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Vulnerability of Quebec drinking-water treatment plants to cyanotoxins in a climate change context

Annie Carrière, Michèle Prévost, Arash Zamyadi, Pierre Chevalier and Benoit Barbeau

ABSTRACT

Cyanobacteria are a growing concern in the province of Quebec due to recent highly publicised bloom episodes. The health risk associated with the consumption of drinking water coming from contaminated sources was unknown. A study was undertaken to evaluate treatment plants' capacity to treat cyanotoxins below the maximum recommended concentrations of 1.5 μg/L microcystin-LR (MC-LR) and the provisional concentration of 3.7 μg/L anatoxin-a, respectively. The results showed that close to 80% of the water treatment plants are presently able to treat the maximum historical concentration measured in Quebec (5.35 μg/L MC-LR equ.). An increase, due to climate change or other factors, would not represent a serious threat because chlorine, the most popular disinfectant, is effective in treating MC-LR under standard disinfection conditions. The highest concentration of anatoxin-a (2.3 μg/L) measured in natural water thus far in source water is below the current guideline for treated waters. However, higher concentrations of anatoxin-a would represent a significant challenge for the water industry as chlorine is not an efficient treatment option. The use of ozone, potassium permanganate or powder activated carbon would have to be considered.

Key words | algal toxins, climate change, cyanobacteria, drinking water, ozone, powdered activated carbon

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INTRODUCTION

The occurrence of cyanobacteria is a growing concern in the province of Quebec, Canada. From 2004 to 2007, 356 cyanobacteria cases were reported, a situation never experienced previously (Ministère du Développement Durable, de l'Environnement et des Parcs 2007). A factor considered to explain this increase in occurrence is climate change. According to the literature, climate change could promote the growth of cyanobacteria due to increases in water temperature, growing season, runoff and nutrient availability (Nõges *et al.* 2003; Arheimer *et al.* 2005; Elliott *et al.* 2006; De Senerpont Domis *et al.* 2007; Jöhnk *et al.* 2008). Studies were conducted in Quebec to evaluate the concentration of cyanotoxins entering the treatment plants. The maximum concentrations measured were 5.35 μg/L equ. microcystin-LR (MC-LR) and 2.3 μg/L anatoxin-a (Robert 2007). It is important to note that the maximum recommended concentration in Quebec is 1.5 μg/L for MC-LR and the provisional value for anatoxin-a is 3.7 μg/L (Institut National de Santé Publique du Québec 2005). The need for treatment was thus obvious. The efficiency of the various treatments reported in the literature has been summarized and the most promising ones were investigated in greater detail. The global objective was to evaluate the vulnerability of the 284 surface water treatment plants of the province of Quebec, considering their actual treatment train, to increase in proliferation of cyanobacteria.

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TREATMENT METHODOLOGY

Cyanotoxins are present in the environment within living cyanobacterial cells (intracellular) or outside the cells (extracellular) when they have been released or when the cells die, either from natural lysis or from shock during the treatment process (algicide, coagulation and filtration). The fraction of extracellular toxins is generally around 30% (Tsuji *et al.* 1996). However, Drikas *et al.* (2001) demonstrated that toxins can be found almost entirely in extracellular form after two days in settling tank solids.

The treatment of intracellular toxins is physical, consisting of removing intact cells from the water. The main technologies are flotation, settling and filtration (granular or membrane), which remove more than 90% of the intracellular toxins (Chorus & Bartram 1999; Agence Française de Sécurité Sanitaire des Aliments et l'Agence Française de Sécurité Sanitaire de l'Environnement et du Travail (AFSSA et AFSSET) 2006).

The treatment of extracellular toxins is based on adsorption, oxidation or biodegradation. The efficiency of these treatments is highly variable (0–100%) and depends both on the toxin and on the treatment. As the treatment of extracellular toxins is more complex and it is possible that toxins exist entirely in that form, this situation was considered in the evaluation of vulnerability. Thus, our focus was directed to adsorption (powdered activated carbon (PAC)) and oxidation strategies (chlorine, ozone, potassium permanganate) that are common in Québec.

In order to evaluate the efficiency of the 284 surface water treatment plants in Quebec, a subgroup of 29 plants was selected (10% of plants) for an in depth investigation conducted through a questionnaire and a telephone interview. For these 29 plants, the efficiency of individual treatment units was calculated based on the kinetic found in the literature. Based on the calculated treatment unit efficiencies, extrapolation was made to the other surface water plants. As the vulnerability of the various water bodies to cyanobacterial blooms was unknown, all plants were considered vulnerable, which is a very conservative hypothesis.

Treatment efficiency

The reaction of algal toxins with oxidants follows a second order reaction (Equation 1, see below) with k_{app} being the apparent kinetic constant ($M^{-1}\,s^{-1}$), [oxidant] being the concentration of oxidant (M^{-1}) and [toxin] being the initial concentration of toxins (M^{-1}) (Rodriguez *et al.* 2007*b*). This equation can be transformed to calculate the log reduction of a toxin according to the CT concept (oxidant exposure × contact time), which is very common in disinfection (Equation 2). The CT is described in Equation (3). Using this approach removes the influence of the water matrix (organic matter) on the oxidation efficiency as it is included in the oxidant consumption. The CT is often simplified by multiplying the residual concentration of oxidant by the exposure time as intermediate oxidant concentrations are not known. This simplification also includes a security factor as only a small fraction of the real oxidant exposure is considered. When Equation (2) is not applied to a batch or plug flow system, a hydraulic efficiency factor (T_{10}/T) must be applied to represent flow conditions in the system under investigation. This factor can be estimated from design handbooks or can be obtained more precisely by tracer studies or computational fluid dynamic modelling. This multiplication approach (effective $CT = CT \times T_{10}/T$) gives conservative results in comparison to more complex hydraulic effect calculations for removal up to 2 log, which is the range of interest. Moreover, this is the approach used in disinfection calculations in Quebec.

$$-\frac{\mathrm{d[toxin]}}{\mathrm{d}t} = k_{app}[\mathrm{oxidant}][\mathrm{toxin}]_o \tag{1}$$

$$\ln\left[\frac{\mathrm{toxin}}{\mathrm{toxin}_o}\right] = -k_{app}CT \tag{2}$$

$$CT = \int_0^t [\mathrm{oxidant}]\mathrm{d}t \tag{3}$$

Much research was conducted during the European Union project "Toxic" on the oxidation of toxins, which documented the kinetic constants for the two toxins of interest (microcystins and anatoxin-a) and the three oxidants considered (Kull *et al.* 2004; Acero *et al.* 2005; Onstad *et al.* 2007; Rodriguez *et al.* 2007*a*,*b*,*c*). These constants are presented in Table 1 for pH varying from 6 to 9.

Equation (2) and the constants reported in Table 1 were used to calculate toxin removal for each plant investigated, considering their characteristics (pH, oxidant residual,

Table 1 | Apparent inactivation kinetic constants of microcystin-LR and anatoxin-a for various oxidants (values in $M^{-1}s^{-1}$)

	pH	Microcystin-LR	Anatoxin-a
Chlorine (as HOCl)	6	158	1.0
	7	100	1.0
	8	33	1.0
	9	10	1.0
Ozone (as O_3)	6	4.1E05	2.5E04
	7	4.1E05	4.0E04
	8	4.1E05	2.0E05
	9	4.1E05	1.4E06
Potassium permanganate (as MnO_4^-)	6	357	2.0E04
	7	357	2.0E04
	8	357	2.0E04
	9	357	2.7E04

Adapted from Rodriguez *et al.* (2007*b*).

contact time, hydraulic efficiency (T_{10}/T)). Figures were also generated to quickly evaluate treatment efficiency according to the prevailing conditions, as presented as an example in Figure 1 for potassium permanganate and MC-LR.

The adsorption of toxins on PAC has also been investigated in numerous studies. The concentration of PAC generally required to remove 90–99% of the toxins is around 20–30 mg/L (Keijola *et al.* 1988), which is higher than usual dosages in Quebec (5 mg/L). The type of PAC (mineral, wood, coconut) greatly affects its efficiency in adsorbing toxins. The most effective type reported is wood because of its large number of mesopores (2–50 nm), which are better able to remove microcystins (Donati *et al.* 1994). However, Mouchet & Bonnelye (1998) obtained 90% or more removal of anatoxin-a and microcystin-LR with 11 mg/L of a mineral base PAC. This highlights the influence of the combination water matrix–PAC on toxin removal efficiency. A relation considering the PAC dosage, the contact time and the organic matter content was developed from reported data (Mouchet & Bonnelye 1998; Cook & Newcombe 2002*a*,*b*; European Commission 2005) for "efficient" carbons (Figure 2). The available data were for MC-LR but anatoxin-a seams to be adsorbed similarly (Mouchet & Bonnelye 1998). Only microcystin-LA seams to be less readily absorbable on PAC, but this toxin is rarely detected according to the literature. It has not been detected in France (AFSSA et AFSSET 2006) and is not measured in Quebec. The relation developed was used to calculate the toxin removal efficiency in the plants investigated, considering their maximum applicable dosage and assuming that "efficient" PAC would be used. The removals calculated were used both for MC-LR and anatoxin-a.

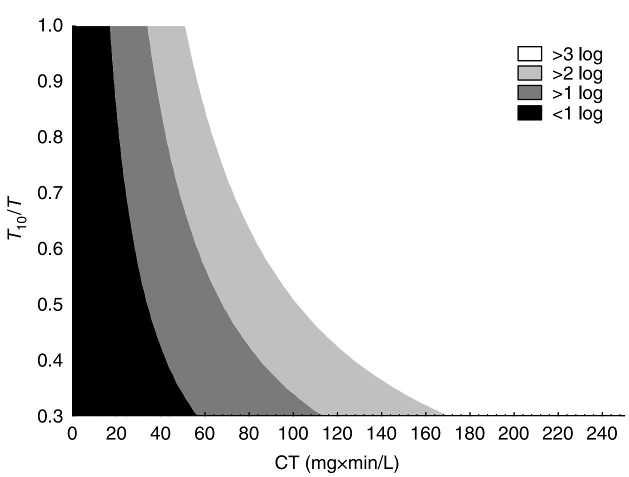

Figure 1 | Predicted microcystin-LR reduction (in log) by $KMnO_4$ for various CT and hydraulic efficiency factors (T_{10}/T) at 20°C (pH independent).

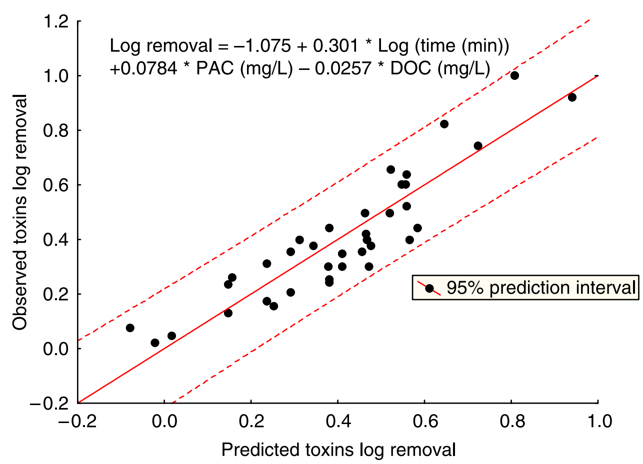

Figure 2 | Predicted cyanotoxins (anatoxin-a and microcystin-LR) removal by powder activated carbon (PAC) application according to contact time, PAC dosage and dissolved oxygen concentration. Adapted from Mouchet & Bonnelye (1998), Cook & Newcombe (2002*a*,*b*) and European Commission under the Fifth Framework Programme and contributing to the implementation of the Key Action "Sustainable Management and Quality of Water" (2005).

Table 2 | Cyanotoxins occurrence scenarios

Scenarios	Microcystin-LR	Anatoxin-a
Historical maximum*	6 μg/L	3 μg/L
Guidance†	30 μg/L	15 μg/L
Climate change‡	60 μg/L	15 μg/L

*Maximum concentrations measured in Quebec as of 2006.
†Design guidance suggested by the Ministry of Environment.
‡Approximately: Average of maximum concentrations under bloom conditions (excluding scum samples).

Occurrence scenario

In order to evaluate the vulnerability of drinking water treatment plants to cyanotoxins, the concentration in the source water must be known, which is often not the case. Moreover, the evolution of these concentrations in the future is not known. To consider these limitations, three occurrence scenarios were proposed (Table 2).

The historic scenario represents the maximum concentration of toxins measured in drinking water sources in Quebec (rounded to the next integer). The hypothesis is suggested that all plants are susceptible to encountering these concentrations of toxins. The guidance scenario represents the maximum concentrations that could be present in source waters if the removals suggested in Quebec (95% removal of microcystins and 75% removal of anatoxin-a) are accepted (Ministère du Développement Durable, de l'Environnement et des Parcs 2008). Finally, the climate change scenario is based on documented maximum concentration in source water worldwide, which are summarized in Table 3. Data shown in Table 3 are from water bodies and not from scum, even if some values are uncertain, according to the authors. The results were obtained using various detection methods (enzyme-linked immunosorbent assay, high performance liquid chromatography, protein phosphatase inhibition assay). As presented, the maximum concentrations are highly variable, with a few exceptions above 100 μg/L. Considering the values presented, a maximum concentration of 60 μg/L was considered in this occurrence scenario. This is twice the concentration of the "guidance" scenario and close to the average value of the maximums presented. The concentration of anatoxin-a was kept at 15 μg/L as no occurrence data was found to justify higher values.

Table 3 | Maximum toxin concentrations measured worldwide in source waters used for drinking water production

Country	Toxins	Maximum concentration (μg/L)	References
Australia	MC total	8	Höger (2003)
Brazil	MC total	1.25–8.8	dos S. Vieira *et al.* (2005) and Costa *et al.* (2006)
Canada	MC-LR	6	Kotak *et al.* (1995)
	MC-LR eq	14.8	Zurawell (2002)
Finland	MC total	37	Lindholm *et al.* (1989)
France	MC-RR	11	Jann-Para *et al.* (2004)
	MC-total	> 100	Maatouk *et al.* (2002) and AFSSA et AFSSET (2006)
Germany	MC total	36	Ueno *et al.* (1996)
	MC total	366	Fastner *et al.* (1999)
	MC-LR eq.	50–220	Höger (2003)
Italy	MC total	14	Messineo *et al.* (2006)
Japan	MC total	378	Tsuji *et al.* (1996)
Korea	MC-LR	0.6–171	Park *et al.* (1998)
Poland	MC total	7	Tsuji *et al.* (1996) and Jurczak *et al.* (2005)
Portugal	MC total	37.0	Ueno *et al.* (1996)
Sri Lanka	MC total	81	Jayatissa *et al.* (2006)
USA	MC total	3.4	Hotto *et al.* (2005)
Zimbabwe	MC total	22.5	Mhlanga *et al.* (2006) and Ndebele & Magadza (2006)

RESULTS

Selection of the participating utilities

Out of the 284 water treatment plants (WTP) using surface waters in Quebec, a total of 29 (≈ 10% of the cohort) were contacted in order to perform a site-specific plant audit evaluating their ability to cope with microcystins and anatoxin-a. The criteria for selecting a WTP were: (i) use of a recognized treatment for cyanotoxins, (ii) history of cyanobacterial blooms in the source water, (iii) geographical coverage of the province and (iv) source water type (lake vs. river). The WTP selected are spread among 12 of the 19 administrative regions of Quebec. Fourteen plants are supplied by river waters while the other 15 are supplied by lakes. Table 4 presents a summary of treatments found in the 29 participating utilities. The treatments used in the 284 WTPs in Quebec are also presented for comparison.

Treatment efficiency

Powder activated carbon

The theoretical maximum toxin removal was calculated for the 11 plants where PAC is used using their maximum PAC dosage capacity (2.5–45 mg/L). The empirical relation developed using published data (Figure 2) predicts MC-LR removal as a function of dissolved organic carbon PAC dosage and contact time for an "efficient" PAC (wood-based and coal-based). PAC performance is known to be greatly impacted by the type of PAC employed, with wood-based PAC generally considered superior to mineral PAC (Donati *et al.* 1994). For the current investigation, it was hypothesized that an "efficient" PAC would be used by the utility in the event of a cyanobacterial bloom. One of the advantages of PAC is its flexibility with respect to changing supplier and the possibility of initiating PAC treatment whenever needed. Although this equation was developed for microcystin adsorption on PAC, it was also employed to predict anatoxin-a removal considering: (i) the limited available information in the literature and (ii) the similar removal obtained by Mouchet & Bonnelye (1998).

Figure 3 presents the predicted adsorption (expressed on a log scale) of cyanotoxins by PAC for the 11 WTP (out of 29) using this process. These WTPs include four which present negligible toxins removal due to the low capacity of PAC dosage (<10 mg/L). The other plants obtain between 0.5 and 2.8 toxins log removal, with mean and median removals of 1.1 and 0.89 log, respectively.

Table 4 | Water treatments applied in surface water treatment plants in Quebec and in the sub-group investigated

	Investigated utilities		All utilities	
Treatments	**N**	**%**	**N**	**%**
Total	29	100%	284	100%
Chlorine	29	100%	276	97%
Ozone	8	28%	42	15%
PAC	11	38%	32	11%
$KMnO_4$	5	17%	5	2%
Filtration	26	90%	136	48%

Oxidants

Chlorine, ozone and potassium permanganate were the three oxidants investigated for their potential to oxidize toxins. Monochloramine and chlorine dioxide were not considered due to their low efficacy against cyanotoxins (Chorus & Bartram 1999). Equation (2) was used to calculate the log removals using the k_{app} values presented in Table 1. The pH, the contact time, the residual concentration of oxidant and the hydraulic efficiency

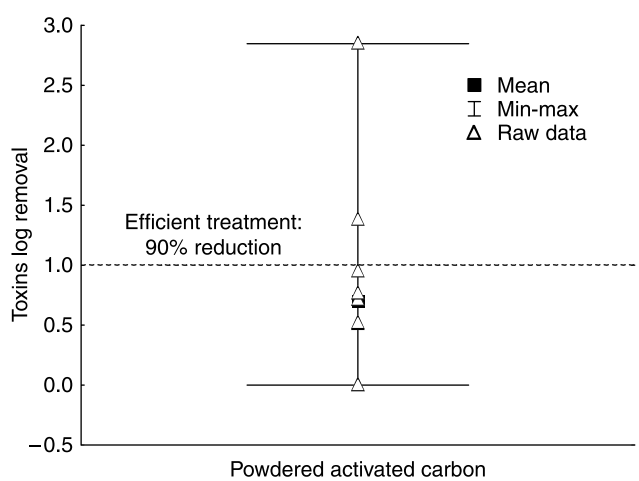

Figure 3 | Cyanotoxins log removal by powder activated carbon application in the sub-sample group.

(T_{10}/T) were obtained from the questionnaire and telephone interviews.

Potassium permanganate is used in 5 plants out of 29, mostly for taste and odour control. The dosages applied were all below 1.0 mg/L. The residual concentrations required to calculate removals were available in only two plants. The other plants do not monitor residual permanganate, which made it impossible to accurately evaluate the removal efficiency in Quebec. The use of permanganate for toxins treatment would require a better process control (i.e. residual concentration measurement). If such a solution is considered, the injection point should precede filtration to retain the added manganese on the filters. An aesthetic guideline of 0.05 mg/L of manganese prevails in Quebec (Santé Canada 2003). All of the current systems inject permanganate in raw waters. Although it may be efficient at oxidising extracellular toxins, it has also been suggested that pre-oxidation may lead to the release of intracellular toxins (Pietsch *et al.* 2002).

The calculated log removals of anatoxin-a and MC-LR by chlorine and ozone are presented in Figure 4. The MC-LR log removals by chlorine vary widely (0.15 to 31 log), reflecting the large differences in CT_{10} values and pH from one WTP to another. As mentioned previously, the use of the hydraulic efficiency factor (T_{10}/T) method is conservative up to 2 log reduction for the worst hydraulic conditions ($T_{10}/T = 0.3$). The calculations exceeding 2 log are thus probably overestimated for low hydraulic efficiency, which is of lower significance from a risk analysis standpoint since a maximum of 1.6 log removal is required considering the worst occurrence scenario (climate change) and the recommended concentrations in treated water (1.5 μg/L).

Chlorine efficiency is largely dependent on the application conditions (residual concentration, contact time before the first user, etc.). It was observed that, under some instances (3 out of 29), the applied CT_{10} were not in accordance with the disinfection requirements in Quebec, which calls for a minimum removal of 4 log of virus and 3 log of *Giardia*.

Using chlorine to oxidize anatoxin-a is not a viable option for the WTP investigated as the maximum removal calculated is under 1 log (Figure 4). On the other hand, WTPs using ozonation provide reductions of both anatoxin-a- and microcystin-LR in excess of 2 log, with the average reduction exceeding 50 log. The maximum removal was artificially set at 200 log due to calculation limitations, but would have been even higher according to the equations. In practice, actual reductions would have been lower due to hydraulic short circuiting. Nevertheless, ozonation is clearly an excellent option for oxidizing these two toxins.

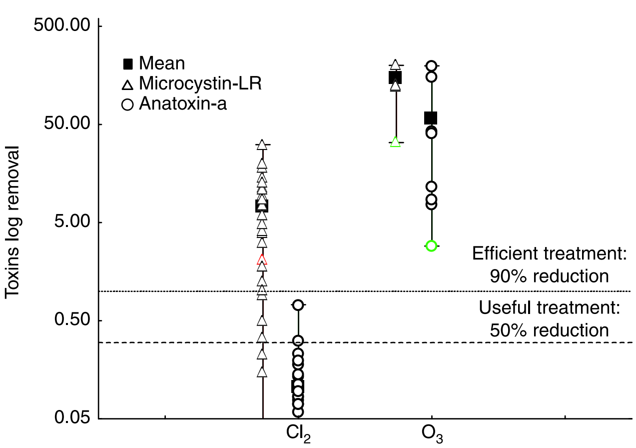

Figure 4 | Microcystin-LR and anatoxin-a log removals by chlorine (HOCL) and ozone in the sub-sample group.

Assessing WTPs vulnerability to occurrence scenario

The efficiency of treatment trains to control MC-LR and anatoxin-a were calculated for the three occurrence scenarios described previously: (i) historical maximums, (ii) proposed guidance for design and (iii) climate change. Results are provided in Figure 5 (MC-LR) and Figure 6 (anatoxin-a). It is important to reiterate that this evaluation

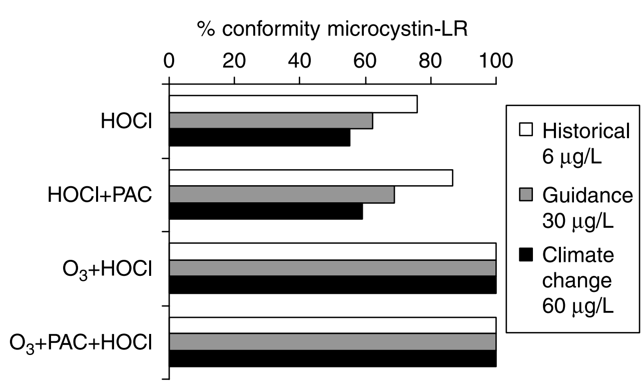

Figure 5 | Percentage of treatment trains able to lower microcystin-LR concentration under the acceptable limit of 1.5 μg/L considering the three source water occurrence scenarios.

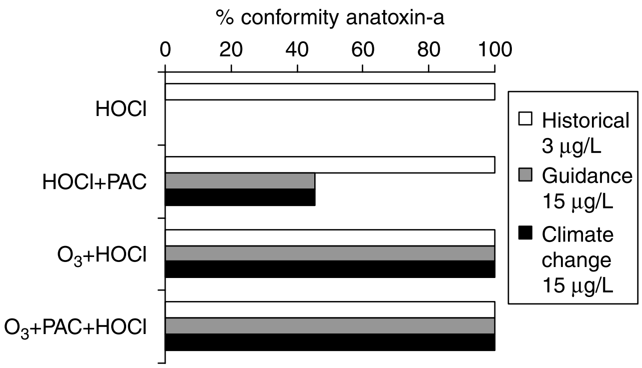

Figure 6 | Percentage of treatment trains able to lower anatoxin-a concentration under the acceptable limit of 3.7 μg/L considering the three source water occurrence scenarios.

considers that all plants are vulnerable to cyanobacterial blooms, which is a very conservative hypothesis.

The proportion of WTPs able to meet each scenario was estimated by summing independently the relative proportion of robust WTP using a given process. For example, 76% of WTPs using chlorine alone were able to face the historical scenario for microcystin, while PAC alone would be a sufficient treatment to meet that scenario for 45% of the plants. Therefore, for a PAC + Cl_2 combination, it was assumed that 45% of the plants for which free chlorine was not sufficient (24%) would become efficient by adding PAC treatment. Consequently, 87% (76% + (24% × 45%)) of WTPs using Cl_2 + PAC are expected to meet this scenario. This approach was preferred to the direct calculation of the combined efficiencies of the 11 plants using both treatments (chlorine and PAC) because their chlorination practices were generally more efficient than the average. This approach would have therefore been less conservative. This difference might be a bias considering the limited number of WTPs investigated. It might also reflects the fact that WTPs currently using PAC are located on microbially challenged source waters, which justify using higher CT conditions. Alternatively, a Monte-Carlo procedure could also have been developed, but it was felt that the data were insufficient to produce meaningful probability distribution functions.

The evaluation of treatment combinations performances for microcystin (Figure 5) indicates that adding ozone solves the issue of microcystin reduction. In addition the other treatment combinations are not very sensitive to the source water occurrence scenarios. For anatoxin-a (Figure 6), a similar conclusion can be drawn for ozone. However, as opposed to microcystin, the occurrence scenario has an important impact on the ability of a treatment train to meet the treated water guideline. It is important to note that anatoxin-a has never been detected above the Quebec current provisional value (3.7 μg/L), which explains why all treatments are able to deal with the historical occurrence scenario.

Using the information developed in Figures 5 and 6, a performance projection was made for the 284 surface WTPs in Quebec for increasing source water toxin concentrations (Figure 7). Approximately 80% of the WTPs are presently able to treat the maximum historical concentration measured to this day in Quebec (5.35 μg/L MC-LR equ.). Also, approximately two out of three WTPs can cope with MC-LR concentrations of 30 μg/L (the Quebec design guidance value). A climate change scenario of 60 μg/L MC-LR only brings this percentage to 60%.

As for anatoxin-a, it represents a more difficult challenge for the water industry. For concentrations above

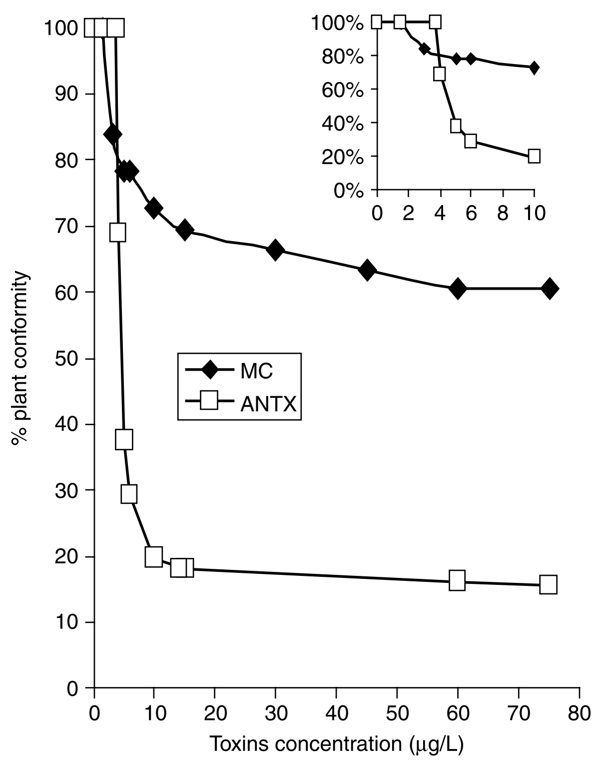

Figure 7 | Projected conformity of the 284 surface water treatment plants in Quebec to increasing concentrations of cyanotoxins in source waters. MC: Microcystin, ANTX: Anatoxin-a.

15 μg/L in source water, only a fraction of the plants using PAC (45%) and those using ozone (100%) are able to deal with this toxin. Potassium permanganate might be a valuable tool to improve anatoxin-a removals. However, significant operational challenges still need to be resolved with this process (residual monitoring, location of injection point).

DISCUSSION

The frequency of cyanobacterial blooms has increased in the last few years in Quebec surface waters. This situation has received a wide coverage in the media and has put the water industry in a reactive mode considering the limited information available on the ability of WTP to face this emerging threat. This study aimed at providing a first portrayal of the vulnerability of Quebec WTPs to cyanotoxins.

Several areas of uncertainty may affect the accuracy of our evaluation. The matters fall into the three main areas and will now be discussed.

Cyanotoxins occurrence in source water

Toxins analytical methods are complex and costly. No legislation in Quebec imposes the requirement to monitor source water concentrations. Consequently, information on source water concentrations is relatively scarce. In addition, cyanobacterial blooms are very dynamic by nature (spatially and temporally). As most water intakes are located at the bottom of water bodies, it is doubtful that results from samples collected at the surface for environmental monitoring can be transposed to source water concentrations. Measured concentrations of cyanotoxins in Quebec source waters (excluding scum samples) appear modest. Predicting future occurrence of algae toxins concentrations in the context of climate change is a hazardous process. That being the case, it was decided to use published information on algal bloom events from other international locations. This approach was deemed reasonable considering that, although the frequency of toxic blooms might be expected to increase, the severity of these blooms should be comparable to other similar events documented in various regions. It is, however, doubtful that such conditions will be experienced by all water utilities. This work could be refined by integrating a source water classification which would rank source water intakes with respect to their vulnerability to algal blooms. Such an evaluation would need to account for source water characteristics as well as water intake characteristics.

Water treatment efficiency

The published data on toxin reduction following various treatments has significantly increased over the last few years. Comprehensive studies have been performed especially of oxidation processes for which second-order kinetic constants have been made available (Kull *et al.* 2004; Acero *et al.* 2005; Rodriguez *et al.* 2007*a*,*b*,*c*; Onstad *et al.* 2007). Some important grey areas do, however, remain. For one, the issue of pre-oxidation is still debated and published data are contradictory. Some authors do not recommend using it because of the potential for release of intracellular toxins. However, it has also been shown that some oxidants, such as ozone, are most likely able to oxidize any released toxins as long as applied CT are sufficient (Hart *et al.* 1998; Mouchet & Bonnelye 1998; Hoeger *et al.* 2002). During our survey, applied CT values were obtained from the utilities for current treatment conditions. There is some uncertainty with respect to the capacity of utilities to maintain their CT under a bloom event assuming that oxidant demand might increase under such scenario.

The accumulation of algal cells within WTPs is another area of concern. Granular media filters and sludge blanket clarifiers are examples of processes which may accumulate algal cells and promote the release of intracellular toxins. Although PAC appears as a potential solution, selecting a good product appears a key factor. During this work, it was assumed that WTP were using an efficient wood-based PAC. Considering the high PAC dosage required (10–20 mg/L), it is uncertain that given physico-chemical treatments (e.g. settler, filters, etc.) could cope with such solid loads increase. Finally, permanganate was identified as a promising treatment solution for anatoxin-a, although only one published paper was identified (Rodriguez *et al.* 2007*b*). However, currently, WTPs in Quebec do not monitor residual potassium permanganate concentrations. Also, they all inject permanganate in raw water whereas settled water would be the optimal location to minimize intracellular toxin release and manganese passage in filtered water in our opinion.

Theoretical performance evalution

Although the current analysis uses theoretical performance prediction based on actual treatment conditions, it is essentially an identical approach to the current requirements for disinfection in North America, which are derived from CT values for *Giardia*, *Cryptosporidium* and viruses. We have assumed that 100% of toxins in source waters would be present as extracellular toxins, the most difficult fraction to treat. In reality, the proportion of extracellular toxin is variable, typically in the order of 30% in normal conditions (Tsuji *et al.* 1996; Chorus *et al.* 2000; Maatouk *et al.* 2002), although higher fractions can prevail when lysis occurs.

The performance calculations were all done for water temperature of 20–25°C, as little information has been published for cold water conditions. However, algal blooms have been observed as late as November in Quebec, at which time water temperature is well below 10°C. Finally, it should be noted that our evaluation was limited to 29 WTPs (10% of the total number). Performance analysis from this subset was extrapolated to the entire set with the usual uncertainty created by this procedure.

CONCLUSIONS

Cyanotoxins are a growing concern in the treatment of surface water in the province of Quebec. In order to evaluate the vulnerability of drinking water utilities to the increased occurrence of toxic algae blooms, an evaluation of the efficiency of surface water plants was performed for both the actual conditions and potential climate change scenario. A performance audit was conducted for 10% of the surface WTPs of Quebec and results were generalized to the 284 plants in the province. Results indicate that 80% of the plants could handle the maximum historical concentrations encountered (5.35 μg/L equ. MC-LR). For anatoxin-a, the highest historical concentration measured (2.3 μg/L) has never exceeded the provisional value in treated waters (3.7 μg/L).

In the context of higher source water toxin concentrations, about 60% of WTP could cope with MC-LR (up to 60 μg/L). However, our investigation indicates that increased anatoxin-a concentrations would be significantly harder to deal with for the water industry, due to its high resistance toward conventional treatment. Therefore, attention should be given to correctly evaluate the risks related to anatoxin-a in treated water, especially considering the limited occurrence data available. Treatment options including PAC and/or potassium permanganate appear promising, although additional research is warranted to evaluate the applicability of these solutions with respect to the impacts on WTPs operation.

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