Toxic cyanobacteria in drinking water sources and within drinking water treatment plants (DWTPs) have been documented, even in regions with historically infrequent blooms. The main objective of the authors’ research was to study the accumulation of potentially toxic cyanobacteria within two full-scale DWTPs (Eastern Canada) fed by water sources considered to have a low risk of cyanobacterial presence. Intensive in vivo measurements were conducted on raw, clarified, filtered, and chlorinated waters. Samples were also taken for microscopic counts, toxin analyses, and water characterization. Cyanobacterial profiles were mapped in the sedimentation and filtration basins using a fluorescence probe. Even though cell numbers at the water intake were below 400 cells/mL, an accumulation of cyanobacterial cells was observed in the sludge bed of clarifiers (more than $1 \times 10^6$ cells/mL) and on the surface of the sedimentation and filtration basins. *Microcystis* and *Gloeotrichia* were the dominant genera. Preozonation of raw water helped with the removal of cells in the clarification process.

**Keywords:** cyanobacteria, cyanotoxin, low-risk source, drinking water treatment, preoxidation

Toxic cyanobacteria in drinking water sources and within drinking water treatment plants (DWTPs) have been increasingly documented across the globe, including Eastern Canada (McQuaid et al, 2011; Merel et al, 2010; Robert, 2008; Svrcek et al, 2004; Carmichael et al, 2001; Lahti et al, 2001). Climate change may increase the dominance of cyanobacteria in lakes, reservoirs, and rivers, posing an increasing challenge to drinking water plants (Elliott, 2012; Paerl et al, 2012). Several studies have focused on the toxicity of cyanobacteria and cyanotoxins and documented their human health effects including gastroenteritis, liver damage, liver cancer, and neurotoxic effects (Gutiérrez-Praena et al, 2012; Merel et al, 2010; Svrcek et al, 2004; Chorus et al, 1999). Because of the harmful effects of cyanobacteria and their associated toxins, water authorities have introduced threshold alert levels (Newcombe et al, 2010) and management plans (Watzin et al, 2006).

The World Health Organization (WHO) proposed two alert levels for the management of drinking sources susceptible to cyanobacterial proliferations: 2,000 and 100,000 cells/mL (Chorus et al, 1999). The WHO also suggests actions to be taken should the cyanobacteria concentration in water samples attain these alert values (Chorus et al, 1999). However, weekly sampling is the maximum frequency proposed by the WHO for cyanobacteria and cyanotoxins sampling. The cyanobacterial intervention program in Québec, Canada, includes supplementary threshold values to define the historic presence of cyanobacteria over the source and the water intake of DWTPs (Ellis, 2009). The Québec action plan requires predefined interventions at a DWTP if at least one raw water sample (before any treatment) taken at the water intake of a plant during the past five years contains more than 10,000 cells/mL. However, these interventions are triggered by the results of monitoring, most often conducted on a weekly or biweekly basis, that may be insufficient to identify critical periods of cyanobacterial presence (Zamyadi et al, 2012a; Newcombe et al, 2010).

The presence of cyanobacteria can cause multiple water quality issues: they can result in the presence of toxins, they are related to taste and odor problems, they can increase disinfection by-product (DBP) formation, and they present serious operational challenges (shorter filter run times and disruption of clarification/filtration) that can lead to treatment interruption (Zamyadi et al, 2012b; Kommineni et al, 2009). DWTPs taking their water from sources prone to large cyanobacterial blooms are susceptible to the accumulation and breakthrough of cells and toxins through water treatment processes. Recent publications provide solid evidence of the accumulation of potentially toxic cyanobacterial cells in clarifiers and filters and the breakthrough of cyanotoxins into drinking water (Zamyadi et al, 2012c; Kommineni et al, 2009). Targeted cyanobacterial monitoring in a DWTP in Québec documented the presence of toxic cyanobacterial scum in processes within a DWTP and the breakthrough of cyanobacterial cells and toxins into treated water (Zamyadi et al, 2012c).
focus of the work by Zamyadi et al (2012c) was on DWTPs fed by sources with a very high risk of cyanobacterial blooms. Few full-scale data are available for water sources considered to have a low risk of elevated cyanobacterial cell numbers. In addition, there is no research available on performance of full-scale pre-oxidation on cell accumulation in treatment plants. The implementation of cyanobacterial surveillance plans in DWTPs has resulted in reports of localized scums observed at the surface of clarifiers and filters, even in sources considered to have low-to-moderate risk of cyanobacterial proliferation. Such detection (see the photograph on page E659) can alarm operators, especially if the cyanobacterial species present are toxic. The significance of localized accumulation and the long-term potential for accumulation and proliferation of cyanobacteria in specific processes such as sludge bed clarifiers, sludge processing, and filters has not been documented. The accumulation of low cell numbers (even below the low alert levels) can lead to major accumulation of cyanobacteria and cyanotoxins as they are captured with solids. The importance of this accumulation in terms of risk, especially for toxin release, needs to be quantified.

Recent observations using an event-based intensive monitoring approach suggest that DWTPs drawing from sources with low levels of recorded blooms (i.e., cyanobacterial cell densities generally less than 2,000 cells/mL) may still be vulnerable to cyanobacterial accumulation (Zamyadi et al, 2012a) and should be investigated. Until recently, cyanobacteria-related issues in Nordic climates were considered rare and restricted to the summer heat-wave periods. Recent observations document toxic cyanobacteria blooms extending from May until November (Robert et al, 2005). Documented events of toxic cyanobacteria breakthrough underline the urgent need for an all-inclusive management strategy focusing on site-specific challenges even at DWTPs, including sources considered at low or moderate risk of cyanobacterial presence.

The main objective of this work is to study the accumulation of potentially toxic cyanobacteria within two full-scale DWTPs fed by water sources considered to have a low risk of cyanobacterial presence. The specific objectives of this study are (1) to evaluate the accumulation of cyanobacterial cells in the blanket clarifiers and gravity filters, (2) to study the impact of pre-oxidation on cell accumulation, (3) to evaluate the potential risk of toxin release associated with localized cyanobacterial accumulation, and (4) to propose pertinent intervention strategies for monitoring and treatment. To the best of the authors’ knowledge, this article reports the first results from a comprehensive cyanobacterial monitoring campaign in two full-scale DWTPs while comparing the impact of their operation on accumulation and removal of cyanobacteria.

**MATERIAL AND METHODS**

**Water source and site description.** The water intakes of two DWTPs located on the Richelieu River in southern Québec were monitored from August to November 2011. The Richelieu River flows from Lake Champlain, which is well known to be highly susceptible to cyanobacterial blooms (McQuaid et al, 2011; Giani et al, 2005), although the river itself generally has only low densities of cyanobacterial cells. This river serves as a source of drinking water for the surrounding municipalities and as a recreational site for boating and fishing. For the period of August to October 2011, the river water turbidity varied between 1.4 and 58 ntu, pH was 7.5±0.3, total phosphorus (TP) concentrations were between 0.14 and 0.23 mg/L, and temperature variations were between 25 and 13°C.

The treatment train used in the studied DWTP1 (Figure 1) includes (1) preozonation (minimum dose of 0.3 and maximum dose of 0.8 mg/L O₃); (2) coagulation using aluminum sulfate (Al₂(SO₄)₃), also known as alum (dry minimum dose of 17 and maximum dose of 42 mg/L), followed by sedimentation; (3) gravity filtration by dual-media sand-anthracite filter; and (4) post-oxidation by chlorine (minimum dose of 1.3 and maximum dose of 1.7 mg/L Cl₂).

The treatment processes used in DWTP2 (Figure 1) are (1) addition of powdered activated carbon (PAC); (2) coagulation using alum (dry minimum dose of 28 and maximum dose of 45 mg/L), followed by sedimentation; (3) gravity filtration by dual-media sand-anthracite filter; and (4) post-oxidation by chlorine (minimum dose of 1.4 and maximum dose of 1.6 mg/L Cl₂).

**In vivo phycocyanin monitoring.** An on-line water quality multi-probe fitted with an in vivo phycocyanin fluorescence self-cleaning “wiped” probe¹ was used in this study (Zamyadi, 2011). A multi-point sequential system using the phycocyanin probe to measure water quality from the raw water intake before any treatment, clarified water, filtered water, and chlorinated water, was installed inside the full-scale DWTPs (Figure 1). Probe in vivo measurements were recorded every 30 min. The phycocyanin probe excites the cyanobacterial phycocyanin at 590 nm (with a pass-band of 565–605 nm) and measures the pigment’s emission at 660 nm. The probe detects light emitted in the range of 640–680 nm.

The phycocyanin probe’s raw readings are given in ratio fluorescent units (RFU). The probe resolution, range of reading, detection limit, and limit of quantification are 0.1, 0–100, 0.2, and 0.7 RFU, respectively (McQuaid et al, 2011). The maximum limit of quantification of the used phycocyanin probe is 250,000 cells/mL. In the presence of cyanobacterial concentrations exceeding the maximum limit of quantification, the probe reading does not exceed 100 RFU.

In vivo phycocyanin probes were also used to measure the spatial distribution of cyanobacterial cells in water in the clarification basin (over the lamella plates) and the filtration basin (over the filter media), shown in Figure 1. Cell density mappings were conducted by measuring fluorescence profiles over two longitudinal transects at three points with equal distances between each point and at three depths. The location of probe measurements in the water over the clarifier is shown in Figure 2. A virtual environment² was used to visualize the data interpolation between measured points using the in vivo probe.

**Sampling procedure.** After the installation of the in vivo probes, from August to November, a total of eight and nine field visits were conducted at DWTP1 and DWTP2, respectively (corresponding dates are shown in Figure 3). These visits were conducted to collect probe records and water samples. Triplicate samples were taken across the treatment processes from raw to treated water in the following order (Figure 1):

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1. Effluent
2. Filtered water
3. Chlorinated water
4. Raw water

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Footnotes:
1. A “wiped” probe is a self-cleaning probe that removes adhering cells from the probe surface.
2. A virtual environment is a software tool used to visualize and analyze complex data sets.
(1) raw water from the pipeline conducting raw water to the treatment facility before any treatment,
(2) water on the surface of the clarification basin,
(3) water over the sludge bed of the clarifier using the sampling valve,
(4) sludge from the sludge bed of the clarifier using the sampling valve,
(5) concentrated sludge in the concentration cone using the sampling valve,
(6) water over the filter, and
(7) filtered water and treated water at the outlet of the reservoir (complete Cl₂ contact time).

Sampling taps were fully flushed before taking samples. Samples collected for total toxins analysis were frozen at −25°C, whereas those collected for dissolved toxins were filtered over 0.45 μm filters to remove cells and cell-bound toxins before preservation at −25°C.

Samples for total suspended solids (TSS), total volatile suspended solids (TVSS), total solids (TS), total volatile solids (TVS), and TP were collected in clean opaque plastic 500-mL bottles. Samples for dissolved organic carbon (DOC) and biodegradable dissolved organic carbon (BDOC) were collected in carbon-free glass 125-mL bottles. Plastic 500-mL bottles were cleaned by rinsing three times with tap water, three times with deionized water, and left to drip dry. Carbon-free glass 125-mL bottles were rinsed using the same procedure and a heated muffle furnace at 500°C. All water sample containers were rinsed three times with sampled water (from the source water or the DWTP’s untreated water) before being filled completely, closed tightly to avoid the presence of air bubbles, put on ice, transferred to the laboratory, and processed the same day.

Analysis of water quality parameters. Taxonomic identification and counts were performed at the genus level using inverted microscopy (Edler et al, 2010; Wetzel et al, 2000) by the Centre d’Expertise en Analyses Environnementales du Québec at Province of Québec’s Ministry of Environment. The pH, turbidity, temperature, and initial and residual chlorine dosage values were collected from the records of the DWTP for the period being studied.

Only field samples for total toxin measurements were submitted to three freeze/thaw cycles before any analysis for total toxins. Microcystins analyses were conducted using an Abraxis Microcystin ELISA Plate. The analyses of microcystins concentrations were measured as micrograms per litre of microcystin-LR equivalent (MC-LR eq). The accuracy of the plates was validated using standard toxin materials. The average standard deviation of triplicate measurements was 3% (Zamyadi et al, 2012c).

Prior to DOC and BDOC analyses, samples were passed through pre-rinsed (1 L ultrapure water) 0.45-mm cellulose nitrate membrane filters. DOC measurements were made on a total organic carbon analyzer. BDOC measurements were conducted following the methods developed by Servais et al (1995).

Standard Methods (2005) 2540 D, 2540 E, 2540 B, and 2540 E were used to analyze samples for TSS (dried at 103–105°C), TVSS (fixed and volatile solids ignited at 550°C), TS (dried at 103–105°C), and TVS (fixed and volatile solids ignited at 550°C), respectively. For TP analysis, method 365.4 (USEPA, 1983) was used. The phosphorus digestion is similar to nitrogen by using Kjeldahl’s type digestion from Standard Methods (2005).

RESULTS AND DISCUSSION

Cyanobacterial cells and cyanotoxins in the raw water of studied DWTPs. In vivo phycocyanin probes were used to monitor the presence of cyanobacteria at the water intake of the studied DWTPs for the entire period of the study (Figure 4). McQuaid et al (2011) calculated an in vivo phycocyanin-fluorescence—
based monitoring threshold of 2.4 RFU (equivalent of 1 mm³/L of cyanobacterial cells) using maximum potential toxin production of cyanobacterial cells present in water samples and in vivo probe readings from the Canadian region of Lake Champlain (2007 and 2008). Figure 4 shows that in either of the studied DWTPs the in vivo measurements for the entire monitoring period remained below the 2.4 RFU threshold value. Figure 3 also confirms these low on-line readings by results of taxonomic cyanobacteria enumeration from the raw water samples. All samples collected for toxin analysis were below the detection limit of the used method (< 0.15 µg/L). The on-line monitoring at the water intake of these facilities (Figures 3 and 4) shows a constant but low flux of cyanobacterial cells entering these facilities. The contribution of these cyanobacterial cells to the raw-water turbidity and plant solid loading can be considered negligible as shown by Zamyadi et al (2012a).

**Fate of cyanobacterial cells and cyanotoxins during the clarification process.** Samples were taken from scums accumulated over the collection launders in the clarifiers of both plants (Figures 5 and 6). Considering the very low cell numbers at the water intake of these DWTPs (Figures 3 and 4), the observation of scums within these plants was surprising (Figure 5, part A, and Figure 6, part A). Figure 5, part A, shows significant localized accumulation of cyanobacteria (more than 30,000 cells/mL) at the surface of the clarifier in DWTP1 for which *Microcystis* was systematically the dominant genus (Figure 5, part A). Even more considerable accumulations were detected at the surface of the clarifier of DWTP2, reaching up to 1.5 × 10⁶ cells/mL (Figure 6, part A). *Microcystis* was dominant in the scum sample from the surface of the clarifier of DWTP2 with 1.1 × 10⁶ cells/mL, but other genera were present in large numbers, namely *Anabaena* (1.6 × 10⁵ cells/mL), *Aphanizomenon* (1.2 × 10⁴ cells/mL), *Pseudanabaena* (8.1 × 10⁴ cells/mL), and *Gloeotrichia* (2.5 × 10⁴ cells/mL). *Oscillatoria*, *Pseudanabaena*, and *Lyngbya* have also been identified in water samples from flocculation basins, surfaces of clarifiers, and surfaces of filters of eight DWTPs in the United States (Kommineni et al, 2009).

Although cell counts were elevated in the scum over the clarifier of DWTP1, MC-LR eq was detected only on Oct. 27, 2011, with a concentration of 10.9 µg/L MC-LR eq, of which 2.1 µg/L MC-LR eq were dissolved. Also, in DWTP2, cyanotoxins were found only on Aug. 19, 2011, at a concentration of 9.3 µg/L MC-LR eq of total toxin and 0.9 µg/L MC-LR eq as dissolved toxin. Toxin concentrations in all other samples taken in scum samples from these plants were always below the detection limit, in agreement with the overall low toxicity of detected cyanobacteria in 2011.

Visual observation of the accumulation of cells revealed that cyanobacterial cells tended to accumulate at one end the clarification basins rather than over the entire surface. The in vivo phycocyanin probe was then used to determine the distribution of cells in the water over the clarification basin. Figure 2 shows only the results of in vivo mapping at two dates when visible scum accumulated over the clarification basin in DWTP2. Fluorescence profiles shown in Figure 2 show the gradient over the length of the clarifier (Figure 2, parts A and B) and the filter (Figure 2, part}
C) based on measurements taken at three depths under three locations. On Aug. 19, 2011, in vivo cyanobacteria probe readings showed a sharp gradient with elevated concentrations of cyanobacteria (> 80 RFU) at one end of the clarifier. The localized surface accumulation of cyanobacteria was located near the wall of the clarifier opposite the feed side. A similar gradient was observed on Sept. 11, 2011, but with much lower cyanobacterial concentrations (< 11 RFU). Similar results were observed during in vivo mapping of cyanobacterial cells in the clarification basin of DWTP1 (data not shown). Because the submerged launders to collect settled water to the filters are located ~ 30 cm below the surface, any surface accumulation represents a risk of passage of cyanobacterial cells into the clarified water. However, in vivo measurements and enumerations show clearly that cyanobacteria did not pass through into clarified water during all events monitored, as shown by the probe results (Figure 4) and cell enumeration (9–96 cells/mL). The location of the submerged transverse launders was distanced sufficiently from the localized area of cyanobacteria accumulation. Moreover, in vivo measurements also show that cyanobacterial concentrations in most of the water volume over the sludge bed remained low (Figure 2, part A). Similar trends were observed in DWTP1 (Figure 4, part A).

Some accumulation of scum, including algae and cyanobacteria, at the outlet of a clarification basin is common because of bottom-flowing density currents. In the two cases shown in Figure 2, the installation of a simple skimming device at that end of the clarifier, such as a trough and a pump, could be considered to remove the accumulated cyanobacterial cells. When cyanobacteria are present in more substantial concentrations in the entire water volume, a surface-wash device or fan can also be used to concentrate the cells toward the collection system. During the bloom season, the operators of DWTP1 and DWTP2 used simple concentration systems including perforated piping for surface spraying combined with a cut polyvinyl chloride pipe as a collection trough. Autolysis of cells in the water could cause toxin release. However, in the studied plants, the cell collection...
systems were put to work immediately upon detection of cells and were kept on line for the rest of the blooms season. Disposal or recycling of the pumped water should be considered with great care because removed cells might release cell-bound toxins resulting from hydraulic stress from pumping (Pietsch et al, 2002). With these results, it can be argued that the localized accumulation of cyanobacterial cells at the surface of the clarifier, although not desirable, did not represent a significant risk of toxin breakthrough into clarified water, even if the bloom had been highly toxic.

The second major concentration site in the treatment plants studied was the sludge bed. In order to quantify the accumulation of cyanobacterial cells in the sludge bed, samples were taken at the surface of the sludge bed, in the middle of the sludge bed, and in the sludge concentrator of the studied DWTPs (Figure 5, parts B, C, and D; Figure 6, parts B, C, and D). Sludge samples taken
FIGURE 5  Cyanobacteria speciation in water samples from DWTP1 clarifier

DWTP—drinking water treatment plant
A—surface of the clarifier, B—surface of sludge bed, C—middle of sludge bed, D—concentrated sludge in DWTP1 equipped with preozonation
Cyanobacteria speciation in water samples from DWTP2 clarifier

A—surface of the clarifier, B—surface of sludge bed, C—middle of sludge bed, D—concentrated sludge in DWTP2 without preozonation
in DWTP1 contained fewer than 1,000 cells/mL in 14 of 16 samples (Figure 5, parts B, C, and D). Cell numbers in samples from the middle and the surface of the sludge bed were at 2,200 cells/mL and 2,500 cells/mL, respectively (Figure 5, parts B and C). In DWTP2, 10 of 18 sludge samples had fewer than 1,000 cells/mL (Figure 6, parts B, C, and D), but concentrations of cyanobacterial cells from samples at the surface were lower except for one sampling event (Figure 6, part B). A maximum accumulation of 13,500 cells/mL with a dominance of Microcystis was observed in the sludge bed of the DWTP2 (Figure 6, part C), a much lower density than the maximum concentration of 11.4 × 10^4 cells/mL observed in a clarifier from a high-risk source for the same period (Zamyadi et al, 2012b). The density of cells in the sludge bed reflects both the influx of cyanobacteria cells relative to the other solids (TSS, coagulants, and PAC) and the sludge retention time set by solid wasting. Overall, the solid retention time in the clarifier of DWTP1 was longer than DWTP2 (calculated using samples taken for measurement of organic carbons and solids in raw and clarified water and clarifier sludge beds), although TSS values in the two sludge beds were similar (data not shown). It would then be expected that the longer solid retention time in the clarifier of the DWTP1 without the addition of PAC would favor the accumulation of cyanobacterial cells. However, a major difference between the operations of these DWTPs is the application of preozonation at the raw water of DWTP1, whereas the only oxidation barrier in DWTP2 is postchlorination. Pre-oxidation—namely chlorine, ozone, and potassium permanganate—has been applied as pretreatment to conventional treatment in the presence of algae and cyanobacteria (Zamyadi et al, 2012d; Merel et al, 2010). These strategies have the potential to increase the overall removal of cyanobacteria cells during coagulation and filtration processes (Ma et al, 2012, 2011; Chen et al, 2009; Plummer et al, 2002; Widrig et al, 1996). Studies indicate that preozonation processes, similar to other oxidants, cause changes in the cell surface characteristics (Miao et al, 2009; Huang et al, 2008; Plummer et al, 2002, 2001). However, preoxidation also causes damage to cyanobacteria cells and promotes the release of organic material contributing to the pool of chlorinated DBP precursors (considering that postchlorination is used as the final treatment), and other cell-bound metabolites including intracellular metabolites, such as taste-and-odor compounds and/or cyanotoxins (Zamyadi et al, 2012d; Miao et al, 2009). However, as a result of low cell numbers and low cell toxicity at the water intake of the studied DWTP, no significant release of DOC or toxins was observed following preozonation.

### Fate of cyanobacterial cells during the filtration and chlorination processes.

Overall, very low numbers of cyanobacterial cells (< 50 cells/mL) were detected in water samples from the water over the filters, in filtered water and in chlorinated treated water of DWTP1 (data not shown). In both plants, filtered water turbidity was always below 0.2 ntu. In accordance, the in vivo readings in both filtered and treated water of DWTP2 were very low (< 0.2 RFU; Figure 4, parts A and B). However, on Aug. 29, 2011, a green scum (> 100,000 cells/mL) was observed on one side of the filtration basin on the surface of the filter in DWTP2 (Figure 7). Sampling the next day, Aug. 30, 2011, also demonstrated major (> 10,000 cells/mL) cyanobacterial presence at the same location (Figure 7). On both dates Gloeotrichia was the dominant genus and Microcystis was identified as the second most abundant genus (Figure 7). Aug. 29, 2011, corresponded with the date that highest cell numbers were observed on the surface of the sludge bed in the clarifier at DWTP2 (Figure 6, part B). Gloeotrichia and Microcystis were detected over the sludge bed of the clarifier on this date (Figure 6, part B).

In the samples taken from the water over the filtration basin only on Aug. 29, 2011, 5.5 µg/L MC-LR eq of total toxin and 0.3 µg/L...
MC-LR eq of dissolved toxin were detected in DWTP2. This date corresponds with the detection of more than 100,000 cells/mL of cyanobacteria on the surface of the filtration basin (Figure 7).

Following the observation of green scum on the surface of the filtration basin, the in vivo phycocyanin probe was used to monitor the distribution of cells in the water over the sedimentation and filtration basins (Figure 2). Figure 2, part C, shows only the results of in vivo monitoring of the major scum over the filtration basin in DWTP2. The mapping of cyanobacterial cells in the filtration basin (Figure 2, part C) showed a nonhomogeneous distribution of cyanobacterial cells in the water volume with high RFU values over the surface and on one side of the water surface.

The total volume of water over the filter media in the filtration basin of DWTP2 and the limited location of the cyanobacteria accumulation (Figure 2, part C) had a dilution effect on total cell numbers and toxin concentrations. As a result of the dilution effects, the cyanobacterial presence in the total water volume over the filter was very low; thus the presence of cyanobacteria over the filter caused no decrease in filter run time. Contrary to these results, Kommineni et al (2009) reported a decrease of filter run time caused by the presence of cyanobacteria inside DWTPs in the United States. Furthermore, cyanobacterial cells were not detected in filtered and treated chlorinated water samples of both DWTPs using microscopic identification, thereby confirming the in vivo probe readings (Figure 4).

Sites of greater risk of toxin accumulation and pertinent intervention strategies. Cyanobacterial cells can accumulate in clarifiers—both in water as scums and/or in the sludge bed—and in filters—both as scums over the filters and/or within the filter bed during a filtration run. On-line quantification of the maximum toxin concentration that could result from the lysis of the accumulated cells over the clarifier would be beneficial to conduct pertinent treatment adjustments. For this purpose, the potential toxin release can be estimated considering the potential amount of toxins present in the scum using unit cell toxin production, cyanobacterial density mapping results (using in vivo probes), and the immediate dilution in the clarifier. Using the maximum Microcystis cellular toxin production (Falconer et al, 1994), McQuaid et al (2011) published the microcystin production per biovolume of Microcystis (0.014 pg microcystin per 1 µm³ Microcystis). Furthermore, the Microcystis biovolume (0.5 mm³/L) equivalent to 1 RFU of the in vivo phycocyanin probe reading has been published recently (Zamyadi et al, 2012a). The average of the in vivo probe readings in the entire volume of water over the submerged launders, which collect the clarified water and conduct it to the filters, is 16 RFU (Figure 7, parts A and B). Thus the maximum microcystin concentration (including cell-bound and released toxins) in this volume of water is calculated to be 0.11 µg/L. It is important to take into consideration that this estimation is presented as the possible worst-case scenario of toxin accumulation in clarifiers.

Actual toxin concentrations in the settled water are set by the concentrations of toxins entering the plant and any contributions from the cells accumulated within the sludge bed and cells in the overlying water. If only the contribution from the accumulated cells in the water over the sludge bed is considered, the resulting toxin concentrations over a period are set by the dilution of the released toxins and also by the rate of toxin release from the cells. In the case of an instantaneous release of toxins, the toxins would not be diluted in the clarifier but would appear in varying extents in the filtration, chlorination contact, and storage basins. However, the rate of release is likely to vary depending on the physiological status of the cells, and it is unlikely that a massive instan-
taneous lysis would occur (Zamyadi, 2012c; Zamyadi et al, 2011; Pietsch et al, 2002). Therefore, the toxin dilution factors in the settled water would vary depending on the duration of the release. These levels of dilution would significantly reduce the risk of the presence of cyanotoxins and their breakthrough to downstream processes. The accumulation of cyanobacterial cells and toxins in the sludge bed can be substantial depending on the number of accumulated cells and their homogenous distribution within the sludge. No toxins were detected in the sludge beds monitored in the studied plants, again reflecting the relative low toxicity of the cyanobacterial blooms present in 2011. However, if the unit cell production of 0.2 pg/cell is applied to the maximum number of cells detected in the sludge bed of these plants (13,500 cells/mL), the potential mass of toxin in the sludge bed represents 0.3 g of microcystin and the resulting maximum concentration remains modest at 0.24 µg/L microcystin.

The application of intervention threshold values restricted to raw water does not take into consideration the major long-term accumulation of potentially toxic cells in the sludge and the risk of toxin release. The authors of this article recommend regular sampling from the sludge during the cyanobacterial bloom season and in situ toxin measurements—e.g., with toxin detection strips/kits—whereby preventive action could be adjusted based on the toxin measurements. The operation strategies along with knowledge of cyanobacterial presence in source water and design of the treatment process are key factors in conducting a cost-effective intervention plan.

Current monitoring strategies (e.g., non-event–based weekly sampling) are not suitable to detect the highly temporal variability of cyanobacterial presence at the water intake of DWTPs. A monitoring strategy including intensive in vivo fluorescence measurements and event-based sampling will identify transient challenging periods for toxic cyanobacteria and provide on-time information for real-time treatment adjustment. In addition, a comprehensive monitoring program (from source to consumers’ taps) to ensure the protection of public health is strongly recommended.

CONCLUSIONS

This article provides detailed evidence of the removal performance for cyanobacterial species by drinking water treatment processes within DWTPs with a low risk of cyanobacterial presence. Accumulation of toxic cyanobacterial cells was observed in these plants over the surface of the clarification and filtration basins. Microcystis and Gloeotrichia were the dominant genera in accumulations over the clarification and filtration basins, respectively. This article demonstrates the extent and duration of cyanobacteria cells and toxin accumulation in sludge beds and filters.

The preozonation of raw water would help with removal of cells in the clarification process. However, it is important to take into consideration the effect of preozonation on cyanobacterial cells and the subsequent effects on water treatment. Thus the benefits of cyanobacteria control and the consequent effects of ozonation, such as DBP formation, must be considered when cyanobacteria blooms are present.

Cyanobacteria intervention strategies should include intensive in vivo probe monitoring from source to treated water, regular sampling from the sludge, and in situ toxin measurements. The prolonged accumulations of cells in sludge bed and filter media convince the authors that further research is required to monitor the breakthrough and accumulation of algal cells, including cyanobacteria, in DWTPs considered at low risk of extreme bloom events.

The available information on the rate of toxin release within the clarifiers of DWTPs, toxin production per cell or per biovolume of different cyanobacterial species present in water bodies, and equivalent in vivo measurements per biovolume of present species, is limited. Although further studies are required to broaden the risk calculations presented in the section titled “Sites of greater risk of toxin accumulation and pertinent intervention strategies” to other cyanobacterial species, the described methodology could be used by the operators of DWTPs to estimate the risk of toxin breakthrough and to identify the proper treatment adjustments.

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FOOTNOTES

1YSI 6600 V2-4 water-quality multiprobe fitted with YSI6131 blue-green algae in vivo phycocyanin fluorescence probe, Yellow Springs Instruments (YSI), Yellow Springs, Ohio (YSI Inc., 2006).
3Whatman, U.K.
4An enzyme-linked immunosorbent assay, Abaxis LLC, Pa.
5Supor 450, PALL Life Sciences, PALL Corp., Port Washington, N.Y.
65310C Sievers Instruments Inc., Boulder, Colo.
7QuickChem, Lachat Instruments, Hach Co., Loveland, Colo.

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