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The effects of combined sewer overflow events on riverine sources of drinking water

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ABSTRACT

This study was set out to investigate the impacts of Combined Sewer Overflows (CSOs) on the microbiological water quality of a river used as a source of drinking water treatment plants. *Escherichia coli* concentrations were monitored at various stations of a river segment located in the Greater Montreal Area including two Drinking Water Intakes (DWIs) in different weather conditions (dry weather and wet weather (precipitation and snowmelt period)). Long-term monitoring data (2002–2011) at DWIs revealed good microbiological water quality with *E. coli* median concentrations of 20 and 30 CFU/100 mL for DWI-1 and DWI-2 respectively. However, *E. coli* concentration peaks reached up to 510 and 1000 CFU/100 mL for both DWIs respectively. Statistical Process Control (SPC) analysis allowed the identification of *E. coli* concentration peaks in almost a decade of routine monitoring data at DWIs. Almost 80% of these concentrations were linked to CSO discharges caused by precipitation exceeding 10 mm or spring snowmelt.

Dry weather monitoring confirmed good microbiological water quality. Wet weather monitoring showed an increase of approximately 1.5 log of *E. coli* concentrations at DWIs. Cumulative impacts of CSO discharges were quantified at the river center with an increase of approximately 0.5 log of *E. coli* concentrations. Caffeine (CAF) was tested as a potential chemical indicator of CSO discharges in the river and CAF concentrations fell within the range of previous measurements performed for surface waters in the same area (~20 ng/L). However, no significant differences were observed between CAF concentrations in dry and wet weather, as the dilution potential of the river was too high. CSO event based monitoring demonstrated that current bi-monthly or weekly compliance monitoring at DWIs underestimate *E. coli* concentrations entering DWIs and thus, should not be used to quantify the risk at DWIs. High frequency event-based monitoring is a desirable approach to establish the importance and duration of *E. coli* peak concentrations entering DWIs.

1. Introduction

Meteorological conditions are known to affect the microbiological contamination of rivers and precipitation has previously been linked to waterborne disease outbreaks (Rose et al., 2000; Curriero et al., 2001; Nichols et al., 2009). Indeed, degraded river water episodes with regards to indicators of fecal contamination (e.g. fecal coliforms, *Escherichia coli*) and pathogens have been reported during and after intense rain events (Atherholt et al., 1998; Kistemann et al., 2002; Signor et al., 2005; Burnet et al., 2014). Different processes are driving these increases: resuspension of contaminated sediments due to increases in river discharges and velocities, increased runoff, decrease in the efficiency of wastewater treatment plants (WWTPs) and possible by-pass of some treatment stages, and combined sewer overflows (CSOs) (Wu et al., 2009; Pachepsky and Shelton, 2011; Passerat et al., 2011; Quilliam et al., 2011; Amirat et al., 2012; Lucas et al., 2014). In dense urban

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areas equipped with combined sewers, the release of a mixture of domestic wastewater and urban runoff waters by CSOs has been shown to be a major source of microbiological contaminants during rainy periods (Gibson III et al., 1998, USEPA 2004, Passerat et al., 2011; Madoux-Humery et al., 2013). CSOs are highly transient phenomena typically discharging during a couple of hours; they can induce very rapid and important increases in the concentration of fecal indicators and pathogens in the receiving waters. In rivers, the importance of the peak of contamination depends on the ratio between the CSO discharge and the river flow rate, the mixing conditions and the concentration of microbial contaminants in the CSO. Some studies have reported increases in the concentration of *E. coli* in rivers of one order of magnitude (Passerat et al., 2011) and even two orders of magnitude (Ouattara et al., 2014) as a result of a CSO discharge.

When river water is used as the source for drinking water production, degraded microbiological water quality can increase the likelihood of treatment breakthroughs and waterborne disease outbreaks. Microbiological water quality impairment at drinking water intakes (DWI) during wet weather combined with a malfunction of the treatment at the drinking water plant have led to waterborne disease outbreaks (O'Neil et al., 1985; Mac Kenzie et al., 1994; Auld et al., 2004; Jagai et al., 2015). To minimize this risk, different measures can be taken: (1) multiple drinking water treatment barriers should be present and provide effective removal of pathogens; (2) drinking water source protection plans should identify potential threats located upstream from DWIs and assess the vulnerability of the DWIs to transient microbiological contamination; (3) regulations on CSO frequency and discharge volumes must be introduced in legislation.

Several countries have implemented rigorous regulations on drinking water treatment based on the surveillance and removal of *Cryptosporidium* considered as a major risk for waterborne disease (Craun et al., 2006), while most regulations rely on widely recognized fecal indicators such as *E. coli* to assess microbiological quality of source water (Ashbolt et al., 2001; Tallon et al., 2005). Thresholds of *E. coli* concentrations in source water have been used to determine the log removal requirements by treatment processes for *Cryptosporidium*, *Giardia* and viruses. In the 2010 revised Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) (United States Environmental Protection Agency (USEPA) 2010) expensive *Cryptosporidium* monitoring is not required unless high densities of *E. coli* (i.e. mean concentration higher than 100 *E. coli*/100 mL) are present in source waters of small systems in the United States (<10,000 people). This *E. coli* threshold is considered to safely predict densities of *Cryptosporidium* below 0.075 oocysts/L in source waters. Below this threshold of 100 *E. coli*/100 mL (Bin 1), treatment requirements are the removals of at least 3 log for *Giardia* and 4 log for viruses that can be met by conventional filtration and disinfection. A recent meta-analysis suggested that *E. coli* can underestimate the presence of *Cryptosporidium* in agricultural source waters, while *E. coli* was considered as a conservative surrogate for *Cryptosporidium* in urban waters (Lalancette et al., 2014).

Wastewater micropollutants (WWMPs) have been used as tracers of sewage contamination in surface waters (Buerge et al., 2003; Benotti and Brownawell, 2007; Weyrauch et al., 2010) as some organic compounds are ubiquitous in sewage waters and could be more persistent in surface waters than some microbial contaminants (Gasser et al., 2010). In the present study, caffeine (CAF) was the WWMP chosen to be investigated as it was always abundant in wastewaters as well as in rivers in urban areas (Viglino et al., 2008; Daneshvar et al., 2012; Guérineau et al., 2014) and was previously proposed as an indicator of recent untreated wastewater discharge through CSOs (Buerge et al., 2006).

In this paper, we set out to investigate the impact of CSOs on river water quality at DWIs located in the Greater Montreal Area as CSOs in drinking water sources can have a measurable health effect (Jagai et al., 2015). Multiple CSO-event based monitoring were also performed in the river to assess *E. coli* peak concentrations at DWIs. This type of monitoring has not previously been conducted as only one similar event (not multiple) has been published (Passerat et al., 2011). This study therefore characterizes the variability of CSO impacts on a river. Our objectives were to: (1) propose a novel statistical approach to analyze the variability of *E. coli* concentrations at DWIs; (2) quantify the short-term and seasonal variability of *E. coli* concentrations upstream and at DWIs; (3) document the baseline and peak events of *E. coli* and WWMPs contamination upstream and at DWIs during dry weather and after confirmed CSO discharges; (4) verify if routine bi-monthly samples can identify high risk periods corresponding to CSO discharge periods.

2. Materials and methods

2.1. Study area

2.1.1. River and DWIs

This study was conducted in a river segment, located in the Greater Montréal area draining a watershed of approximately 146,000 km^2 and used as source for two DWIs (Fig. 1) serving approximately 280,000 inhabitants. The water flowing in the studied river stretch is coming from a lake located upstream that is fed by a river in which sewerage systems serving approximately 1.2 million people discharge. The majority of the population is located approximately 180 km upstream. The study area has a humid continental climate with average annual precipitation falling as rainfall of 625 mm/year and average cumulative precipitation falling as snow of approximately 2000 mm/year, mostly occurring from November to April.

The river flow rate ranged from 473 to 2678 m^3/s (with a median annual value of 1186 m^3/s) between 2002 and 2011 (Hydrology Expertise Center, 2015). The low-flow period occurs at the end of summer; the lowest monthly median value of 776 m^3/s was observed in August. High flow events for the river occur in spring and are attributed to the local snowmelt period in April (with a median monthly value of 1795 m^3/s and a maximum monthly value of 2678 m^3/s) and to the snowmelt in the upstream watershed in May (with a median monthly value of 1460 m^3/s and a maximum monthly value of 2408 m^3/s) (Fig. S1). A detailed discussion on river flows is available in Jalliffier-Verne et al. (2015). The average residence time of the river segment between sampling stations B1 and DWI-2 was estimated to range from 2 to 5 h.

2.1.2. Contamination sources

WWTP-1serving approximately 7600 people and treating 2900 m^3/d discharges on a lake is located upstream from the B1 station (Fig. 1). WWTP-2 treats 240,000 m^3/d and is located downstream of the studied DWIs (Fig. 1). Treatment at WWTP-1 consists of an aerated pond and at WWTP-2 of primary treatment with physico-chemical phosphorus removal; both WWTP effluents are disinfected with UV from May to September. CSO discharges are the main source of microbial contaminants in the studied river segment. In the previous study, concentrations of *E. coli* and WWMPs were observed to follow a diurnal pattern. Concentrations were not heavily diluted, particularly during the snowmelt period (Madoux-Humery et al., 2013). A total of 27 CSO outfalls are located between sampling station B1 and DWI-2 (Fig. 1) and discharge without any treatment during rainfall events and the snowmelt period when the hydraulic capacity of the sewer system (serving approximately 280,000 people) and/or the WWTP-2 is exceeded. Occasionally, a small number of dry weather discharges occur, but

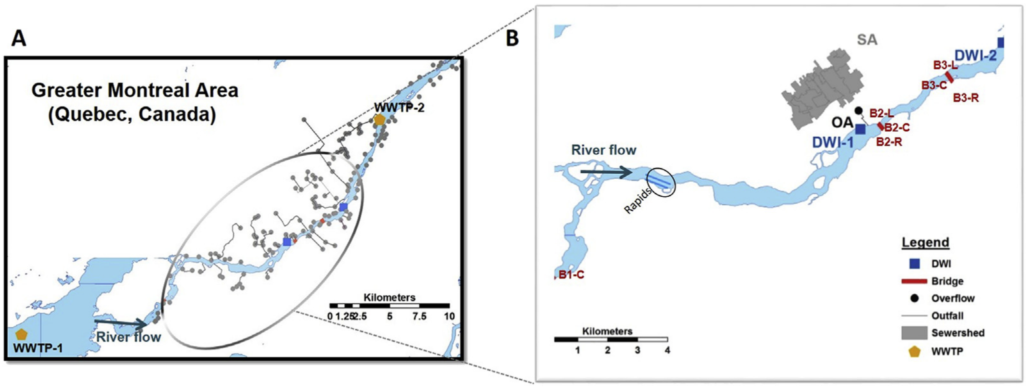

Fig. 1. Maps of (A) the study area and (B) the sampling area.

these are not permitted. A total of 2258 CSO events were reported upstream from DWI-2 during the 2009–2011 period (Ministry of Municipal Affairs Regions and Land Occupancy, 2013).

2.2. Sampling program

A tiered sampling and analysis approach was implemented to compare long-term and short-term monitoring results and to compare various short-term monitoring strategies. A detailed description of the tiered sampling program is provided in Table 1. Local precipitation data were obtained from four nearby rain gauges and a weighted daily average was calculated.

The source water characterization of DWI-1 and DWI-2 was performed by compiling weekly *E. coli* monitoring data available at both DWIs from 2002 to 2011. The river has a width of 520 m at DWI-1 and 260 m at DWI-2 and both intakes are located approximately 70 m from the left bank of the river. Rapids providing mixing are located approximately 8 km upstream from DWI-1 (Fig. 1). Unlike B3, bridge B2 is located downstream of these rapids that mix the discharges of the 6 CSO outfalls located upstream. Bridge B2 is mostly impacted by 18 CSO outfalls located downstream from the rapids and distributed over a distance of 8 km. In addition to the CSO discharges between B1 and B2, B3 is also impacted by the discharges of 9 additional CSO outfalls distributed over 3 km.

A bi-monthly monitoring program was performed at the 9 sampling stations from October 2009 to March 2011 in both dry ($n = 16$) and wet ($n = 11$) weather conditions, except in winter when ice covered the river. River water grab samples were collected in both DWIs and from 3 bridges (B1-C, B2-C and B3-C) (Fig. 1) in order to provide a longitudinal distribution of contaminants across the river. Additionally, transversal sampling was conducted across the river on bridges B2 and B3, i.e. close (approximately 50 m) from the left and right banks of the river (B2-L, B2-R, B3-L, B3-R). Sampling was generally performed at the same hour during the different sampling campaigns and lasted approximately 3 h for the nine stations.

The short-term temporal variation of contaminant concentrations was assessed to evaluate the representativeness of grab sampling results for 9 sampling locations in the study area. Sampling was performed once in dry weather conditions over the course of 6 h at the 2 DWIs and at the bridges (total of 9 sampling stations), every 5 min during 30 min and then each 30 min for the next 6 h ($n = 18$).

A total of 5 specific CSO events were monitored in the river was performed by sampling at bridges B2 and B3 while also monitoring the water quality of a frequently discharging CSO at outfall OA (Fig. 1). Monitoring results of CSO discharges for this outfall OA ($n = 9$) were presented in previous papers (Madoux-Humery et al., 2013; 2015). River samples were collected downstream from the CSO outfall ($n = 36$) on bridges B2 and B3, 3 h after the beginning of the CSO discharge. Samples were collected at center (B2-C and B3-C) and at left (B2-L and B3-L) and right (B2-R and B3-R) banks of the river in order to assess the longitudinal and transversal mixing of CSOs in the river water.

During each sampling campaign, 1-L grab samples were collected at the same depth (approximately 50 cm below the water surface to avoid collecting the surface microlayer) using a plunger equipped with autoclaved bottles. Samples were stored in 250 mL pre-autoclaved in polypropylene bottles in the dark at 4 °C. Microbiological analyses were performed within 6 h after sample collection. For CAF analysis, a sample volume of 40 mL was immediately filtered through 0.45 μm mixed cellulose membranes (Millipore, MA, USA) in pre-cleaned glass bottles (12 h-washing in

Table 1
Tiered sampling program.

Sampling type	Objectives	Meteorological conditions	Statistical analyses
Long-term monitoring	Assess the variability of *E. coli* concentrations from weekly monitoring at DWIs and identify peak concentrations	Dry weather: no precipitation recorded 3 days prior to sampling Wet weather: precipitation exceeded 10 mm/day. *E. coli* concentration for days with precipitation ranging for 0.1 and 10 mm were not included in the analysis	SPC analysis
Short-term monitoring	Assess the representativeness of grab sampling	Dry weather: no precipitation recorded 3 days prior to sampling	CV
Bi-monthly monitoring	Assess the impact of CSO discharges on the river water quality and at DWIs	Dry weather: no precipitation recorded 3 days prior to sampling Wet weather: precipitation and confirmation that CSO occurred (100% of precipitation days lead to CSO discharge)	Kruskal Wallis ANOVA tests
CSO event-based monitoring	Assess the short-term impacts of CSO discharges on river water quality	Wet weather: monitoring of the discharge of CSO at outfall OA (rainy and snowmelt periods)	

25% HCl solution followed by 5 h in oven at 500 °C) and acidified at pH 2 using a formic acid solution (purity 98%) (Fluka Analytical, SIGMA-ALDRICH, Oakville, ON, CA) in order to avoid degradation. The CAF concentration measurements were performed within 3 weeks.

2.3. Analytical methods

A volume of 100 mL were used to enumerate *E. coli* by using plate count on EC-MUG medium (Method 9221F) (American Public Health Association (APHA) et al., 2012) and expressed in CFU/100 mL during the long term monitoring at the DWIs and by using the IDEXX Quanti-Tray 2000 most probable number (MPN) method (IDEXX, ME, USA) and expressed in MPN/100 mL during the sampling campaigns performed in the scope of the present study. Caffeine analyses were performed by an on-line solid-phase extraction combined with liquid chromatography electrospray tandem mass spectrometry with positive electrospray ionisation (SPE-LC-ESI-MS/MS) first developed by Viglino et al. (2008) and modified by Sauvé et al. (2012). The detection limit (6.8 ng/L) was estimated as three times the standard deviation of 5 replicate measurements. All samples were analyzed in duplicate.

2.4. Calculations and statistical methods

Statistics, such as the determination of coefficients of variations (CVs), were performed in Statistica Version 12.5 (Statsoft, OK, USA).

A Statistical Process Control (SPC) analysis was used as a tool to interpret *E. coli* concentrations data at DWIs from 2002 to 2011. Quality Control Charts module based on Shewhart charts were determined to estimate the common variability of *E. coli* concentrations and to detect significant changes of *E. coli* concentration variations. A significant variation is called an upper control limit (UCL) and is generally defined as 3 times standard deviation away from the baseline data.

As contaminant concentrations measured in rivers were neither normally nor log-normally distributed, non-parametric statistical analyses using Spearman's rank correlation and Kruskal Wallis ANOVA tests were performed. Differences between concentrations in dry and wet weather were considered significant if $p < 0.05$, unless stated otherwise.

3. Results

3.1. Long-term monitoring

From 2002 to 2011, *E. coli* concentrations at both DWIs generally reveal good microbiological water quality with *E. coli* arithmetic mean concentrations of 43 and 62 CFU/100 mL observed at DWI-1 ($n = 601$) and DWI-2 ($n = 723$), respectively (Fig. 2). As these concentrations are below the benchmark of 100 *E. coli*/100 mL, according to the USEPA regulations both DWIs are classified in the Bin 1 category.

The data collected at both DWIs were used to investigate seasonal variation of fecal contamination. Seasonal *E. coli* median concentrations varied from 10 to 40 CFU/100 mL at DWI-1 and from 20 to 60 CFU/100mL at DWI-2 (Fig. S2). The range between the lowest and the highest *E. coli* concentrations was approximately 2 orders of magnitude during each season. *E. coli* concentrations were significantly higher during the winter than the summer for both DWIs. However, fewer CSOs occurred during winter (approximately 15% of the total annual CSOs) and the flowrate of the river is approximately 1.5 times higher (Fig. S1) during winter than summer increasing the potential dilution of microbial contaminants. Several factors could explain the higher *E. coli* concentrations in winter: (1) WWTPs located upstream from B1-C release higher concentrations of fecal bacteria in winter as there is no disinfection treatment in WWTPs at this period of the year; (2) *E. coli* survival in river waters is longer in cold water in winter than during summer (water temperature ranging from 0.6 °C in winter to 27.3 °C in summer (median value: 9.1 °C)) (Blaustein et al., 2013; de Brauwere et al., 2014), (3) higher streamflow velocities in the winter compared to the summer lead to greater dispersion of *E. coli* towards the drinking water intakes (Jalliffier-Verne, 2015).

E. coli concentration peaks were observed at both DWIs and reached up to 510 and 1000 CFU/100mL at DWI-1 and DWI-2, respectively (Fig. 2).

In the case of the studied river stretch where there is very limited input of treated wastewaters, the most probable hypothesis to explain the observed peaks of *E. coli* concentration is the release from CSOs upstream of DWIs. Thus, different data mining approaches were tested to highlight the impact of CSOs on *E. coli* concentrations variability at DWIs.

The *E. coli* concentrations were classified with regards to meteorological conditions, i.e. dry weather versus wet weather. At both DWIs, *E. coli* concentrations were not significantly different between dry and wet weather conditions (Fig. 3A) and varied over 2 orders of magnitude between minimum and maximum values. This approach is biased by the fact that high *E. coli* concentrations due to CSOs caused solely by snowmelt and not by precipitation were classified in the dry weather conditions. When we distinguish the data measured during the period when snowmelt could occur from the dry and wet weather data (Fig. 3B), significantly lower values were observed in dry weather as compared to wet weather and during snowmelt. These observations are compatible with an impact of CSOs on the microbiological quality at DWIs.

The SPC was also used as a statistical tool to assess the variability of *E. coli* concentrations. The upper control limit (UCL) estimated by the SPC analysis was 127 *E. coli*/100 mL at DWI-1 and 197 *E. coli*/100 mL at DWI-2 (Fig. 2). A total of 49 and 45 measurements of *E. coli* concentrations at DWI-1 and DWI-2, respectively, exceeded the UCL (Fig. 2). Approximately 80% of the cases occurred during the snowmelt period and wet weather conditions when precipitation exceeded 10 mm/24 h (Table 2) demonstrating the likely discharge of CSOs. No specific explanation could be found for the remaining cases that exceeded UCL (~20%) for both DWIs but technical issues such as repairs or maintenance of the sewer system could be responsible for sewage releases. Overall, approximately 42% of *E. coli* peak events at both DWIs occurred in the presence of precipitation and among these cases, 15% and 70% occurred in low-flow period ($Q <$ 25th percentile) for DWI-1 and DWI-2 respectively. We also observe that 43% and 31% of *E. coli* peak events occurred during the snowmelt period at DWI-1 and DWI-2, respectively, and, among these, 57% and 36% were in high-flow period ($Q >$ 75th percentile).

3.2. Short-term monitoring

Short-term monitoring (over a 6-h period in dry weather conditions) was performed once at each of the 9 sampling stations in the river. No trend of *E. coli* and CAF concentrations variations was observed during the 6 h. Mean CVs were 38% (ranging from 12 to 63%) for *E. coli* (Table 3). The accuracy of the MPN microplate method was previously investigated by Lebaron et al. (2005) and Prats et al. (2008) for a wide range of *E. coli* concentrations (15-5000 MPN/100 mL). CVs ranged from 8 to 68% and increased for *E. coli* concentrations below 300 MPN/100 mL (Lebaron et al., 2005; Prats et al., 2008). Therefore, CVs for *E. coli* were within the range of expected uncertainties of the analytical methods of the MPN enumeration. Mean CVs were 33% (11–45%) for CAF. The

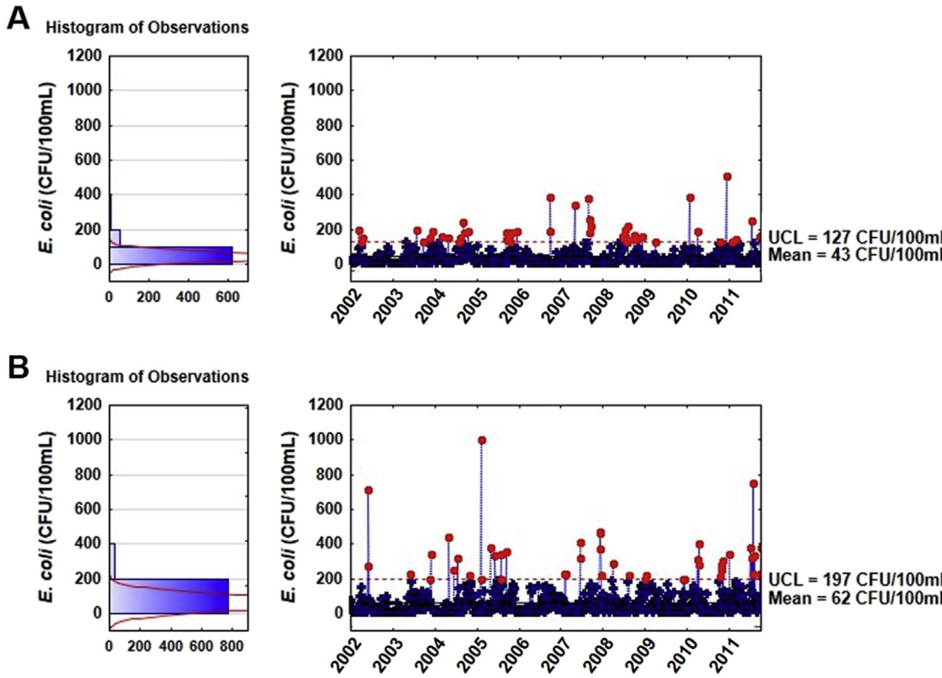

Fig. 2. Quality control chart of long-term *E. coli* monitoring at DWI-1 (A) and DWI-2 (B) from 2002 to 2011. Observations in blue were identified by the SPC analysis as common data and points in red are above the UCL. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

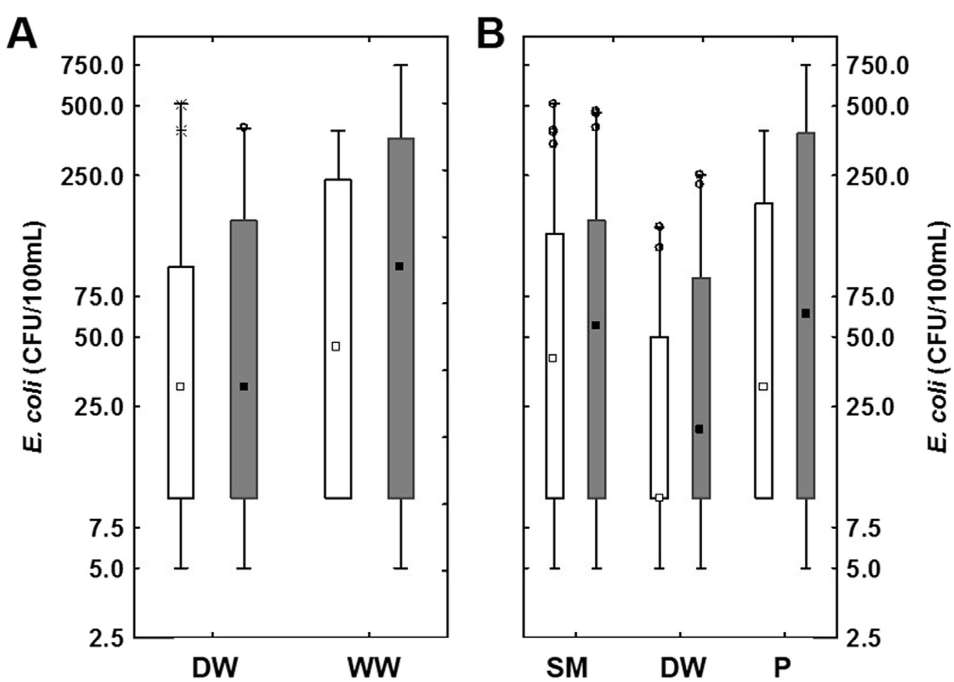

Fig. 3. Box-plot of *E. coli* concentrations (in log scale) measured at DWI-1 (in white) and at DWI-2 (in grey): A. in dry weather (DW) and in wet weather (WW) conditions; B. in the snowmelt period (SM) (data from November 15th to April 15th), in dry weather (DW) conditions and during precipitations (P). Box-plots show 10th and 90th percentile (box), median values (square in the box) and whiskers correspond to the minimum and maximum values. Outliers and extremes are represented by circles and asterisks, respectively, and were both determined using an outlier coefficient of 1.5.

uncertainty relative to WWMP analyses is expected to be approximately 50% (Boleda et al., 2013), as concentrations are close to the detection limit. Thus, the variability of concentrations could be explained by the uncertainties of the analytical methods.

3.3. Bi-monthly monitoring

3.3.1. Dry weather conditions

The *E. coli* concentrations entering the studied river segment at station B1-C were highly variable (approximately 1.5 order of magnitude between maximum and minimum values) in dry

Table 2
Number of events when *E. coli* concentrations measured at DWIs (2002–2011) exceeded the UCL (127 *E. coli*/100 mL at DWI-1 and 197 *E. coli*/100 mL at DWI-2) during snowmelt (SM) period and rainy period (precipitation >10 mm/24 h).

DWI	# events > UCL	**Snowmelt** All flow rate (Flow rate>75th percentile)*	**Precipitations** All flow rate (Flow rate<25th percentile)*	Other conditions (dry conditions, not in the SM period)
DWI-1	49	21 (12)	20 (3)	8
DWI-2	45	14 (5)	20 (14)	11

* Percentiles were determined using 2002–2011 river flowrate data (Hydrology Expertise Center, 2015): 25th percentile: 835 m^3/s - 75th percentile: 1450 m^3/s.

Table 3
Median, mean and CV values of *E. coli* and CAF concentrations for short-term monitoring at sampling points – Dry weather conditions.

Sampling points	*E. coli*				CAF			
	n	Median (MPN/100 mL)	Mean (MPN/100 mL)	CV (%)	n	Median (ng/L)	Mean (ng/L)	CV (%)
B1-C	18	2	2	45.0	18	7.2	6.3	43.7
B2-C	18	5	5	54.4	18	3.4	4.2	45.0
B2-L	18	423	422	63.1	18	6.9	6.1	33.4
B2-R	18	19	18	32.6	18	8.6	8.7	35.1
B3-C	18	136	145	36.4	18	9.0	9.4	37.3
B3-L	18	330	341	34.4	18	14.1	15.0	36.4
B3-R	18	69	68	11.7	18	10.1	10.7	28.9
DWI-1	18	110	111	38.7	18	8.8	8.2	24.0
DWI-2	18	154	156	21.5	18	10.9	10.9	11.2

Table 4
Duration, discharged volume, flowrate and *E. coli* event mean concentration (EMC) characterizing sampled CSO events at outfall OA.

CSO event	Duration of overflows (min)	Overflows discharged volume (m^3)	Flow rate (L/s) average (max)	EMC
				E. coli (MPN/100 mL)
CSO#1	403	3138	130 (560)	3.5×10^6
CSO#2	694	19,530	470 (3490)	1.9×10^6
CSO#3	89	92	17 (50)	4.1×10^6
CSO#4	146	5813	660 (2040)	7.7×10^5
CSO#5	194	7867	630 (2720)	ND

weather conditions (Fig. 4). *E. coli* concentrations measured along the river center were low with a median value of 26 MPN/100 mL in dry weather conditions. No significant gradient of *E. coli* concentrations was observed at the center from upstream to downstream (Fig. 4A).

With regards to transversal sampling at bridge B2, *E. coli* median concentrations were higher at the left bank (B2-L) (0.6 log) and the right bank (0.8 log) than in the center (B2-C). *E. coli* concentrations increased significantly at the shores of bridge B2 but were similar to those measured in the center at bridge B3. At DWIs, *E. coli* concentrations were low with a median value of approximately 25 MPN/100 mL, confirming the good water quality observed during the long term monitoring. Water quality monitoring at the river center is consistent with DWIs located between the shoreline and the center of the river.

No significant difference of CAF median concentrations was observed between the river center and both river banks. CAF median concentrations ranged from 15.6 ng CAF/L to 22.8 ng CAF/L (Fig. S3A) and fell within the range of previous measurements performed for surface water in the same area (Viglino et al., 2008).

3.3.2. Wet weather conditions

E. coli concentrations were more variable in wet weather (2.7 orders of magnitude) than in dry weather (1.5 orders of magnitude). These variations can be explained by: (1) the high variability of CSOs with regards to their occurrence, duration and concentrations released (Madoux-Humery et al., 2013); (2) the higher *E. coli* concentrations discharged by WWTP as the treatment is less effective during rainfall (Lucas et al., 2014); (3) possible upstream wastewater contamination coming from cross-connected sewers (Sauvé et al., 2012) and (4) resuspension of contaminated river sediments (Wu et al., 2009; Quilliam et al., 2011). At B1-C, *E. coli* median concentrations were marginally higher in wet weather (46 MPN/100 mL) than in dry weather (15 MPN/100 mL) (non-significant difference) (Fig. 4A). At the other stations in the river center, namely B2-C and B3-C, significantly higher *E. coli* concentrations were measured in wet weather than in dry weather conditions (Fig. 4A). *E. coli* median concentrations at the river center increased from 46 (B1-C) to 170 MPN/100 mL (B3-C) in wet weather conditions demonstrating the cumulative impacts of CSO discharges at the river center. A significant increase of *E. coli* concentrations between dry and wet weather conditions was observed at both DWIs (Fig. 4A). *E. coli* concentrations measured at river banks, namely B2-L and B2-R as well as B3-L and B3-R, were significantly higher than concentrations observed at the river center B2-C and B3-C (Fig. 4B). CSO discharges are located along the river close to the banks; thus, their impacts were more important and quantifiable at the river bank monitoring stations.

No significant variations of CAF concentrations were observed between dry and wet weather conditions at the river center as well as at river shores (Fig. S3). The dilution potential of the studied river is so high that differences in CAF concentrations discharged by CSOs could not be detected with actual detection limits (Madoux-Humery et al., 2013). However, significant correlations were established between *E. coli* and CAF ($\rho = 0.35$, $p < 0.05$, $n = 99$) (Fig. S4) in wet weather conditions confirming the presence of a

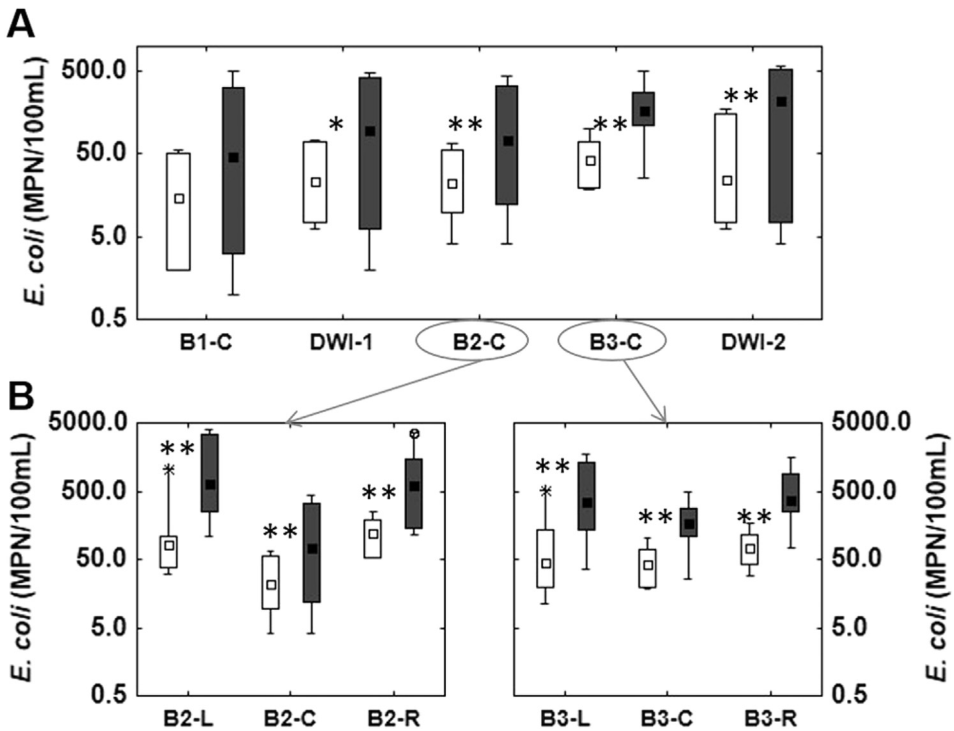

Fig. 4. Box-plots of *E. coli* concentrations (in log scale) during dry weather (white) and wet weather (dark grey). A. Longitudinal profiles in the river center at B1-C, DWI-1, B2-C, B3-C and DWI-2. B. Transversal profiles at bridges B2 (B2-L, B2-C, B2-R) and B3 (B3-L, B3-C, B3-R). Asterisks * denote significant difference ($p < 0.05$) and ** highly significant difference ($p < 0.01$) between dry and wet weather conditions (Non parametric statistical analysis performed on non log-transformed data). Box-plots show 10th and 90th percentile (box), median values (square in the box) and whiskers correspond to the minimum and maximum values. Outliers and extremes are represented by circles and asterisks, respectively, and were both determined using an outlier coefficient of 1.5.

human source of contamination.

3.4. CSO event based monitoring

CSO discharges were monitored during the snowmelt period and in summer at the sewage overflow outfall OA. The results of event-based monitoring of *E. coli* of 5 CSO events are presented in Table 4. The impact of these CSOs on the river water quality was measured 3 h after the beginning of the CSO events by monitoring *E. coli* concentrations at bridges B2 and B3 (Fig. 5). *E. coli* concentrations at bridges B2 and B3 during bi-monthly in wet weather are also reported on Fig. 5.

The differences of *E. coli* concentrations observed between the two bridges can be explained by differences in mixing conditions, the number of discharge points and their location. Given the strong mixing of the rapids upstream from B2, there is a stronger mixing upstream from B2 than from B3; B3 is also more impacted by CSO outfalls located on both banks of the river than B2. At bridge B2, *E. coli* concentrations measured for most CSO events were significantly higher at B2-L and marginally higher at B2-R than concentrations measured during the bi-monthly monitoring. *E. coli* concentrations were in the same range at the bridge center (B2-C) during the bi-monthly monitoring as well as for CSO event based monitoring. At bridge B3, CSO events #2, #4 and #5 fall exceed median wet weather concentrations by 2 orders of magnitude at the bridge center and banks (B3-C, B3-L and B3-R).

4. Discussion

4.1. Comparison of sampling strategies

Numerous studies have shown the impact of CSOs on the microbiological quality of receiving rivers (Marsalek et al., 1996; Gibson III et al., 1998, Kim et al., 2005; Rechenburg et al., 2006; Passerat et al., 2011). However, few studies have simultaneously monitored CSO discharges and their associated plumes in a river, mainly because of logistic and technical difficulties. This study presented results of river monitoring during several CSO discharges of outfall OA. Other discharges to the river also occurred simultaneously and the sampling program implemented allowed for an analysis of cumulative impacts of CSO discharges to the river. Outfall OA is a major outfall in this area with regards to its discharge frequency as 38 CSO events per year occurred on average and thus it was a useful model CSO for initiating river sampling.

Table 5 enables the comparison, for each event monitored, the flux of *E. coli* transported by the river at station DWI-1 (within a 3-h period) with the 3-h duration flux of *E. coli* released by a single CSO at outfall OA located immediately downstream. Data from Table 5 shows that for CSO events #1, #2 and #4, a single CSO released between 6.4 and 35.4 times more *E. coli* than those transported by the river highlighting the major impact of one single CSO discharge into the river. In contrast, during CSO#3 event, both fluxes were of the same order of magnitude (Table 5) highlighting that *E. coli* concentrations measured at bridges 3 h after the beginning of this event were in the range or even lower than during the bi-monthly wet weather monitoring.

As the main objective of monitoring fecal indicators at the water intakes is to evaluate periods of recurring and peak vulnerability to fecal contamination, it is paramount to understand whether long term bi-weekly or weekly sampling is capable of detecting prolonged periods of peak contamination. Our results show that (1) routine sampling, i.e. every week for 10 years (2) bi-monthly *E. coli* wet or dry weather monitoring clearly underestimate peak *E. coli* concentrations arriving at DWI during and/or after CSO events, as

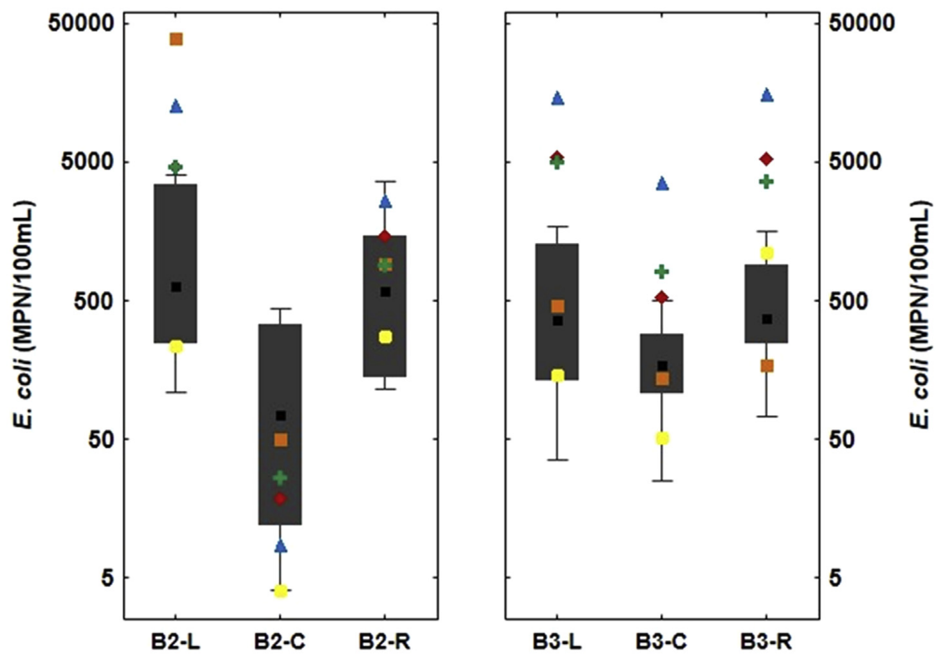

Fig. 5. Box-plots of *E. coli* concentrations (in log scale) at bridges B2 (B2-L, B2-C, B2-R) (left panel) and B3 (B3-L, B3-C, B3-R) (right panel) during wet weather (dark grey boxes). *E. coli* concentrations measured during specific CSO event-based monitoring: CSO#1 (orange square), CSO#2 (blue triangle), CSO#3 (yellow circle), CSO#4 (red diamond) and CSO#5 (green cross). Box-plots show 10th and 90th percentile (box), median values (square in the box) and whiskers correspond to the minimum and maximum values. Outliers and extremes are represented by circles and asterisks, respectively, and were both determined using an outlier coefficient of 1.5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Flux of *E. coli* (MPN/3 h) transported by the river at DWI-1 in wet weather and released at OA for different studied CSO events.

CSO event	A: Flux of *E. coli* transported by the river at DWI-1 (MPN/3 h)[a]	B: Flux of *E. coli* released by a single CSO (OA) (MPN/3 h)[b]	Ratio between fluxes B and A
CSO#1	1.4×10^{13}	9.1×10^{13}	6.4
CSO#2	6.1×10^{12}	2.1×10^{14}	35.4
CSO#3	5.7×10^{12}	3.8×10^{12}	0.7
CSO#4	6.4×10^{12}	4.5×10^{13}	7
CSO#5	6.8×10^{12}	ND	ND

[a] Flux A was calculated by multiplying daily average flow rate of the river by the median of *E. coli* concentration at DWI-1 in wet weather for a 3-h duration.
[b] Flux B was determined by multiplying *E. coli* concentration by the volume of CSO released for a 3-h duration. Details on loads calculation methodology are available in Madoux-Humery et al. (2015).

evidenced by the large increases observed during event based sampling. In addition, as the number of samples increases from long-term sampling, the standard deviation and 95th percentile decrease (McBride, 2005). Therefore, although the probability of capturing a peak concentration increases with the number of samples, reliance on the traditional statistics (i.e., mean, median, 95th percentiles) of a long-term data set could result in spurious conclusions regarding the vulnerability of a drinking water intake. The SPC analysis of long-term data provides a more robust estimate of the variability of *E. coli* for drinking water production. Short-term bimonthly compliance monitoring should not be used to quantify the risk at DWIs during wet weather as this type of random sampling will not likely capture peak concentrations. On the other hand, grab sampling even if done frequently over the course of CSO discharges as performed during this study does not provide a satisfactory estimation of the full duration of peak events that may challenge the treatment barriers and potentially lead to breakthrough unless the high frequency sampling continues over many hours e.g. > 20 h as demonstrated by Passerat et al. (2011). Dry weather short-term monitoring (over the course of 6 h) showed that the concentrations showed variability within the uncertainties of analytical methods; however, similar wet-weather short-term monitoring would likely have produced different results, but was not characterized given the large number of sampling locations and focus on the OA CSO discharge.

Short-time high frequency compliance monitoring, such as every hour during CSO discharges, is challenging to implement at DWIs. From a practical perspective, *E. coli* concentrations would only be known 24 h after sample processing, thus not particularly useful for adapting drinking water treatment operations in response to rapidly changing raw water conditions. Therefore, on line monitoring certainly appears to be a desirable approach to establish the importance and duration of *E. coli* peak concentrations entering DWIs. The use of online monitoring of *E. coli* concentrations has been recently proposed by Ryzinska-Paier et al. (2014) for karstic waters; the device is based on the measurement of a specific enzymatic activity of *E. coli*, the glucuronidase activity. Even if technical problems must still to be solved for the online use of the automated device for river waters, it is promising technology that in the near future will surely provide an opportunity to monitor wet-weather events, identify periods of sustained elevated microbiological contamination and determine reference conditions for drinking water treatment process selection and design.

4.2. Vulnerability of DWIs

As the revised regulation of the LT2ESWTR (United States Environmental Protection Agency (USEPA) 2010) on the design of the treatment processes is based on average *E. coli* concentrations without taking into account peak concentrations, there is no guarantee that, during high concentrations of microbial contaminants periods, the treatment line will be efficient enough to adequately remove the pathogens. Furthermore, CSOs resulting from snowmelt are known to discharge high *E. coli* concentrations, contradicting the common belief that CSO concentrations are likely to be highly diluted during this period (Madoux-Humery et al., 2013). Typical CSO discharges during the snowmelt period are also long duration events and may impact DWIs even when the potential for dilution of the river is high. As drinking water treatment is less effective in cold water temperature with regards to pathogen removal (Payment et al., 2000), the snowmelt period (April–May in this case) could be highlighted as a critical period for drinking water quality.

The different *E. coli* patterns observed at the two bridges monitored clearly show that the location of the intake is critical in determining its vulnerability, as fecal contamination in this case is clearly higher nearer the shores. With regards to drinking water source protection plans implemented in the province of Ontario, Canada, the vulnerability of DWIs is based on: (1) the depth of the intake; (2) the distance from the shore and (3) the number of recorded drinking water issues related to the intake (Government of Ontario, (2009a)). According to their detailed methodology, a deep (>3 m) intake located in the main stream of a river or in the center of a lake (>200 m from the shore) is considered less vulnerable in both dry and wet weather conditions (Government of Ontario, (2009b)). Indeed, if episodes of fecal contamination are not highlighted by long-term source water monitoring, DWIs located on large lakes or rivers with a high potential of dilution will not be classified as vulnerable.

5. Conclusions

- Long-term and dry weather monitoring generally demonstrated a good microbiological river water quality. However, *E. coli* concentrations at DWIs are significantly higher during the winter and their annual variability require event based monitoring to identify peaks of contamination. SPC analysis allowed to identify *E. coli* peaks of concentrations in almost a decade of routine monitoring data at DWIs. Almost 80% of these concentrations were linked to CSO discharges caused by precipitation that exceeded 10 mm or snowmelt.
- Bi-monthly monitoring program over a period of one year identified significant increases of *E. coli* concentrations between dry and wet weather conditions highlighting the impact of CSOs.
- CAF concentrations were correlated with *E. coli*, demonstrating a human origin of observed fecal contamination.
- Wet-weather monitoring showed that *E. coli* concentrations during or following CSO discharges increase significantly (1) at DWIs, suggesting that specific CSO event based monitoring has to be performed to allow the detection of *E. coli* peak concentrations (2) close to river banks, confirming the location of outfalls close to shores (3) at river center, demonstrating the cumulative impacts of CSOs along the river.
- Current *E. coli* weekly compliance monitoring at DWIs underestimate *E. coli* peak concentrations and should not be used to quantify the risk at DWIs during wet weather. High frequency event-based monitoring certainly appears a desirable approach to establish the importance and duration of *E. coli* peaks concentrations entering DWIs.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2015.12.033.

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