# Reducing Disinfection Byproduct Formation in Water Treatment Plants

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**Abstract:** River Nile contains significant concentrations of algae with an average annual value of 6189±296 unit/ml. Pre-chlorination doses of 4.77 to 6 mg/L are applied to Greater Cairo WTPs leading to the formation of annual average total trihalomethanes (TTHMs) of 30 to 125µg/L. Five of these WTPs, namely Obour, Shubra El-Kheima, Amerea, Fostat and North Helwan, where the maximum TTHMs concentration exceeds the allowable limit (100µg/L), were studied for 10 consecutive months. This study proposes a strategy for controlling the formation of THMs compounds in these WTPs by applying proper pre-chlorination doses that keeps THMs compounds below limit and satisfies residual chlorine requirements. The highest values for raw water algae count (6063±486, 6023±583unit/mL) and total organic carbon (4.44±0.399, 4.14±0.512 mg/L) were recorded at Shubra El-Kheima and Obour WTPs, respectively. Optimum pre-chlorination dose was determined using the jar test. Concentration of THMs compounds (Chloroform, bromodichloromethane, dibromochloromethane and bromoform) as well as TTHMs concentration were used as indicators to determine optimum pre-chlorination dose for each WTP. The optimum pre-chlorination dose for Obour and Shoubra Elkheima WTPs was 5 mg/L, while for the other three WTPs was 4 mg/L. Applying the optimum pre-chlorination dose, and a 1 mg/L post-chlorination dose, to one full-scale stream in each of the five WTPs led to reduction in TTHMs concentration of 29%, 26.2%, 25.5%, 27.9% and 24.4% for Obour, Shubra El-Kheima, Amerea, Fostat and North Helwan WTPs, respectively. The mean residual chlorine concentration in final effluent was below the maximum limit.
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## 1. Introduction

Chlorination has been one of the major effective drinking water disinfection strategies to treat water from illness-producing microorganism such as bacteria and viruses. However, chlorination has introduced some possible risks due to the formation of disinfection byproducts (DBPs) through disinfection process. DBPs have severed harmful health effects on animals and humans (MOE 2006). One class of these DBPs is THMs that appear in water due to chlorination process, when chlorine reacts with natural organic matter present in water.

Chlorine is used in water treatment plants (WTPs) at different stages of treatment. Pre-chlorination is used to maintain chlorine residual for the entire treatment process. The coagulation, flocculation, and filtration processes were thought also to be improved by pre-chlorination of water, and nuisance algae growths in settling basins were reduced (Chowdhuryet al., 2007). In pre-chlorination, the chlorine is usually injected into the raw water just before entering clarifiers. Pre-chlorination was the most accepted practice of disinfection in the past. However, nowadays much surface water contain organic matter that can combine with free chlorine to form potentially carcinogenic THMs, such as Chloroform, Bromodichloromethane (BDCM), Dibromochloromethane (DBCM) and Bromoform (Gang et al., 2002).

Rodriguez et al. (2002) indicated that the reaction rates of chlorine in water are dependent on several factors such as water source characteristics, treatment type, contact time and the characteristics of the distribution system. Besides the kinetics of THM formation, consumption of chlorine was also investigated. Chlorine consumption and THMs formation were very rapid during the first hours of the reaction followed by a more gradual decay and formation after 7 hours. According to Rodriguez et al., (2002), the rapid and slow decay rates are likely due to different competing reactants, such as the oxidation of inorganic compounds (rapid) and substitution reactions with NOM (relatively slow). Chlorine dose and also the residual chlorine actually considered the most critical factors in disinfection process in order to determine the final concentrations to which people could be exposed. The kinetics of the formation of THMs can be different, depending on the chlorine dose, water pH, water temperature and organic matter content. Several research studies have been conducted to examine how residence time affects THMs

formation. These studies have shown that as residence time increases, the concentration of THMs increases.

Chen and Weisel (1998) conducted experiments to examine the concentrations of DBPs in a conventional treatment plant that used chlorine to disinfect the water supply. Over 100 samples were collected in four groups, each group representing an increasing residence time from the point of disinfection. The average concentrations for TTHMs at days zero, one, two and three or more were 25±14, 30±16, 29±15 and 30±14 µg/L, respectively.

Le Bel et al. (1997) performed an experiment on a conventional water treatment system that used chlorine for primary and secondary disinfection. Four sampling points were used at an increasing distance from the treatment plant i.e. the first sample point was located at the nearest distance from WTP and the fourth was located at the farthest distance from WTP. At the first, second, third and fourth points, total THMs levels were analyzed and the results were 24.8, 37.5, 48.4 and 61.4 µg/L, respectively. These results indicate the direct relationship between the contact time of pre- chlorination dose and the concentration of formed THMs.

The maximum limit as set by WHO (1993) for THMs compounds (Chloroform, BDCM, DBCM and Bromoform) are 200, 60, 100 and 100 µg/L, respectively. Egyptian Ministry of Health and Population (2007) sets the maximum allowable limit for the accumulative TTHMs concentration of the four THMs compounds to 100 µg/L.

Table (1) illustrates the mean, minimum and maximum annual TTHMs' concentrations measured at the effluent of Greater Cairo Water Treatment Plants during the period from January to December 2017.

Table (1) Mean, Minimum and Maximum Annual TTHMs concentrations In Greater Cairo WTPs

| WTP | TTHMs "µg/L" | | |
|---|---|---|---|
| | Mean | Minimum | Maximum |
| Tebeen | 64.76±14.65 | 35.73 | 87.60 |
| Kafr El-Elw | 69.67±16.941 | 41.53 | 110.87 |
| North Helwan | 71.02±17.54 | 34.53 | 126.28 |
| Maadi | 67.29±18.23 | 40.96 | 117.20 |
| Fostat | 75.00±20.04 | 43.30 | 110.83 |
| Roda | 63.90±15.32 | 40.29 | 84.76 |
| Rod el Farg | 65.44±13.98 | 42.29 | 88.81 |
| Amerea | 74.46±16.37 | 49.08 | 88.74 |
| Mostrod | 77.44±14.97 | 38.10 | 126.66 |
| Shoubra El-Kheima | 81.67±13.66 | 57.68 | 124.33 |
| Obour | 83.09±18.36 | 60.20 | 113.98 |

It can be observed from Table (1) that the annual mean concentration of TTHMs falls below the maximum allowable limit (100 µg/L) set by Egypt Health and Population (2007). However, the annual maximum concentration of TTHMs for Kafr El-Elw, North Helwan, Maadi, Fostat, Mostrod, Shubra el Khema and Obour WTPs exceed the allowable limit set by WHO (1993) and Egyptian Ministry of Health and Population (2007). Hence, the objective of this study is to propose a strategy for controlling the formation of THM compounds in five WTPs, namely North Helwan, Fostat, Amerea, Shubra El-Kheima and Obour by applying proper pre-chlorination doses that keeps THMs compounds below limit and satisfies residual chlorine requirements.

## 2. Materials and Methods

### 2.1 Experimental Work Plan

Five WTPs serving Greater Cairo, namely, North Helwan, Fostat, Amerea, Shubra El-Khiema and Obour were selected to conduct the study. Raw water samples were collected from the intake of each of the five WTPs at the beginning of each month for 10 consecutive months. These samples were tested for turbidity, algae count and total organic carbon (TOC). Jar test, simulating clarification process, was then performed for each raw water sample collected to determine the optimum pre-chlorination dose. The optimum pre-chlorination dose was then applied in full scale to one stream of each of the five WTPs for the rest of the month to test its validity. At the end of the month, a treated water sample from the effluent of the ground reservoir was collected to measure the concentration of THMs compounds and hence investigate the effect of applying the optimum pre-chlorination dose resulting from the jar test on the treated water. The above steps were repeated for ten consecutive months, to account for the seasonal changes and temperature variations. Figure (1) illustrates water treatment flow line at each of the five WTPs as well as samples' locations and measurement taken at each location.

**2.3 Characteristics of Raw Water**

Raw water samples collected using 20 L plastic bags from the intakes of the five WTPs under study were tested at the beginning of the month for 10 consecutive months. Turbidity, algae count and total organic carbon (TOC) were measured according to the Standard Methods (EPA, 2005).

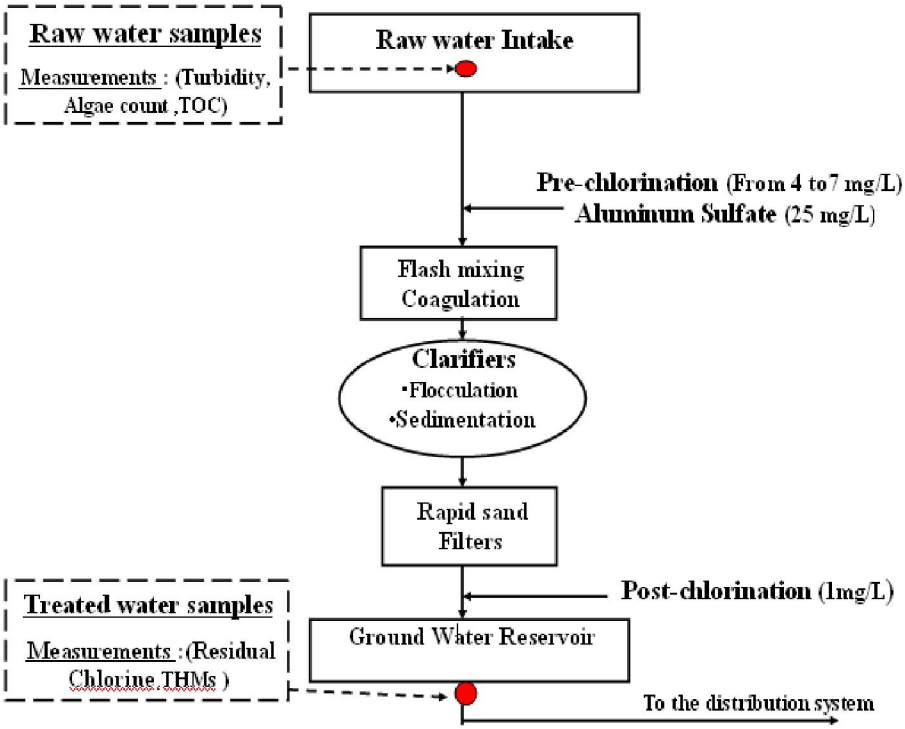



**Figure (1)** Samples' Locations and Measurements Taken at Each of the Five WTPs

**2.4 Jar Test**

Jar-test is a useful tool used to simulate physical-chemical water treatment (Aragones et al., 2009). A jar test was conducted for each raw water sample of the five WTPs under study. The experiments were carried out in a multiple stirrer jar-test apparatus (Novatech Int.). Pre-chlorination doses ranging from 3 to 8 mg/L and fixed aluminum sulfate dose of 25mg/L were added to the raw water sample in each beaker of each of the jar tests. Flash mixing speed and retention time were fixed for all jars at 120 rpm and 120 sec, respectively. Flocculation speed and retention time were set at 25 rpm and 20 min, respectively. After flocculation, beakers were left to settle for 120 min.

After settling, concentration of THMs compounds as well as TTHMs was measured for each jar to determine the concentration of Chloform, BDCM, DCBM and Bromoform according to Standard Methods (EPA, 2001). For the purpose of this study, the optimum pre-chlorination dose for each WTP was selected as the one that achieves the minimum concentration for both TTHMs and THMs compounds.

**2.5 Characteristics of Treated Water Samples**

The optimum pre-chlorination dose obtained from the jar test as well as fixed post-chlorination dose of 1mg/L was applied to one testing stream in each of the five WTPs. Treated water samples were collected, at the end of each of the 10 months from the effluent of the ground reservoir at each of the studied WTPs. The concentration of THMs compounds as well as residual chlorine was measured according to Standard Methods (U.S.EPA 1998). The resulting THMs concentrations were compared to the corresponding THMs concentration of the same five WTPs recorded at the previous year before the study. The residual chlorine was compared to the allowable residual chlorine range sated for drinking water according to Egypt Health and Population ministerial decree 458/2007.

**3. Analysis and Results**

**3.1 Characteristics of Raw Water and Treated Water before Study**

The five WTPs under study are thoroughly investigated to stand on the current characteristics of raw water and treated water for comparison purposes at the end of the study. Raw water samples from each of the five WTPs under study were tested monthly for

turbidity, algae count and TOC for the ten month period of this study. Also, the pre and post-chlorination doses currently applied in the five WTPs are recorded. For the sake of investigating the effect of optimizing the pre-chlorination dose on the characteristics of the treated water, samples from the effluent of the ground reservoir in all five WTPs were tested for THMs and residual chlorine. Table (2) illustrates the current status of the five WTPs, in terms of raw water and treated water characteristics. Values presented in Table (2) show the mean values of the ten month period of the study as well as the standard deviation.

It can be noted that the highest values for raw water algae count and TOC were recorded at the inlet of Shubra El-Kheima WTP followed by Obour WTP. On the contrary, North Helwan WTP possessed the lowest values of the measured parameters. This can be attributed to the geographical location of these WTPs with respect to the River Nile flow. North Helwan WTP is located at the upstream of the River Nile compared to the other four plants, while Shoubra El-Kheima is at the down stream. During the flow of the River Nile from North Helwan WTP to Shoubra El-Kheima WTP, agricultural, industrial as well as municipal wastewater is being disposed in the Nile, thus causing the increase in the measured parameters.

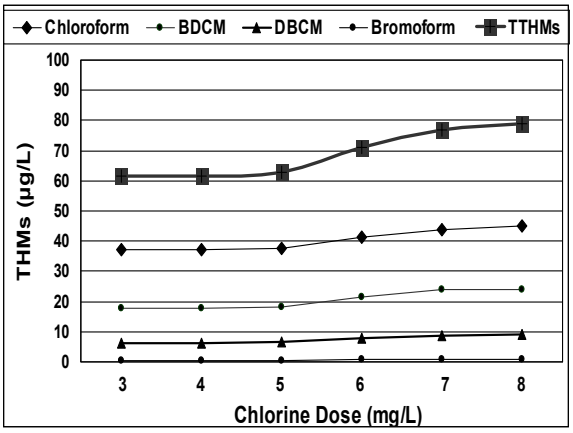
**Table (2)** Mean Results of Raw and Treated Water Samples Taken From the WTPs under Study

| WTP | Chlorine Dose (mg/L) | | Raw Water | | | Treated Water | |
|---|---|---|---|---|---|---|---|
| | Pre | Post | Turbidity (NTU) | Algae Count (unit/mL) | TOC (mg/L) | TTHMs (µg/L) | Residual Chlorine (mg/L) |
| Obour | 5.87 | 1 | 10.62±2.22 | 6023±583 | 4.14±0.512 | 83.09±17.89 | 1.68±0.19 |
| Shubra El- Kheima | 6.01 | 1 | 11.13±2.30 | 6063±486 | 4.44±0.399 | 81.67±19.04 | 1.55±.0.12 |
| Amrea | 4.94 | 1 | 10.25±2.32 | 6000±459 | 4.09±0.421 | 74.46±16.58 | 1.75±0.23 |
| Fostat | 5.00 | 1 | 9.80±2.13 | 5950±369 | 3.97±0.511 | 75.00±20.19 | 1.70±0.18 |
| North Helwan | 4.77 | 1 | 9.61±2.20 | 5713±245 | 3.91±0.344 | 71.02±18.33 | 1.79±0.24 |

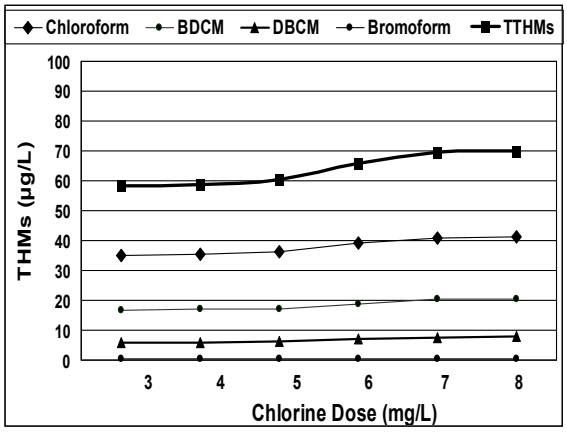
As expected, the highest pre-chlorination dose was the one applied at Shoubra El-Kheima (6.01 mg/L) and Obour (5.87 mg/L) WTPs to account for the high organic content of raw water. As a result, these two WTPs experienced the highest TTHMs concentration in the treated effluent. It can be noticed that as TOC decreased, pre-chlorination dose decreased and the resulting TTHMs concentration also decreased. This can be attributed to the direct relationship between formed THMs and both TOC, as an indicator of organic precursor, and chlorine dose at the five WTPs under study.

**3.2Jar Test Results**

A jar test was conducted on each of the five raw water samples taken from the WTPs under study using pre-chlorination doses ranging from 3-8 mg/L. The concentration of four THMs compounds and that of TTHMs were measured after settling. Figures (2 a, b, c, d and e) illustrate the effect of increasing pre-chlorination dose on the concentration of the four THMs compounds as well as the TTHMs concentration for Obour, Shubra El-Kheima, Amerea, Fostat and North Helwan WTPs respectively. The presented results account for the fourth month of the study, as an example.




(2a)

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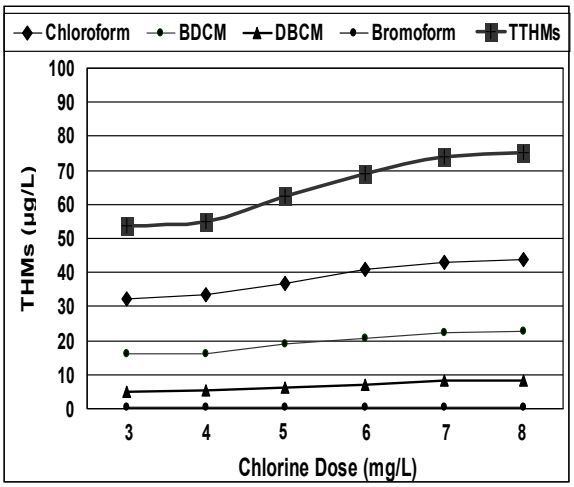


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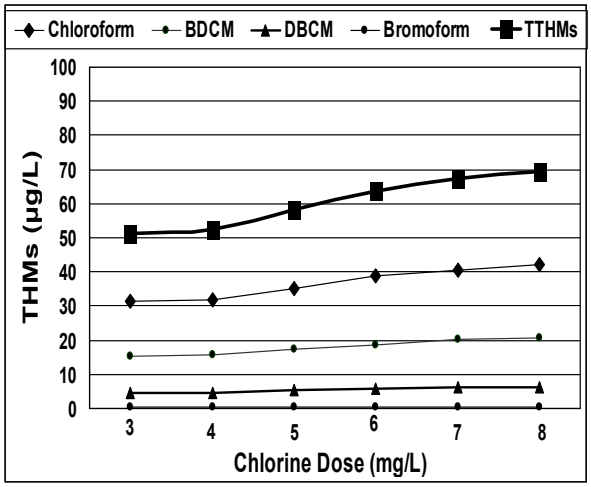


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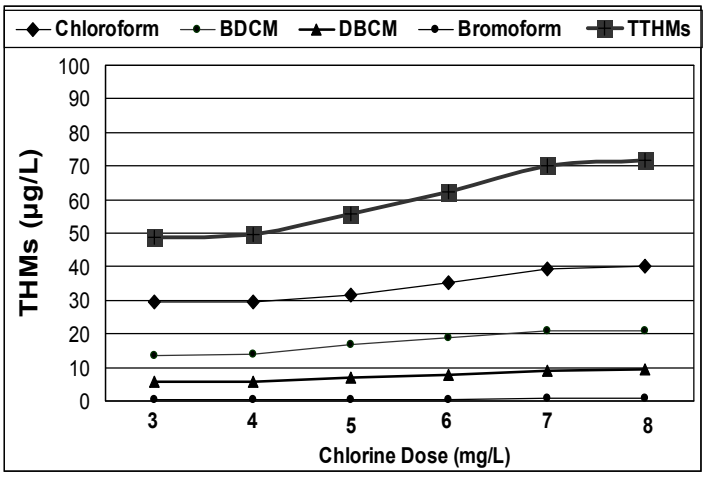


(2e)

**Figure (2a, b, c, d and e)** Concentration of TTHM and THMs compounds after Jar Test for (a) Obour, (b) Shubra El- Kheima, (c) Amerea, (d) Fostat and (e) North Helwan WTPs

It can be noted that, the concentration of THMs compounds and consequently TTHMs increased as the pre-chlorination dose increased at each of the five WTPs. The pattern of increase of each of the four THMs compounds as well as the TTHMs in each of the five WTPs is divided into 3 segments. In the first segment, the rate of increase in THMs formation is low due to the rapid consumption of chlorine by inorganic matter. This segment lies between pre-chlorination doses of 3 to 5 mg/L for both Obour and Shubra El-Kheima, and 3 to 4 mg/L for the other three WTPs. The second segment is located between 5 and 7 mg/L of pre-chlorination dose for both Obour and Shubra El-Kheima, and 4 to 7 mg/L for the other three WTPs. This second part is characterized by a relatively higher linear increase in THMs formation compared to the first segment. This can be attributed to the reaction of added chlorine with available organic material in raw water. The third and last segment lies between pre-chlorination doses of 7-8 mg/L where a slight increase in total TTHMs formation rate can be observed.

The same jar test was repeated ten times, once every month to test the variation in the value of the optimum pre-chlorination dose obtained from the jar test, if any. Figure (3) summarizes the results of the mean TTHMs concentration obtained from the jar tests conducted on the five WTPs at the beginning of each of the ten months of the study period. It is observed that there is no significant variation in the values of the optimum pre-chlorination dose obtained from the jar test during the ten months. Therefore, it can be concluded that the optimum pre-chlorination dose for Obour and Shoubra El-kheima WTPs is 5 mg/L, while for the other three WTPs is 4 mg/L.

**3.3 Analysis of Treated Water after Jar Test**

The optimum pre-chlorination dose obtained from the jar test at the beginning of each month for each of the five WTPs under study was applied to a full-scale testing stream in the corresponding WTP for validation in real environment during that month. A fixed post-chlorination dose of 1mg/L was also applied at the inlet of the ground reservoir at each of the five WTPs. THMs compounds as well as residual chlorine were measured at the effluent of the plant to investigate the effect of applying the optimum pre-chlorination dose of 5 mg/L to Obour and Shoubra El-Kheima WTPs and 4 mg/L to the other WTPs. The treated water TTHMs concentration from the testing stream, after applying the optimum dose obtained from the jar test is compared with the corresponding value before the study at the same month of the preceding year.

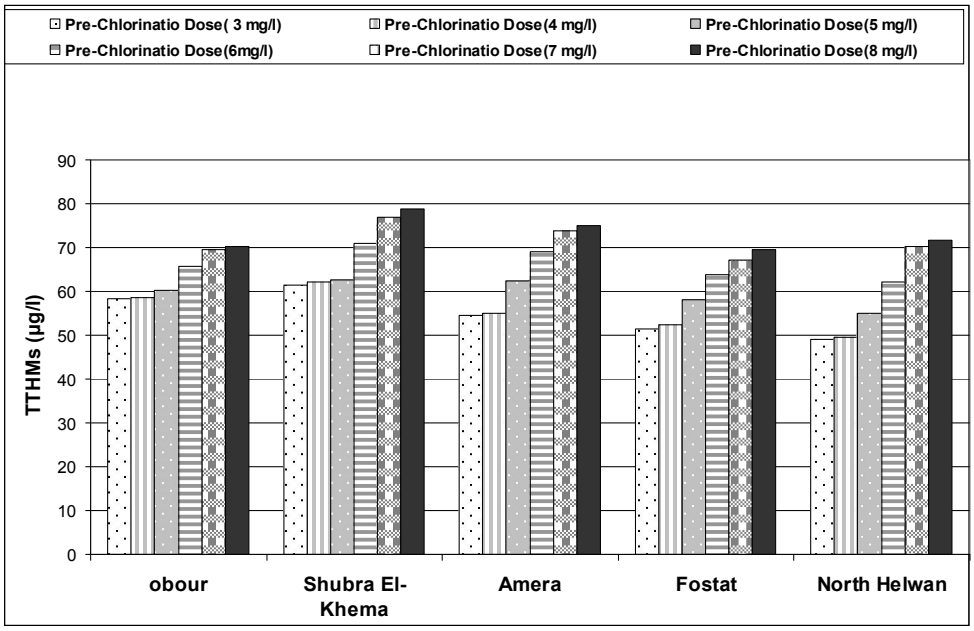


**Figure (3)** Results of the Average TTHMs Concentration Obtained From the Jar Tests Conducted on the Five WTPs

Figure (4) shows the maximum value of TTHMs measured over the ten month study period for each of the five WTPs after applying the optimum pre-chlorination dose and the corresponding values before this study.

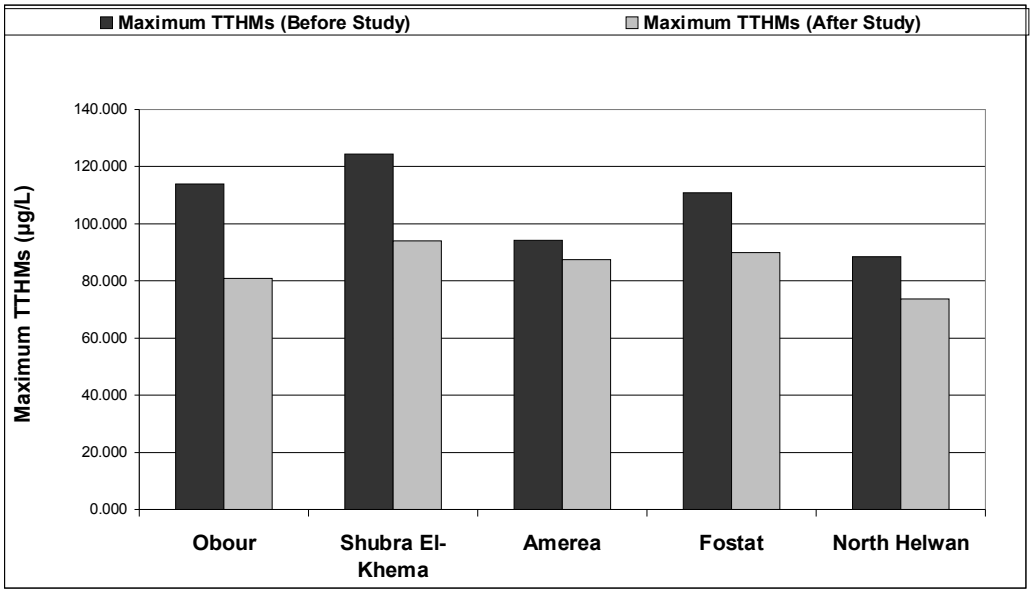


**Figure (4)** Maximum Value of TTHMs before and After the Study

The maximum TTHMs concentration of treated water at the effluent of the testing stream at each of the five WTPs was 80.9±8.03, 94.1±13.33, 87.4±13.98, 89.9±18.33and 73.6±14.09 µg/L, respectively. Thus, reduction in TTHMs concentration were 29%, 26.2%, 25.5%,18.8% and 24.4% for Obour, Shubra El-Khema, Amerea, Fostat and North Helwan WTPs, respectively. It can be noted that TTHMs concentrations as well as the concentration of THMs compounds fall below the maximum allowable limit of 100 µg/L (Egypt Ministry of Health and Population, 2007).

## 4. Conclusions

The objective of this study is to propose a strategy for reducing the concentration of TTHM and its compounds in five WTPs in Greater Cairo, namely North Helwan, Fostat, Amerea, Shubra El-Kheima and Obour, where currently the maximum concentrations are above allowable limits.

Jar test was conducted on raw water samples from each of the five WTPs for 10 consecutive months to determine the optimum pre-chlorination dose. The optimum pre-chlorination dose, the one that keeps THM compounds below limit and satisfies residual chlorine requirements, was determined as 5 mg/L for Obour and Shoubra El-kheima WTPs, while for the other three WTPs was 4 mg/L. The maximum TTHMs concentration of treated water at the effluent of the testing stream at each of the five WTPs was 80.9±8.03, 94.1±13.33, 87.4±13.98, 89.9±18.33and 73.6±14.09 µg/L, respectively. Thus, reduction in TTHMs concentration were 29%, 26.2%, 25.5%,18.8% and 24.4% for Obour, Shubra El-Khema, Amerea, Fostat and North Helwan WTPs, respectively.

The mean residual chlorine concentration in the treated water of the five WTPs falls between 0.5 and 5.0 mg/L which is below the maximum limit set by Egypt Health and Population (2007).

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