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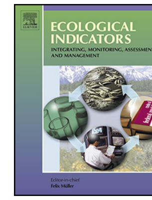

Case study

Source apportionment of non-storm water entries into storm drains using marker species: Modeling approach and verification

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ABSTRACT

Inappropriate non-storm water entries into the storm drains and the resulting direct discharge into the natural environment on dry-weather days, is a challenging environmental issue in the cities worldwide. To make a preliminary evaluation of non-storm water entry situations, this study presented an approach for source apportionment of non-storm water entries into storm drains based on marker species and a chemical mass balance (CMB) model using a Monte Carlo statistical simulation. Compared with deterministic approaches, this method is capable of accounting for the measurement errors and the impact of variability of the source marker profiles resulting from heterogeneities and therefore presents the most likely range of estimated source contributions. This method was verified using measured data in a catchment in Shanghai, China, covering 374 ha. Here, inappropriate entries of sanitary wastewater, semiconductor wastewater, and groundwater into storm drains can be identified using acesulfame and citric acid, chloride, fluoride and sulfate, and total hardness, respectively, as markers. Using the measured marker profiles, the apportioned source flows were estimated with high precision in comparison to the investigated data, with a relative error less than 11%. Apportioned data revealed strong sanitary source connections to storm drains (i.e., 45.8% of the total sewage output), which were mainly from old residential communities with direct sewer connections to the storm pipes. Additionally, it revealed illicit semiconductor wastewater discharge contributed to 75% of the fluoride load, 52% of the sulfate load, and 32% of the chloride load, despite its low flow component of 9.2%. Therefore, a primary correction strategy of applying end-of-storm pipe control treatment, as well as reconnecting industrial source to the sewer network, was presented. Moreover, the marker library data associated with a variety of source types is expected to provide clear evidence for various non-storm water entry situations in future studies.

1. Introduction

A storm drain system is designed to prevent the accumulation and retention of urban storm water runoff on city surfaces and discharge the accumulated waters into receiving waters. On dry-weather days, however, non-storm water discharges also find their way into storm water drainage systems, resulting in the release of untreated sewage in the surface water system (Field et al., 1994; US EPA, 2004). If these loadings are not identified and corrected (e.g., by only considering wet-weather storm water runoff), little improvement in receiving water quality may occur. Therefore, investigation of these loadings can be a demanding task.

Most of the current urban drainage network inspections are predominantly conducted using physical methods, such as CCTV (closed circuit television), temperature based thin-film cabling examination and flow measurements (Hoes et al., 2009; Tafuri and Selvakumar, 2002; Yin and Xu, 2010). However, these methods are labor-intensive when conducting a thorough assessment of the condition of the entire system. Alternatively, chemical or biological markers may be employed to trace and quantify non-storm water sources with inappropriate entry into storm drains (Field et al., 1994; Irvine et al., 2011), thereby making a preliminary evaluation of non-storm water entry situations, as well as presenting a basic strategy for storm drain investigation and correction.

Recent studies have shed light on the utility of markers to identify raw sewage discharge into surface waters, which might occur during rainfall events through combined sewer overflows (CSOs), and during dry weather through leaking sewers and improperly functioning septic tanks (Kurissery et al., 2012; Sousa et al., 2014; Ufnar et al., 2006). In addition, studies have been performed to detect and quantify source inputs such as sewage exfiltration into

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groundwater aquifer (Barrett et al., 1999; Buerge et al., 2009; Fenz et al., 2005; Leschik et al., 2009; Schmidt et al., 2013; Wolf et al., 2012), and groundwater or rainfall-derived infiltration into sewers (Benedittis and Bertrand-Krajewski, 2005; Houhou et al., 2010; Kracht et al., 2007; Shelton et al., 2011), which have demonstrated the usefulness of these markers. However, source apportionment of non-storm water entries into storm drains remains challenging, not only to determine ideal markers and parallel quantification of a blend of source types such as sanitary wastewater, industrial wastewater, and groundwater, but also to advance a method for analytical uncertainty arising from scattered sources throughout large areas of a catchment. From this perspective, the validation of source apportionment results is anticipated to strengthen the discussion of the marker-based approach.

The goal of this study is to develop a marker-based approach to identify potential non-storm water source categories and their contributions to storm drain discharge on dry-weather days. The study site is a catchment where non-storm water sources with inappropriate entries into storm drains were investigated thoroughly, including sources from sanitary wastewater, industrial wastewater, and groundwater. Data from these different inputs and the catchment outlet were analyzed for the selected markers and combined in a developed source apportionment approach to elucidate the source entry into storm drains on dry-weather days, which were then compared with those determined by direct investigation to verify this approach.

2. Materials and methods

2.1. Site description

The study site is a catchment typical of high-density urbanized areas (approximately 270 inhabitants/ha) in Shanghai's downtown area. The site is a mixed residential and industrial area that covers 374 ha; the south-western area is mainly focused on semiconductor industrial activities. This area is served by a separate sewer and storm drainage system. According to a sewage output survey in 2008, the annual flow of all sewage sources in this catchment was 12,831,743 m^3, which is equivalent to an average of 35,155 m^3/d (Xu et al., 2014). Despite the separate sewer system that intercepts the sewage sources into a nearby wastewater treatment plant, non-storm water sources also find their way into storm drains on dry-weather days and contribute significant pollutant loadings to local watercourses, even resulting in a severe foul stench phenomenon.

To elucidate non-storm water connections to the storm drains, an on-site investigation was conducted during the period from January 2009 to May 2009, with the support of Shanghai Municipal Sewage Company Ltd. and the Municipality and Water Affairs Office of Xuhui District, Shanghai. For each discovered illicit source, its discharge was measured using velocity-profile flow meters (Nivus PCM Pro, Germany), and continuous flow data were acquired and analyzed over a one-week period. The confirmed sewer pipe connections to the storm drains and their non-storm water discharges were mapped (Fig. 1). Of the 5 industrial sources totaling sewage output of 6456 m^3/d in the study site, the semiconductor enterprise with the largest industrial sewage output of 3104 m^3/d was found illicit connection to the storm drains. Specifically, the illicit discharge was from the enterprise's third-stage project, with a measured flow of 1959 m^3/d. The reason is probably that the semiconductor enterprise processing large volumes of water may find sanitary sewer flow-carrying capacity inadequate, leading to improper removal of excess water through the storm drain system. However, besides one semiconductor enterprise discharge connecting to the storm pipe, the remaining 149 illicit sources scattered throughout the catchment were characterized as sanitary sewage, totaling 15,346 m^3/d. Moreover, statistics on sanitary sewage discharge into storm drains was shown in Table 1.

Attention should also be paid to groundwater infiltrating into the storm drains in this catchment. The available local groundwater information (SGSI, 2011–2013) showed that the dry-weather groundwater table of this study site fluctuated between 2.67 and 3.14 m, i.e., 1.1–1.6 m below ground surface, which is related to relatively rich groundwater recharge through local rainfall that averages 1200 mm annually. By comparison, the dry-weather water level within the storm drains had a range of 2.21–2.60 m (Xu et al., 2014). Therefore, it can be determined that the intrusion of extraneous waters into storm drains instead of storm drains exfiltration occurs throughout the catchment, because storm pipes lie below the groundwater table. With respect to the groundwater inflow rate, a flow balance calculated for this study site indicated that non-storm groundwater infiltration into the storm drains was approximately 3624 m^3/d, which was calculated as the difference between the sum of the sewage flows and the measured non-storm water outflow under non-pumping events (Xu et al., 2014).

2.2. Selection of marker species

Source apportionment of non-storm water entries into storm drains is primarily based on marker species. Generally, an ideal marker should allow the unambiguous elucidation of the source, have a low affinity for sediments, and represent conservative behavior, i.e., no significant concentration change due to physical, chemical, or biological processes.

2.2.1. Sanitary sewage

Previously, the primary parameters for identifying sanitary sewage inputs have included ammonia, potassium, *Enterococci*, *Escherichia coli*, and surfactants (Field et al., 1994; US EPA, 2004). Although they have potential advantages, these parameters may have some defects as ideal markers. For example, ammonia is reactive and likely to be converted into nitrate under aerobic conditions; even within a closed storm drainage system, re-aeration through slotted manholes and covered road gullies could provide aerobic conditions within water that are necessary for nitrification (Huisman et al., 2004). Additionally, in the areas where storm drains lie below the groundwater table, infiltrated groundwater of O_2-rich can also be larger for pipe oxygen input. Bacterial markers have disadvantages such as limited source specificity and relatively short survival in water. In this study, two chemical indicators, i.e., the artificial sweetener acesulfame and citric acid were employed as markers of sanitary wastewater input. Artificial low-calorie sweeteners are consumed in considerable quantities in foods and beverages. After ingestion, some sweeteners passing through the human metabolism largely unaffected, are quantitatively excreted via urine and feces, and thus reach the environment associated with domestic wastewater. In particular, acesulfame K (ACE, 6-methyl-1,2,3-oxathiazin-4(3*H*)-one-2,2-dioxide potassium salt) has been found to be quite persistent in surface waters and meets the criteria of an ideal marker for the detection of domestic wastewater in water bodies (Buerge et al., 2009). Citric acid (CA, 2-hydroxy-1,2,3-propanetricarboxylic acid) can be used as an additive to add an acidic taste to food and soft drinks, and is also an ingredient in detergents and cleaning products. Due to its non-toxicity, it is currently being marketed as an environmentally friendly alternative to the detergent composition such as tri-polyphosphate. From this perspective, citric acid can be considered as a potential marker for gray water in sanitary wastewater.