Introduction of an adsorption process into a surface water treatment system and its effect on disinfectant use

Małgorzata Wolska, Halina Urbańska-Kozłowska and Marek Mołczan

ABSTRACT

The study was conducted in a full-scale water treatment facility where surface water is treated. The analysis of required disinfectant dosage changes and disinfectant usage was conducted in a time period starting 6 months before introducing adsorption on granular activated carbon (GAC) into the treatment system, and continuing for 6 months after adsorption introduction. During the analyzed time period, both chlorine and chlorine dioxide were used. They were dosed separately and rapidly mixed into a pipeline before the clean water tank. Both short-term and long-term disinfectant consumption was studied. This is due to the different reaction rates of the disinfecting agents used. Introducing GAC adsorption contributed significantly to limiting organic substances in water undergoing disinfection, which resulted in average reductions of 51% for both disinfectants. During the first month after introducing adsorption only a small increase in disinfectant demand was found, connected with an increase in 22 °C cultivated bacteria count in water to be disinfected. The increase in organic substances removal achieved by the use of adsorption did not result in a reduction of analyzed trihalomethanes (THM), whose concentrations were low for both cases and amounted to 2.1–7.9 μg/dm^3 and 1.6–5.2 μg/dm^3 with and without adsorption respectively.

Key words | adsorption, chlorine, chlorine dioxide, disinfection, organic substances, ozone

Małgorzata Wolska
Halina Urbańska-Kozłowska
Marek Mołczan (corresponding author)
Municipal Water and Sewage Company,
Na Grobli 14-16, 50-421 Wrocław,
Poland
E-mail: *marek.molczan@pwr.edu.pl*

Małgorzata Wolska
Marek Mołczan
Faculty of Environmental Engineering,
Wroclaw University of Science and Technology,
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław,
Poland

INTRODUCTION

The disinfection process, used at the end of each treatment system for water for human consumption, serves both to deactivate microorganisms present in water and their dormant forms and to protect against secondary water contamination in the water distribution network. Therefore, it is very important to select correct disinfectant dosages due to reactions with contaminants in the distribution network and to ensure deactivation of microorganisms present in water (Hallam *et al.* 2002; Digiano & Zhang 2005).

Rational disinfection is connected not only with the removal of microorganisms and their dormant forms, but also with the removal of food substrates necessary for microorganism re-growth (Flemming *et al.* 2002; Al-Jasser 2007; Wang *et al.* 2014; Prest *et al.* 2016) and organic substances which are precursors of disinfection by-products (Fang *et al.* 2010; Plewa *et al.* 2010; Richardson *et al.* 2010; Bond *et al.* 2011). The level of contamination of water undergoing disinfection is in fact one of the factors determining disinfectant dosage value. Therefore, in treating water, especially surface water, it is important to ensure effective organic substance removal. As has been repeatedly found (Matilainen *et al.* 2010; Yapsakli & Çeçen 2010; Xu *et al.* 2011; Altmann *et al.* 2014), coagulation and adsorption processes most effectively reduce the content of these substances, and consequently reduce the required disinfectant dosage.

Disinfectant dosage value is also dependent on the type of oxidant used. Chlorine is still used for disinfection, due to its low cost, its reactivity and large bactericidal potential. The

doi: 10.2166/ws.2019.001

usage of free chlorine, apart from its concentration, depends on other factors, including water temperature (T) and pH, and the concentrations of reduced non-organic and organic compounds and non-organic nitrogen and phosphorus forms. Therefore, it is difficult to establish the required chlorine dosage and to determine the residual chlorine content. Determining these parameters requires knowledge of not only the quality of water undergoing disinfection, but also the water distribution system (Korshin *et al.* 1997; Rossman 2006). Optimizing disinfection is often the reason for water treatment system upgrading. One of the main directions of such improvements in recent years has been the introduction of adsorption processes with the use of granulated activated carbon (GAC), often preceded by ozonation. Therefore, it was justifiable to conduct a study comparing disinfectant dosages and their consumption before and after introducing an adsorption process at a water treatment plant.

METHODS OF STUDY

Raw water

The study was conducted at the Mokry Dwór Water Treatment Plant in Wrocław, during a time period starting from 6 months before GAC adsorption process application and ending 6 months later. The treatment plant is supplied by two rivers with varied characteristics. Nysa Kłodzka is a mountain river with basin dominated by forests and meadows. Oława river has a lowland nature with basin exploited by agricultural use.

Water treatment schemes

Before the system upgrading, the water underwent the following steps in sequence in the treatment system: coagulation (hydraulic-type rapid mixers and mechanical-type flocculation), sedimentation (horizontal tanks), filtration through a quartz sand bed (gravity rapid filters), pH assessment and disinfection with ozone, chlorine and chlorine dioxide. After the system improvement, an adsorption process on granulated activated carbon was introduced, being placed after ozonation and before pH correction and disinfection (Figure 1). The upgrading consisted of filling half (12) of the original number (24) of quartz sand filters with WG-12 activated carbon (manufactured by Gryf Skand), whose detailed properties are given in Table S1 (Supplementary Material, available with the online version of this paper). This resulted in an increase in water velocity through the quartz sand filters, which after the upgrading (Table 1) was still lower than the commonly recommended velocities for rapid filtration. Key performance parameters of sand and GAC filters are given in Table 1. The filters were put into operation in two stages, where during each stage six filters were introduced, with a pause of 11 days. After filling, the activated carbon was flushed multiple times before being connected to the treatment system.

Disinfection and sampling points

For the evaluation of the effect of the adsorption system on the required disinfectant dosage and consumption, samples were taken (Figure 1) for water after ozonation (sampling point 3)), after the adsorption process (4), from the clean water tank inlet (5) and from the pumping station, pumping water into the distribution system (6), water after a longer contact time with the disinfectant). The water contact time with the reagent being dosed was in the range of 6.1–14.1 min, which allows for determining the instantaneous disinfectant dosage. On the other hand, water pumped into the distribution network was characterized by a long water–disinfectant contact time in the range of

Table 1 | Filter performance parameters after system upgrading

Parameter	Unit	Sand filters	GAC filters
Flow rate range	m^3/h	2,666–3,716	2,666–3,716
Filter numbers	–	12	12
Single filter surface area	m^2	75.4	75.4
Bed depth	m	1.2	1.5
Water velocity range	m/h	2.95–4.11	2.95–4.11
Contact time range	min	17.5–24.4	21.9–30.5
Backwash frequency	day	1–3	14–21
Air backwash time	min	15–20	1–3
Air backwash intensity	m/h	26.5	26.5
Water backwash time	min	15–20	10–15
Water backwash intensity	m/h	27.8	20.0

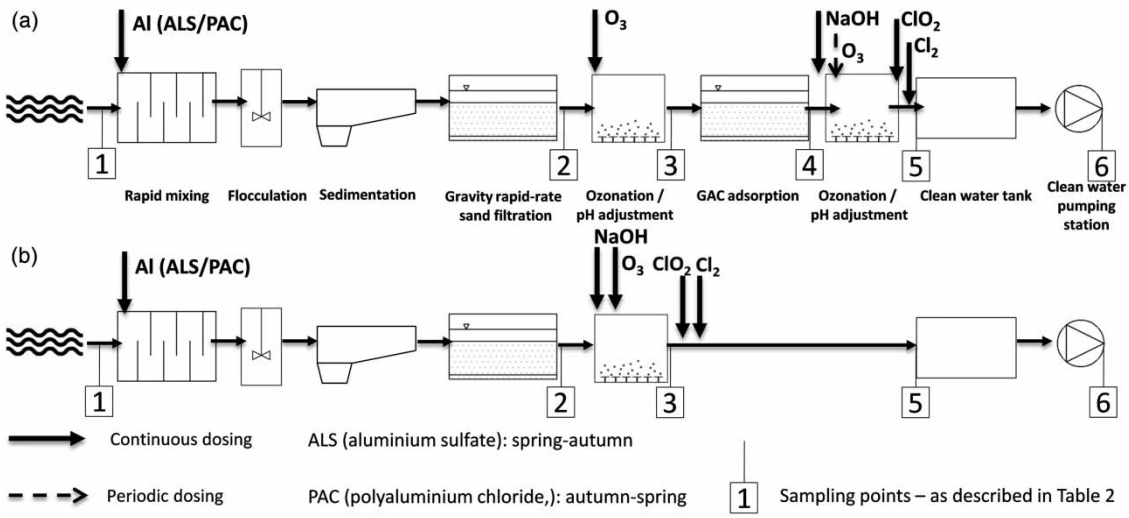

Figure 1 | Treatment trains before (b) and after (a) system upgrading.

3.6–9.3 h, which allowed for determining the disinfectant consumption on reactions with organic contaminants and those reduced in treated water.

In the water samples collected, measurements of pH, color, turbidity and organic substance content measured as total organic carbon (TOC) and UV absorbance at 254 nm (UV_{254}) were performed. In water samples after disinfection, the chlorine and chlorine dioxide concentrations were also measured. Furthermore, once a month the individual THM contents were determined along with their sum. In all samples, the total 22 °C and 37 °C cultivated microbial counts (total cell number, TCN) were also analyzed (Table 2).

Final disinfection chemicals (ClO_2 and Cl_2) were dosed and mixed with water separately (mixers inside the pipeline), with a minimal distance between dosing points. ClO_2 dosing was proportional to the water flow. Supplementary Cl_2 dosing was based on several additional criteria including Cl_2 concentration and number of bacteria at the sixth sampling point and many sampling points positioned on the water supply network. The same dosing criteria were kept before and after treatment system upgrading. During the period preceding the introduction of the adsorption process the disinfectant dosages were in the ranges of 1.16–4.76 (average of 2.06) gCl_2/m^3 and 0.00–0.41 (average of 0.22) $gClO_2/m^3$. On the other hand, after the introduction of the adsorption process the ranges of these values during the period of the study were 0.45–3.02 (average of 0.93) gCl_2/m^3 and 0.0–0.35 (average of 0.25) $gClO_2/m^3$.

All of the analysis was performed at the MPWiK (Municipal Water and Wastewater Company) laboratory according the accredited laboratory standards.

RESULTS AND DISCUSSION

The treated surface water was characterized by a large composition variability, which decreased significantly after coagulation and sedimentation processes. However, in water flowing into disinfection (before the upgrading) or into adsorption (after the upgrading) a significant composition variability was still found (Table 2). This concerned, above all, the concentration of organic substances measured as TOC, especially substances absorbing ultraviolet radiation (Figure 2).

At the same time, it was found that introducing the adsorption process resulted in a decrease in TOC concentration variability before disinfection. Due to the effective organic substance removal by the adsorption process, a lower demand for disinfectant was found, and consequently with a small decrease in disinfectant dosage, a larger residual post-disinfection chlorine concentration was found.

For water undergoing disinfection, both before and after upgrading, UV absorbing substances had significant importance for natural organic matter (NOM) quality and quantity characterization, and their content was proportional to TOC concentration (Figure 3).

Table 2 | A comparison of basic parameters of water before adsorption, after adsorption, and for water introduced into the distribution network before and after GAC adsorption application (sampling points marked as shown in Figure 1)

	Before system upgrading			After system upgrading		
Parameter	**MIN**	**AVG**	**MAX**	**MIN**	**AVG**	**MAX**
Raw water (1)						
Temperature, °C	0.1	7.0	22.0	0.5	12.6	26.0
Turbidity, NTU	4.1	14.4	36.8	4.8	15.0	51.7
Color, mgPt/dm^3	7.0	11.7	23.0	7.0	12.9	30
pH, -	7.1	7.9	8.8	7.3	7.7	8.1
Abs. at UV – 254 nm, m^{-1}	6.86	10.0	18.4	6.52	10.9	28.8
TOC, mg/dm^3	4.24	5.28	7.01	2.53	4.6	8.06
TCN 37 °C, 24 h, cfu/cm^3	35	172	1,490	27	287	3,073
TCN 22 °C, 72 h, cfu/cm^3	705	5,261	73,700	265	6,647	220,500
Ozonated water (3)						
Temperature, °C	0.2	7.5	21.0	1.0	14.8	23.5
Turbidity, NTU	0.1	0.2	0.8	0.1	0.2	0.8
Color, mgPt/dm^3	1.0	2.0	8.0	1.0	2.2	9.0
pH, -	7.6	8.0	8.6	6.9	7.4	7.9
Abs. at UV – 254 nm, m^{-1}	2.42	4.70	8.24	2.20	4.20	6.69
TOC, mg/dm^3	3.17	3.90	4.66	3.03	4.20	6.37
TCN 37 °C, 24 h, cfu/cm^3	0	0	4	0	3	30
TCN 22 °C, 72 h, cfu/cm^3	0	48	825	0	446.2	2,800
Water after GAC adsorption (4)						
Temperature, °C	–	–	–	1.0	14.5	23.5
Turbidity, NTU	–	–	–	0.1	0.2	0.8
Color, mgPt/dm^3	–	–	–	1.0	1.2	6.0
pH, -	–	–	–	6.9	7.4	7.8
Abs. at UV – 254 nm, m^{-1}	–	–	–	0.04	1.60	3.78
TOC, mg/dm^3	–	–	–	0.61	2.40	3.39
TCN 37 °C, 24 h, cfu/cm^3	–	–	–	0	8	62
TCN 22 °C, 72 h, cfu/cm^3	–	–	–	148	3,895	43,200
Water from the clean water pumping station (6)						
Temperature, °C	0.5	7.2	22.0	0.2	16.1	23.5
Turbidity, NTU	0.1	0.1	0.4	0.1	0.2	0.3
Color, mgPt/dm^3	1.0	1.7	6.0	1.0	1.1	2.0
pH, -	7.2	7.8	8.4	7.6	7.8	8.1
Abs. at UV – 254 nm, m^{-1}	2.11	4.10	6.99	0.38	1.50	3.06
TOC, mg/dm^3	3.39	3.90	4.98	1.20	2.60	3.16
TCN 37 °C, 24 h, cfu/cm^3	0	0	3	0	0	4
TCN 22 °C, 72 h, cfu/cm^3	0	0	4	0	1	5

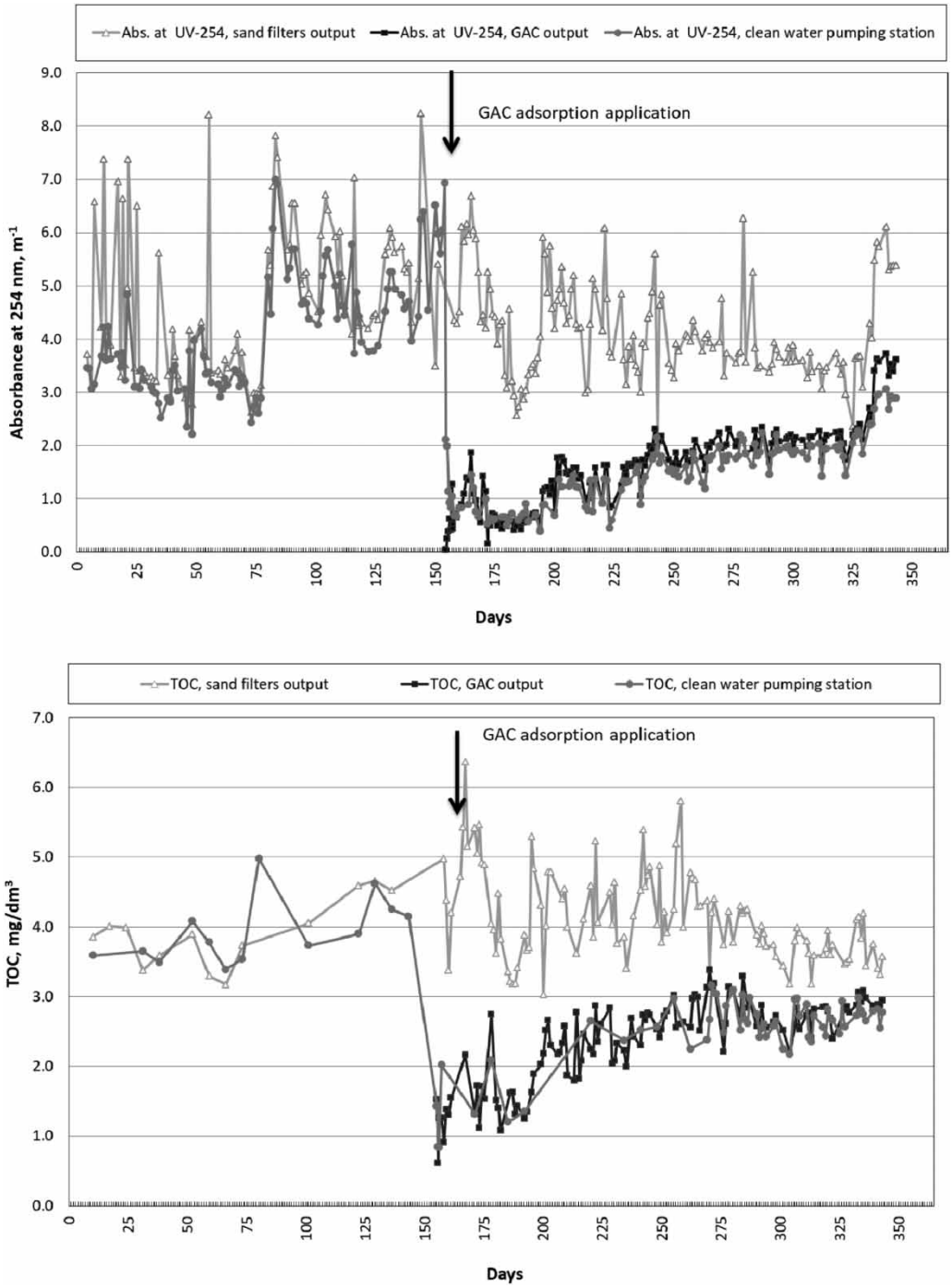

Figure 2 | Variability in organic substance content in water for disinfection before and after system upgrading.

It must be stressed that introducing the carbon bed filters resulted in a TOC reduction in water undergoing disinfection of on average of 74%, while for UV-254 absorbing substances the adsorption effectiveness ranged from 91% in the initial GAC bed operating period to 32% during the winter period at a water temperature of about 2 °C (Figure 4).

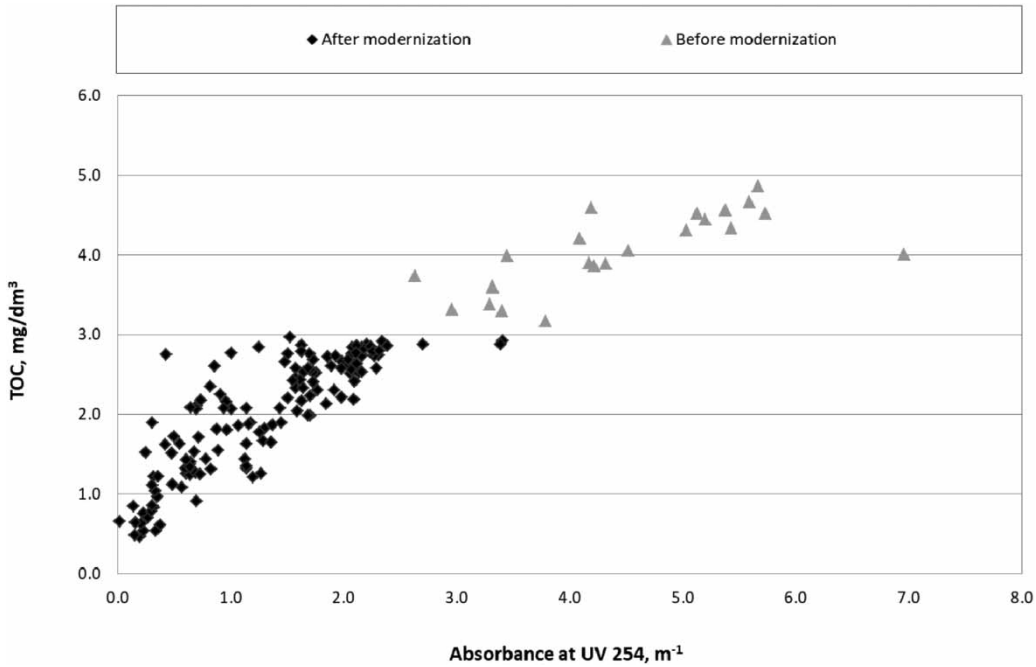

Figure 3 | TOC content as a function of absorbance at 254 nm in water flowing into disinfection before and after system upgrading.

However the final GAC adsorption efficiency must be interpreted as a cumulative result of progressive exhaustion of adsorption capacity and temperature effect on biomass activity.

Pre-ozonated water (before system upgrading) did not contain microorganisms, yet after introducing the adsorption process into the treatment system, water flowing into the disinfection process (outflow from GAC filters) contained a very

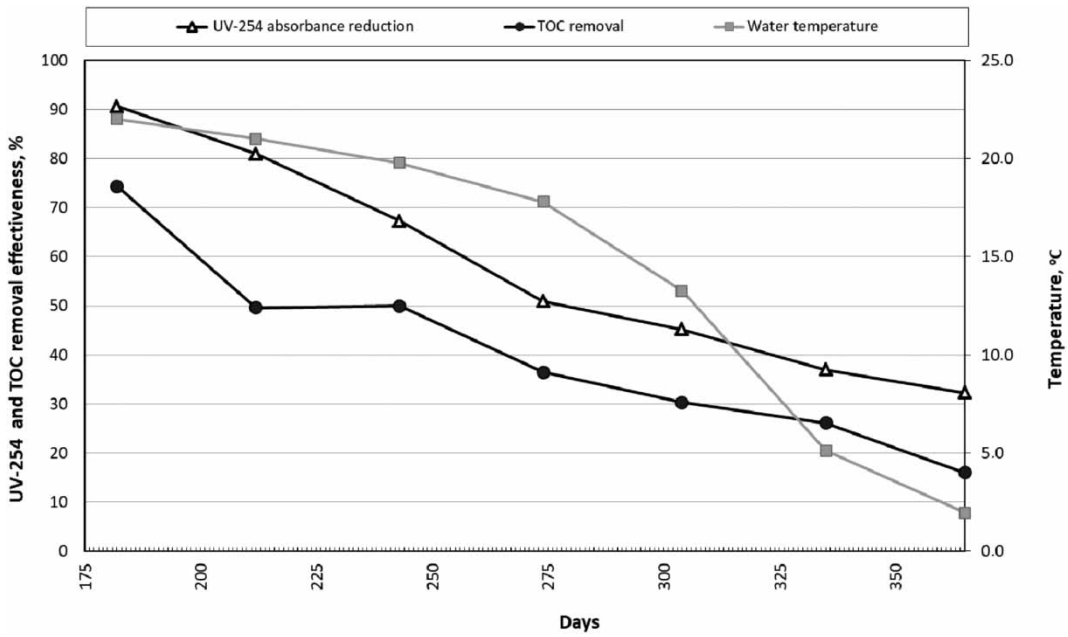

Figure 4 | Effect of GAC filter lifetime and water temperature on adsorption effectiveness (TOC removal and UV-254 absorbance reduction).

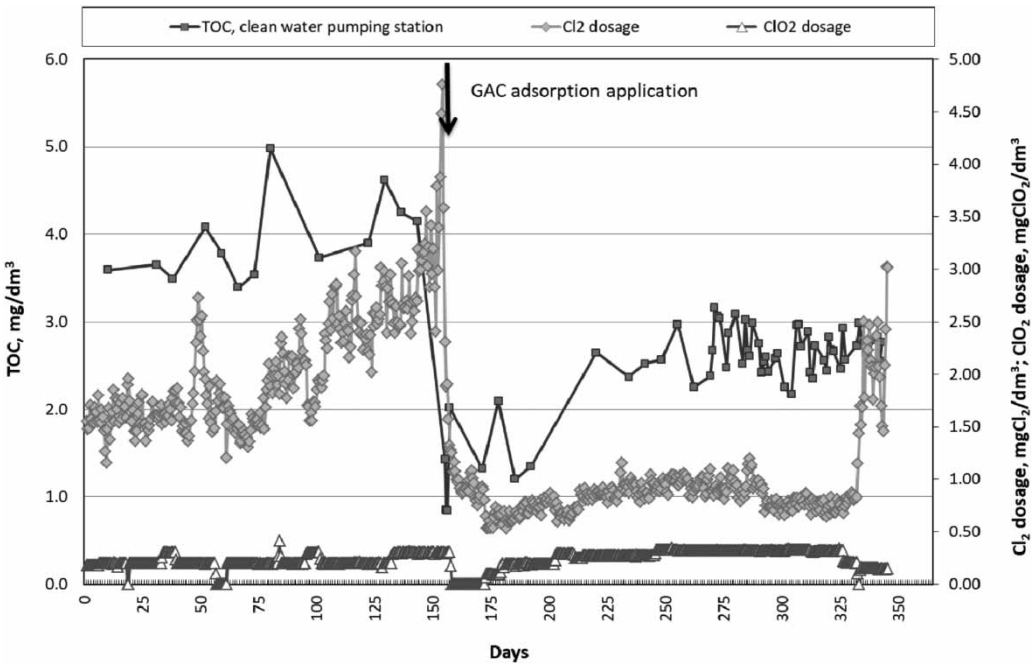

Figure 5 | Variability in chlorine and chlorine dioxide dosages vs TOC in treated water.

large number of microorganisms, both 22 °C and 37 °C cultivated ones (Table 2). It was no surprise because activated carbon is well known as a home to an ecosystem of bacteria and protozoans due to its well-suited surface and macropores (Yapsakli & Çeçen 2010). The increase was also perhaps significant in that the bed operating parameters varied greatly during this period, as before the start of operation the bed were cyclically filled and flushed with water. This increase in bacteria occurred immediately after the start of GAC bed operation (Figure S1, Supplementary Material, available with the online version of this paper), and after this period (about half a month) a stabilization occurred with a decrease in the number of bacteria in water after adsorption.

The disinfectant dosages that were used depended, above all, on the organic substance content in treated water, and therefore after the introduction of adsorption these dosages could be significantly decreased. However, despite the increase in the quality of water undergoing disinfection, periodically in cases of input water quality decreases (flood or meltwaters) chlorine dosages were increased, with chlorine dioxide dosages affected to a smaller degree (Figure 5).

It must be stressed that in the initial period of filter operation the disinfectant dosages were decreased gradually to ensure biostability of the water being introduced into the distribution network. This means that in the initial period of operation, the residual concentration of disinfectants was greater than before the system improvement with a slight decrease in disinfectant dosages. This signifies a lower demand for chlorine and chlorine dioxide caused by lower concentrations of organic substances which react with used disinfectants. This relationship concerns both instantaneous disinfectant usage as well as the reductions in their concentration after a longer reaction time (Figure 6).

In the majority of samples of treated water, low concentrations of THM and their sums were found, being in the ranges of 2.1–7.9 μg/dm^3 and 1.6–5.2 μg/dm^3 before and after the system upgrading respectively. In relation to the studied water source, it is suggested that the coagulation process was responsible for removing trihalomethane precursors. The role of ozonation and adsorption was very limited in this case. Despite a THM content on the detection threshold, a relationship well known from literature (Korshin *et al.* 1997) was found between THM creation and values of the absorbance indicator at 254 nm (Figure S2, Supplementary Material, available online).

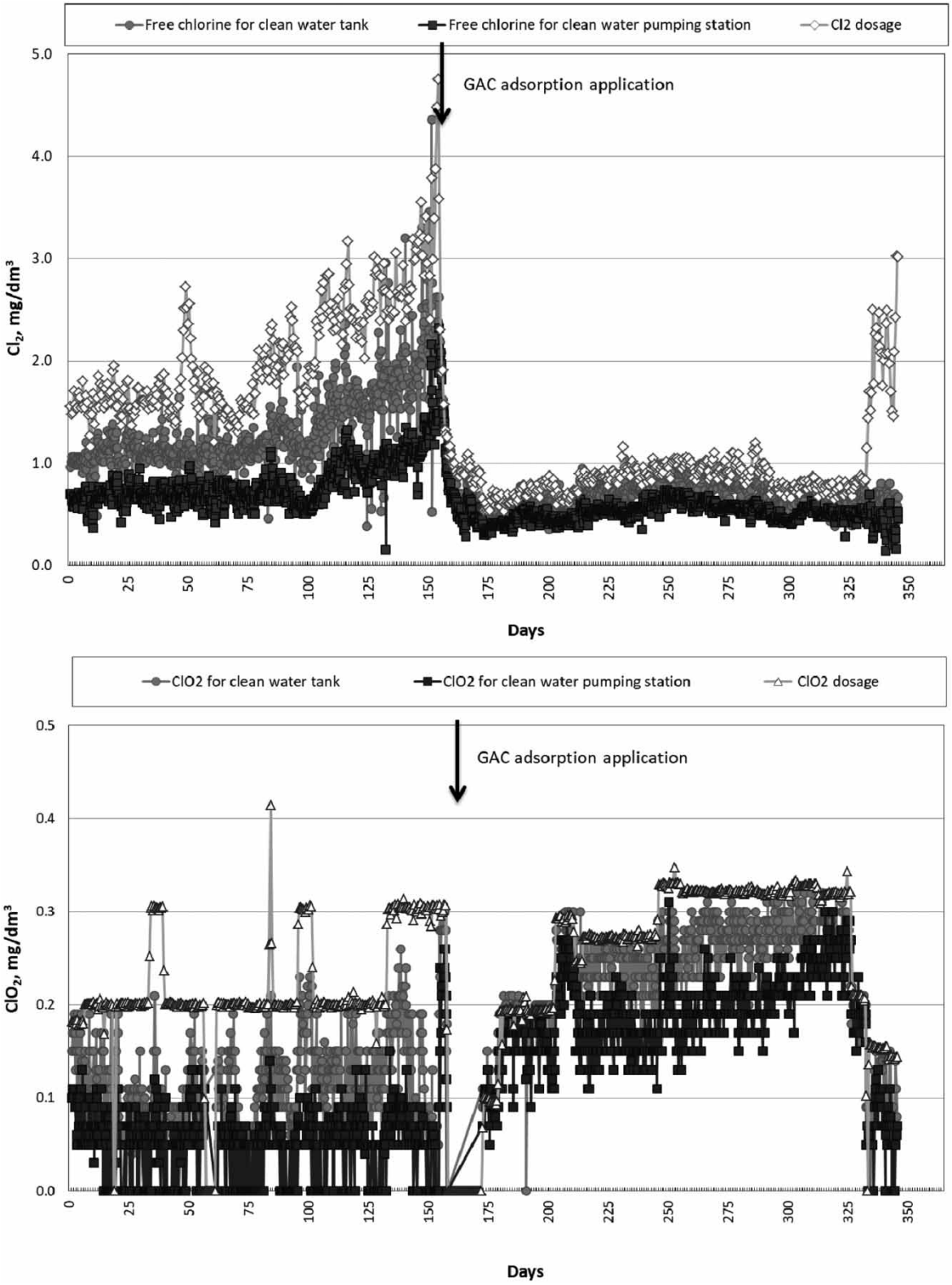

Figure 6 | Residual chlorine and chlorine dioxide concentration after short (minutes, clean water tank) and long (hours, clean water pumping) contact time.

CONCLUSIONS

This study has shown the following:

1. A 60–80% organic substance adsorption effectiveness (as TOC), with preferential removal of those substances absorbing UV light (75–90%), during the first month after the introduction of GAC filters into the water treatment system was noted.
2. An increased effectiveness in removing organic substances in the system with adsorption was found for the entire study period.
3. Due to the introduction of adsorption filters, increased amounts of bacteria were flushed into the water, yet their presence did not significantly influence disinfectant demand.
4. The adsorption process allowed for a decrease in chlorine dosage, with an average reduction of 51%. Small changes in chlorine dioxide dosage resulted from a technical strategy which aimed to limit chlorine dosages.
5. Despite the use of reduced chlorine dosages, its concentration in water introduced into the water distribution network was larger after the improvement than before.
6. The adsorption process did not significantly change THM precursor content, whose removal was dominated by the coagulation process. However ΣTHM values observed for treated water were lower after (1.6–5.2 $\mu g/dm^3$) than before (2.1–7.9 $\mu g/dm^3$) GAC adsorption application.

REFERENCES

Al-Jasser, A. O. 2007 Chlorine decay in drinking water transmission and distribution systems: pipe service age effect. *Water Research* **41** (2), 387–396.

Altmann, J., Ruhl, A. S., Zietzschmann, F. & Jekel, M. 2014 Direct comparison of ozonation and adsorption onto powdered activated carbon for micropollutant removal in advanced wastewater treatment. *Water Research* **55**, 185–193.

Bond, T., Huang, J., Templeton, M. R. & Graham, N. 2011 Occurrence and control of nitrogenous disinfection by-products in drinking water – a review. *Water Research* **45** (15), 4341–4354.

Digiano, F. A. & Zhang, W. 2005 Pipe section reactor to evaluate chlorine–wall reaction. *Journal AWWA* **97** (1), 74–85.

Fang, J., Ma, J., Yang, X. & Shang, C. 2010 Formation of carbonaceous and nitrogenous disinfection by-products from the chlorination of *Microcystis aeruginosa*. *Water Research* **44** (6), 1934–1940.

Flemming, H.-C., Percival, S. L. & Walker, J. T. 2002 Contamination potential of biofilms in water distribution systems. *Water Science & Technology: Water Supply* **2** (1), 271–280.

Hallam, N. B., West, J. R., Forster, C. F., Powell, J. C. & Spencer, I. 2002 The decay of chlorine associated with the pipe wall in water distribution systems. *Water Research* **36** (14), 3479–3488.

Korshin, G. V., Li, C. W. & Benjamin, M. M. 1997 Monitoring the properties of natural organic matter through UV spectroscopy: a consistent theory. *Water Research* **31** (7), 1787–1795.

Matilainen, A., Vepsäläinen, M. & Sillanpää, M. 2010 Natural organic matter removal by coagulation during drinking water treatment: a review. *Advances in Colloid and Interface Science* **159** (2), 189–197.

Plewa, M. J., Simmons, J. E., Richardson, S. D. & Wagner, E. D. 2010 Mammalian cell cytotoxicity and genotoxicity of the haloacetic acids, a major class of drinking water disinfection by-products. *Environmental and Molecular Mutagenesis* **51** (8–9), 871–878.

Prest, E. I., Hammes, F., van Loosdrecht, M. C. M. & Vrouwenvelder, J. S. 2016 Biological stability of drinking water: controlling factors, methods, and challenges. *Frontiers in Microbiology* **7**, 45. doi: 10.3389/fmicb.2016.00045.

Richardson, S. D., DeMarini, D. M., Kogevinas, M., Fernandez, P., Marco, E., Lourencetti, C., Ballesté, C., Heederik, D., Meliefst, K., McKague, A. B., Marcos, R., Font-Ribera, L., Grimalt, J. O. & Villanueva, C. M. 2010 What's in the pool? A comprehensive identification of disinfection by-products and assessment of mutagenicity of chlorinated and brominated swimming pool water. *Environmental Health Perspectives* **118** (11), 1523–1530.

Rossman, L. A. 2006 The effect of advanced treatment on chlorine decay in metallic pipes. *Water Research* **40** (13), 2493–2502.

Wang, H., Masters, S., Edwards, M. A., Falkinham III, J. O. & Pruden, A. 2014 Effect of disinfectant, water age, and pipe materials on bacterial and eukaryotic community structure in drinking water biofilm. *Environmental Science and Technology* **48** (3), 1426–1435.

Xu, W., Gao, B., Wang, Y., Yang, Z. & Bo, X. 2011 Role of Al_{13} species in removal of natural organic matter from low specific UV absorbance surface water and the aggregates characterization. *Chemical Engineering Journal* **171** (3), 926–934.

Yapsakli, K. & Çeçen, F. 2010 Effect of type of granular activated carbon on DOC biodegradation in biological activated carbon filters. *Process Biochemistry* **45** (3), 355–362.

First received 11 March 2018; accepted in revised form 13 December 2018. Available online 2 January 2019