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Research article

Cumulative effects of fecal contamination from combined sewer overflows: Management for source water protection

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ABSTRACT

The quality of a drinking water source depends largely on upstream contaminant discharges. Sewer overflows can have a large influence on downstream drinking water intakes as they discharge untreated or partially treated wastewaters that may be contaminated with pathogens. This study focuses on the quantification of *Escherichia coli* discharges from combined sewer overflows (CSOs) and the dispersion and diffusion in receiving waters in order to prioritize actions for source water protection. *E. coli* concentrations from CSOs were estimated from monitoring data at a series of overflow structures and then applied to the 42 active overflow structures between 2009 and 2012 using a simple relationship based upon the population within the drainage network. From these estimates, a transport-dispersion model was calibrated with data from a monitoring program from both overflow structures and downstream drinking water intakes. The model was validated with 15 extreme events such as a large number of overflows ($n > 8$) or high concentrations at drinking water intakes. Model results demonstrated the importance of the cumulative effects of CSOs on the degradation of water quality downstream. However, permits are typically issued on a discharge point basis and do not consider cumulative effects. Source water protection plans must consider the cumulative effects of discharges and their concentrations because the simultaneous discharge of multiple overflows can lead to elevated *E. coli* concentrations at a drinking water intake. In addition, some CSOs have a disproportionate impact on peak concentrations at drinking water intakes. As such, it is recommended that the management of CSOs move away from frequency based permitting at the discharge point to focus on the development of comprehensive strategies to reduce cumulative and peak discharges from CSOs upstream of drinking water intakes.

1. Introduction

The quality of drinking water sources can be heavily influenced by discharges of untreated, treated and partially treated wastewater upstream (Borchardt et al., 2004; Dorner, 2004; Marsalek and Rochfort, 2004). Discharges of untreated waters from combined sewers occur when stormwater enters the system and the hydraulic capacity of the sewer is reached so that water is deviated to overflow structures. Combined sewer overflows (CSOs) can occur during precipitation events (McLellan et al., 2007; Semadeni-Davies et al., 2008) or during the snowmelt period for which fewer discharge restrictions exist (Madoux-Humery et al., 2013).

Many large older cities are concerned with contamination originating with CSOs upstream of their drinking water intakes (McLellan et al., 2007; Patz et al., 2008). In urban areas, intense precipitation events generating runoff can be a challenge with regards to contaminant loads to receiving waters (Field et al., 2003). Health effects have been observed in a region where CSOs were located upstream of a drinking water source (Jagai et al., 2015). In order to ensure adequate water quality and thus the protection of public health, tools are needed to prioritize actions for reducing

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risk, particularly as many overflow structures can be present upstream of drinking water intakes or recreational areas. Statistical methods are not sufficient for detailed explanations of the processes and accumulation effects of contaminant concentrations at intakes (Puri et al., 2009).

The concentration of fecal indicator bacteria in surface waters is a function of their input in the system, their survival, fate and transport. Transport processes such as advection and dispersion must be considered (De Marsily, 1986; Ferguson et al., 2003). Interactions between water and sediments also influence the concentration of bacteria through deposition and resuspension processes (Pachepsky and Shelton, 2011). The importance of the inactivation of bacteria as a removal process depends on the travel time from discharge point to the point of interest because travel times on the order of hours may not lead to order-of-magnitude changes in concentrations. However, factors such as temperature and solar radiation (Whitman et al., 2004), precipitation (Cho et al., 2010), soil type (Ferguson et al., 2003; Vidon et al., 2008), co-occurring contaminants and nutrients (Shelton et al., 2014) can influence the occurrence and survival of fecal bacteria in water. Generally, a first order decay reaction has been used to describe the inactivation of fecal indicators such as *Escherichia coli* (Dorner et al., 2006).

Various pathogen or bacterial indicator fate and transport models have been developed and applied to surface water systems such as rivers (Dorner et al., 2006; Servais et al., 2007), lakes and reservoirs (Brookes et al., 2004) and coastal regions (McCorquodale et al., 2004). However, few studies have focused on urban waters impacted with CSOs. CSO discharges are intermittent with *E. coli* concentrations that can vary over several orders of magnitude during and among events (Madoux-Humery et al., 2013). In older urban areas, a large number of CSOs can occur upstream of drinking water intakes and there is a need to mitigate risks associated with these highly variable discharges.

With available data and existing models, a methodology was developed to estimate the impacts of CSOs on water quality in an urban area and assist municipalities with source water protection decision-making. This study links water quality data that are typically collected by municipal water providers at drinking water intakes, data of overflow occurrences as sampled by the municipalities for regulatory purposes (e.g. SOMAE, 2013) and river flows from gauging stations (e.g. CEHQ, 2006). The general objective of this study was to characterize the impacts of CSOs in source waters in order to propose management strategies. Specific objectives were to: 1) analyze *E. coli* concentrations discharged by a series of overflows at a CSO structure, 2) extend the sampled concentrations from the individual CSO structure to a large area for which detailed results are not available, 3) model the diffusion and dispersion of *E. coli* from CSOs, 4) determine the importance of individual and cumulative effects of CSO discharges for source water protection and 5) propose solutions for the management of overflows to reduce risk to drinking water sources.

2. Methodology

2.1. Study site

The study site was selected as representative of urban source waters in regions with upstream CSOs. It consists of a river draining a fluvial lake (Québec, Canada) as described by Jalliffier-Verne et al. (2014). Its watershed, the Ottawa River Watershed, is one of the largest in Eastern Canada (146,000 km^2) (Benyahya et al., 2009). The river flows over 51 km through a highly urbanized region (Supplementary Materials Figure S1). A 20 km section of the river located upstream of three drinking water intakes and a dam that partly controls the flowrate of the river was investigated. The drinking water intakes, A, B and C (Fig. S1), are under the influence of 42 active sewer overflows. To be considered as active, the sewer overflows must have discharged at least once between 2009 and 2012. The overflows convey untreated wastewater mixed with stormwater to the river. Overflow systems are unequally distributed along the river. There are 29 overflow structures on the north shore and 13 along the south shore, upstream of drinking water treatment plants B and C. The ‘A’ intake isn't influenced by the CSOs, as they are located downstream.

2.2. Overflows

Data from overflows have been provided by municipalities through a provincial program for monitoring wastewater overflow structures from 2009 to 2012 (SOMAE, 2013). Available data are the dates that sites were visited, the method of recording overflows, the presence or absence of an overflow marker, and the total duration of the overflow for locations equipped with monitoring devices. Three types of recording methods were used: 1) overflow markers (typically consisting of a piece of wood attached to a string that will move if an overflow occurs), 2) continuous data recorders and, 3) automatic data recorders.

In the sector studied, 31% of overflows were equipped with floating overflow markers, 33.3% with continuous data recorders and 35.7% with automatic data recorders. For overflow markers, weekly observations were made, thus even if two overflows occur in one week, it was recorded as having only occurred once and the exact date the overflow occurred is not provided and flowrate or duration of the discharge are not available. Continuous data recorders record the total duration of overflows between two visits of a technician. For continuous data recorders, no data on the number of overflows or the exact day of the overflow were available. For automatic data recorders, the logger record overflows on a daily basis. Every 24 h, the device sends its data, but the 24 h can start from noon to noon or from midnight to midnight. Thus, there remains a 24-h uncertainty in the data (Mailhot and Talbot, 2014). On average, the overflow markers were visited 1.8 times a week, continuous data recorders were recorded 5.3 times per week and the frequency of records from automatic loggers was 6.3 times a week. Tables S1–S6 (Supplementary Materials) provide details on the record type and statistics of overflows draining to the river.

River flowrates do not change significantly as a result of local precipitation events that generate overflows. Inflows from CSOs represent a maximum 5.8% of the total flowrate of the river, based on data from SOMAE (2013) and Madoux-Humery et al. (2013)). Thus, the dilution of fecal matter by stormwater and snowmelt can be ignored to simplify loadings to the river by using a direct fecal load from the population. There were no fecal loads from wastewater recovery facilities. Loads from urban stormwater inputs could be important as sewer cross-connections can occur (Sauvé et al., 2012). However, stormwater loads from surface runoff are low as compared to CSOs and were not considered.

2.3. *Escherichia coli* concentrations

E. coli were selected as indicators to model fecal contamination as they are used for the design of drinking water treatment plants in Quebec (MDDEP, 2012). The ratio of *E. coli* to *Cryptosporidium* is high for untreated wastewaters in an urban area, thus for CSOs, *E. coli* can be considered as a conservative indicator (Lalancette et al., 2014), especially when travel times are short.

Data on fecal contamination discharges were available from Madoux-Humery et al. (2013, 2014, 2016), including uncertainty estimates for *E. coli* and flowrate measurements. Time series