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Source tracking of leaky sewers: A novel approach combining fecal indicators in water and sediments

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ABSTRACT

In highly urbanized areas, surface water and groundwater are particularly vulnerable to sewer exfiltration. In this study, as an alternative to Microbial Source Tracking (MST) methods, we propose a new method combining microbial and chemical fecal indicators (*Escherichia coli* (*E. coli*)) and wastewater micropollutants (WWMPs) analysis both in water and sediment samples and under different meteorological conditions. To illustrate the use of this method, wastewater exfiltration and subsequent infiltration were identified and quantified by a three-year field study in an urban canal. The gradients of concentrations observed suggest that several sources of fecal contamination of varying intensity may be present along the canal, including feces from resident animal populations, contaminated surface run-off along the banks and under bridge crossings, release from contaminated banks, entrainment of contaminated sediments, and most importantly sewage exfiltration. Calculated exfiltration–infiltration volumes varied between 0.6 and 15.7 m^3/d per kilometer during dry weather, and between 1.1 and 19.5 m^3/d per kilometer during wet weather. WWMPs were mainly diluted and degraded below detection limits in water. *E. coli* remains the best exfiltration indicator given a large volume of dilution and a high abundance in the wastewater source. WWMPs are effective for detecting cumulated contamination in sediments from a small volume source and are particularly important because *E. coli* on its own does not allow source tracking.

1. Introduction

Dense urban areas, with their high loads of contaminants to sewer networks, render drinking water sources vulnerable to sewer overflows, sewer exfiltration and discharges of contaminated runoff. Surface and groundwaters are particularly vulnerable to sewer exfiltration as aging and poorly maintained infrastructures carry untreated wastewater containing high concentrations of contaminants (Kuroda et al., 2011; Sercu et al., 2011). Sewer exfiltration can be significant; reported rates range from 0.02 to 167 L d^{-1} cm^{-2} (Rutsch et al.,

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2008) representing 1–13% of wastewater dry-weather flow (Fenz et al., 2005; Musolff et al., 2010). Fluxes from sewer leakage are dynamic and can increase during precipitation events when water levels in the sewer systems increase, thereby increasing the hydraulic potential (Musolff et al., 2010; Wolf et al., 2004). The detection of multiple non-point and point sources of fecal contamination from leaking sewers in a dense urban area constitutes significant monitoring and conceptual challenges, especially when attempting to identify the source of fecal contamination.

Escherichia coli (*E. coli*) is a widely used fecal indicator bacteria (FIB) and has been identified as the best bacterial indicator to predict sanitary risks in surface waters (Edberg et al., 2000). Indeed, the quality of a drinking water source and its treatment requirements are determined based on established threshold values of *E. coli* concentrations (United States Environmental Protection Agency (USEPA), 2010a). Despite being widely used, the application of *E. coli* data to identify the extent of fecal discharges or to confirm their source has significant limitations. The occurrence of *E. coli* in water or soil is dependent on a multitude of environmental factors including temperature, predation, solar radiation and salinity (Brookes et al., 2004; Cho et al., 2010a) making source identification challenging (Vital et al., 2012). Furthermore, a shift in fecal bacteria sources in relation to hydrologic conditions can occur (Ashbolt et al., 2010; Wu et al., 2011) and hydrologic events (rain or severe weather conditions) can increase *E. coli* concentrations by several orders of magnitude (Cho et al., 2010b; Amirat et al., 2012; Dorner et al., 2007). As *E. coli* is present in surface water as a free-floating colloid or associated with very fine particles it has varying settling velocities (Wu et al., 2009; Garcia-Armisen and Servais, 2009) and can be prone to re-suspension (Cho et al., 2010b). Finally, *E. coli* concentrations in sediments can vary according to the heterogeneity of the studied material (organic matter, presence of silt and clay, grain size, etc.) (Cho et al., 2010b; Garzio-Hadzick et al., 2010; Pachepsky and Shelton, 2011), but *E. coli* tends not to vary substantially in soils with low organic matter content and low proportion of fine particles (Garzio-Hadzick et al., 2010).

The mass exchange between freshwater sediments and the water column is complex, involving hyporheic exchanges, and net settling of fine particles is determined by re-entrainment rather than by the intrinsic velocity (Jamieson et al., 2005). While significant correlations between *E. coli* concentrations in sediments and the water column have been reported (Wu et al., 2009; Byappanahalli et al., 2003), a review by Pachepsky and Shelton (2011) concluded that the opposite is more generally the case. One conclusion of this review is that *E. coli* or FC (fecal coliform) concentrations in the water column and underlying sediments are poorly correlated in the absence of turbulence and resuspension (base flow conditions). In that case, FC concentrations in the water column are not determined by their release from sediment but are rather derived from external sources (wildlife, leaching from sewer lines, etc.). To add to the complex dynamics between sediment and bulk water, die-off rates appear lower in the sediments than in the water column and less sensitive to temperature effects (Garzio-Hadzick et al., 2010; Pachepsky and Shelton, 2011).

An important limitation of *E. coli* is that it is not human specific (Sercu et al., 2009) making other animals potential contributors to *E. coli* densities. Microbial source tracking (MST) is in expansion as a result of the microbial indicators' high spatial and temporal variability, and variable dynamics of growth and mortality (Harwood et al., 2013) and is promising in light of recent advances. However, a large round robin study on 41 MST methodologies raised significant issues about their sensitivity, cross reactivity and specificity highlighting remaining challenges in their development (Boehm et al., 2013).

An alternative approach to discerning between human and non-human sources of *E. coli* is to pair *E. coli* monitoring with the detection of specific wastewater micropollutants (WWMPs), such as carbamazepine (CBZ), caffeine (CAF), acetaminophen (ACE) and theophylline (THEO). The selection of the tracer WWMPs is generally based on their specificity, persistence and abundance. Recent studies have demonstrated the usefulness of combining WWMPs and FIBs to confirm human sources and quantify the discharge of wastewater in combined sewer overflows, storm sewers, urban streams and rivers (Kuroda et al., 2011; Daneshvar et al., 2012; Madoux-Humery et al., 2013; Sauvé et al., 2012). CAF and CBZ are detected at high concentrations in raw wastewater, ranging from 20 to 300 μg/L for CAF and from 0.1 to 5 μg/L for CBZ (Sauvé et al., 2012), and have been frequently detected in surface water (Daneshvar et al., 2012; Sauvé et al., 2012; Buerge et al., 2006; Heberer, 2002) and in groundwater (Kuroda et al., 2011; Fenz et al., 2005; Heberer, 2002; Gasser et al., 2011; Hillebrand et al., 2012; Nakada et al., 2008; Seiler et al., 1999). CBZ is considered as a cumulative tracer of raw and treated wastewater because of its persistence in surface and groundwater and its detection at low concentrations (Kuroda et al., 2011; Daneshvar et al., 2012; Gasser et al., 2011). Finally, THEO, which is used for the treatment of bronchial asthma, is present in soft-drinks and is also a metabolite of CAF.

To target critical zones susceptible to contamination in urban water systems subjected to wastewater exfiltration from surrounding sewer systems, we propose a new method combining the analysis of microbial and chemical fecal indicators (*E. coli* and WWMPs (CAF, CBZ, THEO, ACE)), both in water and sediment samples. In order to identify and quantify wastewater infiltration, the fate of indicators in the water column and sediment was monitored in an urban canal during dry weather (DW) and wet weather (WW), which constitutes a strong case study to illustrate the use of this combination of indicators because of its relatively simple hydraulics. The simple hydraulics allows for a reliable estimation of the apportionment of sources of fecal contamination and the verification of estimates of common parameters (i.e. inactivation coefficients, settling rates) governing the fate of fecal contaminants. This would not be possible in natural waters as they are more complex and have greater temporal variability. This system enables the full-scale testing of fecal source tracking methods in water and sediments in a semi-controlled environment, which to the best of our knowledge has not been done before.

The main objective of this study was to locate and quantify sources of fecal contamination, namely wastewater from