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Research Application Summary

Management of chlorine decay and formation of disinfectant by-products in drinking water: A case of Gaborone City, Botswana

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Abstract

Chlorine is used in most countries as a disinfectant to control multiplication of pathogenic bacteria in potable water. However, water suppliers have two major challenges in management of chlorine disinfection in water distribution systems (WDS): decay and disinfectant by-products (DBPs) formation. This is a preliminary study to investigate the occurrence of chlorine decay and DBPs formation and how they are affected by water quality factors after water treatment in Gaborone city WDS. The study was conducted by water analysis for chlorine residual, DBPs and water quality factors (natural organic matter, iron, manganese, heterotrophic plate counts, temperature and pH) that may influence chlorine decay and DBPs formation in a WDS. Water samples analyzed were from treatment plants, reservoirs and customers' taps. The results demonstrate that there is a high chlorine dosage at treatment plants, low chlorine residual at remote areas of the network, high rate of chlorine decay and presence of DBPs in the WDS. Water quality factors that are suspected to be contributing to chlorine decay and formation of DBPs are organic compounds, high temperature and biofilm growth. However, other factors related to hydraulic conditions can also influence chlorine decay in a WDS. Therefore, the study recommends (1) further investigation of the effects of organic compounds, temperature/seasons and growth of biofilms on chlorine decay, (2) assessment of DBPs level and compliance to regulations in the WDS, (3) modelling and evaluation of the effects of hydraulic performance on chlorine decay in the WDS, and (4) optimization of booster locations and dosages to maintain chlorine residual within the standard limits across entire WDS.

Key words: Botswana, chlorine decay, disinfectant by-products, Gaborone, occurrence, water quality factors

Résumé

Le chlore, est très souvent utilisé comme un désinfectant pour contrôler la multiplication des bactéries pathogènes dans l'eau potable. Cependant, les fournisseurs d'eau rencontrent deux difficultés majeures durant le processus de désinfection à base de chlore dans les systèmes de distribution d'eau (SDE) : la décomposition et la formation de sous-produits

désinfectants (SPDs). Cette étude préliminaire vise à examiner la décomposition et de formation de SPDs et comment ceux-ci sont affectés par les facteurs de qualité de l'eau après traitement dans le SDE de la ville de Gaborone. L'étude a été menée à travers une analyse de résidus du chlore et des SPDs dans l'eau et des facteurs de qualité d'eau (matière organique naturelle, fer, manganèse, bactéries hétérotrophes, température et pH) qui pourraient influencer la décomposition du chlore et la formation des SPDs. Les échantillons d'eau analysés étaient obtenus des stations de traitement, réservoirs et robinets des clients. Les résultats ont démontré qu'il y a un fort dosage de chlore au niveau des stations de traitement, un faible taux de chlore résiduel dans les zones éloignées du réseau, un taux élevé de chlore décomposé et une présence des SPDs dans le SDE. Les facteurs de qualité d'eau qui sont supposés contribuer à la décomposition du chlore et à la formation des SPDs sont les composantes organiques, la température élevée et la formation du biofilm. Cependant, les autres facteurs liés aux conditions hydrauliques peuvent aussi influencer la décomposition du chlore. L'étude recommande donc (1) une investigation plus approfondie des effets des composantes organiques, température/saisons et la formation du biofilm sur la décomposition du chlore, (2) une évaluation du niveau des SPDs et la conformité à la réglementation dans le SDE, (3) modélisation et évaluation des effets de la performance hydraulique sur la décomposition du chlore dans le SDE, et (4) l'optimisation des dosages pour maintenir le chlore résiduel dans les limites standard dans tout le SDE entier.

Mots clés: Botswana, Décomposition du chlore, sous-produits de désinfection, Gaborone, apparition, facteurs de qualité de l'eau

Introduction

Potable water supplied to cities and towns undergo rigorous treatment processes to prevent waterborne diseases and safeguard public health. Chlorine disinfection is one of the key water treatment process used to manage growth of microbial organisms in potable water in most developing countries. However, many water suppliers experience challenges of maintaining residual chlorine across the water distribution systems (WDS). One of the major challenge is chlorine decay due to reaction with substances in the bulk of the water and at the wall of pipes and storage facilities (Rossman *et al*., 1994; Deborde and VonGunten, 2008). Major factors that contribute to chlorine decay are flow velocity, water age, pH, temperature, natural organic matter (NOM), iron, manganese, bromide, pipe materials, biofilms, accumulated sediments and corrosion (Rossman *et al*., 1994). Low level of chlorine in WDS due to decay may increase growth of pathogenic bacteria should contamination occur in the WDS. Pathogenic bacteria may lead to outbreaks of cholera, diarrhea and typhoid and also infections in the elderly, infants and patients with weakened immune systems (Payment *et al*., 1991; Franco *et al*., 2004). Guidelines and standards have been set to regulate residual chlorine level in WDS. For example, the guideline limits for World Health Organization (WHO) is between 0.4-0.6 mg/L (WHO, 2014) while the standard limit in Botswana is between 0.3-0.6 mg/L in WDS and 0.6-1.0 mg/L at dosing points (CSO, 2009).

The second challenge is chlorine reaction with NOM in water to form disinfectant by-products (DBPs) (Deborde and VonGunten, 2008). About 600 DBPs have been identified

in drinking water some of which are toxic and carcinogenic (Pavlov *et al*., 2004; Krasner *et al*., 2006). The most dominant chlorinated DBPs are; Trihalomethanes (THMs), Haloacetic acids (HAAs) and Halonitromethanes (HNMs) (Chowdhury *et al*., 2009; Chu *et al*., 2011). The major factors that influence formation of the DBPs are NOM, chlorine dosage, temperature, pH, water age and bromide (Liang and Singer, 2003; Brown *et al*., 2011). Many studies have associated long-time exposure to some DBPs to human health problems such as bladder and colon cancer (Villanueva *et al*., 2004; 2007; Wright *et al*., 2004), reduced gestation period and low birth weight (Wright *et al*., 2004), genetic malformations and still birth (Wright *et al*., 2003) and growth reduction in infants (Hinckley *et al*., 2005). The most regulated DBPs in WDS are trihalomethanes (THMs). For example, the maximum limit for THMs in Botswana, USA, Canada and Japan is 100 mg/L, Australia 30 mg/L and Switzerland 25 mg/L (Golfinopoulos and Nikolaou, 2005; CSO, 2009; Wang *et al*., 2015).

Therefore, it is very important to manage chlorine residual in drinking water from the treatment plant to customer's taps in a manner that balances protection from microbial contamination and minimizes formation of DBPs. In order to effectively manage chlorine disinfection, understanding the factors contributing to loss of chlorine residual and formation of DBPs in a WDS is very essential. The objectives of this study were to (1) investigate the occurrence of chlorine decay and DBPs formation in the WDS, and (2) evaluate the water quality factors that contribute to chlorine decay and DBPs formation in Gaborone city WDS.

Materials and methods

The study was conducted in two areas of Gaborone city WDS, i.e., Gaborone West distribution zone (GWDZ) and Phakalane distribution zone (PDZ) (Fig. 1). GWDZ is supplied by treated water from Mmamashia water treatment plant (MWTP) through Oodi reservoir

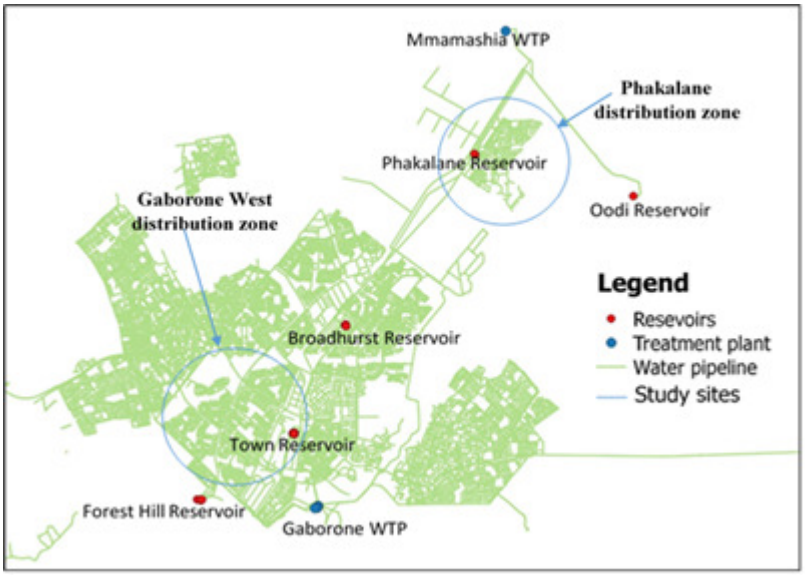

Figure 1. Study area

(OR) and Phakalane reservoir (PR). Data used in the study were collected by analyzing water quality in the months of March and April 2016. The sample points were chosen to enable evaluation of the overall changes and occurrences of chlorine residual, DBPs and water quality factors from the treatment plants to the customer's tap. The sample points selected from GWDZ were raw water (RW) supplied to GWTP, treated water (TW) before leaving GWTP, water at FHR and water from two customer's taps (CT) within the network. Similarly, water sample points from PDZ were RW and TW from MWTP, water from OR, PR and two CT. Sample collection, preservation and storage were performed as prescribed in the Standard Methods for Examination of Water and Wastewater (SMEWW) protocol (APHA, AWWA, and WEF, 2012). Chlorine residual concentration was tested from the sites during sampling by hand held colorimeter using DPD (N,N-diethyl-p-phenylenediamine) free and total chlorine reagent (www.cawst.org). DBPs and organic compounds were analyzed by liquid-liquid extraction and Two-Dimensional Gas Chromatography Time of Flight Mass Spectroscopy (GC×GC-TOFMS) using a modified United State Environmental Protection Agency (USEPA) method 551 to only detect the parameters without qualification (Hodgeson and Cohen A I, 1990). UVA-254 (Ultraviolet absorbance at wave length 254) used as surrogate for NOM was measured by UV spectrophotometer. Iron and manganese were analyzed by Flame Atomic Absorption Spectrometer (FAAS) using SMEWW method 7000B. Heterotrophic plate count (HPC) was analyzed by membrane filtration using SMEWW method 9215D.

Results and discussion

Chlorine residual. Figure 2 shows the results for chlorine residual at PDZ and GWDZ. Chlorine residual in the TW leaving both treatments plants into the distribution network was above the maximum standard limit of 1.0 mg/L. Chlorine residual at the first customer's taps (CT-1) and second (CT-2) were always lower than the minimum limit of 0.3 mg/L. The large difference between chlorine residual levels at injection points and customer's taps is an indication that significant loss of chlorine is occurring in the WDS. High rate of chlorine injection at dosing points is suspected to be a potential source of formation of DBPs. Low level of chlorine at the customer's taps may subject the WDS to risk of microbial growth if contamination occurred.

Disinfectant-by products. Table 1 shows the results of DBPs and some selected organic compounds detected in the water samples and their average parcentage area of chromatograms. The results demonstrate that there are possibilities for DBPs formation in the WDS because of detection of bromochloronitromethane and chemical compounds containing chloromethane. Bromochloronitromethane is a DPB that forms mainly in chlorinated water having bromide. The presence of DBPs in drinking water is well documented in many studies. For example Abdel Azeem *et al*. (2014) studied THMs in WDS of Fayoum city (Egypt) and reported that there is significant occurrence of THMs although it is less than the maximum standard limit of 100 μg/L. Rodriguez *et al*. (2003) studied the occurrence and seasonal variation of THMs in water treatment plants and customer's taps in WDS of Québec (Canada) and demonstrated that THMs were 1.3 to 2.5 times higher at customer's taps than treatment plants.

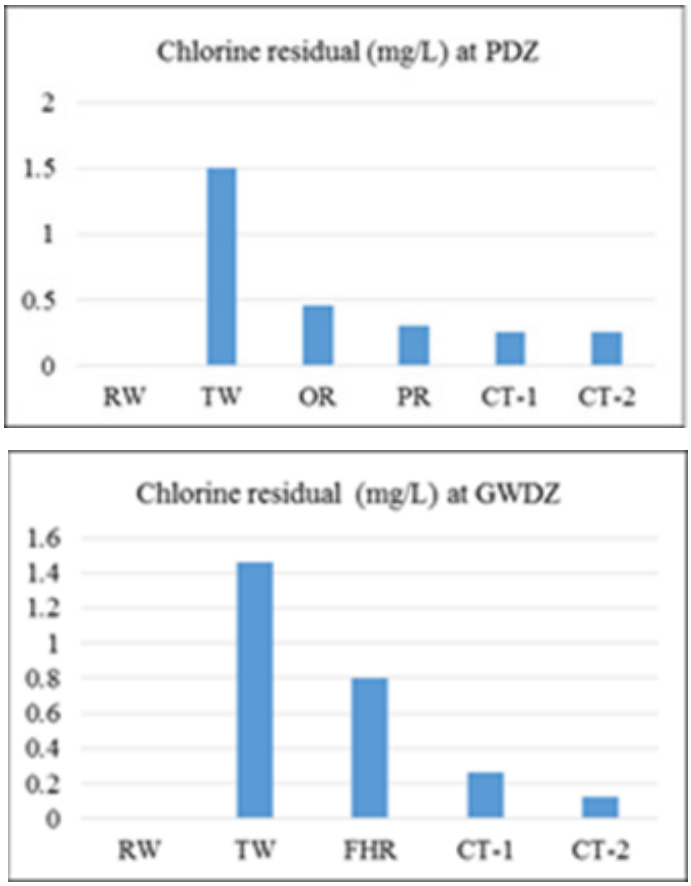

Figure 2. Average chlorine residual concentration at PDZ and GWDZ

Organic compounds. Many organic compounds were detected in the water samples. Some are presented in Table 1 with their percentage area of chromatograms. The most frequently detected organic compounds in the samples were propane 1-bromo-2-methyl, heptanone 7,7,7-trichloro, and heptane 2,2-dimethyl. Figure 3 shows the result for UVA-254 used as surrogate for NOM. Results indicate significant absorbance of ultraviolet light at wavelength 254 by the water even after treatment at both PDZ and GWDZ suggesting existence of substantial amount of NOM. The detection of many organic compounds and relatively high level of UVA-254 is an indication that NOM may probably be contributing to chlorine decay and DBPs formation in the WDS.

Temperature and pH. Water temperature and pH in the months of March and April 2016 when the study was conducted ranged between 27^0C to 28^0C and 6.5 to 7.5, respectively. The existence of aqueous chlorine species highly depend on the pH of water. The appropriate pH range for effective water disinfection by the aqueous chlorine species is 6 to 9 (Deborde and VonGunten, 2008). Generally Gaborone experiences a high temperature variation. The average minimum temperature is about 4^0C occurring in July during winter period and the maximum is about 32^0C occurring in January during summer. A study of WDS under controlled

Table 1. DPBs and some organic compounds detected in PDZ and GWDZ in Gaborone, Botswana

Compounds	% area	Compounds	% area	Compounds	% area
Succinic anhydride	0.020	Acetaldehyde, ethylhydrazone	2.139	Oxetane, 3,3-dimethyl-	0.651
Propane 1-bromo-2-methyl-	42.570	Oxalic acid, isobutyl propyl ester	5.805	Nonane, 1-iodo-	0.002
Acetic acid ethenyl ester	19.001	4-trichloromethylphenyl chloromethane	0.003	Cyclobutane, ethyl-	3.140
1,2-Ethanediol, diacetate	0.220	Bromochloronitromethane	0.001	Octane, 2,2,6-trimethyl-	0.269
2-Heptanone, 7,7,7-trichloro-	3.310	Heptane, 2,2-dimethyl-	6.184	Heneicosane	0.003
Hydrazine carboxamide	0.009	2- Heptanone, 7,7-dichloro-	28.044	Methane, isocyanato-	1.000

conditions by Mutoti *et al*. (2007) observed that for every rise in temperature of water in pipe network by 10^0C, chlorine decay in the bulk of water may increase threefold. Also Rodriguez *et al*. (2003) demonstrated that THMs level was 2.5 to 5 times higher in summer than winter seasons in WDS of Québec (Canada).

Iron and manganese. Figure 4 shows the results for iron and manganese content in water at PDZ and GWDZ. The results indicate that iron concentration in RW at MWTP was quite low (< 0.25 mg/L) while that at GWTP was high (> 2 mg/L). The iron in RW is significantly removed during the treatment processes to less than the minimum standard limit of 0.3 mg/L. Manganese concentration was negligible in RW at both treatment plants and is effectively removed by the treatment processes. Therefore, it is unlikely that iron and manganese are contributing to chlorine decay in the WDS.

Heterotrophic plate counts. Figure 5 shows the results for HPC in CFU/100 mL incubated at 35^0C for 48 hours in m-HPC agar at PDZ and GWDZ. The results indicate a very high

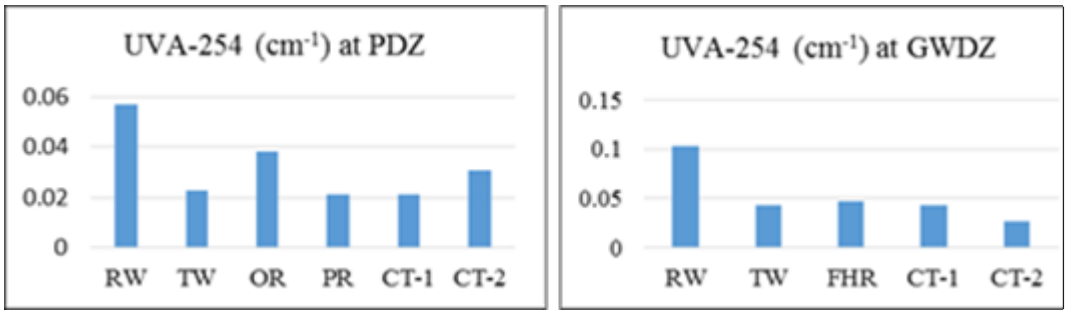

Figure 3. Average UVA-254 for PDZ and GWDZ

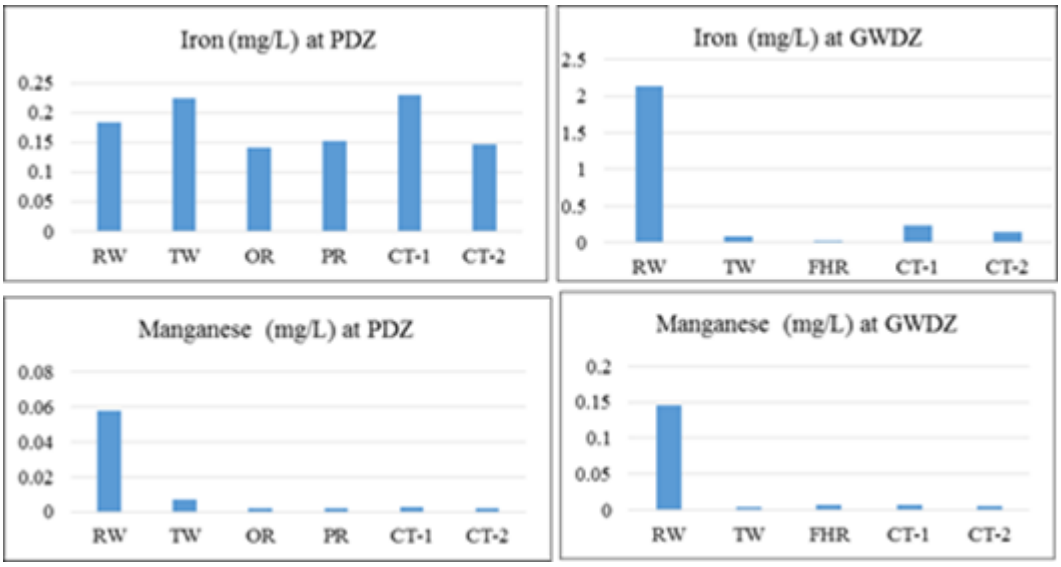

Figure 4. Average iron and manganese concentration at PDZ and GWDZ

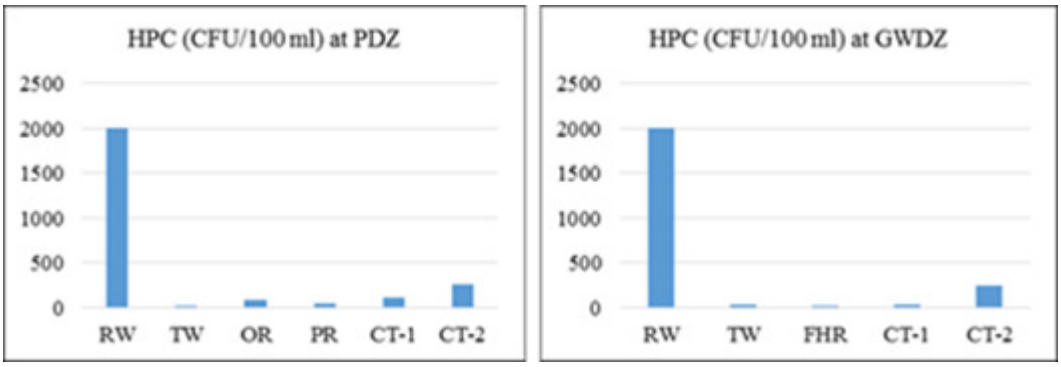

Figure 5. Average HPC at PDZ and GWDZ

HPC in RW (> 2000 CFU/100mL), very low HPC in TW at the treatment plant and reservoirs and increased amount of HPC between 100 to 300 CFU/100 mL at the customer's taps. The level of HPC was very low in TW at the treatment plants and reservoirs where residual chlorine is high and increased at customer's taps where residual chlorine is low. The increased amount of HPC in the customer's taps suggest the existence of habitats in the pipe network that are favorable for growth of microorganisms and loss of chlorine residual in the WDS (Lu *et al.*, 1999). These could be biofilms, corrosion materials and accumulated deposits.

Conclusion

This study revealed that significant loss of residual chlorine occurs in the WDS leading to low residual concentration at the customer's taps. High dosages of chlorine injected at the treatment plants are suspected to be a potential source for DBPs formation in the WDS. Analysis of water quality factors revealed that there is a significant number of organic compounds and amount of NOM (indicated by results of UVA-254 as surrogate) in water after treatment. These are suspected to be contributing to the chlorine decay and DBPs formation supported by high temperature in the network. Also growth of biofilms is suspected to exist in the pipe network due to increased level of HPC in the customer's taps. The biofilms are likely contributing to high chlorine demand in the WDS. Other factors related to the hydraulic conditions and pipe materials may also be contributing to the decay of chlorine in the WDS. Therefore, the study recommends further work to (1) investigate the effects of organic matter, temperature/seasons and biofilms growth on chlorine decay, (2) investigate the level of DBPs formation and compliance to regulation in the WDS, (3) model and evaluate the effects of hydraulic performance (flow velocity, system operation and water age) on chlorine decay in the WDS, and (4) optimize the booster locations and dosages so that chlorine residual is maintained within the standards limits in the WDS.

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