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Assessment Of Water Quality in Chlorinated Drinking Water Distribution Networks Regarding to Trihalomethanes Formation

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Water quality - Water treatment - Disinfection - Trihalomethanes - WaterGEMS.

Abstract

Chlorine disinfection in traditional water treatment plants is a popular and low-cost method for disinfecting raw water before it is distributed to consumers in Egypt. Nevertheless, the chlorination process in the presence of natural organic matter and decreased water quality due to uncontrollable population results in formation of high concentrations of carcinogenic disinfection by-products, from which trihalomethanes (THMs). In this paper, the water quality of Assiut drinking water network (ADWN) was assessed in terms of THMs studying different water quality parameters. An extended period simulation based on a modelling software WaterGEMS was employed to obtain the critical locations to be examined according to key parameters namely: water age, residual chlorine concentration, water velocity, and type of storage. The study concluded that THMs concentrations from all critical locations in Assiut drinking water network would not go over the Egyptian regulatory threshold and US Environmental Protection Agency (EPA) guidelines. Some locations in ADWN showed zero residual chlorine concentration at different times a day. It is recommended that more chlorine injection points should be installed in various locations based on water quality modelling and in-field analysis. Even more, an investigated domestic roof tank should be critically operated under a planned scheme of monitoring and maintenance due to its deteriorated water quality. A wash valve chamber should be installed in the surrounding area of El-Molimen water treatment plant, that would be periodically employed by the central operator to clean the network at those locations.

1. Introduction

The purpose of water treatment, whether it comes from the surface or ground resources, is to remove impurities and pathogens using a combination of biological, chemical, and physical processes to make it safe for humans. Some of these treatment procedures occur naturally in

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the environment, while others are used in man-made and designed water treatment plants (WTPs). Due to the unlimited increase of population, a critical negative impact would be anticipated that raise the natural organic matter (NOM) concentrations in raw water resources in addition to growth of pathogenic microorganisms. The risk could be reflected on the water quality that reach drinking water networks, that must be periodically investigated to monitor the possible impacts of these uncontrollable changes [1]. Filtration and its preceding processes in traditional WTPs focus on the physical removal of pollutants in the raw water [2]. Chemical disinfection is still necessary to kill or inactivate pathogens such as bacteria, giardia, and viruses, in addition to physical removal [3]. Commonly used disinfectants include chlorine, chloramines (chlorine plus ammonia), ozone, ultraviolet light, and chlorine dioxide. From which, chlorine is considered the most employed disinfectant especially in developing countries like Egypt. Chlorine disinfection is a critical step in preventing the spread of potentially fatal waterborne illnesses [4].

Recently, there has been a global concern about the disinfection by-products (DBPs) generated from using chlorine as disinfectant during water treatment. DBPs are produced inexorably as a result of complicated reaction of organic and/or NOM, halides (i.e., Br^{-} and I^{-}) in water with disinfectants. NOM is made up of a complex combination of chemical molecules that generated due to vegetation decay and human activities. They include different proportions like carbohydrates, hydrophilic, carboxylic and amino acids in addition to humic substances. Humic acids are a substantial component of the soluble portion (aromatic chemicals), which react with chlorine to produce trihalomethanes (THMs) [3]. These mentioned compounds are considered as genotoxic mutagens and toxic. Additionally, According to previous epidemiological studies, DBPs are linked to an increased risk of bladder and colon cancer, as well as premature birth and stillbirth [5] [6]. THMs are the most common DBPs in chlorinated drinking water, accounting for roughly 13.7 percent of the halogenated DBPs detected in 12 US drinking water treatment plants [3]. THMs comprise of four principal proportions: chloroform, bromoform, bromodichloromethane and dibromochloromethane. THMs are determined by Egyptian laws using a mean threshold of 100 g/L and a minimum of four seasonal samples collected at the end of drinking water networks every year. According to the United States Environmental Protection Agency (US EPA), the maximum allowed levels of THMs in drinking water should not exceed 80 μg/L [7].

Nevertheless, limited studies were carried out about the fate of THMs in Egypt and this type of research is still in exploratory stage. A study on Cairo drinking water distribution system has been conducted to examine the concentrations and distribution of THMs. The results showed that, the concentrations of THMs in drinking water in Cairo had wide variation. Out of 70 examined samples, 26 samples were exceeded 100 µg/L (the maximum allowable THMs concentrations according to Egyptian standards). Another study was conducted in Beni-Suif during February 1997 to May 1998, Fowl city from October 1998 to January 1999, and Meet Fars city from May 1999 to August 1999. The treatment plants used the conventional treatment process including alum addition, pre-chlorination, flash mixing, flocculation, sedimentation, rapid sand filtration, and post-chlorination. Beni-Suif city has three water treatment plants, it was found that, the mean concentrations of THMs were as follows 179.13 µg/L for the first plant, 52.69 µg/L for the second plant, and 87.83 µg/L for the last one. Fowl city has one treatment plant and the mean THMs concentration was found

to be 19.4 µg/L. As for Meet Fars city which intakes its raw water from an irrigation canal (Meet Tanah), the mean THMs concentration was found to be 51.93 µg/L [8].
Therefore, this research was carried out to assess the safety of Assiut drinking water network (ADWN) in terms of THMs and its compatibility with the local standards (Egyptian code of practice) as well. Different water quality key parameters were taken into consideration to investigate the critical locations in the network. They include chlorine concentration, water velocity, type of storage, and water age. Water age was estimated using a simulation software (WaterGEMS) based on the full details of ADWN collected from the central operators. In addition, the microbiological quality of ADWN in terms of Chlorophyll concentration have been investigated.

2. Materials and Methods

2.1. Assiut drinking water network description

The current research is dedicated to study the water quality of Assiut city drinking water network (ADWN), which is showed in Fig. 1. The total pipeline lengths of ADWN are about 77.5 km including fittings and valve chambers of different diameters. The used pipes are cast iron (CI), Asbestos, and glass fiber Reinforced Plastic (GRP) with diameters ranged from 200 to 1000 mm. The smaller diameters are not considered in this study. The ADWN has around 100 junctions, whose levels range from 50 to 65 m. The drinking water demands at those junctions are estimated based on the surrounding served population in the relation to the total demand (see supplementary files). The drinking water in the ADWN is continuously supplied by eight water treatment plants with a total production of 124000 m^3/day (Table 1).

Table (1): Water treatment plants that supply drinking water into ADWN

No.	Pumping station	Pumps				Average production (m^3/day)
		No. of main pumps	Q/pump (L/s)	H (m)	Working hours	
1	Nazlet Abdellah (S)	3	300	50	24	85417
2	El- Helaly (S)	2	200	50	24	15247
3	El- Walideya (A)	6	30	40	24	9421
4	El- Baladya club (A)	2	30	40	24	1814
5	El- Gamaa (C)	2	30	40	16	752
6	El-Sadreya (Poster)	3	100	50	24	Poster
7	El- Moallemeen (A)	During the study was out of service				
8	El- Arbaeen (C)	2	30	40	16	1360
9	Qebly El-Hamara (A)	8	30	40	24	9770
Total demand (m^3/day)						123781

* S: Surface water treatment plant, A: Artesian well water treatment plant, C: Compact unit's plant

In addition, two tanks were considered in this study, one of them is a high-elevated tank operated by the central operator in Assiut (Tank 1: Old El-Gamaa HET). While Tank 2 is a domestic tank which is randomly operated by unskilled labour without any scheduled plan. The other high-elevated tanks in the ADWN were out of service during the study period.

Both surface and compact water treatment plants intake their raw water from the Nile River and its branches. The employed treatment plan is pre-chlorination, flash mixing, coagulation and flocculation, rapid sand filtration, and post-chlorination. Pre- and post-chlorination result in more formation of THMs inside the treatment plants thanks to high NOM concentration during the treatment process [9]. The employed treatment approach is not dedicated to remove the formed THMs, which means that these concentrations are further conveyed into the ADWN. On the other hand, the artesian wells pump their water from 40 m below ground level without any disinfection, since they depend on hydraulic mixing with the chlorinated water pumped into ADWN.

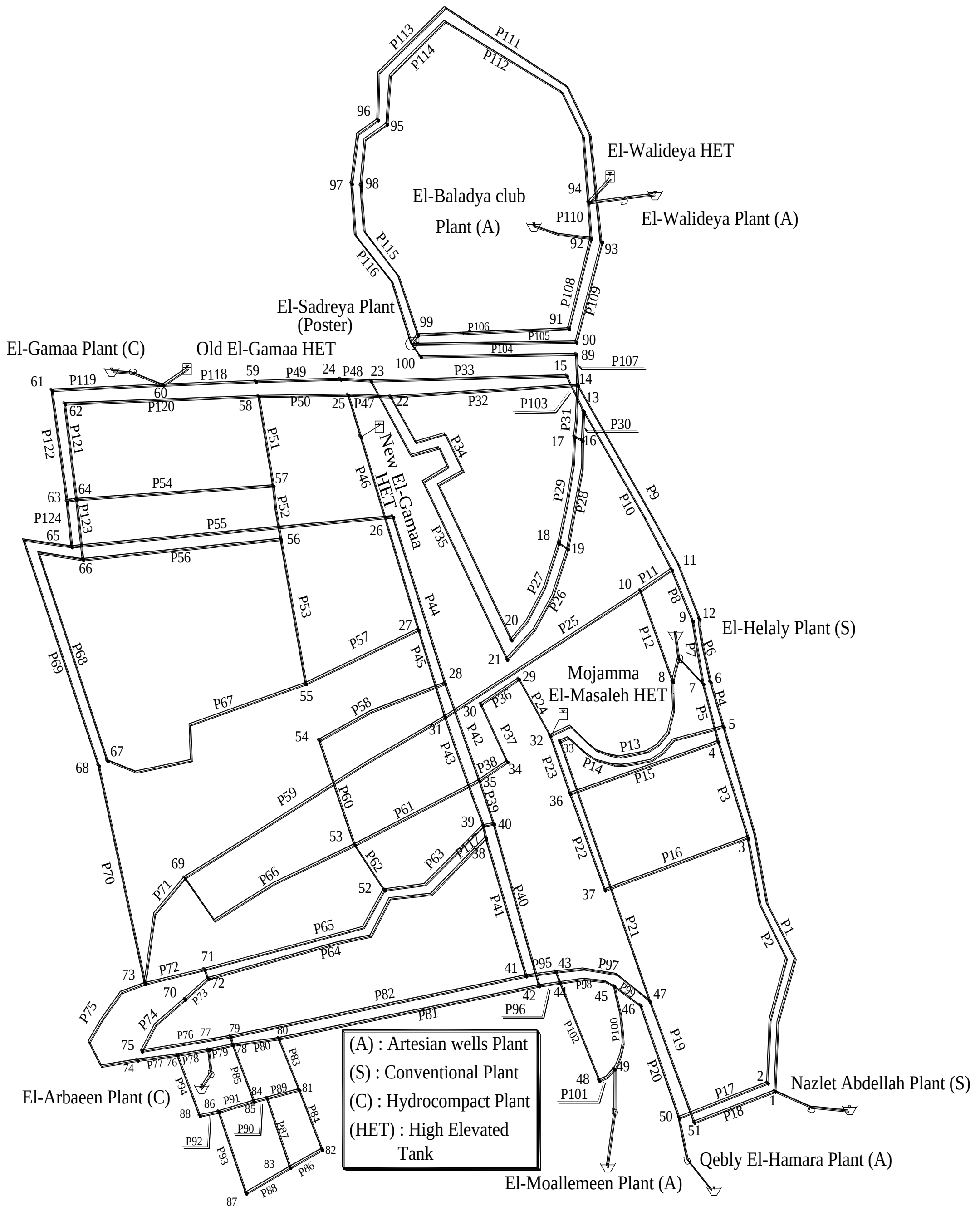

Fig. (1): The main Assiut drinking water network (ADWN)

WaterGEMS software was employed to simulate the hydraulic and water quality modelling of ADWN under extended period simulation (EPS) considering the diurnal curve of demands (Fig. 2) and data obtained from the central operator. The diurnal curve considers the water demands at the junctions in a periodic way over in 24 hours [10].

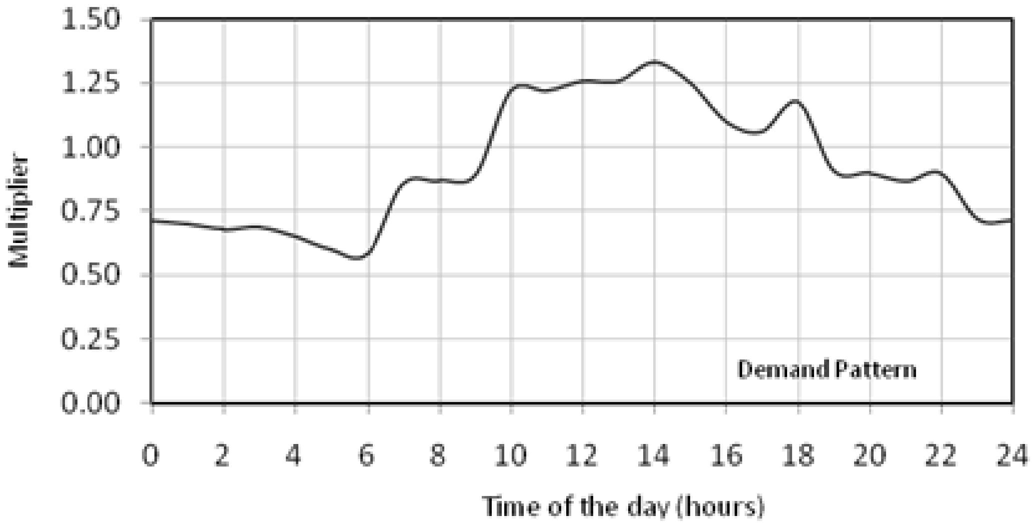

Fig. (2): A Diurnal curve of demands in ADWN

WaterGEMS is a powerful software serving to simulate and analyze pressurized distribution networks whatever their characteristics. Many benefits could be obtained by employing WaterGEMS, for example, performing steady-state and extended period simulation analysis of water distribution networks regarding to variable supply and demand patterns. Water quality parameters could be also simulated like water age and constituents monitoring. In addition, fire flow analysis could be determined according to extreme conditions. Link to geographic information system shapefiles and databases is available as well [11].

2.2. Analytical methods

Different samples were analysed from various locations in ADWN to assess the network safety in terms of THMs concentrations based on the extended period simulation performed using WaterGEMS. The considered parameters were water age, residual chlorine concentration, type of storage, and velocity. A series of 40 mL brown vials supplemented by sodium thiosulphate that inhibit further chemical reaction after sampling were used. pH meter (The Oyster pH meter, EXTECH instruments No: 601208) was used for determination of pH value. THMs concentrations were measured by liquid/liquid extraction followed by gas chromatographic (Gas Chromatograph-GC) provided with electron capture detector at certain quantification and reporting limits and equipped by column CP SIL 19 CB. Laboratory duplicates were analysed within each analytical batch. The absolute difference must not exceed the assigned repeatability limit of each individual sample. Laboratory spiked blank (LSB) was analysed within each batch, where the estimated recovery shall be within 80-110%. Residual chlorine concentrations, NH_3, Chlorophyll, TKN, and conductivity were analysed according to standard methods guidelines.

3. Results and discussions

3.1. Effect of maximum water age on THMs concentration

To investigate the effect of maximum water age on the concentration of THMs, the ADWN model was analysed using WaterGEMS software under extended period simulation (EPS) estimating maximum water age over 24 h. As shown in Fig. 3, junction No. 20 (J20) of 10.8 h was found with the highest maximum water age in ADWN. The measured THMs concentration at this location peaked at 46.99 µg/L, which is lower than the threshold set by US Environmental Protection Agency (EPA) at 80 µg/L and Egyptian standards (100 µg/L), i.e., safe to be municipally consumed [12]. In addition, Fig. 3 shows the positive relationship between the water age and THMs concentration in ADWN, which implies the serious effect of the extended retention time of chlorinated water in the presence of NOM in the network. Conversely at lower water ages, the contact time between residual chlorine and NOM would not be long enough to increase the concentration of THMs.
Chloroform has the dominant fraction (28.22 µg/L) among the four THMs components at the maximum water age (Table 2) as observed by earlier researchers [13][14]. High levels of Chloroform in chlorinated water networks is attributed to the reaction between residual chlorine and NOM, which usually come from personal care products, pharmaceuticals, plasticizers, fragrances, etc. [15]. Fortunately, the Chloroform concentration is extremely safe in accordance to EPA's threshold of 300 µg/L in the ADWN. It is worth to be noted that the acute health problems such as renal tubular necrosis and liver toxicity resulted from long-term chloroform exposure are scarce and related to high concentrations [16].

Table (2): Concentrations of THMs components at the maximum water age (µg/L)

Location	Water Age (h)	Chloroform	Bromodichloromethane	Dibromochloromethane	Bromoform
J20	10.81	28.22	14.30	4.21	0.26

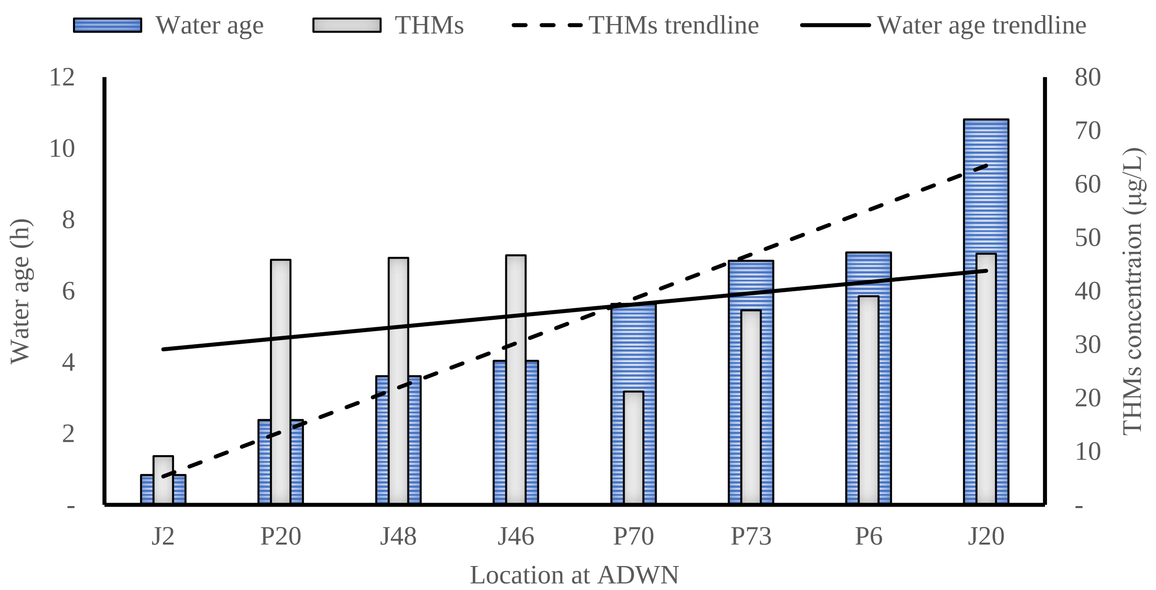

Fig. (3): Effect of water age on THMs concentration at different locations at ADWN

Refer to Fig. 3, the high levels of THMs concentrations at P20, J48 and J46 although low water ages are likely related to the estimated residual chlorine concentrations (0.00 mg/L) at most times of the day. The result which may be interpreted by high NOM contamination of ADWN at these locations (Fig. 1) [6], that rapidly reacted with residual chlorine and formed THMs in the short time (~ 3 h) [8]. Taking a look at the geometry of ADWN, it was observed that the elevation of this part of the network which includes P20, J46 and J48 is lower than the surrounding area by average 6.0 m. The lower elevation of this location results in the accumulation of contaminants which reacts quickly with incoming residual chlorine, resulting in high concentrations of THMs accordingly. Therefore, the central operator should consider a wash valve chamber that should be employed periodically to clean the network at those locations.

3.2. Effect of conductivity and pH value on THMs concentrations

As shown in Fig. 4, the THMs concentrations are conversely correlated to conductivity. Amaras Oriya et al. [17] experienced strong negative correlations between conductivity and THMs concentration in different locations in Sri Lanka. It was also reported that conductivity plays an indirect role in THMs formation since one of the favourable precursors for THMs is hydrophobic NOM. As water conductivity increases, aggregation of NOM into large moieties due to its water repellence would occur. Nevertheless, the aggregation decreased at lower conductivity values, thus dispersing small-grained NOM moieties in water. The surface reactivity of those small NOM moieties is likely higher than large moieties thanks to its improved reactivity sites [18]. Consequently, the formation of THMs increases in low conductivity water.

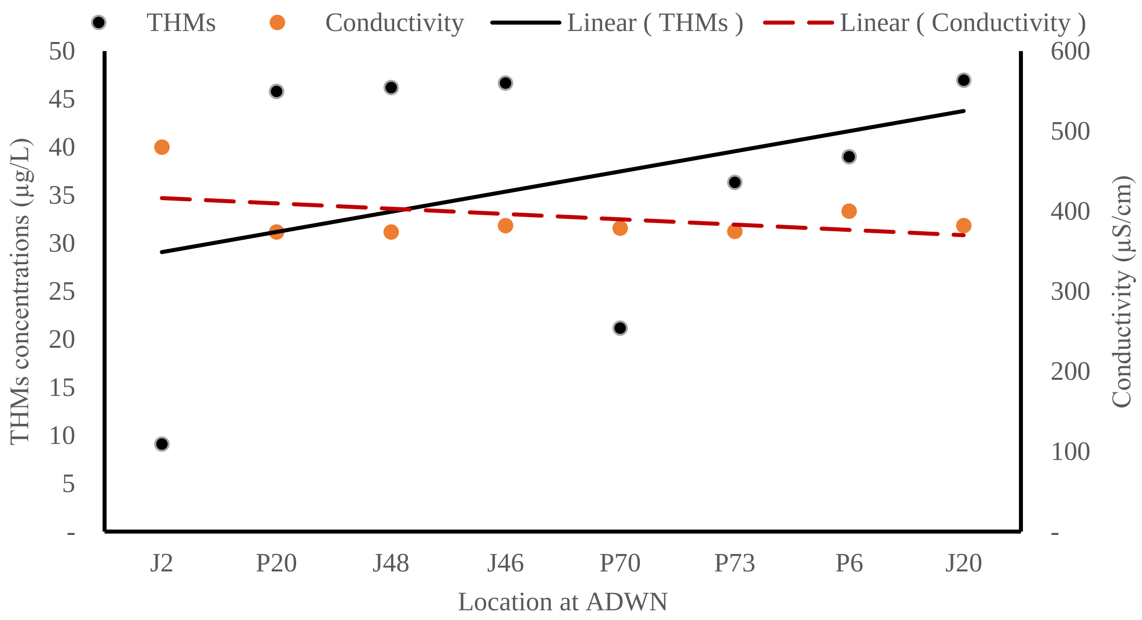

Fig. (4): THMs concentrations in relation to conductivity values in ADWN

No relationship between pH value and concentrations of THMs in ADWN could be established. The values of pH are relatively constant at the different locations (~ 7.43), which is completely safe according to EPA guidelines and Egyptian standards (6.5 – 8.5).

3.3. Water storage assessment in the ADWN in terms of THMs concentrations

Two different available tanks in ADWN were selected to represent the network in terms of storage type. Tank 1 represents a high-elevated tank which is operated by the ADWN central operator in Assiut, while Tank 2 is a domestic roof tank which is operated randomly without a scheme. As shown in Table 3, both tanks provide safe drinking waters regarding to the analysed water quality parameters, from which THMs concentrations. However, THMs level is higher at Tank 2 that operated randomly with unskilled labours. This result is coincided with the Total Kjeldahl Nitrogen (TKN) and Chlorophyll values, which depict high tank contamination. In addition, a trace concentration of NH_3 was observed at Tank 2, which implies active NOM reactions aerobically and/or anaerobically. Therefore, it is strong recommended to plan a strict scheme to operate and maintain Tank 2 to safely provide drinking water at long-term to consumers. In addition, air vent pipes with suitable diameters (~ Φ200 mm) should be installed on the tank's roof to provide sufficient aeration in the entire tank.

Table (3): THMs concentration at two different available tanks in ADWN

Tank	**NH_3**	**Chlorophyll**	Bromodi-chloro-methane	Dibromo-chloro-methane	Chloroform	THMs
Tank 1	**0.00**	**0.01007**	**16.96**	**8.55**	**2.56**	**28.27**
Tank 2	**0.063**	**0.09111**	**21.18**	**10.58**	**3.53**	**35.63**

*Tank 1: regularly operated by the ADWN central operator in Assiut (Old El-Gamaa HET-Fig. 1)
*Tank 2: a domestic roof tank which is operated randomly without a scheme

3.4. Chlorophyll and TKN correlations with THMs concentrations

One of the symptoms of deteriorated water quality condition is the increase of the chlorophyll concentration. Chlorophyll allows plants (including algae) to photosynthesize to convert simple molecules into NOM. With these concentrations in the presence of residual chlorine in a water network, high levels of THMs concentrations would be expected. As shown in Fig. 5, a positive correlation between Chlorophyll and THMs concentrations is observed. THMs concentrations increased from 9.10 to 46.99 µg/L as Chlorophyll concentration increased from 0.001 to 0.058 mg chlorophyll/L of water. The results are supported by the inverse trendline of water velocity in ADWN, which decreased from 0.61 to 0.00 m/s as THMs and Chlorophyll concentrations augmented. Decreased water velocity provide a relevant sufficient time to trigger the reaction between the residual chlorine and NOM forming THMs in the network [8] [19].

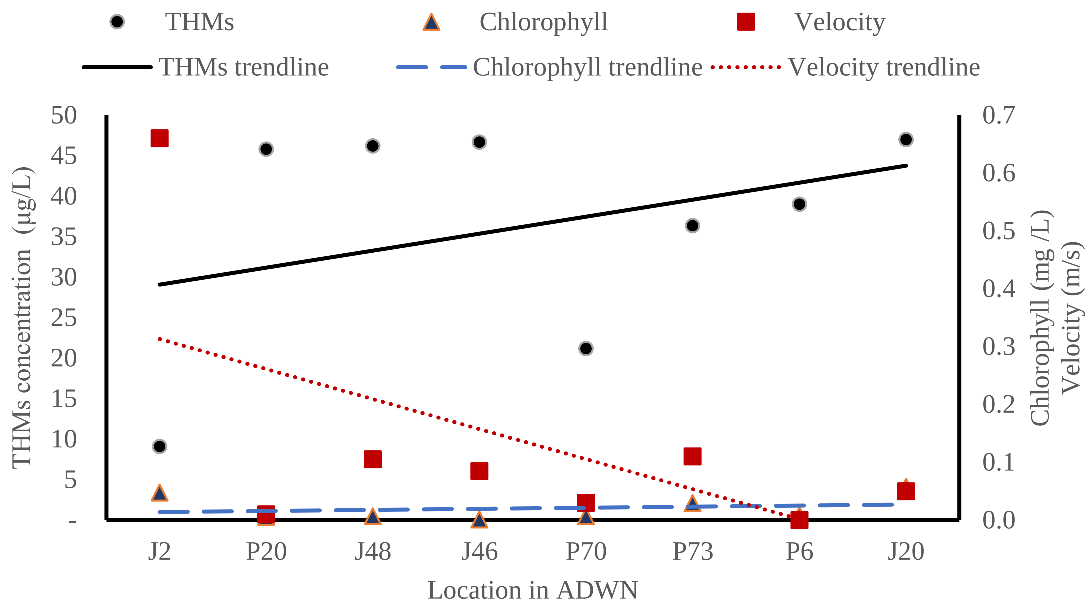

Fig. (5): The relationship between THMs concentration, velocity, and Chlorophyll in ADWN

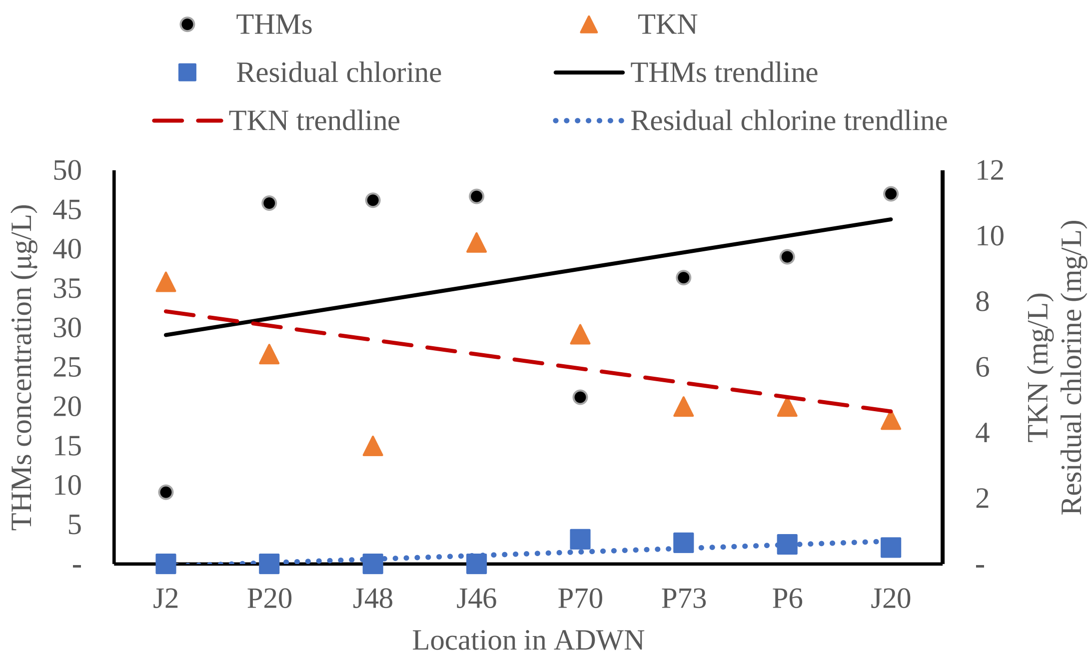

Fig. (6): Influence of TKN on THMs concentration in ADWN

As depicted in Fig. 6, decreased concentrations of TKN in comparison to high levels of THMs indicates significant consumption of organic nitrogen and increased uptake of residual chlorine [20]. This result could be observed in Fig. 6 from the inverse relationship between TKN and residual chlorine in different locations in ADWN as well. Since high levels of organic nitrogen contained in TKN resulted in increased levels of chlorine disinfection by-products. Thus, the residual chlorine is expected to be decreased to form them. However, the inverse relationship between TKN and THMs is attributed to that the reaction between organic nitrogen measured in TKN goes to the direction of production other DBPs such as halo acetic acids (HAA) namely di-HAA, tri-HAA, and halogenated nitromethanes rather than THMs [21]. In other words, more TKN in the presence of low residual chlorine concentrations means low THMs concentrations. However, low TKN concentration but more residual chlorine results in higher THMs concentrations as shown in Fig. 6.

4. Conclusions

The current research aims to check the water quality safety of the chlorinated Assiut drinking water network (ADWN) in terms of trihalomethanes (THMs). The investigated parameters were pH value, TKN, Chlorophyll, NH_3, and residual chlorine concentration. WaterGEMS software was employed to extended period simulate the ADWN to obtain the water age at different locations in the network and study its effect on THMs concentrations. It is concluded that the ADWN is safe in terms of THMs concentrations (Max. obtained THMs = 46.99 μg/L) and other investigated parameters as well. Peak chloroform of 28.22 μg/L amounted the main and largest compound of THMs. No relationship between pH value and concentrations of THMs in ADWN could be established. The values of pH are relatively constant at the different locations (~ 7.43), which is completely safe according to EPA guidelines and Egyptian standards (6.5 – 8.5). On the other hand, one location of a domestic roof tank with deteriorated operation and maintenance scheme should be seriously considered to safely supply potable water to consumers. In addition, air vent pipes with suitable diameters (~ Φ200 mm) should be installed on the tank's roof to provide sufficient aeration in the entire tank.

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تقييم جودة المياه في شبكات توزيع مياه الشرب المكلورة فيما يتعلق بتكوين ثلاثي الهالوميثان

الملخص العربي:

يعد تطهير الكلور في محطات معالجة المياه التقليدية في مصر أسلوبًا شائعًا وغير مكلف لتطهير المياه الخام قبل توزيعها على المستهلكين. ومع ذلك، فإن عملية الكلورة في وجود المواد العضوية الطبيعية وانخفاض جودة المياه بسبب تزايد عدد السكان غير الخاضع للسيطرة تؤدي إلى تكوين تركيزات عالية من المنتجات الثانوية للتطهير المسببة للسرطان مع مرور الزمن، والتي منها ثلاثي الميثان (Trihalomethanes: THMs). في هذا البحث، تم تقييم جودة المياه لشبكة مياه الشرب بأسيوط (Assiut Drinking Water Network: ADWN) من حيث تركيزات THMs بدراسة معايير مختلفة لجودة مياه الشرب. كما تم استخدام نمذجة ومحاكاة الفترة الممتدة بناءً على برنامج WaterGEMS للحصول على المواقع الحرجة التي سيتم فحصها وفقًا لمعايير الدراسة الرئيسية وهي: عمر الماء، تركيز الكلور المتبقي، سرعة الماء، وكيفية التخزين.

وقد خلصت الدراسة إلى أن تركيزات THMs من جميع المواقع الحرجة في شبكة مياه الشرب بأسيوط لن تتجاوز القيمة القياسية المصرية وإرشادات وكالة حماية البيئة الأمريكية (Environmental Protection Agency: EPA) حيث بلغت أقصى قيمة بالشبكة ٤٦,٩٩ ميكروجرام/لتر، مما يجعل الشبكة آمنة من هذا الجانب. كمـــا أوضحت الدراسة أن مركب الكلوروفورم هو المركب الأساسي والأكبر من بين المركبات الأربعة الأساسية المكونة لثلاثي الميثان THMs بنسبة تتجاوز ٦٠٪. وتُعزى القيم العالية من الكلوروفورم في شبكة مياه الشرب بأسيوط المكلورة إلى التفاعل بين الكلور الحر المتبقي والمواد العضوية بالشبكة، والتي تتكون عادةً نتيجة استخدام منتجات العناية الشخصية، والمستحضرات الطبية، والعطور، إلخ.

ومع ذلك، فقط أظهرت الدراسة بعض الملاحظات الواجب تداركها وتلافيها من قبل الشركة المسئولة عن تشغيل وصيانة الشبكة. ومن بينها، فقد لوحظ ببعض المواقع في شبكة مياه الشرب بمدينة أسيوط انعدام وجود تركيزات للكلور الحر المتبقي في أوقات مختلفة خلال اليوم، مما يخالف توصيات الكود المصري بأنه لا يجب ألا يقل تركيز الكلور الحر المتبقي عند نقطة الاستخدام عن ٠,٢ مجم/لتر. لذلك يوصى مؤلفو هذا البحث بتركيب المزيد من نقاط حقن الكلور في مواقع مختلفة بالشبكة بناءً على نمذجة جودة المياه والتحليل الميداني لتركيزات الكلور الحر المتبقي، بما لا يؤثر سلبا على صحة الإنسان بالزيادة غير المناسبة لكميات الكلور حال حقنها.

كما يوصي البحث أيضا بضرورة تركيب غرفة (أو غرف) صمام غسيل في المنطقة المحيطة بمحطة تنقية مياه الشرب في منطقة المعلمين (متوقفة خلال فترة الدراسة)، الغرف التي يجب تشغيلها بشكل دوري من قبل الشركة المسئولة لتنظيف وتطهير الشبكة في ذلك الحيز. حيث لوحظ ارتفاع التلوث بها متمثلا في ارتفاع تركيزات ثلاثي الميثان THMs والكلوروفيل والنيتروجين العضوي وانعدام تركيز الكلور الحر المتبقي في اغلب فترات اليوم. الأمر الذي يعزز من ضرورة حقن الكلور بمنطقة قريبة منها مع التطهير الدوري للحفاظ علي جودة المياه بذلك الحيز، خاصة وأن منسوبها يدنو عن المنطقة المحيطة بها بأعماق تزيد عن خمسة أمتار.

علاوة على ذلك، لوحظ تدهور جودة المياه بخزان علوي فوق إحدى المنشآت بالمدينة، حيث وصل تركيز النوشادر الحر به الى ٠,٠٦٣ مجم/لتر والكلوروفيل الى ٠,٠٩١ مجم/لتر (أعلى قيم بالشبكة، ولكنها آمنة حسب توصيات الكود المصري)، الأمر الذي يحتم فحصه بشكل عاجل ودوري وفقًا لخطة مراقبة وصيانة من قبل فنيين وعمال مدربين. كما يوصي بتركيب مواسير تهوية بأقطار وأعداد مناسبة (~ ٢٠٠ مم) على سطح الخزان لتوفير تهوية كافية داخله، وتفادي حدوث تحللات عضوية لاهوائية.