.050	0.150	0.140	0.050	0.150	0.020	0.100	0.120	0.020	0.030	0.020	ND	0.090	ND	0.020	0.080
	0.170	0.210	0.070	0.180	0.190	0.110	0.110	0.140	0.030	0.130	0.150	0.020	0.030	ND	ND	ND	0.030	0.040	0.100
	0.150	0.160	0.090	0.020	0.130	0.130	0.230	0.100	0.090	0.120	0.140	0.030	0.050	ND	ND	ND	0.030	0.050	0.110
	0.180	0.210	0.250	0.100	0.080	0.130	0.180	0.070	0.090	0.160	0.240	0.020	0.030	ND	ND	0.020	0.070	0.060	0.080
	0.110	0.200	0.150	0.020	0.060	0.070	0.060	0.030	0.030	0.130	0.180	0.020	0.030	ND	ND	ND	ND	0.060	0.100
	0.100	0.190	0.280	0.090	0.190	0.060	0.200	0.070	0.080	0.120	0.220	0.030	0.020	ND	ND	ND	0.020	0.050	0.110
	0.060	0.210	0.350	0.080	0.170	0.100	0.240	0.130	0.090	0.190	0.210	0.020	0.020	ND	ND	ND	0.040	0.060	0.100
	0.130	0.260	0.380	0.110	0.250	0.030	0.230	0.110	0.110	0.170	0.220	0.020	ND	ND	ND	ND	0.080	0.040	0.130
		0.270	0.370	0.030	0.230	0.170	0.230	0.070	0.080	0.140	0.130	0.020	ND	ND	ND	ND	0.060	0.060	0.090
		0.200	0.150	0.070	0.350	0.040	0.030	0.100	0.050	0.090	0.170	0.020	ND	ND	ND	ND	0.050	0.050	ND
			0.360	0.090	0.220	0.160	0.220	0.100	0.040	0.060	0.210	0.020	ND	ND	ND	0.020	0.020	ND	0.100
				0.090	0.230	0.140	0.110	0.130	0.120	0.170	0.170	0.020	0.030	ND	ND	ND	0.030	ND	0.130
										0.090	0.180	0.020	0.020	ND	ND	ND	0.050	0.050	
										0.070	0.180	0.020				ND	ND		
												0.030				ND			
MIN	0.060	0.130	0.070	0.020	0.060	0.020	0.020	0.030	0.020	0.060	0.100	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
MAX	0.240	0.270	0.380	0.230	0.350	0.170	0.240	0.180	0.150	0.190	0.240	0.090	0.120	0.020	0.020	0.090	0.080	0.060	0.130
Average	0.151	0.200	0.224	0.093	0.184	0.103	0.139	0.102	0.073	0.124	0.172	0.028	0.040	0.020	0.020	0.038	0.044	0.047	0.092

ND: Not detected, the shaded cell not sampled

Table 7-2 : Chlorite Concentration (ppb) at Desalination Plants, Reservoirs and Mosques.

	Desalination Plants							**Reservoirs**				**Mosques**							
	Q-power	**RLA**	**RasGirtas**	**RAF A1**	**RAF A**	**RAF B2**	**RAF B**	**AP**	**NS**	**D**	**WB**	**141 AP**	**600 AP**	**82 NS**	**266 NS**	**1077 D**	**1146 D**	**1164 WB**	**1066 WB**
	31.66	86.76	6.03	36.89	64.73	44.16	47.9	150.63	123.93	154.74	132.99	235.8	250	261.21	243.72	247.4	214.92	192.35	183.97
	51.45	29.28	100.08	59.85	70.17	47.24	51.1	157.87	131.11	158.41	125.69	250.22	190.01	302.18	251.23	290.74	248.79	306.47	251.23
	95.76	97.68	80.44	59.11	85.59	53.67	37.34	163.91	122.16	201.24	173.2	249.25	209.8	248.19	233.42	236.7	213.15	215.84	259.1
	98.25	97.88	24.83	65.8	73.35	36.49	94.47	140.18	92.64	173.34	176.51	233.72	196.8	253.52	220.84	169.63	192.25	203.09	162.74
	87.86	89.23	12.79	77.63	100.82	45.35	102.98	175.81	119.04	151.61	164.14	234.01	204.52	218.11	230.56	232.85	194.99	207.6	180.86
	98.63	160.48	61.7	53.71	50.69	66.18	85.32	170.65	108.73	163.6	150.55	206.17	187.42	220.26	203.27	240.93	176.95	228.74	258.9
	148.02	67.65	63.71	48.31	27.01	89.35	83.17	170.76	119.03	149.76	193.73	ND	84.73	198.19	209.25	254.26	253.13	289.53	245.68
	205.47	170.76	ND	50.31	69.5	61.81	75.71	ND	77.43	178.22	168.71	257.8	238.43	171.2	156	299.78	293.09	293.97	297.25
	71.48	85.25	110.49	75.84	78.67	52.85	114.67	173.28	109.06	161.66	216.75	226.07	174.14	234.24	218.13	326.64	285.89	303.59	352.48
	63.73	113.28	56.54	59.33	91.06	83.23	165.11	185.53	130.15	214.78	176.14	244	194.71	248.22	214.35	290.37	343.87	299.23	325.63
	80.79	113.88	164.44	68.46	112.02	50.29	168.68	219.9	238.9	256.34	317.61	237.91	ND	227.91	209.53	374.77	353.66	350.12	370.68
		127.57	230.76	ND	83.67	35.29	94.46	134.6	155.11	214.45	255.37	207.46	182.46	232.68	218.97	436.36	317.5	368.08	303.22
		49.31	41.22	211.99	134.48	429.92	634.08	227.13	101.91	201.03	183.08	ND	129.19	119.82	118.49	353.2	334.9	294.55	356.73
			93.97	67.43	143.87	125.38	164.47	189.73	144.62	201.14	293.03	188.85	234.41	151.85	171.76	395.51	313.46	323.9	390.13
				87.88	49.23	83.99	133.09	216.69	210.84	228.02	325.25	100.27	194.62	252.78	252.4	366.96	361.92	303.01	235.78
										242.21	220.21	256.77	197.79	243.46	242.92	359.51	344.39	265.53	
										172.44	320.12	264.98				394.28	275.5		
												223.07				218.21			
MIN	31.66	29.28	6.03	36.89	27.01	35.29	37.34	134.6	77.43	149.76	125.69	100.27	84.73	119.82	118.49	169.63	176.95	192.35	162.74
MAX	205.47	170.76	230.76	211.99	143.9	429.92	634.08	227.13	238.9	256.34	325.25	264.98	250	302.18	252.4	436.36	361.92	368.08	390.13
Average	93.92	99.15	79.42	71.90	82.32	87.01	136.84	176.91	132.31	189.59	211.36	226.02	191.27	223.99	212.18	304.89	277.55	277.85	278.29

ND: Not detected, the shaded cell not sampled

Table 7-3: Chlorate Concentration (ppb) at Desalination Plants, Reservoirs and Mosques.

	Desalination Plants							**Reservoirs**				**Mosques**							
	Q-power	**RLA**	**RasGirtas**	**RAF A1**	**RAF A**	**RAF B2**	**RAF B**	**AP**	**NS**	**D**	**WB**	**141 AP**	**600 AP**	**82 NS**	**266 NS**	**1077 D**	**1146 D**	**1164 WB**	**1066 WB**
	134.65	53.07	180.61	195.63	181.28	128.55	132.88	110.71	145.82	25.89	38.97	66.62	68.18	50.42	52.46	24.77	33.94	33.93	39.87
	112.74	106.74	75.63	44.07	60.08	110	90.18	49.05	123.36	91.22	65.1	75.46	87.12	51.61	59.46	29.69	48.4	51.53	31.18
	88.67	112.09	168.45	68.33	90.2	93.65	178.59	63.26	108.39	31.04	38.52	57.14	74.89	46.49	41.94	25.07	40.04	10.66	56.05
	138.46	57.85	193.5	141.37	156.7	186.68	87.15	64.85	56.74	58.95	64.39	47.13	45.93	55.44	57.25	28.69	45.74	55.18	97.3
	118.39	46.198	692.9	121.21	70.02	117.53	63.47	82.83	143.05	55.15	67.66	69.38	85.27	ND	ND	29.77	60.2	56.78	41.83
	83.18	61.08	241.59	156.65	109.82	103.72	95.97	62.87	112.63	6.52	52.69	33.2	51.04	2.33	25.1	30.74	30.73	1.86	107.98
	39.22	36.69	123.5	191.96	199.45	188.16	91.33	99.97	137.02	160.22	95.67	4.05	46.98	50.78	60.89	1.71	56.67	72.03	90.45
	43.31	41.16	282.74	167.87	151.31	162.26	201	11.02	130.57	174.85	108.9	ND	ND	48.82	53.33	39.69	81.11	59.34	ND
	159.14	112.22	89.48	85.47	71.58	131.73	125.83	44.24	125.15	129.63	ND	60.78	92.22	ND	ND	70.72	47.77	30.62	36.84
	159.49	88.22	121.6	191.72	119.44	81.24	71.38	54.32	100.66	97.58	67.69	50.12	ND	ND	ND	8.98	ND	33.16	42.72
	177.54	43.71	147.26	80.98	ND	85.92	39.29	ND	53.88	113.05	40.7	ND	327	7.36	ND	43.85	52.53	41.44	34.35
		57.91	100.16	348.73	ND	111.66	35.58	120.29	88.91	96.77	63.32	28.84	47.8	ND	ND	ND	ND	ND	12.86
		157.67	188.22	136.73	152.92	59.2	ND	ND	147.65	140.21	ND	310.86	150.38	110.24	81.02	ND	40.3	ND	32.21
			96.82	129.19	52.36	72.92	45.99	49.2	100.55	84.66	37.79	46.63	46.67	96.86	141.21	ND	4.17	ND	43.45
					154.37	128.08	93.07	51.14	70.191	134.94	73.31	165.21	ND	28.36	31.28	2.44	1.03	27.22	68.62
										99.99	58.67	56.98	68.66	42.52	42.1	4.42	ND	83.69	
										200.69	ND	ND				ND	208.17		
												50.93				364.59			
MIN	39.22	36.69	75.63	44.07	52.36	59.2	35.58	11.02	53.88	6.52	37.79	4.05	45.93	2.33	25.1	1.71	1.03	1.86	12.86
MAX	177.54	157.67	692.9	348.73	199.5	188.16	201	120.29	147.65	200.69	108.9	310.86	327	110.24	141.21	364.59	208.17	83.69	107.98
Average	114.07	74.97	193.03	147.14	120.73	117.42	96.55	66.44	109.64	100.08	62.38	74.89	91.70	49.27	58.73	50.37	53.63	42.88	52.55

ND: Not detected, the shaded cell not sampled

Table 7-4: Bromoform Concentration (ppb) at Desalination Plants, Reservoirs and Mosques.

	Desalination Plants							**Reservoirs**				**Mosques**							
	Q-power	**RLA**	**RasGirtas**	**RAF A1**	**RAF A**	**RAF B2**	**RAF B**	**AP**	**NS**	**D**	**WB**	**141 AP**	**600 AP**	**82 NS**	**266 NS**	**1077 D**	**1146 D**	**1164 WB**	**1066 WB**
	40.58	42.12	0.01	24.11	2.62	25.83	38.67	35.69	32.02	0.01	7.71	50.23	19.93	31.42	3.25	0.01	0.01	2.83	5.95
	42.31	48.54	ND	40.55	1.58	22.72	21.71	20.48	28.85	0,01	19.36	18.22	53.25	22.64	19.75	ND	ND	35.67	9.45
	49.62	39.51	1.76	50.14	13.59	26.69	34.32	72.97	37.61	0.01	8.61	25.63	26.3	37.17	18.02	ND	ND	ND	16.56
	36.63	34.61	1.75	48.96	9.55	24.58	21.32	30.26	19.5	2.05	7.78	24.33	24.05	21.83	4.02	8.07	1.62	7	7.51
	24.27	39.27	4.01	55.99	11.12	25.45	21.7	25.14	24.75	1.65	6.1	55.26	55.97	15.04	12.5	1.39	1.44	6.73	17.93
	16.34	24.22	4.29	72.95	9.71	19.51	27.74	21.52	9.94	3.48	9.04	39.78	26.43	11.35	6.85	1.1	3.52	10.51	17.33
	15.93	22.46	4.22	64.69	16.01	32.02	19.9	31.31	23.4	5.94	14.33	36.08	37.18	21.83	17.44	4.16	5.52	16.68	8.14
	17.58	23.98	4.79	47.63	9.94	30.6	32.6	36.08	24.54	4.36	7.29	29.57	29.72	20.88	7.71	5.37	4.36	7.87	5.43
	14.57	22.15	3.99	45.95	11.89	13.74	16.44	23.3	16.03	4.2	7.21	1.3	24.17	12.59	9.53	4.36	4	5.11	7.06
	14.59	20.61	4.48	33.39	10.74	11.39	14.38	21.34	14.64	4.06	14.16	24.51	25.03	12.67	9.27	4.03	4.25	6.52	5.88
	12.16	19.46	4.16	24.99	8.38	9.92	12.55	17.2	14.4	4.59	12.28	25.32	27.46	10.43	9.28	4.11	4.18	5.84	6.53
		21.65	4.52	31.76	9.14	9.33	12.65	12.63	11.4	4.22	11.89	25.54	19.77	9.72	9.1	4.24	4.13	6.46	5.82
		3.78	4.18	24.16	7.93	6.72	10.85	14.84	13.27	4.08	9.91	27.2	19.06	12.13	8.62	4.18	4	5.61	6.66
			20	28.59	10.69	6.88	8.39	11.95	13.54	5.58	8.99	20.85	27.82	10.82	10.22	3.97	5.32	7.13	6.73
				23.93	8.93	7.55	11.98	14.67	18.62	4.46	10.51	20.26	36.74	16.29	14.82	4.99	4.39	6.01	8.42
										3.9	20.35	27.94	29.61	17.47	14.83	4.26	3.99	8.97	
										5.29	11.39	39.42				3.96	4.98		
												27.57				4.82			
MIN	12.16	3.78	0.01	23.93	1.58	6.72	8.39	11.95	9.94	0.01	6.1	1.3	19.06	9.72	3.25	0.01	0.01	2.83	5.43
MAX	49.62	48.54	20	72.95	16.01	32.02	38.67	72.97	37.61	5.94	20.35	55.26	55.97	37.17	19.75	8.07	5.52	35.67	17.93
Average	25.87	27.87	4.78	41.19	9.45	18.20	20.35	25.96	20.17	3.62	10.99	28.83	30.16	17.77	10.95	3.94	3.71	9.26	9.03

ND: Not detected, the shaded cell not sampled

Table 7-5: pH on- Site Measurement at Desalination Plants, Reservoirs and Mosques

	Desalination Plants							**Reservoirs**				**Mosques**							
	Q-power	**RLA**	**RasGirtas**	**RAF A1**	**RAF A**	**RAF B2**	**RAF B**	**AP**	**NS**	**D**	**WB**	**141 AP**	**600 AP**	**82 NS**	**266 NS**	**1077 D**	**1146 D**	**1164 WB**	**1066 WB**
	7.97	8.25	7.76	7.68	7.66	7.94	8.24	7.85	7.92	7.93	7.83	7.36	7.76	8.33	8.05	8.34	8.34	8.25	8.28
	7.59	7.56	7.53	7.44	7.39	7.67	7.74	7.61	7.68	7.6	7.75	7.79	7.7	8.01	8.01	7.79	7.91	7.84	7.34
	7.89	7.69	7.53	7.53	7.35	7.69	7.73	7.72	7.62	7.47	7.68	7.58	7.52	7.77	7.47	7.56	7.59	7.58	7.79
	7.76	7.69	7.37	7.58	7.6	8.17	7.86	7.72	7.8	7.76	7.71	8.2	7.97	7.43	7.74	7.62	7.81	8.07	7.84
	8.01	7.86	7.67	7.59	7.39	8.03	7.83	7.69	7.45	7.71	7.52	8.07	8.1	7.72	7.87	8.01	7.9	7.85	8.01
	7.83	7.56	7.6	7.78	7.6	8.14	7.91	7.33	7.83	7.81	7.51	7.68	7.45	8.04	8.03	7.76	7.83	7.98	7.95
	7.78	7.86	7.85	7.88	7.68	8.13	8.18	7.97	7.84	7.75	7.84	8.07	8.02	8.13	7.97	8.01	7.98	7.98	7.23
	8.06	7.7	7.85	7.76	7.64	8.07	8.13	7.92	7.88	7.81	7.8	8.18	7.92	8.16	7.87	8.19	8	8	7.94
	8.29	8.01	7.79	7.8	7.54	7.9	7.82	7.83	7.78	7.75	7.76	8.14	8.26	7.94	7.91	7.97	7.75	7.77	7.94
	8.33	8.17	7.79	7.6	7.34	8.14	8.01	7.72	7.59	7.69	7.8	8.09	8.29	8.41	8.42	7.7	7.66	7.98	8.34
	7.95	7.87	7.68	7.68	7.97	8.1	8.04	7.88	7.75	7.76	7.65	8.04	8.26	7.86	8.4	8.25	8.3	8.1	8
		7.35	7.48	7.98	7.83	8.3	8.16	8.05	7.96	7.72	8.15	8.45	7.66	8.2	8.35	8.16	8.26	8.06	8.18
		7.34	7.32	7.77	7.71	8.43	8.19	7.75	8	7.98	7.8	8.24	8.3	8.3	8.47	8.06	8.18	8.06	8.17
			7.64	7.73	7.79	8.3	8.06	8.14	7.73	8.01	7.56	8.34	8.13	8.12	8.39	8.06	8.22	8.1	8.3
				7.74	7.79	8.08	8.14	8.11	7.22	7.74	8.02	8.41	7.98	8.05	8.19	8.08	8.39	8.08	7.76
										8.04	7.62	8.42	7.91	7.78	7.82	8.11	8.33	7.8	
										7.82	7.79	7.93				8.24	7.72		
												8.03				7.92			
MIN	7.59	7.34	7.32	7.44	7.34	7.67	7.73	7.33	7.22	7.47	7.51	7.36	7.45	7.43	7.47	7.56	7.59	7.58	7.23
MAX	8.33	8.25	7.85	7.98	7.97	8.43	8.24	8.14	8	8.04	8.15	8.45	8.3	8.41	8.47	8.34	8.39	8.25	8.34
Average	7.95	7.76	7.63	7.70	7.62	8.07	8.00	7.82	7.74	7.79	7.75	8.06	7.95	8.02	8.06	7.99	8.01	7.97	7.94

The shaded cell not sampled

Table 7-6 : On site Water Temperature Measured (^oC) at Desalination Plants, Reservoirs and Mosques.

	Desalination Plants							Reservoirs				Mosques							
	Q-power	RLA	RasGirtas	RAF A1	RAF A	RAF B2	RAF B	AP	NS	D	WB	141 AP	600 AP	82 NS	266 NS	1077 D	1146 D	1164 WB	1066 WB
	36.7	31.4	37.3	37.6	43.4	40.3	40.5	33.9	39.6	32.4	33.9	31.2	32.2	26.4	25.3	23.4	23.4	23.9	25.5
	32.8	32.5	31.3	34.6	37.9	37.9	40.7	35	33.6	30.7	35	30	32.2	27	30.1	24.7	25	25	22.1
	35.9	35.4	33.6	35.5	35.7	37.9	37.7	34.7	35	30.7	30.2	31.9	31.6	25	25	23.8	24.7	24.5	27.1
	37	33.4	34.7	35.8	38.1	37.9	37.1	35.7	38.5	32.4	32.2	39.6	35.5	33.4	27	25	28.3	27.4	31.3
	40.4	35.9	37.1	41.2	40.8	43.4	41.6	35.2	40.5	33.3	33	37.1	36.2	42.1	41.1	27.6	29.5	29.4	33.5
	39.5	35.4	37.9	41	41.8	42	43	39.1	41.9	36.1	35.7	36.4	36.4	43.7	32.9	32.5	32.5	32.5	36.1
	37.1	32.2	36.6	38.4	40.5	41	42.3	39.1	42.2	37.8	36.4	39.6	40.1	36.7	34.5	34.15	36	35.6	37.5
	39.1	33.7	38.1	42.2	43.4	43.5	43.7	43.3	44.9	38.7	38	37.4	38.2	44	39.5	38.4	37.8	37	35.7
	41.9	38.1	38.7	42.4	43.2	42	41.7	42.4	45.6	37.5	35.3	36.8	35.4	44.4	37.4	34.4	34.8	35.3	36.1
	41.8	36.8	40.2	39.8	42.1	41.2	44.2	38.5	42.4	37.8	38.6	39.1	40.3	34.7	29.9	35.6	35.7	35.7	27.4
	41.2	39.1	40.1	41.6	43.7	42.5	44.7	40.5	42.5	37.9	38.5	32.7	40.7	40.5	34	36.7	36.3	38.6	36.6
		37.7	39.3	43.8	45.2	45	45.9	43.1	43.7	37.8	39.4	34.2	39.3	39.3	33.1	37.7	36.4	36.5	29.2
		39.4	40.7	44.7	44.7	44.9	45.7	41.4	44	39.4	40.6	46	39.3	40	32.7	37.7	38	38	38.8
			41.1	43.3	43.5	44.8	45.1	43.6	44	41.4	43.7	35.6	40.1	45.7	39.8	39.6	39.2	39.2	32.7
				42.3	43.3	42.8	43.2	41.4	43	40.2	41.1	33.4	41.3	36.8	32.5	41.6	36.5	41.1	36.1
										39.9	39.5	35.2	30.4	18.7	25.4	40.3	38.6	35.9	
										38	40.3	40.1				40.9	35.7		
												35				34.5			
MIN	32.8	31.4	31.3	34.6	35.7	37.9	37.1	33.9	33.6	30.7	30.2	30	30.4	18.7	25	23.4	23.4	23.9	22.1
MAX	41.9	39.4	41.1	44.7	45.2	45	45.9	43.6	45.6	41.4	43.7	46	41.3	45.7	41.1	41.6	39.2	41.1	38.8
Average	38.49	35.46	37.62	40.28	41.82	41.81	42.47	39.13	41.43	36.59	37.14	36.18	36.83	36.15	32.51	33.81	33.44	33.48	32.38

The shaded cell not sampled

Table 7- 7: Water Conductivity Measured On-Site (µs/cm) at Desalination Plants, Reservoirs and Mosques.

	Desalination Plants							**Reservoirs**				**Mosques**							
	Q-power	**RLA**	**Ras-Girtas**	**RAF A1**	**RAF A**	**RAF B2**	**RAF B**	**AP**	**NS**	**D**	**WB**	**141 AP**	**600 AP**	**82 NS**	**266 NS**	**1077 D**	**1146 D**	**1164 WB**	**1066 WB**
	132.3	155.4	188.7	190.5	176.8	139.7	156.9	166.6	155.9	188.5	182.8	189.8	240	158.9	148.4	185.9	165.6	184.9	190.6
	130.4	126.7	193.1	195.2	138.8	151	140.2	159.2	157.9	193.6	188.9	191.1	205.1	149.9	151.8	193	349	314	179
	148.9	164	187	183.6	182.6	142.1	151.6	177.7	193	192.3	176.8	170.3	169.3	324.1	320	206.1	199.2	180.4	164.1
	131.8	155	188	180.1	141.4	153.9	152.9	171	146.1	188	180.2	179.7	182.8	157.2	155.2	368	188.4	181.7	185.7
	144.3	154.3	196	191	172.3	139.1	156.1	161.7	155.6	188.5	184	175.2	173.1	160.1	177.3	189.9	189.2	180.7	173.4
	127.2	150.6	204.2	190.4	155.2	114.8	175.1	160.7	154.5	186.2	178.6	176.2	175.5	153.5	150.2	182.9	189.8	174.9	179.2
	152.7	142.3	193.9	193.5	139.8	165.3	150.9	163.5	149.8	188.1	178.9	180.1	186.1	152.2	152.2	203.8	196.5	187.3	182.9
	126.3	155.9	194.1	195.1	165.4	147.4	149.2	160.1	159.1	196.6	195.3	186.8	192.3	157.7	159.3	191.6	189.1	206	192.2
	127.7	152.9	190.9	203.9	155.9	119.9	156.4	187	172.6	210.6	189.4	182.9	179.5	175.5	178.6	197.7	189.7	169.9	190.1
	126.6	158	170.5	180.2	213.3	133.5	156.3	168.7	168.2	196	179.4	177.9	182.5	169.9	170.2	186.9	181.1	201.3	186.4
	437	173.4	196.6	199.9	147.9	125.1	149.9	168.4	156.4	189.7	171.7	181.3	188.9	167.3	163.8	183.2	191.1	199.4	184.8
		164.6	275.9	205.2	154.5	95.3	143.8	167.3	153.4	195.3	181.2	176.5	259.2	154	150.5	192.4	197.4	188.4	194.4
		156.4	251.6	338	269.4	111.5	139	162.2	159.7	196	274.9	191.1	218.5	158.7	158.7	195.7	195.7	200.2	188
			211.6	290.8	168.9	142.8	161.7	158.6	283.9	188.3	203.3	203.8	280.8	187.2	190.1	193.9	192.5	228	183.9
				633	170.1	161.5	156.5	227.8	384	199.2	183.7	214.8	190.2	230	189.9	198	187	188.4	183.1
										196.4	171.1	259.6	171.9	145.6	146.6	198.2	202.9	188.2	
										189.7	211.4	190.2				204.5	183.1		
												170.8				187.1			
MIN	126.3	126.7	170.5	180.1	138.8	95.3	139	158.6	146.1	186.2	171.1	170.3	169.3	145.6	146.6	182.9	165.6	169.9	164.1
MAX	437	173.4	275.9	633	269.4	165.3	175.1	227.8	384	210.6	274.9	259.6	280.8	324.1	320	368	349	314	194.4
Average	162.29	154.58	203.01	238.03	170.15	136.19	153.10	170.70	183.34	193.12	190.09	188.78	199.73	175.11	172.68	203.27	199.25	198.36	183.85

The shaded area not sampled

8. APPENDIX B: TABLES FOR PHYSICAL AND CHEMICAL PARAMETERS MEASRUED ON-SITE AND ANALYSIED IN LABORATORY

Table 8-1: Reading at Q-power Desalination Plant (RLB).

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory									
			Water Temp. °C	pH	Turbidity. NFU	Conduc. µ s/cm	ClO_2 mg/L	Br^- mg/l	Cl^- mg/l	BrO_3^- ppb	ClO_3^- ppb	ClO_2^- ppb	$CHBr_3$ ppb	$CHCl_3$ ppb	$CHCl_2Br$ ppb	$CHClBr_2$ ppb
1	6/3/2014	10:20	36.7	7.97	0.50	132.3	0.24	ND	5.39	ND	134.65	31.66	40.58	ND	ND	ND
2	19/3/2014	9:30	32.8	7.59	0.30	130.4	0.12	ND	5.46	ND	112.74	51.45	42.31	ND	ND	ND
3	31/3/2014	9:00	35.9	7.89	0.05	148.9	0.16	0.17	2.73	ND	88.67	95.76	49.62	ND	0.78	1.15
4	16/4/2014	9:00	37.0	7.76	0.04	131.8	0.24	ND	2.77	ND	138.46	98.25	36.63	ND	0.72	0.89
5	29/5/2014	8:06	40.4	8.01	0.05	144.3	0.17	ND	3.28	ND	118.39	87.86	24.27	ND	ND	0.01
6	12/6/2014	7:39	39.5	7.83	0.09	127.2	0.15	0.11	3.12	ND	83.18	98.63	16.34	ND	ND	ND
7	19/6/2014	6:56	37.1	7.78	0.11	152.7	0.18	ND	3.92	ND	39.22	148.02	15.93	ND	ND	1.35
8	26/6/2014	8:18	39.1	8.06	0.04	126.3	0.11	ND	4.26	ND	43.31	205.47	17.58	ND	ND	1.35
9	30/6/2014	9:09	41.9	8.29	0.17	127.7	0.10	ND	3.97	ND	159.14	71.48	14.57	ND	ND	ND
10	6/7/2014	9:45	41.8	8.33	0.31	126.6	0.06	ND	3.32	ND	159.49	63.73	14.59	ND	ND	ND
11	9/7/2014	8:43	41.2	7.95	0.27	437.0	0.13	ND	2.92	ND	177.54	80.79	12.16	ND	ND	ND

ND: not detected

Table 8-2: Reading at RLA Desalination Plant.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity NFU	Conduc. µ s/cm	ClO2 mg/L	Br- mg/l	Cl- mg/l	BrO3$^-$ ppb	ClO3$^-$ ppb	ClO2$^-$ ppb	CHBr3 ppb	CHCl3 ppb	CHCl2Br ppb	CHClBr2 ppb
1	06/03/14	11:00	31.4	8.25	0.49	155.4	0.22	ND	1.77	ND	53.07	86.76	42.12	ND	0.01	0.01
2	19/3/2014	8:40	32.5	7.56	0.40	126.7	0.17	ND	1.70	ND	106.74	29.28	48.54	ND	ND	ND
3	31/3/2014	8:40	35.4	7.69	0.45	164.0	0.13	0.15	1.49	ND	112.09	97.68	39.51	0.01	1.63	0.7
4	16/4/2014	9:50	33.4	7.69	0.22	155.0	0.17	ND	1.91	ND	57.85	97.88	34.61	ND	1.05	0.63
5	29//2014	8:45	35.9	7.86	1.10	154.3	0.21	ND	3.73	ND	46.20	89.24	39.27	ND	ND	ND
6	12/6/2014	8:09	35.4	7.56	0.25	150.6	0.16	0.10	3.81	ND	61.08	160.48	24.22	ND	ND	1.48
7	19/6/2014	7:32	32.2	7.86	0.11	142.3	0.21	ND	3.78	ND	36.69	67.65	22.46	ND	ND	2.13
8	26/6/2014	7:41	33.7	7.70	0.10	155.9	0.20	0.02	4.37	ND	41.16	170.76	23.98	ND	ND	1.35
9	30/6/2014	10:48	38.1	8.01	0.46	152.9	0.19	ND	4.14	ND	112.22	85.25	22.15	ND	ND	1.38
10	06/07/14	10:15	36.8	8.17	1.96	158.0	0.21	ND	4.92	ND	88.22	113.28	20.61	ND	ND	ND
11	09/07/14	9:24	39.1	7.87	0.22	173.4	0.26	ND	3.79	ND	43.71	113.88	19.46	ND	ND	ND
12	14/8/2014	8:02	37.7	7.35	0.19	164.6	0.27	0.10	3.70	ND	57.91	127.57	21.65	ND	ND	ND
13	21/8/2014	9:49	39.4	7.34	0.28	156.4	0.20	0.00	3.47	ND	157.67	49.31	3.78	0.01	0.01	0.01

ND: not detected

Table 8-3: Reading at Ras-Girtas (RLC) Desalination Plant.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory									
			Water Tem. °C	pH	Turbidity NFU	Conduct. µ s/cm	ClO_2 mg/L	Br^- mg/l	Cl^- mg/l	BrO_3^- ppb	ClO_3^- ppb	ClO_2^- ppb	$CHBr_3$ ppb	$CHCl_3$ ppb	$CHCl_2Br$ ppb	$CHClBr_2$ ppb
1	6/3/2014	12:30	37.3	7.76	0.50	188.7	0.24	0.00	2.74	ND	180.61	6.06	0.01	ND	0.01	ND
2	19/3/2014	10:00	31.3	7.53	0.31	193.1	0.16	ND	3.21	ND	75.63	100.08	ND	ND	ND	ND
3	31/3/2014	8:50	33.6	7.53	0.07	187.0	0.16	0.18	3.69	ND	168.45	80.44	1.76	0.01	0.66	ND
4	16/4/2014	10:45	34.7	7.37	0.15	188.0	0.12	ND	3.80	ND	193.50	24.83	1.75	0.01	0.96	ND
5	29/5/2014	9:27	37.1	7.67	0.07	196.0	0.07	ND	5.09	ND	692.91	12.79	4.01	4.96	2.45	ND
6	12/6/2014	8:42	37.9	7.60	0.17	204.2	0.09	0.29	3.52	ND	241.59	61.70	4.29	ND	ND	ND
7	19/6/2014	8:15	36.6	7.85	0.28	193.9	0.25	0.07	3.58	ND	123.50	63.71	4.22	ND	ND	ND
8	26/6/2014	8:58	38.1	7.85	0.02	194.1	0.15	0.02	3.71	ND	282.74	ND	4.79	ND	ND	ND
9	30/6/2014	11:03	38.7	7.79	0.05	190.9	0.28	0.04	3.98	ND	89.48	110.49	3.99	ND	ND	ND
10	6/7/2014	10:52	40.2	7.79	0.17	192.3	0.35	0.07	3.62	ND	121.60	56.54	4.48	ND	ND	ND
11	9/7/2014	9:24	40.1	7.68	0.64	196.6	0.38	ND	3.51	ND	147.26	164.44	4.16	ND	ND	ND
12	6/8/2014	10:52	39.3	7.48	0.20	275.9	0.37	ND	3.16	ND	100.16	230.76	4.52	ND	ND	ND
13	18/8/2014	9:15	40.7	7.32	0.85	251.6	0.15	0.00	3.35	ND	188.22	41.22	4.18	0.01	0.01	0.01
14	21/8/2014	10:25	42.1	7.64	0.42	211.6	0.36	0.00	4.31	ND	96.82	93.97	20.00	0.01	0.01	0.01

ND: not detected

Table 8-4: Reading at RAF A1 Desalination Plant.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity. NFU	Conduc. µ s/cm	ClO_2 mg/L	Br^- mg/l	Cl^- mg/l	BrO_3^- ppb	ClO_3^- ppb	ClO_2^- ppb	$CHBr_3$ ppb	$CHCl_3$ ppb	$CHCl_2Br$ ppb	$CHClBr_2$ ppb
1	6/3/2014	9:30	37.6	7.68	0.23	190.5	0.23	0.00	5.41	ND	195.63	36.89	24.11	ND	0.01	0.01
2	17/3/2014	9:50	34.6	7.44	0.08	195.2	0.07	ND	4.49	ND	44.07	59.85	40.55	ND	ND	ND
3	27/3/2014	11:20	35.5	7.53	0.06	183.6	0.17	ND	1.23	ND	68.33	59.11	50.14	ND	ND	ND
4	6/4/2014	10:30	35.8	7.58	0.25	180.1	0.05	ND	1.23	ND	141.37	65.80	48.96	0.01	1.25	1.42
5	15/4/2014	10:30	41.2	7.59	0.13	191.0	0.18	0.11	0.87	ND	121.21	77.63	55.99	0.01	0.61	1.43
6	8/5/2014	8:43	41.0	7.78	0.02	190.4	0.02	ND	1.24	ND	156.65	53.71	72.95	ND	ND	2.74
7	27/5/2014	7:34	42.2	7.76	0.03	195.1	0.02	ND	1.61	ND	167.87	50.38	47.63	ND	ND	ND
8	11/6/2014	6:45	42.4	7.80	0.51	203.9	0.09	0.08	4.74	ND	85.47	75.84	45.95	ND	ND	2.08
9	15/6/2014	7:34	38.4	7.88	0.01	193.5	0.10	ND	0.95	ND	191.96	48.31	64.69	ND	ND	2.04
10	17/6/2014	6:46	39.8	7.60	0.38	180.2	0.08	0.11	2.89	ND	191.72	59.33	33.39	ND	ND	2.4
11	25/6/2014	6:57	41.6	7.68	0.03	199.9	0.11	ND	3.65	ND	80.98	68.46	24.99	ND	ND	1.35
12	2/7/2014	7:40	43.8	7.98	0.78	205.2	0.03	0.23	4.87	ND	348.73	ND	31.76	ND	2.62	1.98
13	10/7/2014	9:20	44.7	7.77	0.83	338.0	0.07	0.15	11.34	ND	ND	211.99	24.16	ND	2.66	2.08
14	17/7/2014	8:52	43.3	7.73	1.35	290.8	0.09	ND	19.34	ND	136.73	67.43	28.59	ND	ND	1.6
15	7/8/2014	7:25	42.3	7.74	0.91	633.0	0.09	0.22	119.27	ND	129.20	87.88	23.93	ND	ND	1.77

ND: Not detected

Table 8-5: Reading at RAF A Desalination Plant.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity. NFU	Conduc. µs/cm	ClO_2 mg/L	Br^- mg/l	Cl^- mg/l	BrO_3^- ppb	ClO_3^- ppb	ClO_2^- ppb	$CHBr_3$ ppb	$CHCl_3$ ppb	$CHCl_2Br$ ppb	$CHClBr_2$ ppb
1	6/3/2014	10:20	43.4	7.66	0.15	176.8	0.16	0.00	3.70	ND	181.28	64.73	2.62	0.01	0.01	0.01
2	17/3/2014	10:00	37.9	7.39	0.07	138.8	0.21	000	4.40	ND	60.08	70.17	1.58	ND	ND	ND
3	27/3/2014	8:40	35.7	7.35	0.03	182.6	0.14	ND	5.10	ND	90.20	85.59	13.59	ND	ND	ND
4	6/4/2014	8:30	38.1	7.6	0.17	141.4	0.15	ND	7.34	ND	156.70	73.35	9.55	0.01	0.6	0.22
5	15/4/2014	10:40	40.8	7.39	0.19	172.3	0.19	0.04	12.44	ND	70.02	100.82	11.12	0.01	0.45	0.22
6	8/5/2014	9:14	41.8	7.6	0.10	155.2	0.13	ND	9.49	ND	109.82	50.69	9.71	ND	ND	ND
7	15/5/2014	7:58	40.5	7.68	0.17	139.8	0.08	ND	4.90	ND	199.45	27.01	16.01	ND	ND	1.06
8	27/5/2014	7:59	43.4	7.64	0.39	165.4	0.06	0.01	7.29	ND	151.31	69.50	9.94	ND	ND	ND
9	11/6/2014	7:08	43.2	7.54	0.07	155.9	0.19	0.15	5.90	ND	71.58	78.67	11.89	ND	ND	ND
10	17/6/2014	7:08	42.1	7.34	0.06	213.3	0.17	ND	21.76	ND	119.44	91.06	10.74	ND	ND	ND
11	25/6/2014	7:19	43.7	7.97	0.14	147.9	0.25	ND	4.29	ND	ND	112.02	8.38	ND	ND	ND
12	2/7/2014	7:58	45.2	7.83	0.06	154.5	0.23	0.13	5.38	ND	ND	83.67	9.14	ND	ND	ND
13	10/7/2014	9:44	44.7	7.71	0.67	269.4	0.35	0.22	5.87	ND	152.92	134.48	7.93	ND	ND	ND
14	17/7/2014	9:10	43.5	7.79	0.22	168.9	0.22	ND	7.95	ND	52.36	143.87	10.69	ND	ND	ND
15	7/8/2014	7:57	43.3	7.79	0.32	170.1	0.23	ND	9.07	ND	154.37	49.23	8.93	ND	ND	ND

ND: Not detected

Table 8- 6: Reading at RAF B2 Desalination Plant.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity. NFU	Conduc. µ s/cm	ClO2 mg/L	Br- mg/l	Cl- mg/l	BrO3− ppb	ClO3− ppb	ClO2− ppb	CHBr3 ppb	CHCl3 ppb	CHCl2Br ppb	CHClBr2 ppb
1	6/3/2014	10:30	40.3	7.94	0.39	139.7	0.16	ND	1.53	ND	128.55	44.16	25.83	0.01	0.01	0.01
2	17/3/2014	11:30	37.9	7.67	0.09	151.0	0.02	ND	3.32	ND	110.00	47.24	22.72	ND	ND	ND
3	27/3/2014	10:00	37.9	7.69	0.06	142.1	0.08	ND	2.05	ND	93.65	53.67	26.69	ND	ND	ND
4	6/4/2014	9:50	37.9	8.17	0.05	153.9	0.14	ND	3.70	ND	186.68	36.49	24.58	0.01	0.80	0.48
5	15/4/2014	11:40	43.4	8.03	0.16	139.1	0.11	0.12	1.41	ND	117.53	45.35	25.45	0.01	0.88	0.36
6	8/5/2014	10:00	42.0	8.14	0.12	114.8	0.13	ND	2.07	ND	103.72	66.18	19.51	ND	ND	1.44
7	15/5/2014	8:27	41.0	8.13	0.09	165.3	0.13	ND	7.21	ND	188.16	89.35	32.02	ND	ND	1.93
8	27/5/2014	8:35	43.5	8.07	0.15	147.4	0.07	ND	2.81	ND	162.26	61.81	30.60	ND	ND	ND
9	11/6/2014	7:50	42.0	7.90	0.08	119.9	0.06	0.10	2.52	ND	131.73	52.85	13.74	ND	ND	ND
10	17/6/2014	7:35	41.2	8.14	0.07	133.5	0.10	ND	4.26	ND	81.24	83.23	11.39	ND	ND	ND
11	25/6/2014	7:52	42.5	8.10	0.09	125.1	0.03	ND	2.91	ND	85.92	50.29	9.92	ND	ND	ND
12	2/7/2014	8:25	45.0	8.30	0.01	95.3	0.17	0.10	1.53	ND	111.66	35.29	9.33	ND	ND	ND
13	10/7/2014	10:14	44.9	8.43	0.05	111.5	0.04	0.05	2.87	ND	59.20	429.92	6.72	ND	ND	ND
14	17/7/2014	9:47	44.8	8.30	0.00	142.8	0.16	0.13	5.65	ND	72.92	125.38	6.88	ND	ND	ND
15	7/8/2014	8:30	42.8	8.08	0.64	161.5	0.14	ND	9.64	ND	128.08	83.99	7.55	ND	ND	ND

ND: Not detected

Table 8-7: Reading at RAF B Desalination Plant.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity. NFU	Conduc. µ s/cm	ClO2 mg/L	Br- mg/l	Cl- mg/l	BrO3− ppb	ClO3− ppb	ClO2− ppb	CHBr3 ppb	CHCl3 ppb	CHCl2Br ppb	CHClBr2 ppb
1	6/3/2014	11:30	40.5	8.24	0.19	156.9	0.16	ND	1.91	ND	132.88	47.90	38.67	ND	0.01	0.01
2	17/3/2014	9:30	40.7	7.74	0.04	140.2	0.02	ND	1.39	ND	90.18	51.10	21.71	ND	ND	ND
3	27/3/2014	9:20	37.7	7.73	0.15	151.6	0.02	ND	2.45	ND	178.59	37.34	34.32	ND	ND	ND
4	6/4/2014	9:00	37.1	7.86	0.17	152.9	0.05	ND	3.04	ND	87.15	94.47	21.32	0.01	0.75	0.69
5	15/4/2014	11:30	41.6	7.83	0.10	156.1	0.11	ND	2.85	ND	63.47	102.98	21.70	0.01	0.53	0.42
6	8/5/2014	9:45	43	7.91	1.69	175.1	0.23	ND	8.59	ND	95.97	85.32	27.74	ND	ND	1.6
7	15/5/2014	8:15	42.3	8.18	0.11	150.9	0.18	ND	3.54	ND	91.33	83.17	19.90	ND	ND	1.54
8	27/5/2014	8:22	43.7	8.13	0.07	149.2	0.06	ND	4.25	ND	200.30	75.71	32.60	ND	ND	ND
9	11/6/2014	7:36	41.7	7.82	0.04	156.4	0.20	0.10	4.67	ND	125.83	114.67	16.44	ND	ND	1.49
10	17/6/2014	7:23	44.2	8.01	0.00	156.3	0.24	0.10	5.00	ND	71.38	165.11	14.38	ND	ND	1.41
11	25/6/2014	7:37	44.7	8.04	0.03	149.9	0.23	ND	2.69	ND	39.29	168.68	12.55	ND	ND	1.39
12	2/7/2014	8:11	45.9	8.16	0.36	143.8	0.23	0.11	1.75	ND	35.58	94.46	12.65	ND	ND	ND
13	10/7/2014	9:59	45.7	8.19	0.20	139.0	0.03	0.26	1.79	ND	ND	634.08	10.85	ND	ND	1.35
14	17/7/2014	9:25	45.1	8.06	0.46	161.7	0.22	ND	1.55	ND	45.99	164.47	8.39	ND	ND	ND
15	7/8/2014	8:14	43.2	8.14	0.86	156.5	0.11	ND	2.65	ND	93.07	133.09	11.98	ND	ND	1.39

ND: Not detected

Table 8-8: Reading for Airport Water Reservoir.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	**pH**	**Turbidity. NFU**	**Conduc. µ s/cm**	**ClO2 mg/L**	**Br- mg/l**	**Cl- mg/l**	**BrO3− ppb**	**ClO3− ppb**	**ClO2− ppb**	**CHBr3 ppb**	**CHCl3 ppb**	**CHCl2Br ppb**	**CHClBr2 ppb**
1	2/3/2014	9:45	33.9	7.85	0.33	166.6	0.12	0.08	2.80	ND	110.71	150.63	35.69	0.01	0.01	0.01
2	12/3/2014	8:30	35.0	7.61	0.30	159.2	0.03	0.09	3.55	ND	49.05	157.87	20.48	ND	ND	ND
3	24/3/2014	9:00	34.7	7.72	0.13	177.7	0.18	ND	2.00	ND	63.26	163.91	72.97	ND	ND	ND
4	2/4/2014	10:30	35.7	7.72	0.53	171.0	0.15	ND	1.55	ND	64.85	140.18	30.26	ND	0.94	1.27
5	9/4/2014	8:40	35.2	7.69	0.06	161.7	0.14	ND	3.71	ND	82.83	175.81	25.14	ND	1.17	0.83
6	5/5/2014	9:30	39.1	7.33	0.14	160.7	0.10	ND	4.68	ND	62.87	170.65	21.52	ND	5.30	ND
7	14/5/2014	8:19	39.1	7.97	0.04	163.5	0.07	ND	5.91	ND	99.97	170.76	31.31	ND	ND	2.21
8	28/5/2014	7:12	43.3	7.92	0.11	160.1	0.03	ND	3.77	ND	11.02	ND	36.08	ND	ND	ND
9	10/6/2014	7:56	42.4	7.83	0.06	187.0	0.07	0.02	5.91	ND	44.24	173.28	23.30	ND	ND	1.39
10	16/6/2014	6:45	38.5	7.72	0.22	168.7	0.13	0.08	5.67	ND	54.32	185.53	21.34	ND	ND	1.41
11	24/6/2014	7:32	40.5	7.88	0.15	168.4	0.11	0.07	4.92	ND	ND	219.90	17.20	ND	ND	1.45
12	29/6/2014	7:58	41.4	7.75	0.41	162.2	0.10	ND	3.11	ND	ND	227.13	14.84	ND	ND	ND
13	7/7/2014	9:43	41.4	8.11	0.47	227.8	0.13	0.04	18.48	ND	51.14	216.69	14.67	ND	ND	1.69
14	14/7/2014	11:07	43.6	8.14	0.18	158.6	0.10	0.07	8.33	ND	49.20	189.73	11.95	ND	ND	ND
15	6/8/2014	8:14	43.1	8.05	0.40	167.3	0.07	ND	4.51	ND	120.29	134.60	12.63	ND	ND	ND

ND: Not detected

Table 8-9: Reading for New Salwa Water Reservoir.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity. NFU	Conduc. μ s/cm	ClO_2 mg/L	Br^- mg/l	Cl^- mg/l	BrO_3^- ppb	ClO_3^- ppb	ClO_2^- ppb	$CHBr_3$ ppb	$CHCl_3$ ppb	$CHCl_2Br$ ppb	$CHClBr_2$ ppb
1	3/3/2014	9:00	39.6	7.92	0.17	155.9	0.15	0.00	3.05	ND	145.82	123.93	32.02	0.01	0.01	0.01
2	13/3/2014	10:05	33.6	7.68	0.01	157.9	0.03	ND	3.49	ND	123.36	131.11	28.85	ND	ND	ND
3	25/3/2014	8:00	35.0	7.62	0.01	193.0	0.09	ND	4.43	ND	108.39	122.16	37.61	ND	ND	ND
4	2/4/2014	8:30	38.5	7.80	0.07	146.1	0.02	ND	3.46	ND	56.74	92.64	19.50	0.01	0.94	0.55
5	13/4/2014	9:30	40.5	7.45	0.27	155.6	0.03	0.14	5.00	ND	143.05	119.04	24.75	ND	0.76	0.63
6	6/5/2014	10:43	41.9	7.83	0.74	154.5	0.09	0.01	7.50	ND	112.63	108.73	9.94	4.55	ND	ND
7	14/5/2014	10:49	42.2	7.84	0.66	149.8	0.09	ND	5.98	ND	137.02	119.03	23.40	ND	ND	1.2
8	28/5/2014	9:09	44.9	7.88	0.11	159.1	0.03	ND	5.06	ND	130.57	77.43	24.54	ND	ND	ND
9	10/6/2014	10:14	45.6	7.78	0.09	172.6	0.08	ND	5.98	ND	125.15	109.06	16.03	ND	ND	1.57
10	16/6/2014	10:36	42.4	7.59	0.36	168.2	0.09	0.12	6.06	ND	100.66	130.15	14.64	ND	ND	1.47
11	23/6/2014	6:22	42.5	7.75	0.13	156.4	0.11	ND	5.51	ND	53.88	238.90	14.40	ND	ND	ND
12	1/7/2014	8:08	43.7	7.96	0.19	153.4	0.08	ND	3.67	ND	88.91	155.11	11.40	ND	ND	ND
13	6/7/2014	10:52	44.0	8.00	0.07	159.7	0.05	ND	3.82	ND	147.65	101.91	13.27	ND	ND	ND
14	14/7/2104	9:10	44.0	7.73	0.41	283.9	0.04	0.10	6.86	ND	100.55	144.62	13.54	ND	ND	1.38
15	6/8/2014	6:49	43.0	7.22	0.32	384.0	0.12	0.03	14.87	ND	70.19	210.84	18.62	ND	ND	1.41

ND: Not detected

Table 8-10: Reading for West Bay Water Reservoir.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity. NFU	Conduc. μ s/cm	ClO_2 mg/L	Br^- mg/l	Cl^- mg/l	BrO_3^- ppb	ClO_3^- ppb	ClO_2^- ppb	$CHBr_3$ ppb	$CHCl_3$ ppb	$CHCl_2Br$ ppb	$CHClBr_2$ ppb
1	6/3/2014	12:00	33.9	7.83	0.46	182.8	0.14	ND	3.87	ND	38.97	132.99	7.71	0.01	ND	ND
2	16/3/2014	8:30	35.0	7.75	0.05	188.9	0.10	ND	2.47	ND	65.10	125.69	19.36	ND	ND	ND
3	25/3/2014	8:30	30.2	7.68	0.16	176.8	0.16	0.22	2.19	ND	38.52	173.20	8.61	ND	ND	ND
4	3/4/2014	8:30	32.2	7.71	0.03	180.2	0.12	0.12	3.19	ND	64.39	176.51	7.78	ND	0.56	0.05
5	10/4/2014	8:00	33.0	7.52	0.08	184.0	0.15	ND	3.89	ND	67.66	164.14	6.10	0.01	0.44	0.05
6	6/5/2014	7:15	35.7	7.51	0.40	178.6	0.14	ND	3.46	ND	52.69	150.55	9.04	ND	ND	ND
7	13/5/2014	8:17	36.4	7.84	0.78	178.9	0.24	ND	3.20	ND	95.67	193.73	14.33	ND	ND	ND
8	26/5/2014	7:47	38.0	7.80	0.28	195.3	0.18	ND	3.14	ND	108.90	168.71	7.29	ND	ND	ND
9	9/6/2014	7:11	39.5	7.62	0.46	171.1	0.18	0.13	3.75	ND	58.67	220.21	20.35	ND	ND	ND
10	15/6/2014	6:36	35.3	7.76	0.37	189.4	0.22	ND	3.48	ND	ND	216.75	7.21	ND	ND	ND
11	22/6/2104	6:36	38.6	7.80	0.02	179.4	0.21	0.13	4.23	ND	67.69	176.14	14.16	ND	ND	ND
12	29/6/2014	6:36	38.5	7.65	0.30	171.7	0.22	ND	3.57	ND	40.70	317.61	12.28	ND	ND	ND
13	2/7/2014	6:35	39.4	8.15	0.26	181.2	0.13	0.12	3.50	ND	63.32	255.37	11.89	ND	ND	ND
14	8/7/2014	7:53	40.6	7.80	0.10	274.9	0.17	0.11	3.66	ND	ND	183.08	9.91	ND	ND	ND
15	13/7/2014	8:19	40.3	7.79	0.52	211.4	0.18	ND	5.90	ND	ND	320.12	11.39	1.37	0.01	0.01
16	5/8/2014	9:57	43.7	7.56	0.71	203.3	0.21	ND	3.20	ND	37.79	293.03	8.99	ND	ND	ND
17	14/8/2104	11:01	41.1	8.02	0.29	183.7	0.17	0.07	3.63	ND	73.31	325.25	10.51	ND	ND	ND

ND: Not detected

Table 8- 11: Reading for Duhail Water Reservoir.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity. NFU	Conduc. µ s/cm	ClO2 mg/L	Br- mg/l	Cl- mg/l	BrO3− ppb	ClO3− ppb	ClO2− ppb	CHBr3 ppb	CHCl3 ppb	CHCl2Br ppb	CHClBr2 ppb
1	6/3/2014	9:30	32.4	7.93	0.32	188.5	0.10	0.00	2.90	ND	25.89	154.74	0.01	ND	0.01	0.01
2	16/3/2014	9:20	30.7	7.60	0.06	193.6	0.13	ND	3.12	ND	91.22	158.41	ND	ND	ND	ND
3	26/3/2014	9:30	30.7	7.47	0.03	192.3	0.13	0.25	2.49	ND	31.04	201.24	ND	ND	ND	ND
4	3/4/2014	8:00	32.4	7.76	0.01	188.0	0.10	0.11	3.32	ND	58.95	173.34	2.05	0.01	0.61	0.02
5	10/4/2014	10:30	33.3	7.71	0.20	188.5	0.13	ND	4.00	ND	55.15	151.61	1.65	ND	0.45	ND
6	6/5/2014	8:56	36.1	7.81	0.11	186.2	0.12	ND	3.67	ND	6.52	163.60	3.48	ND	5.26	ND
7	13/5/2014	9:58	37.8	7.75	0.01	188.1	0.16	ND	3.12	ND	160.22	149.76	5.94	ND	ND	ND
8	25/5/2014	9:02	38.7	7.81	0.15	196.6	0.13	ND	3.21	ND	174.85	178.22	4.36	ND	ND	ND
9	9/6/2014	7:42	37.8	7.72	0.25	195.3	0.14	0.04	3.76	ND	96.77	214.45	4.22	ND	ND	ND
10	15/6/2104	7:58	37.5	7.75	0.04	210.6	0.12	ND	3.45	ND	129.63	161.66	4.2	ND	ND	ND
11	22/6/2104	8:26	37.8	7.69	0.07	196.0	0.19	0.11	3.95	ND	97.58	214.78	4.06	ND	ND	ND
12	30/6/2104	7:03	37.9	7.76	0.18	189.7	0.17	0.07	3.84	ND	113.05	256.34	4.59	ND	ND	ND
13	8/7/2014	8:59	39.4	7.98	0.06	196.0	0.09	0.14	3.33	ND	140.21	201.03	4.08	ND	ND	ND
14	13/7/2104	9:26	39.9	8.04	0.49	196.4	0.09	ND	5.66	ND	99.99	242.21	3.90	1.35	ND	ND
15	5/8/2014	11:17	41.4	8.01	0.55	188.3	0.06	ND	3.30	ND	84.66	201.14	5.58	ND	ND	ND
16	12/8/2014	8:26	38.0	7.82	0.14	189.7	0.07	0.17	3.50	ND	200.69	172.44	5.29	1.47	2.64	ND
17	19/8/2014	9:42	40.2	7.74	0.12	199.2	0.17	ND	3.37	ND	134.94	228.02	4.46	ND	ND	ND

ND: Not detected

Table 8- 12. Reading for Mosque Number141 near by Airport Reservoir.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbi dity. NFU	Conduc. µ s/cm	ClO2 mg/L	Br- mg/l	Cl- mg/l	BrO3 − ppb	ClO3− ppb	ClO2− ppb	CHBr3 ppb	CHCl3 ppb	CHCl2Br ppb	CH ClB r2 ppb
1	12/3/2014	10:00	30.0	7.79	0.17	191.1	0.09	0.03	4.52	ND	75.46	250.22	18.22	ND	ND	ND
2	24/3/2014	9:30	31.2	7.36	0.17	189.8	0.04	0.00	6.41	ND	66.62	235.80	50.23	0.01	0.01	0.01
3	9/4/2014	9:30	31.9	7.58	0.21	170.3	0.05	ND	2.38	ND	57.14	249.25	25.63	ND	0.9	0.82
4	21/4/2014	9:11	39.6	8.20	0.01	179.7	0.02	ND	3.32	ND	47.13	233.72	24.33	ND	ND	1.73
5	5/5/2014	7:40	39.6	8.07	0.10	180.1	0.02	ND	2.51	ND	4.045	ND	36.08	ND	ND	ND
6	14/5/2014	9:00	36.4	7.68	0.11	176.2	0.03	ND	2.25	ND	33.20	206.17	39.78	4.58	5.29	ND
7	25/6/2014	9:02	37.1	8.07	0.04	175.2	0.02	ND	2.44	ND	69.38	234.01	55.26	ND	ND	1.94
8	28/5/2014	7:23	37.4	8.18	0.28	186.8	0.02	0.37	3.40	ND	ND	257.80	29.57	ND	ND	1.66
9	1/6/2014	7:55	36.8	8.14	0.01	182.9	0.03	0.06	4.40	ND	60.78	226.07	1.30	ND	26.24	1.58
10	10/6/2014	8:36	39.1	8.09	0.03	177.9	0.02	ND	2.87	ND	50.12	244.00	24.51	1.35	ND	1.35
11	17/6/2014	8:58	32.7	8.04	0.66	181.3	0.02	ND	2.99	ND	ND	237.91	25.32	1.31	ND	1.36
12	23/6/2014	10:04	34.2	8.45	0.01	176.5	0.02	ND	3.23	ND	28.84	207.46	25.54	1.33	ND	1.38
13	29/6/2014	10:55	46.0	8.24	0.04	191.1	0.02	ND	5.15	ND	310.86	ND	27.20	1.3	2.73	1.95
14	1/7/2014	11:13	35.6	8.34	0.58	203.8	0.02	ND	21.6	ND	46.63	188.85	20.85	ND	ND	1.35
15	7/7/2014	11:36	33.4	8.41	0.45	214.8	0.02	0.15	19.44	ND	165.21	100.27	20.26	ND	ND	1.51
16	14/7/2014	8:23	40.1	7.93	0.06	190.2	0.02	ND	3.82	ND	ND	264.98	39.42	ND	ND	1.98
17	17/7/2014	9:01	35.2	8.42	0.71	259.6	0.02	0.08	30.27	ND	56.98	256.77	27.94	ND	ND	1.69
18	6/8/2014	10:40	35.0	8.03	0.41	170.8	0.03	ND	2.08	ND	50.93	223.07	27.57	0.01	0.53	1.38

ND: Not detected

Table 8- 13: Reading for Mosque Number 600 near by Airport Reservoir.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity. NFU	Conduc. µ s/cm	ClO2 mg/L	Br- mg/l	Cl- mg/l	BrO3− ppb	ClO3− ppb	ClO2− ppb	CHBr3 ppb	CHCl3 ppb	CHCl2Br ppb	CHClBr2 ppb
1	12/3/2014	9:00	32.2	7.76	0.83	240.0	0.12	0.04	4.45	ND	68.18	250.00	19.93	0.00	0.01	0.01
2	24/3/2014	10:30	32.2	7.70	0.05	205.1	ND	0.00	6.24	ND	87.12	190.01	53.25	0.01	0.01	0.01
3	2/4/2014	10:00	31.6	7.52	0.77	169.3	0.06	ND	2.50	ND	74.89	209.80	26.30	ND	0.67	0.73
4	9/4/2014	8:50	35.5	7.97	0.01	182.8	0.03	ND	3.35	ND	45.93	196.80	24.05	ND	ND	1.59
5	5/5/2014	10:00	36.4	7.45	0.10	175.5	0.05	ND	2.22	ND	51.04	187.42	26.43	ND	5.28	ND
6	14/5/2014	9:27	36.2	8.10	0.05	173.1	0.03	ND	2.37	ND	85.27	204.52	55.97	ND	ND	1.88
7	28/5/2014	8:07	40.1	8.02	0.24	186.1	0.03	ND	2.59	ND	46.98	84.73	37.18	ND	ND	ND
8	10/6/2014	7:50	38.2	7.92	0.12	192.3	0.03	0.05	4.02	ND	ND	238.43	29.72	ND	ND	1.62
9	16/6/2014	8:20	35.4	8.26	0.05	179.5	0.02	0.08	3.63	ND	92.22	174.14	24.17	1.38	2.67	1.93
10	24/6/2014	9:49	40.3	8.29	0.01	182.5	0.02	ND	3.36	ND	ND	194.71	25.03	1.31	ND	1.38
11	29/6/2014	10:08	40.7	8.26	0.21	188.9	ND	ND	5.16	ND	327.00	ND	27.46	ND	2.76	2.00
12	1/7/2014	10:46	39.3	7.66	0.50	259.2	ND	ND	22.35	ND	47.80	182.46	19.77	ND	ND	1.35
13	7/7/2014	11:24	39.3	8.30	0.54	218.5	ND	0.28	21.23	ND	150.38	129.19	19.06	ND	ND	1.62
14	17/7/2014	8:38	40.1	8.13	0.43	280.8	ND	0.09	32.66	ND	46.67	234.41	27.82	ND	ND	1.56
15	14/7/2014	8:45	41.3	7.98	0.04	190.2	0.03	0.01	3.84	ND	ND	194.62	36.74	ND	ND	2.43
16	6/8/2014	11:10	30.4	7.91	0.04	171.9	0.02	ND	2.14	ND	68.66	197.79	29.61	0.01	1.46	1.51

ND: Nott detected

Table 8-14: Reading at Mosque Number 82 near by New Salwa.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory									
			Water Tem. °C	**pH**	**Turbidity. NFU**	**Conduc. µ s/cm**	**ClO2 mg/L**	**Br- mg/l**	**Cl- mg/l**	**BrO3− ppb**	**ClO3− ppb**	**ClO2− ppb**	**CHBr3 ppb**	**CHCl3 ppb**	**CHCl2Br ppb**	**CHClBr2 ppb**
1	3/3/2014	9:30	26.4	8.33	0.58	158.9	0.02	0.00	2.71	ND	50.42	261.21	31.42	ND	0.01	0.01
2	13/3/2014	9:30	27.0	8.01	0.06	149.9	ND	ND	3.05	ND	51.61	302.18	22.64	ND	ND	ND
3	25/3/2014	8:30	25.0	7.77	0.25	324.1	ND	ND	3.74	ND	46.49	248.19	37.17	ND	ND	ND
4	2/4/2014	10:00	33.4	7.43	0.18	157.2	0.2	ND	5.27	ND	55.44	253.52	21.83	0.01	0.46	0.44
5	13/4/2014	10:48	42.1	7.72	0.33	160.1	ND	0.01	6.57	ND	ND	218.11	15.04	ND	ND	ND
6	6/5/2014	11:08	43.7	8.04	1.04	153.5	ND	ND	6.28	ND	2.33	220.26	11.35	ND	5.27	ND
7	14/5/2014	11:11	36.7	8.13	0.44	152.2	ND	ND	6.62	ND	50.78	198.19	21.83	ND	ND	1.34
8	28/5/2014	9:41	44.0	8.16	0.13	157.7	ND	ND	4.08	ND	48.82	171.20	20.88	ND	ND	ND
9	10/6/2014	11:08	44.4	7.94	0.09	175.5	ND	0.30	5.76	ND	ND	234.24	12.59	ND	ND	ND
10	16/6/2014	6:52	34.7	8.41	0.04	169.9	ND	ND	8.84	ND	ND	248.22	12.67	ND	ND	ND
11	23/6/2014	10:29	40.5	7.86	0.36	167.3	ND	ND	4.82	ND	7.36	227.91	10.43	ND	ND	ND
12	26/6/2014	8:35	39.3	8.20	0.06	154.0	ND	ND	4.29	ND	ND	232.68	9.72	ND	ND	ND
13	1/7/2014	8:24	40.0	8.30	0.06	158.0	ND	ND	4.92	ND	110.24	119.82	12.13	ND	ND	ND
14	7/7/2014	9:34	45.7	8.12	0.57	187.2	ND	0.09	10.77	ND	96.86	151.85	10.82	ND	ND	ND
15	14/7/2014	7:12	36.8	8.05	0.52	230.0	ND	0.03	13.19	ND	28.36	252.78	16.29	ND	ND	1.4
16	6/8/2014	9:30	38.7	7.78	0.12	145.6	ND	ND	3.27	ND	42.52	243.46	17.47	0.01	0.51	0.37

ND: Not detected.

Table 8- 15: Reading at Mosque Number 266 near by New Salwa Reservoir.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity . NFU	Conduc . µ s/cm	ClO2 mg/L	Br- mg/l	Cl- mg/l	BrO3− ppb	ClO3− ppb	ClO2− ppb	CHBr3 ppb	CHCl3 ppb	CHCl2Br ppb	CHCl Br2 ppb
1	6/3/2014	10:10	25.3	8.05	0.13	148.4	0.02	0.00	2.96	ND	52.46	243.72	3.25	0.01	0.01	ND
2	13/3/2014	10:45	30.1	8.01	0.16	151.8	0.02	ND	3.37	ND	59.457	251.23	19.75	ND	ND	ND
3	25/3/2014	9:10	25.0	7.47	0.08	320.0	ND	ND	4.19	ND	41.94	233.42	18.02	ND	ND	ND
4	2/4/2014	11:00	27,0	7.74	0.03	155.2	ND	ND	4.96	ND	57.25	220.84	4.02	0.01	0.95	0.10
5	13/4/2014	11:04	41.1	7.87	0.16	177.3	ND	0.02	6.72	ND	ND	230.56	12.50	ND	ND	ND
6	6/5/2014	11:37	32.9	8.03	0.39	150.2	ND	0.03	6.2	ND	25.10	203.27	6.85	ND	5.31	ND
7	14/5/2014	11:33	34.5	7.97	0.21	152.2	ND	ND	6.57	ND	60.89	209.25	17.44	ND	ND	ND
8	28/5/2014	10:17	39.5	7.87	0.07	159.3	ND	ND	4.26	ND	53.33	156.00	7.71	ND	ND	ND
9	10/6/2014	11:30	37.4	7.91	0.10	178.6	ND	0.28	5.74	ND	ND	218.13	9.53	ND	ND	ND
10	16/6/2014	7:23	29.9	8.42	0.08	170.2	ND	ND	9.49	ND	ND	214.35	9.27	ND	ND	ND
11	23/6/2014	11:07	34.0	8.40	0.29	163.8	ND	0.03	7.69	ND	ND	209.53	9.28	ND	ND	ND
12	26/6/2014	8:58	33.1	8.35	0.13	150.5	ND	ND	4.69	ND	ND	218.97	9.10	ND	ND	ND
13	1/7/2014	8:47	32.7	8.47	0.20	158.7	ND	ND	4.78	ND	81.02	118.49	8.62	ND	ND	ND
14	7/7/2014	10:05	39.8	8.39	0.29	190.1	ND	0.12	9.28	ND	141.21	171.76	10.22	ND	ND	ND
15	14/7/2014	7:39	32.5	8.19	0.21	189.9	ND	0.03	11.3	ND	31.28	252.40	14.82	ND	ND	ND
16	6/8/2014	10:00	25.4	7.82	0.23	146.6	ND	ND	3.45	ND	42.10	242.92	14.83	ND	1.31	0.29

ND: not detected, less than detection limit of the instrument.

Table 8- 16: Reading at Mosque Number 1077 near by Duhail Reservoir.

#	**Date of collection**	**Time of collection a.m**	**Measured on site**					**Measured on laboratory**								
			Water Tem. °C	**pH**	**Turbidity. NFU**	**Conduc. µ s/cm**	**ClO_2 mg/L**	**Br^- mg/l**	**Cl^- mg/l**	**BrO_3^- ppb**	**ClO_3^- ppb**	**ClO_2^- ppb**	**$CHBr_3$ ppb**	**$CHCl_3$ ppb**	**$CHCl_2Br$ ppb**	**$CHClBr_2$ ppb**
1	6/3/2014	10:00	23.4	8.34	0.33	185.9	0.02	0.00	3.07	ND	24.77	247.40	0.01	0.01	ND	ND
2	16/3/2014	10:00	24.7	7.79	0.12	193.0	ND	ND	3.29	ND	29.69	290.74	ND	ND	ND	ND
3	26/3/2014	10:30	23.8	7.56	0.01	206.1	ND	0.25	2.53	ND	25.07	236.70	ND	ND	ND	ND
4	3/4/2014	8:40	25.0	7.62	0.30	368.0	0.09	ND	2.85	ND	28.69	169.63	8.07	ND	ND	ND
5	10/4/2014	9:30	27.6	8.01	0.10	189.9	ND	ND	2.98	ND	29.77	232.85	1.39	0.01	0.46	0.01
6	24/4/2014	11:00	32.5	7.76	0.20	182.9	ND	ND	3.88	ND	30.74	240.93	1.10	ND	0.88	ND
7	6/5/2014	9:17	34.15	8.01	0.22	203.8	ND	ND	3.58	ND	1.71	254.26	4.16	ND	5.29	ND
8	13/5/2014	10:39	38.4	8.19	0.05	191.6	ND	ND	3.08	ND	39.69	299.78	5.37	ND	ND	ND
9	26/5/2014	9:32	34.4	7.97	0.55	197.7	ND	ND	3.21	ND	70.72	326.64	4.36	ND	ND	ND
10	9/6/2014	7:20	35.6	7.70	0.11	186.9	ND	0.27	3.36	ND	8.98	290.37	4.03	ND	ND	ND
11	15/6/2014	9:02	36.7	8.25	0.11	183.2	ND	0.10	3.87	ND	43.85	374.77	4.11	ND	ND	ND
12	22/6/2014	7:23	37.7	8.16	0.20	192.4	ND	0.04	3.70	ND	ND	436.36	4.24	ND	ND	ND
13	30/6/2014	8:05	37.7	8.06	0.60	195.7	ND	0.06	3.63	ND	ND	353.20	4.18	ND	ND	ND
14	6/7/2014	9:20	39.6	8.06	0.50	193.9	ND	0.06	3.50	ND	ND	395.51	3.97	ND	ND	ND
15	13/7/2014	11:41	41.6	8.08	0.32	198.0	ND	0.12	3.45	ND	2.44	366.96	4.99	ND	ND	ND
16	20/7/2014	10:01	40.3	8.11	0.60	198.2	ND	ND	3.32	ND	4.42	359.51	4.26	ND	ND	ND
17	5/8/2014	9:47	40.9	8.24	0.02	204.5	ND	ND	5.58	ND	ND	394.28	3.96	1.35	ND	ND
18	14/8/2014	8:49	34.5	7.92	0.59	187.1	ND	0.28	4.01	ND	364.59	218.21	4.82	1.47	2.67	ND

ND: Not detected.

Table 8- 17: Reading at Mosque Number 1146 near by Duhail Reservoir.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory									
			Water Tem. °C	pH	Turbidity. NFU	Conduc. µ s/cm	ClO2 mg/L	Br- mg/l	Cl- mg/l	BrO3− ppb	ClO3− ppb	ClO2− ppb	CHBr3 ppb	CHCl3 ppb	CHCl2 Br ppb	CHClBr2 ppb
1	6/3/2014	12:30	23.4	8.34	0.43	165.6	0.03	0.22	3.07	ND	33.94	214.92	0.01	0.01	0.01	0.01
2	16/3/2014	11:45	25.0	7.91	0.12	349.0	0.05	ND	3.19	ND	48.40	248.79	ND	ND	ND	ND
3	26/3/2014	11:00	24.7	7.59	0.13	199.2	0.06	0.25	2.58	ND	40.04	213.15	ND	ND	ND	ND
4	3/4/2014	9:30	28.3	7.81	0.07	188.4	ND	ND	3.03	ND	45.74	192.25	1.62	0.01	0.64	0.01
5	11/4/2014	10:00	29.5	7.9	0.16	189.2	0.03	ND	3.99	ND	60.20	194.99	1.44	0.01	ND	ND
6	6/5/2014	9:50	32.5	7.83	0.88	189.8	0.03	ND	3.72	ND	30.73	176.95	3.52	4.57	5.3	ND
7	13/5/2014	11:03	36.0	7.98	0.23	196.5	0.07	ND	3.05	ND	56.67	253.13	5.52	ND	ND	ND
8	26/5/2014	9:54	37.8	8.00	0.04	189.1	ND	ND	3.22	ND	81.11	293.09	4.36	ND	ND	ND
9	9/6/2014	8:48	34.8	7.75	0.13	189.7	0.02	0.06	3.31	ND	47.77	285.89	4.00	ND	ND	ND
10	15/6/2014	9:24	35.7	7.66	0.16	181.1	0.04	0.10	3.86	ND	ND	343.87	4.25	ND	ND	ND
11	22/6/2014	7:50	36.3	8.30	0.78	191.1	0.08	0.03	3.91	ND	52.53	353.66	4.18	ND	ND	ND
12	30/6/2014	8:27	36.4	8.26	0.43	197.4	0.06	0.05	3.93	ND	ND	317.50	4.13	ND	ND	ND
13	6/7/2014	9:42	38.0	8.18	0.86	195.7	0.05	0.07	3.36	ND	40.30	334.90	4.00	ND	ND	ND
14	13/7/2014	12:00	39.2	8.22	2.71	192.5	0.02	ND	3.43	ND	4.17	313.46	5.32	ND	ND	ND
15	20/7/2014	11:24	36.5	8.39	1.17	187.0	0.03	ND	3.31	ND	1.03	361.92	4.39	ND	ND	ND
16	5/8/2014	10:08	38.6	8.33	0.12	202.9	0.05	ND	5.40	ND	ND	344.39	3.99	1.35	ND	ND
17	14/8/2014	9:13	35.7	7.72	0.14	183.1	ND	0.17	3.65	ND	208.17	275.50	4.98	1.43	ND	ND

Table 8-18: Reading at Mosque Number 1164 near by West Bay Reservoir.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity. NFU	Conduc. µ s/cm	ClO_2 mg/L	Br^- mg/l	Cl^- mg/l	BrO_3^- ppb	ClO_3^- ppb	ClO_2^- ppb	$CHBr_3$ ppb	$CHCl_3$ ppb	$CHCl_2Br$ ppb	$CHClBr_2$ ppb
1	6/3/2014	11:00	23.9	8.25	0.43	184.9	0.04	0.00	3.30	ND	33.93	192.35	2.83	ND	ND	ND
2	16/3/2014	9:30	25.0	7.84	0.03	314.0	0.02	ND	2.84	ND	51.53	306.47	35.67	ND	ND	ND
3	26/3/2014	11:45	24.5	7.58	0.03	180.4	0.06	0.23	2.29	ND	10.66	215.84	ND	ND	ND	ND
4	3/4/2014	9:00	27.4	8.07	0.02	181.7	0.02	0.05	3.03	ND	55.18	203.09	7.00	0.01	0.62	0.10
5	10/4/2014	9:30	29.4	7.85	0.13	180.7	0.04	ND	3.53	ND	56.78	207.60	6.73	ND	0.54	0.06
6	6/5/2014	7:38	32.5	7.98	0.18	174.9	0.05	ND	3.39	ND	1.86	228.74	10.51	ND	5.30	ND
7	13/5/2014	8:44	35.6	7.98	0.20	187.3	0.06	ND	3.01	ND	72.03	289.53	16.68	ND	ND	ND
8	26/5/2014	8:06	37.0	8.00	0.83	206.0	0.06	ND	3.15	ND	59.34	293.99	7.87	ND	ND	ND
9	9/6/2014	7:03	35.3	7.77	0.01	169.9	0.05	ND	3.47	ND	30.62	303.59	5.11	ND	ND	ND
10	15/6/2014	7:32	35.7	7.98	0.04	201.3	0.06	0.39	3.96	ND	33.16	299.23	6.52	ND	ND	ND
11	22/6/2014	8:40	38.6	8.10	0.39	199.4	0.04	ND	5.73	ND	41.44	350.12	5.84	1.37	ND	ND
12	29/6/2014	6:59	36.5	8.06	1.39	188.4	0.06	ND	3.42	ND	ND	368.08	6.46	ND	ND	ND
13	8/7/2014	8:12	38.0	8.06	0.13	200.2	0.05	0.34	3.39	ND	ND	294.55	5.61	ND	ND	ND
14	13/7/2014	10:17	39.2	8.10	0.18	228.0	ND	ND	3.22	ND	ND	323.90	7.13	ND	ND	ND
15	5/8/2014	11:15	41.1	8.08	0.29	188.4	ND	ND	3.47	ND	27.22	303.01	6.01	ND	ND	ND
16	14/8/2014	7:33	35.9	7.80	0.23	188.2	0.05	0.09	3.55	ND	83.69	265.53	8.97	1.31	ND	ND

ND: Not detected.

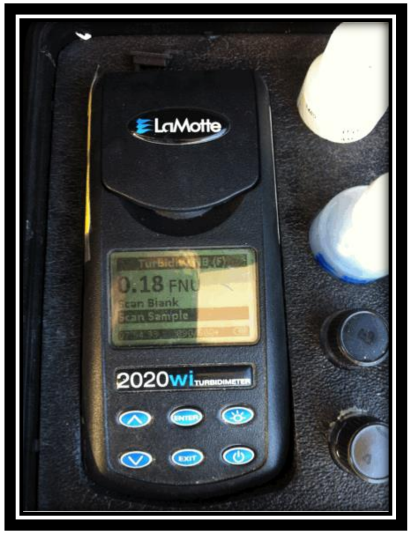
Table 8-19: Reading at Mosque Number 1066 near by West Bay Reservoir.

#	Date of collection	Time of collection a.m	Measured on site					Measured on laboratory								
			Water Tem. °C	pH	Turbidity. NFU	Conduc. µ s/cm	ClO2 mg/L	Br- mg/l	Cl- mg/l	BrO3− ppb	ClO3− ppb	ClO2− ppb	CHBr3 ppb	CHCl3 ppb	CHCl2Br ppb	CHClBr2 ppb
1	4/3/2014	7:05	25.5	8.28	0.43	190.6	0.04	0.077	3.38	ND	39.868	183.97	5.95	0.01	0.01	0.01
2	26/3/2014	10:00	22.1	7.34	0.02	179.0	0.02	0.229	2.30	ND	31.18	251.23	9.45	ND	ND	ND
3	3/4/2014	8:40	27.1	7.79	0.02	164.1	ND	0.032	2.26	ND	56.05	259.10	16.56	0.01	0.64	0.33
4	10/4/2014	9:30	31.3	7.84	0.35	185.7	0.08	ND	3.94	ND	97.30	162.74	7.51	0.01	0.66	0.07
5	6/5/2014	8:10	33.5	8.01	0.12	173.4	0.10	ND	3.43	ND	41.83	180.86	17.93	ND	5.29	ND
6	13/5/2014	9:15	36.1	7.95	0.38	179.2	0.11	ND	3.05	ND	107.98	258.9	17.33	ND	ND	ND
7	26/5/2014	8:29	37.5	7.23	0.79	182.9	0.08	ND	3.15	ND	90.45	245.61	8.14	ND	ND	ND
8	9/6/2014	7:27	35.7	7.94	0.05	192.2	0.10	0.110	3.54	ND	ND	297.25	5.43	ND	ND	ND
9	15/6/2014	7:52	36.1	7.94	0.09	190.1	0.11	0.072	4.00	ND	36.84	352.48	7.06	ND	ND	ND
10	22/6/2014	8:57	27.4	8.34	0.98	186.4	0.10	ND	6.16	ND	42.72	325.63	5.88	1.37	ND	ND
11	29/6/2014	7:19	36.6	8.00	0.44	184.8	0.13	ND	3.39	ND	34.35	370.68	6.53	ND	ND	ND
12	8/7/2014	8:32	29.2	8.18	2.34	194.4	0.09	0.090	3.40	ND	12.86	303.22	5.82	ND	ND	ND
13	13/7/2014	10:46	38.8	8.17	1.34	188.0	ND	ND	3.26	ND	32.21	356.73	6.66	ND	ND	ND
14	5/8/2014	11:35	32.7	8.30	0.18	183.9	0.10	0.089	3.47	ND	43.45	390.13	6.73	ND	ND	ND
15	14/8/2014	7:55	36.1	7.76	0.21	183.1	0.13	0.105	3.49	ND	68.62	235.78	8.42	ND	ND	ND

9. Appendix C: Images of Portable Devices and Equipment's Used in the Study.

pH, Temp., Cond.

EPA: Method 150.1, 170.1 and 120.1



Turbidity

Method 180.1

Chlorine dioxide

Palintest Chronoamperiometric Method

Nitrogen Gas Cylinder
used for purging

Author with Icebox used to
keep the samples

Measuring portable
devices

Dionex ICS 5000, used to analyse chlorite, chlorate, and bromate

Vehicle used as mini lab and for transportation samples

Headsapace Samples for THMs analysis

10. Appendix D: Images of Collection Points

Desalination Plant

Reservoirs

Ablution area in Mosques

11. Appendix E: Sampling Procedures and Analysis.

Adding the preservatives in KM's Lab

Flushing water

Measurements on-site

Purging of water sample with N2 gas

Labeling the sample

Filling the request

Transportation the samples

Sample Preparation

Sample Analysis at the Central Food Lab. Supreme Council of Health.