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Using surrogate data to assess risks associated with microbial peak events in source water at drinking water treatment plants

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ABSTRACT

A monitoring strategy was implemented at two drinking water treatment plants in Quebec, Canada, to evaluate microbial reduction performances of full-scale treatment processes under different source water conditions. β-D-glucuronidase activity in source water was automatically monitored in near-real-time to establish baseline and event conditions at each location. High-volume water samples (50–1,500 L) were collected at the inflow and the outflow of coagulation/flocculation, filtration, and UV disinfection processes and were analysed for two naturally occurring surrogate organisms: *Escherichia coli* and *Clostridium perfringens*. Source water *Cryptosporidium* data and full-scale *C. perfringens* reduction data were entered into a quantitative microbial risk assessment (QMRA) model to estimate daily infection risks associated with exposures to *Cryptosporidium* via consumption of treated drinking water. Daily mean *E. coli* and *Cryptosporidium* concentrations in source water under event conditions were in the top 5% (agricultural site) or in the top 15% (urban site) of what occurs through the year at these drinking water treatment plants. Reduction performances of up to 6.0-log for *E. coli* and 5.6-log for *C. perfringens* were measured by concentrating high-volume water samples throughout the treatment train. For both drinking water treatment plants, removal performances by coagulation/flocculation/sedimentation processes were at the high end of the range of those reported in the literature for bacteria and bacterial spores. Reductions of *E. coli* and *C. perfringens* by floc blanket clarification, ballasted clarification and rapid sand filtration did not deteriorate during two snowmelt/rainfall events. QMRA results suggested that daily infection risks were similar during two rainfall/snowmelt events than during baseline conditions. Additional studies investigating full-scale reductions would be desirable to improve the evaluation of differences in treatment performances under various source water conditions.

1. Introduction

Drinking waterborne outbreaks occurring in affluent nations since 2000 were recently compiled in literature reviews (Moreira and Bondelind 2017; Hrudey and Hrudey 2019). Heavy rain and inadequate treatment of surface water sources were potential causative factors for outbreaks caused by *Cryptosporidium, Giardia*, norovirus, and *Shigella sonnei*. Hrudey & Hrudey (2019) concluded that the occurrence of waterborne outbreaks after heavy rainfall is certainly common enough to justify increased vigilance for such events. As the frequency and the magnitude of extreme rainfall events are projected to increase under climate change scenarios (IPCC, 2014), enhanced focus on the management of weather events has been recommended in future revisions of guidance documents for drinking water quality (Khan et al., 2015; Howard et al., 2016).

The quantitative microbial risk assessment (QMRA) approach can be valuable to calculate risks associated with hazardous events and support risk management decisions (Medema and Ashbolt, 2006; Medema and Smeets, 2009; Smeets et al., 2010; Petterson and Ashbolt, 2016). In QMRA, microbial reduction per-

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formances by physicochemical and disinfection processes are generally assumed to follow first-order kinetics with respect to the micro-organisms' influent concentrations (Haas et al., 1999). The concentration of an organism in treated drinking water is therefore expected to be directly proportional to its source water concentration. Several studies showed that microbial concentrations in surface water increase by orders of magnitude over short periods during heavy rainfall and snowmelt events (Atherholt et al., 1998; Kistemann et al., 2002; Signor et al., 2005; Dorner et al., 2007; Sylvestre et al., 2020b). Consequently, weather events could be critical drivers of the infection risk to water consumers (Signor et al., 2007). There are, however, limited high-resolution data on the microbial reduction performance of drinking water treatment processes to investigate whether the first-order assumption holds under variable microbial loads at the source.

Full-scale microbial reduction performances are typically assessed with naturally occurring (i.e. not spiked) surrogate microorganisms because pathogen concentrations are too low after treatment barriers. Surrogate organisms can be detected after full-scale treatment by concentrating high-volume water samples on-site (Payment et al., 2002; Hijnen et al., 2007). Spores of sulphite-reducing clostridia (including *Clostridium perfringens*) have been recommended as conservative surrogates for index protozoan pathogens (*Cryptosporidium, Giardia*) removal through conventional treatment (Payment and Franco 1993; Hijnen et al., 2000; WHO, 2017). Thermotolerant coliforms (including *Escherichia coli*) were found to be a proper surrogate for an index bacterial pathogen (*Campylobacter*) removal by rapid sand filtration (Hijnen et al., 1998) and inactivation by ozonation (Smeets and Medema, 2006).

Identifying microbial peaks in source water can be challenging because these events can occur within a short time frame (Burnet et al., 2019). Culture-based methods are of limited value for identifying these peaks because they typically require 24-hour incubation periods. Alternatively, β-D-glucuronidase (GLUC) activity, a conservative biochemical proxy-parameter for bacterial faecal pollution, can be automatically monitored in source water in near-real-time (Ryzinska-Paier et al., 2014; Koschelnik et al., 2015; Demeter et al., 2020). This technology has recently supported the development of monitoring programs to characterize microbial peaks at drinking water intakes (Burnet et al., 2019; Sylvestre et al., 2020a; Sylvestre et al., 2020b) and to inform an investigation of the removal of human enteric viruses by full-scale drinking water treatment processes (Sylvestre et al., 2021).

The objective of this study was to evaluate microbial reduction performances of full-scale treatment processes at two drinking water treatment plants under different source water conditions. An event-based sampling strategy informed by online GLUC activity monitoring and meteorological conditions was implemented to capture variations in performance between baseline and event conditions. Source water pathogen data and surrogate organism reduction data were entered into a QMRA model to assess human health risks associated with the consumption of drinking water.

2. Material and methods

2.1. Catchment and drinking water treatment descriptions

Two drinking water treatment plants (DWTPs) were selected for this study. DWTP A abstracts raw water from a small agricultural river (annual average flow rate of the river is 16 m^3/s) situated in southern Quebec. The microbial water quality of source water at DWTP A can be influenced by four combined sewer overflows (CSOs) and a municipal wastewater treatment plant (WWTP) discharging 10 km upstream of the drinking water intake. At the WWTP, human sewage is treated through an aerated pond and discharged into the river at an average rate of 10,000 m^3/day. Cattle and swine manure is applied for agriculture in the catchment area. Buffer strips of at least 3 m from the river are required (Gouvernement du Québec, 2018).

During the sampling campaigns, DWTP A was operated at a capacity of approximately 3500 $m^3\ d^{-1}$, about 20% of the design rate (18,000 $m^3\ d^{-1}$). During water treatment, potassium permanganate ($KMnO_4$; 0.6 mg L^{-1}) was first added to the raw water. After permanganate oxidation, polyaluminum chloride (PACl; PAX-XL8: 110 mg L^{-1}) and cationic polyacrylamide (C-492; dosing rate: 0.11 mg L^{-1}) were added in water at pH 6.2 and temperature of approximately 10 °C and processed by Ultrapulsator® floc blanket clarification (Suez, Quebec, Canada). The settled water was then filtered by four single-media sand filters (0.8 m h^{-1}; 140 cm sand) and disinfected by a medium pressure UV system (fluence: 40 mJ cm^{-2}; Trojan UV Swift; Trojan Technologies, Schöllkrippen, Germany) and chlorine dioxide (ClO_2). Unit processes present in the treatment train and the location of sampling points are illustrated in Fig. 1. Supervisory Control and Data Acquisition (SCADA) data (flow rate, coagulant dosage, turbidity, pH, disinfectant residual, and temperature measurements) were obtained for the studied periods. Treatment processes were optimized for turbidity reduction during sampling campaigns (turbidity $<$ 1.0 NTU in settled water; turbidity $<$ 0.1 NTU at individual filter effluents).

The characterization of the catchment and the treatment barriers of DWTP B is detailed elsewhere (Sylvestre et al., 2021). Briefly, DWTP B is supplied by a large urban river under the influence of around 180 CSOs and 14 municipal WWTPs. During the sampling period, DWTP B was operated at about 40% of the design rate (120,000 $m^3\ d^{-1}$). The raw water was processed by ACTIFLO® microsand ballasted clarification and was then treated by a combination of inter-ozonation and granular activated carbon (GAC) filtration, referred to as biological activated carbon (BAC) filtration. The filtered water was disinfected with a low-pressure UV system (fluence: 40 mJ cm^{-2}) and sodium hypochlorite (NaOCl). Treatment processes were optimized for turbidity reduction during sampling campaigns.

2.2. Sampling campaigns

2.2.1. Definition of baseline and event conditions

At each DWTP, an automated rapid on-site monitoring system (ColiMinder^{TM} VWM GmbH, Vienna, Austria) was installed approximately one month before evaluating microbial reduction performances. During this period, the GLUC activity level was measured at frequencies varying between 1 and 3 h. Variations in raw water quality were investigated during the autumn at DWTP A. Three sampling campaigns were carried out under baseline conditions (Baseline-A1, Baseline-A2, Baseline-A3) and one campaign was undertaken under event conditions (Event-A1). Baseline conditions were defined as dry weather conditions (48-hour total rainfall = 0 mm). Event conditions were established using two criteria: wet weather conditions (48-hour total rainfall $>$ 40 mm) and a relative change in GLUC activity (variation $>$ +5 mMFU/100 mL over 1 h). A relative change in GLUC activity was chosen to ensure the characterization of the whole GLUC activity peak. A change of 5 mMFU/100 mL was set based on observed changes during three rainfall events at this DWTP (Supplementary Figure 1) and two rainfall/snowmelt events previously characterized at an urban DWTP (Sylvestre et al., 2020b). Single grab sample (baseline conditions) and sequential grab samples (event conditions; n=3) of raw, settled (200 L), filtered (1000 L), and UV disinfected (1500 L) waters were collected to match theoretical mean hydraulic residence times through clarification (3 h), filtration and UV disinfection (2 h) (A. Verroneau, *personal communication*). Additionally, under event conditions, six 30 to 40-litres samples of raw water were

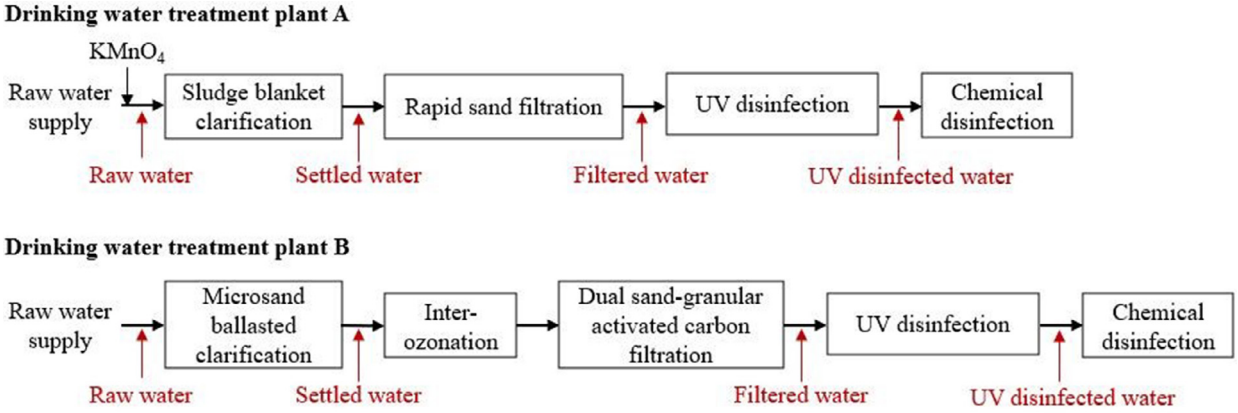

Fig. 1. Unit processes involved in the treatment train of drinking water treatment plants A and B and the location of sampling points (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

filtered on-site over 24 h to estimate the daily mean *Cryptosporidium* concentration.

Three campaigns under baseline conditions (Baseline-B1, Baseline-B2, Baseline-B3) and two campaigns under event conditions (Event-B1, Event-B2) were carried out during the spring freshet at DWTP B. Online GLUC activity measurements were used in early February 2018 to trigger grab sampling of raw water (Event-B1). This first campaign was undertaken to evaluate how a planned discharge of raw sewage at an upstream WWTP influenced source water quality at DWTP B. Discharge circumstances and a general characterization of the WWTP are provided elsewhere (Sylvestre et al., 2021). In early March 2018, a short-term increase in GLUC activity of approximately 20 mMFU/100 mL was observed in the absence of recent snowmelt events (48-hour total snowmelt < 2 cm) and rainfall events (48-hour total rainfall $= 0$ mm). An increase in GLUC activity of 20 mMFU/100 mL in dry weather conditions was considered relevant for event-based sampling because similar increases were observed in this study during the planned discharge of raw sewage (Event-B1) and during two wet weather events previously characterized at an urban DWTP (Sylvestre et al., 2020b). Event-based samples were collected over four days to quantify the reduction by treatment processes during this GLUC activity peak (Event-B2). Baseline campaigns were carried out after Event-B2 at GLUC activity levels approximately 20 mMFU/100 mL below levels observed during Event-B1 and Event-B2. Single grab sample (baseline conditions) and sequential grab samples (event conditions; n=4) of raw, settled (200 L), filtered (1000 L), and UV disinfected (1500 L) water were collected to match theoretical mean hydraulic residence times through clarification (0.5 h), ozonation, filtration, and UV disinfection (1.5 h) (M. Marchand, *personal communication*). Additionally, grab 25 to 30 l-samples were filtered on-site to estimate the mean *Cryptosporidium* concentration in raw water under baseline conditions ($n = 3$) and event conditions ($n = 3$).

2.2.2. Sample concentration

Raw water samples were concentrated with Hemoflow HF80S filters (Fresenius, Ontario, Canada) for the enumeration of *Cryptosporidium*. Concentrates were shipped overnight in coolers at 4 °C to the Centre d'expertise en analyse environnementale du Québec (CEAEQ) in Quebec City, QC, and processed within 48 h of sampling. The Hemoflow concentration method was also used to concentrate naturally occurring *E. coli* and *C. perfringens* spores in raw, settled, filtered and UV-disinfected water samples. One tank was filled with 50 L of settled water. Multiple tanks of 1000 L were filled with 1000–1500 L of filtered water or UV-disinfected water. The water was pumped through the Hemoflow HF80S filter (Fresenius, Ontario, Canada) at a minimum speed of 4 l per minute. The overpressure over the filter was increased to a maximum of 0.7 bar until the water filtrate was pressed through the walls of the straws with a speed of around 0.9 L/min (Veenendaal and Brouwer-Hanzens, 2007). Installations with four Hemoflow-filters in parallel were built to concentrate high-volume water samples faster ($<$ 6.5 h). The concentration process was stopped when the concentrate volume only filled the hoses. Filtrate water was pumped through the hoses once and then collected in a sterile bottle. The total end volume was approximately 600 mL. Samples were kept at 4 °C and analysed within 24 h.

The recovery rate of the Hemoflow concentration method was evaluated for raw water samples collected at each DWTP. The recovery rate was calculated as the ratio of the surrogate concentration in an un-concentrated (grab) sample to its concentration in a Hemoflow concentrated sample (100 L at DWTP A, 20 L at DWTP B). Recovery rates of 103% for *E. coli* and 125% for *C. perfringens* were measured at DWTP A. A recovery rate of 124% was measured for *C. perfringens* at DWTP B but no recovery rate was determined for *E. coli* at DWTP B. Recovery rates of 100% were assumed for the calculations of all *E. coli* and *C. perfringens* concentrations.

2.2.3. Sample processing and analysis

Hemoflow-filter eluate volumes for enumeration of *Cryptosporidium* oocysts were approximately 500–700 mL. Post-concentration was carried out by centrifugation to obtain a final volume between 20 and 50 mL and a packed pellet volume between 2 and 5 ml. Between 20 and 50% of the packed pellet volume was then processed by immunomagnetic separation (IMS) before sample staining and examination following USEPA method 1623.1 (USEPA, 2012). Sample-specific recovery rates were measured for each sample collected under baseline and event conditions. Fluorescently-labelled controls (Colorseed^{TM}) were spiked at a target dose of 98–100 (oo)cysts in the raw water sample before careful manual mixing and on-site concentration using the Hemoflow method.

Volumes of Hemoflow-filter eluates for the enumeration of surrogate organisms were approximately 600 mL. From these volumes, two aliquots of 100–200 mL were taken to detect *E. coli* and *C. perfringens* spores. *E. coli* was enumerated by the defined substrate technology using the IDEXX Quanti-Tray/2000 System with Colilert reagent (APHA, 2005). Spores of *C. perfringens* were enumerated on m-CP medium as described previously (Armon and Payment, 1988).

2.3. Statistical analysis

2.3.1. Exceedance probabilities for source water microbial concentrations

Exceedance probabilities (EPs) were calculated to determine probabilities that source water concentrations would be exceeded based on historical monitoring data. Temporal variations in concentrations were assumed to be lognormally distributed. The parameters of the lognormal distributions were inferred from *E. coli* data collected weekly for 5 years (2013–2017) and *Cryptosporidium* data collected monthly for approximately 2 years between 2012 and 2016. Estimations and inferences were carried out in a Bayesian framework using Markov Chain Monte Carlo (MCMC), as previously described (Sylvestre et al., 2020a,c). EPs were computed for daily mean source water *Cryptosporidium* concentrations adjusted for the recovery efficiency and daily mean source water *E. coli* concentrations. This model was implemented using R (v3.4.1). The R code is provided in the Supplementary Material.

2.3.2. Quantification of reduction by treatment processes

The reduction performance of each treatment process was evaluated by comparing the inflow concentration (C_{in}) and the outflow concentration (C_{out}) of the surrogate organism. Point estimates of reduction (i.e., removal or inactivation) representing the log-reduction (LR) across a treatment unit (paired sample) were calculated by the following equation:

$$\mathrm{LR} = \log_{10}\left(\frac{C_{in}}{C_{out}}\right) \tag{1.1}$$

The average percent reduction, expressed as effective log-reduction ($\mathrm{LR}_{\mathrm{effective}}$), was calculated as follows:

$$\mathrm{LR}_{\mathrm{effective}} = \log_{10}\left(\frac{\bar{C}_{in}}{\bar{C}_{out}}\right) \tag{1.2}$$

This approach for quantifying the $\mathrm{LR}_{\mathrm{effective}}$ assigns equal weights to concentrations. The standard error of the mean log-reduction ($\sigma_{\overline{\mathrm{LR}}}$) was evaluated to provide a simple measure of uncertainty of the LR. It can be regarded as the dispersion of the LR across a treatment unit (paired sample) around the mean LR. The standard error was calculated as follows:

$$\sigma_{\overline{\mathrm{LR}}} = \frac{S_{\mathrm{LR}}}{\sqrt{n}} \tag{1.3}$$

where S_{LR} is the standard deviation of all LRs evaluated across a treatment unit (paired sample) and n is the sample size. Non-detects were replaced by a detection limit of 1 organism per volume of sample. Each treatment step was assumed to behave as a plug-low reactor operated hydraulically at a steady state during the sampling period.

2.3.3. Quantitative microbial risk assessment

Site-specific raw water *Cryptosporidium* data and *C. perfringens* reduction data were entered in a QMRA model to quantify daily risks of infection by *Cryptosporidium* via consumption of treated drinking water. A linear low-dose approximation to the single-hit dose–response relationship was adopted to simplify calculations. The risk of infection associated with exposure to more than one oocyst was assumed to be negligible. The daily probability of infection under baseline conditions $\mathrm{P}_{\mathrm{inf.\ baseline}}$ was calculated as follows:

$$\mathrm{P}_{\mathrm{inf.\ baseline}} = C_{\mathrm{baseline}} \cdot 10^{-\mathrm{LR}_{\mathrm{baseline}}} \cdot \mathrm{V} \cdot \mathrm{r} \tag{1.4}$$

where C_{baseline} is the *Cryptosporidium* concentration in raw water adjusted for the recovery efficiency under baseline conditions, $\mathrm{LR}_{\mathrm{baseline}}$ is the total reduction of *C. perfringens* by treatment processes under baseline conditions, V is the ingested volume of drinking water per person per day, and r is the probability that any single ingested *Cryptosporidium* oocyst succeeds in infecting the host. C_{baseline} were not measured at DWTP A. We assumed that C_{baseline} was the arithmetic mean *Cryptosporidium* concentration in source water evaluated with monthly sampling for 2 years.

The daily probability of infection under event conditions was evaluated as follows:

$$\mathrm{P}_{\mathrm{inf.\ event}} = \bar{C}_{\mathrm{event}} \cdot 10^{-\overline{\mathrm{LR}}_{\mathrm{event}}} \cdot \mathrm{V} \cdot \mathrm{r} \tag{1.5}$$

where $\bar{C}_{\mathrm{event}}$ is the mean *Cryptosporidium* concentration in raw water adjusted for the recovery efficiency under event conditions and $\overline{\mathrm{LR}}_{\mathrm{event}}$ is the reduction of *C. perfringens* by treatment processes under event conditions. It was conservatively assumed that: 1) all detected *Cryptosporidium* oocysts in raw water were human infectious, 2) the reduction of bacterial spores was equivalent to the reduction of oocysts (Teunis et al., 1997; Barbeau et al., 2000), and 3) free chlorine did not inactivate *Cryptosporidium parvum* oocysts (Venczel et al., 1997). The ingested volume V was set to 1 litre per person per day and the single oocyst infectivity r was set to 0.2 to be consistent with the QMRA model applied in the WHO Guidelines for drinking-water quality (GDWQ) (WHO, 2017).

E. coli reduction data were not entered into a QMRA model because concentrations of bacterial pathogens in source water were not available and *E. coli* reductions by chlorine disinfection processes were not measured. However, the risk of infection by bacterial pathogens should be very low at these sites because, in general, bacteria are very sensitive to chlorine (Petterson and Stenström, 2015).

3. Results

3.1. Agricultural drinking water treatment plant A

Temporal variations in GLUC activity, *E. coli* concentrations, and *C. perfringens* concentrations in raw water during fall 2017 at DWTP A are illustrated with a time series plot (Fig. 2A). The GLUC activity decreased from 30 mMFU/100 mL in mid-October to 5 mMFU/100 mL in November. Four GLUC activity peaks of similar duration (approximately 24 h) and different amplitudes (40–160 mMFU/100 mL) were measured during this period. The performance of treatment processes was assessed during a GLUC activity peak with an amplitude of 40 mMFU/100 mL. Temporal variations in turbidity and daily rainfall are illustrated in Supplementary Figure 1. The relationship between these parameters and GLUC activity at this site is discussed elsewhere (Sylvestre et al., 2020b). At the source, exceedance probabilities (EP) for *E. coli* during Baseline-A2 and Baseline-A3 were 14% and 38% (Table 1). The EP during Event-A1 was 0.8% (3 days per year). The EP for *Cryptosporidium* in event conditions was also low (5.4%). Mean raw water *C. perfringens* concentrations were 0.5-log higher under event conditions (109 CFU/100 mL, n=6) than under baseline conditions (39 CFU/100 mL, n=3).

In the treatment train, *E. coli* was detected in all filtered water samples (n=6) and *C. perfringens* was detected in all filtered and UV-disinfected water samples (n=6) (Fig. 3). *E. coli* concentrations in UV-disinfected water samples were not reported because autofluorescence potentially led to false-positive results. The hourly abstraction flow rate and the turbidity of settled water were similar under baseline and event conditions (Supplementary Table 1). The water temperature was 10 °C lower during Baseline-A3 compared to Baseline-A1, Baseline-A2 and Event-A1. Effective log-reductions by floc blanket clarification were similar under event and baseline conditions for both surrogate organisms (*E. coli*: event = 2.9-log, baseline = 2.8-log; *C. perfringens*: event = 2.9-log, baseline = 3.3-log) (Supplementary Table 2). Effective log-reductions by rapid sand filtration were higher under event con-

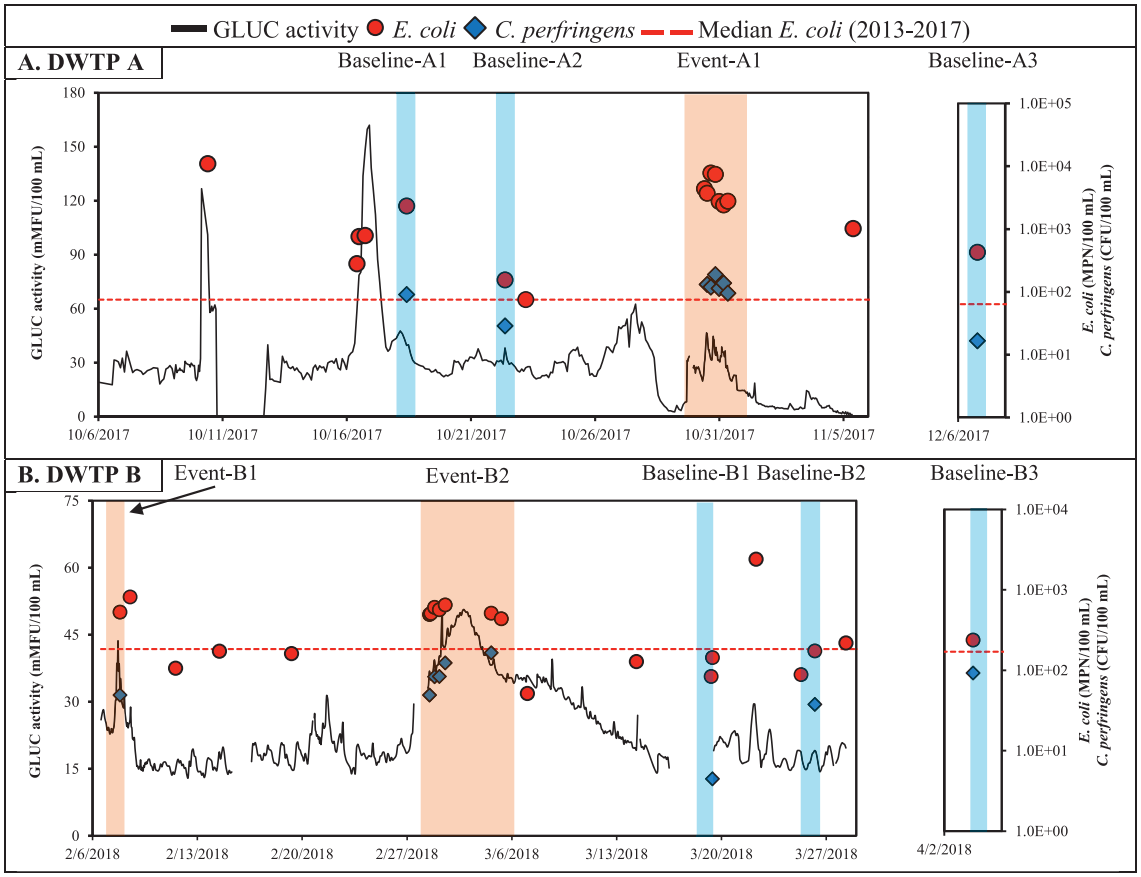

Fig. 2. Time series of β-D-glucuronidase (GLUC) activity, *E. coli* concentrations and *C. perfringens* concentrations in raw water at drinking water treatment plants (DWTPs) A and B. Red dashed lines represent median *E. coli* concentrations calculated with routine monitoring data collected weekly from 2013 to 2017. Shaded red rectangles indicate targeted event conditions. Shaded blue rectangles indicate targeted baseline conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Exceedance probabilities (EPs) for daily mean *E. coli* concentrations and daily mean *Cryptosporidium* concentrations evaluated under baseline and event conditions. EPs were computed from the median value and the 95% credible interval (CI) of the parameter values of the log-normal distribution. .

		E. coli Concentration (CFU/100 mL)	EP (95 CI)	*Cryptosporidium* Concentration (oocysts/L)	EP (95 CI)
DWTP A	Baseline-A1	1785	0.023 (0.012, 0.035)	(*)	(*)
	Baseline-A2	129	0.380 (0.332, 0.427)	(*)	(*)
	Baseline-A3	428	0.141 (0.106, 0.175)	(*)	(*)
	Event-A1	3340	0.008 (0.003, 0.014)	1.48	0.053 (0.000, 0.152)
DWTP B	Baseline-B1	134	0.544 (0.505, 0.580)	0.11	0.394 (0.180, 0.668)
	Baseline-B2	161	0.486 (0.449, 0.524)	0.08	0.452 (0.218, 0.775)
	Baseline-B3	238	0.365 (0.329, 0.402)	(*)	(*)
	Event-B1	467	0.189 (0.161, 0.220)	0.36	0.196 (0.043, 0.386)
	Event-B2	572	0.149 (0.122, 0.176)	0.85	0.109 (0.000, 0.252)

(*) Not available.

ditions in comparison to baseline conditions for both surrogate organisms (*E. coli*: event = 1.2-log, baseline = 0.6-log; *C. perfringens*: event = 1.7-log, baseline = 0.5-log). However, the standard errors of the mean log-removal ($\sigma_{\overline{LR}}$) were > 0.5-log for rapid sand filtration in baseline conditions. Time series of the log-reductions of surrogate organisms by floc blanket clarifiers and rapid sand filters under event conditions show that the removal performance was stable during event conditions (Fig. 4A). Overall, UV disinfection had a negligible effect on the inactivation of *C. perfringens*. For *C. perfringens*, the total effective log-reduction were similar in baseline and event conditions (*C. perfringens*: event = 4.5-log, baseline = 4.3-log) but a low total effective log-reduction was measured during one baseline (Baseline-A2 = 3.6-log). As a result, the daily infection risks for *Cryptosporidium*, calculated using the *C. perfringens* reduction performance results, was 0.4-log higher during Baseline-A2 than during Event-A1.

3.2. Urban drinking water treatment plant B

The baseline GLUC activity was stable at a level of approximately 15 mMFU/100 mL during spring 2018 at DWTP B (Fig. 2B). The GLUC activity peaked at 44 mMFU/100 mL in early February following a planned discharge of raw sewage at a wastewater treatment plant located around 5 km upstream of the drinking water intake. At the beginning of March, the GLUC activity increased from 20 to 50 mMFU/100 mL within 4 days and then slowly decreased for two weeks to return to the baseline level. The performance of treatment processes was assessed during this long peak

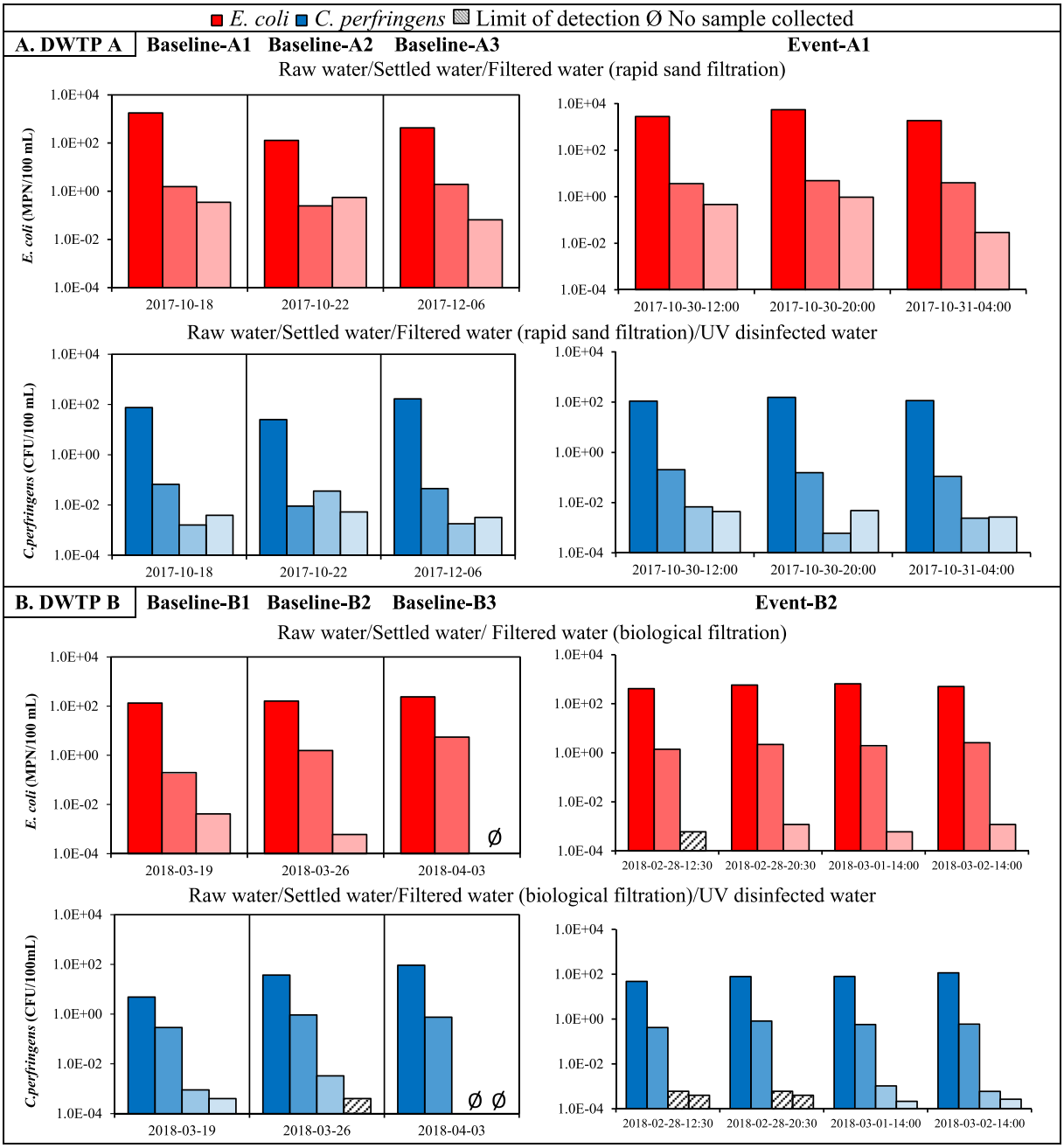

Fig. 3. Histograms for *E. coli* (red) and *C. perfringens* (blue) concentrations in raw water, settled water, filtered water and UV-disinfected water under baseline and event conditions at drinking water treatment plants (DWTPs) A and B. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

event. Temporal variations in turbidity, ammonia, river flow rate, daily rainfall, daily snow cover are illustrated in Supplementary Figure 1. The relationship between these parameters and GLUC activity at this site is discussed elsewhere (Sylvestre et al., 2021). At the source, EPs for *E. coli* ranged between 14% and 18% under event condition and between 36% and 54% under baseline conditions (Table 1). EPs for *Cryptosporidium* were less than or equal to EPs for *E. coli*, in baseline and event conditions. Mean *C. perfringens* concentrations during event conditions (95 CFU/100 mL, $n = 6$) were 0.5-log higher in comparison to baseline conditions (30 CFU/100 mL, n=3), as previously observed at DWTP A.

In the treatment train, *E. coli* was detected in 83% of the filtered water samples and *C. perfringens* was detected in 66% of the UV-disinfected water samples (Fig. 3B). The abstraction flow rate, the water temperature, and the turbidity of settled water were similar under baseline and event conditions (Supplementary Table 2). Effective log-reductions by ballasted clarification were higher under event conditions in comparison to baseline conditions for both surrogate organisms (*E. coli*: event = 2.4-log, baseline = 1.9-log; *C. perfringens*: event = 2.1-log, baseline = 1.8-log). Effective log-reductions by biological filtration were also higher under event conditions than baseline conditions for both surrogate organisms (*E. coli*: event = 3.4-log, baseline = 2.5-log; *C. perfringens*: event = 2.9-log, baseline = 2.4-log). However, log-reductions by biological filtration were only measured twice during baseline conditions. The log-reductions of surrogate organisms by ballasted clarification and biological filtration were stable under event conditions (Fig. 4B). UV disinfection had a small effect on *C. perfringens*

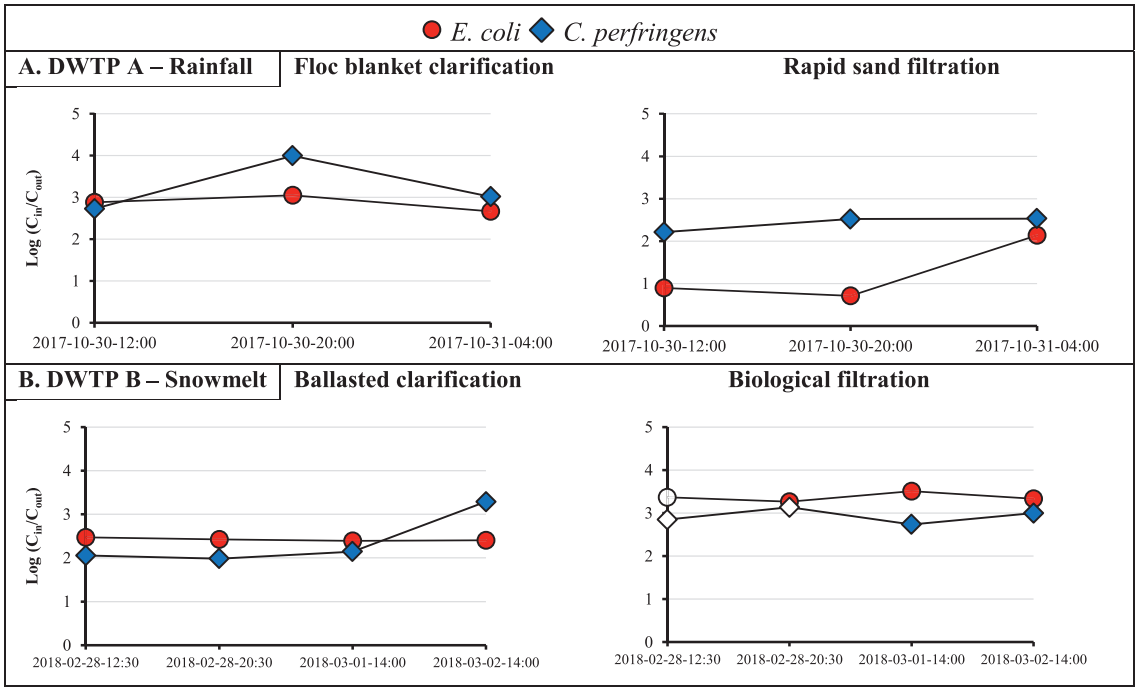

Fig. 4. Short-term variations in reductions of *E. coli* (red circles) and *C. perfringens* (blue diamond) by clarification and filtration processes under event conditions at drinking water treatment plants (DWTPs) A and B. White circles and diamonds represent minimum removal performance values due to the inability to quantify surrogate organisms in filtered water (below the detection limit). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Daily infection risks per person per day for *Cryptosporidium* under baseline and event conditions at drinking water treatment plants (DWTPs) A and B.

	Sample id.	Source water *Cryptosporidium* (oocyst/L)	Reduction *C. perfringens* (log-units)	Daily risk (inf./per/day)
DWTP A	Baseline-A1	0.43	4.2	5.42 E-06
	Baseline-A2	0.43	3.6	2.16 E-05
	Baseline-A3	0.43	4.9	1.08 E-06
	Event-A1	1.48	4.5	9.36 E-06
DWTP B	Baseline-B1	0.11	4.0	2.20 E-06
	Baseline-B2	0.08	5.2	1.01 E-07
	Event-B2	0.85	5.4	6.77 E-07

inactivation (effective log-inactivation < 1.0-log). . The total effective log-reduction for *C. perfringens* were similar in baseline and event conditions (*C. perfringens*: event = 5.4-log, baseline = 4.7-log). The *Cryptosporidium* concentration was approximately 1.0-log higher during the event conditions than in baseline conditions (Table 2). However, as observed at DWTP A, daily infection risks for *Cryptosporidium*, calculated using the *C. perfringens* reduction performance results, were not higher during event conditions than baseline conditions. The daily infection risk was 1.3-log higher during Baseline-B1 than during Event-B2.

4. Discussion

The collection of high-resolution data on the microbial reduction performance is needed to determine whether source water peak events are critical drivers of the infection risk to water consumers. In this study, an event-based sampling strategy using locally derived GLUC activity levels was implemented at two DWTPs to monitor the full-scale performance of physicochemical and disinfection processes under different source water conditions.

For both DWTPs, removal performances by coagulation/flocculation/sedimentation processes were at the high end of the range of those reported for bacteria and bacterial spores (Hijnen and Medema, 2010). High reduction performances at DWTP A may in part be attributed to the presence of pre-oxidation with potassium permanganate ($KMnO_4$) before coagulation, and in part to the type of clarifier. Previous investigations have shown that permanganate pre-oxidation inactivates *E. coli* (Cleasby et al., 1964) and improves the removal of particles by coagulation/flocculation (Liu et al., 2013). A mean removal performance of 3.7-log for *C. perfringens* by floc blanket clarification with pre-ozonation was previously reported for a DWTP supplied by an agricultural river in Quebec (Payment and Franco, 1993). It should be emphasized that treatment processes of DWTP A were optimized for turbidity reduction and operated at approximately 20% of their nominal design capacity under baseline and event conditions. The effective log-removals of *E. coli* and *C. perfringens* by floc blanket clarification were similar or lower under event conditions than under baseline conditions. The removal performance of a floc blanket clarifier used in DWTP A should not theoretically be influenced by the particle concentration in source water. The aggregation of micro-sized particles in a fluidized bed (floc blanket) is typically approximated as a first-order process by assuming that the size of the flocs in the fluidized bed is independent of the incoming primary particles (Bache and Gregory, 2007). However, changes in temperature and turbidity can cause preferential currents in the sludge blanket resulting in lower performances. These results and flocculation theory suggest that floc blanket clarifiers as operated could not buffer a short-term increase in microbial concentration caused by a rainfall event. The removal performances by rapid sand filtration at DWTP A were

higher under event conditions than under baseline conditions. Still, removal performances by rapid sand filtration were highly variable based on paired samples, which we suspect are caused by processes of retention and release rather than actual performances of the filters.

High reduction performances by ballasted clarification at DWTP B may be attributed to the incorporation of a ballasted media (typically silica sand) within the incoming stream of flocs. It has been shown that ballasted clarification is more robust than conventional systems for removing turbidity regardless of rapid changes in water quality (Kumar et al., 2016). A mean removal performance of 2.0-log of aerobic bacterial endospores by ballasted clarification was previously reported at pilot-scale (Huertas et al., 2001). In our study, higher removal performances of *C. perfringens* by ballasted clarification were observed at turbidity levels of 12–24 nephelometric turbidity units (NTU) (Event-B2, Baseline-B3) than at slightly lower levels of 6–7 NTU (Baseline-B1, Baseline-B2). Our companion study shows that the removal of enteric viruses by ballasted clarification also increased during this event (Sylvestre et al., 2021). Further research on the impact of initial particle concentrations on the aggregation of micro-organisms during ballasted flocculation would be relevant to determine whether this process operates under steady-state conditions or dynamic conditions in response to source water conditions.

The combination of inter-ozonation and GAC filtration, referred to as biological activated carbon (BAC) filtration, considerably reduced *E. coli* concentrations (1.7 to 3.5-log) and *C. perfringens* concentrations (2.4 to 3.1-log). The reduction of *C. perfringens* by these processes may be underestimated because non-detects were replaced by a detection limit (1 organism/volume) for 3 out of 6 samples. It is likely that *C. perfringens* was mainly removed by GAC filtration because inactivation of environmental *C. perfringens* under full-scale conditions is expected to be small (<0.5-log) at a Ct_{10}-value of around 0.6 mg L^{-1} min^{-1} (Hijnen et al., 2002). Conversely, the inactivation of *E. coli* was most likely driven by ozonation. Between 2.0- and 3.0-log-inactivation of *E. coli* were previously reported under full-scale conditions at Ct_{10}-values between 0.5 and 1.0 mg L^{-1} min^{-1} and water temperature below 10 °C (Smeets et al., 2006). Higher *C. perfringens* reduction performances were measured under event conditions than under baseline conditions. This variation does not appear to be related to the *C. perfringens* concentration or the turbidity level in settled water. Low inactivation (< 1.0-log) of *C. perfringens* were found for UV medium pressure lamps (DWTP A) and UV low pressure lamps (DWTP B) operated at a fluence of 40 mJ cm^{-2}. These inactivation performances were lower than those previously reported at a fluence of 40 mJ cm^{-2}, for which inactivation of *C. perfringens* approximated 1.0-log at a full-scale municipal wastewater treatment plant with low pressure lamps (Gehr et al., 2003). Inactivation of environmental spores of sulfite-reducing clostridia (SSRC) of 2.4-log were obtained at pilot-scale with medium pressure lamps (Hijnen et al., 2004).

At the two DWTPs, daily infection risks by *Cryptosporidium* via consumption of treated drinking water were not higher under studied event conditions than under all baseline conditions. The relative impact of short-term contamination events on infection risks has been previously investigated by evaluating pathogen concentrations in source water and assuming treatment performances from literature data. Signor et al. (2007) demonstrated that most of the annual risk at a DWTP abstracting raw water from a small agricultural river was attributable to runoff event periods. Smeets et al. (2007) evaluated *Cryptosporidium* data measured routinely in the treated water of eight DWTPs with similar physical treatment processes. By contrast, they found that average treated water concentrations were similar at sites, independently of their average *Cryptosporidium* concentration at the source. The authors hypothesized that "well operated" conventional treatment may be more effective in removing high concentrations of micro-organisms than low concentrations. Results from our study also suggested that physical treatment processes optimized for turbidity reduction can effectively manage short-term increases in microbial concentrations. Nonetheless, our findings should be interpreted within their context. During the studied conditions, turbidity levels in source water were moderate (DWTP A: $\bar{x}$ = 28 NTU; DWTP B: $\bar{x}$ = 15 NTU) and treatment processes were optimized for turbidity reduction. Although turbidity reduction after filtration is not a direct indicator of pathogen control, it is an effective process control indicator. For example, the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) award 0.5 or 1.0-log additional *Cryptosporidium* credit for achieving filter effluent turbidity < 0.1 NTU (USEPA, 2010). Sedimentation effluent turbidity targets (typically < 1 NTU) are also recommended by industry optimization programs (USEPA, 2010); these targets could also be useful to manage short-term fluctuations in source water microbial contamination. However, pathogens can peak before turbidity (Dorner et al., 2007; St-Pierre et al., 2009; Sylvestre et al., 2020b). In these situations, achieving sedimentation or filter effluent turbidity targets may not indicate adequate pathogen removal.

Our study has several limitations given its design. We only considered approximately one month of GLUC activity measurements to define local thresholds for event conditions. At DWTP A, trends in GLUC activity showed large and rapid increases following rainfall events suggesting the contribution of local sources to faecal contamination at the water intake; therefore, event conditions were based on a locally derived rate of increase in GLUC activity and meteorological conditions. Low EPs for daily mean *E. coli* and *Cryptosporidium* concentrations under event conditions confirm that treatment performances were assessed during a period of degraded source water quality at this site. Nevertheless, amplitudes of GLUC activity peaks were much higher following rainfall events in early and mid-October than during the targeted event; therefore, periods of poorer source water quality may occur earlier in autumn. Periods of high GLUC activity levels at urban DWTP B were less pronounced and sudden than those observed in the smaller agricultural catchment. As discussed in Sylvestre et al. (2021), this relatively low reactivity most probably reflects the cumulative discharge from multiple upstream wastewater facilities and runoff from upper catchment areas. EPs for daily mean *E. coli* and *Cryptosporidium* concentrations under event conditions ranged between 10 and 15%, which may be relatively high to conclude that performances were assessed during a period of poor source water quality.

Also, to evaluate log-reduction performances, the hydraulic mean retention time of water was assumed to be a valid approximation of the actual detention time of micro-organisms. However, it has been pointed out that micro-organisms entering a treatment train following a microbial peak in raw water may be retained in physical processes and remobilized over time (Hijnen, 2009; Smeets et al., 2007). Higher loads of micro-organisms removed by ballasted clarification during a contamination event are not likely to be remobilized through treatment because settled sludges are continuously pumped from the bottom of the clarifier and recycled via hydro-cyclone to separate the silica sand from the sludge. However, remobilization could occur in floc blanket clarifiers. To maintain a steady volume fluidized bed, excess material (so-called sludge bleed) is withdrawn from the fluidized bed at a flow rate of approximately 1% of the inflow at an alum dose of 50 mg L-1 (Ives 2001); thus, remobilization of micro-organisms in settled water could occur during a period equivalent to the mean residence time of the flocs. Remobilization of pathogens from filtration processes could also happen by the end of the filter cycle before turbidity increases. The collection of composite filtered water samples for

an extended period following periods of poor source water quality may be valuable to improve process control strategies for filter operations. Overall, the assessment of full-scale treatment performances during source water events was logistically challenging and costly. The development of automated sampling devices and faster concentration methods would be needed to collect larger sample sizes.

5. Conclusions

The reduction of surrogate micro-organisms was evaluated at two full-scale drinking water treatment plants in Quebec, Canada, under varying source water conditions. The following conclusions are drawn:

- Naturally occurring surrogate data provide valuable information for the assessment of full-scale performances of physicochemical and disinfection processes. Reduction performances of up to 6.0-log for *E. coli* and 5.6-log for *C. perfringens* were measured by concentrating high-volume water samples (15–1500 L) throughout the treatment train.
- For both drinking water treatment plants, removal performances by coagulation/flocculation/sedimentation processes were at the high end of the range of those reported in the literature for bacteria and bacterial spores. Reductions of *E. coli* and *C. perfringens* by floc blanket clarification, ballasted clarification and rapid sand filtration did not deteriorate during two snowmelt/rainfall events. Additional studies investigating full-scale reduction during microbial peak events in source water would be desirable to validate our findings, especially at drinking water treatment plants subjected to severe water quality changes at the source.
- Site-specific quantitative microbial risk assessment (QMRA) using source water *Cryptosporidium* data and full-scale *C. perfringens* reduction data suggested that daily infection risks by *Cryptosporidium* via consumption of treated drinking water were not higher under peak event conditions than under baseline conditions. However, small sample sizes due to the important time required to concentrate high-volume water samples limited the analysis of differences in treatment performances between baseline and event conditions.
- Online β-D-glucuronidase activity monitoring was valuable to establish baseline and event conditions at the agricultural drinking water treatment plant. Daily mean *E. coli* and *Cryptosporidium* concentrations under peak event conditions were in the top 5% of what occurs through the year based on historical routine monitoring data. The value of β-D-glucuronidase activity monitoring was moderate at the urban site for the study period. Exceedance probabilities in peak event conditions were 15% for *E. coli* and 11% for *Cryptosporidium*.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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