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Indicator bacteria and associated water quality constituents in stormwater and snowmelt from four urban catchments

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SUMMARY

Four indicator bacteria were measured in association with physico-chemical constituents and selected inorganics during rainfall, baseflow and snowmelt periods in storm sewers of four urban catchments in a northern Swedish city. The variation patterns of coliforms, *Escherichia coli*, enterococci and *Clostridium perfringens* concentrations were assessed in manually collected grab samples together with those of phosphorus, nitrogen, solids, and readings of pH, turbidity, water conductivity, temperature and flow rates to examine whether these constituents could serve as potential indicators of bacteria sources. A similar analysis was applied to variation patterns of eight selected inorganics typical for baseflow and stormwater runoff to test the feasibility of using these inorganics to distinguish between natural and anthropogenic sources of inflow into storm sewers. The monitored catchments varied in size, the degree of development, and land use. Catchment and season (i.e., rainy or snowmelt periods) specific variations were investigated for sets of individual stormwater samples by the principal component analysis (PCA) to identify the constituents with variation patterns similar to those of indicator bacteria, and to exclude the constituents with less similarity. In the reduced data set, the similarities were quantified by the clustering correlation analysis. Finally, the positive/negative relationships found between indicator bacteria and the identified associated constituent groups were described by multilinear regressions. In the order of decreasing concentrations, coliforms, *E. coli* and enterococci were found in the highest mean concentrations during both rainfall and snowmelt generated runoff. Compared to dry weather baseflow, concentrations of these three indicators in stormwater were 10 (snowmelt runoff) to 10^2 (rain runoff) times higher. *C. perfringens* mean concentrations were practically constant regardless of the season and catchment. The type and number of variables associated with bacteria depended on the degree of catchment development and the inherent complexity of bacteria sources. The list of variables associated with bacteria included the flow rate, solids with associated inorganics (Fe and Al) and phosphorus, indicating similar sources of constituents regardless of the season. On the other hand, bacteria were associated with water temperature only during rain periods, and somewhat important associations of bacteria with nitrogen and pH were found during the periods of snowmelt. Most of the associated constituents were positively correlated with bacteria responses, but conductivity, with two associated inorganics (Si and Sr), was mostly negatively correlated in all the catchments. Although the study findings do not indicate any distinct surrogates to indicator bacteria, the inclusion of the above identified constituents (flow rate, solids and total phosphorus for all seasons, water temperature for rainfall runoff, and total nitrogen and pH for snowmelt only) in sanitary surveys of northern climate urban catchments would provide additional insight into indicator bacteria sources and their modeling.

1. Introduction

Fecal contamination of urban receiving waters affects directly human health, where such waters serve for raw drinking water supply or body-contact recreation, and motivates investigations of sources of fecal microorganisms, including stormwater discharges (Marsalek and Rochfort, 2004). Such contamination incidents were recently reported in Sweden, where a series of contamination episodes contributed to the impairment of drinking water supplies in several municipalities, during the period from 2010 to 2011 (Hrudey and Hrudey, 2014; Widerström et al., 2014). The search for sources of impairment included studies of microbiological quality of urban stormwater discharged into the

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water bodies of concern. In general, such studies also serve to assess the state of the urban sewer infrastructure, including the degree of separation of wastewater and stormwater in separate sewer systems (Panasiuk et al., 2015).

Sources of potentially pathogenic microorganisms in urban stormwater are numerous and, for operational efficiency, are typically assessed by investigating fecal indicator bacteria (Metcalf et al., 2013). Common sources of microorganisms in stormwater include: (i) animal feces and droppings (domestic pets, urban wildlife, and rodents in sewers); (ii) catchment surface and land use activities (land wash; lack of sanitation, including poor solid waste collection; urban farming and gardening), and (iii) the sources related to urban infrastructure issues (cross-connections between storm and sanitary sewers, accumulation of sediments in catch basins and sewers, and growth of bacteria in nutrient-rich standing waters in storm sewer systems) (Olyphant et al., 2003; H.A.C. Jeng et al., 2005; H.C. Jeng et al., 2005; Coulliette and Noble, 2008; Rowny and Stewart, 2012; Panasiuk et al., 2015). To ensure high protection of freshwater resources and the robustness of bacteria detection processes, different strains of indicator bacteria with varying environmental survival characteristics are used as surrogates of pathogens in stormwater monitoring to estimate the risk of pathogens transport into the receiving waters with stormwater runoff (Gerba, 2000). The indicator bacteria used widely for assessing the quality of raw and finished drinking water, and of recreational waters in Sweden and elsewhere include total coliforms, *Escherichia coli*, enterococci and *Clostridium perfringens* (98/83/EC; 2000/60/EC; 2006/7/EC).

Transport of bacteria by stormwater is a highly dynamic complex process characterized by greatly varying bacteria concentrations, resulting from time-varying contributions of bacteria from continuous or intermittent sources, transport of bacteria attached to solids, and their survival dynamics including die off and regrowth in the water phase (Gonzalez et al., 1992). Thus, transport and survival of indicator bacteria may be further affected by specific stormwater quality constituents, including suspended solids (transport vectors), nutrients, and possibly others, which may provide a protective buffer and/or nutrition for microorganisms. Indicator bacteria transported by suspended solids survive longer than those in the free water phase, because of their increased protection against ambient conditions (including solar irradiation) and the supply of nutrients associated with certain types of solids (H.A.C. Jeng et al., 2005; H.C. Jeng et al., 2005; Chudoba et al., 2013). Hence, there is a great variation in indicator bacteria concentrations in stormwater reported in numerous studies, review papers and stormwater quality databases (Duncan, 1999; Marsalek and Rochfort, 2004) and most authors attempt to explain this variation by catchment characteristics, rainfall/runoff processes, stormwater quality, and climate characteristics (particularly air and water temperatures) (McCarthy et al., 2008, 2012; Desai and Rifai, 2010; Hathaway et al., 2010; Tiefenthaler et al., 2011; Harmel et al., 2016).

Interactions between indicator bacteria and stormwater quality (particularly the presence of solids and nutrients) depend on the catchment characteristics with respect to the degree of development, land use types, human activities, sewers and local climate, including the rainfall regime and air temperatures (Brezonik and Stadelmann, 2002; Ghafouri and Swain, 2005; Tiefenthaler et al., 2011). Stormwater from low-imperviousness catchments carries higher counts of coliform bacteria originating from the ambient environment (soils and vegetation), wildlife feces and recreational activities (Desai and Rifai, 2010; Tiefenthaler et al., 2011), and the survival of such bacteria may be supported by the presence of solids and nutrients (H.A.C. Jeng et al., 2005; H.C. Jeng et al., 2005; Chudoba et al., 2013). On the other hand, stormwater runoff from more developed catchments yields higher bacteria concentrations attributed to the presence of debris (solid waste), human activities, and animal feces (Desai and Rifai, 2010; Hathaway et al., 2010).

Ambient environmental conditions, including air temperatures and sun radiation, also affect bacteria fluxes and inactivation, as reported mostly for natural waters (Noble et al., 2004). In warmer climate catchments, McCarthy et al. (2012) found the sources, growth, and die-off of indicator bacteria to be more important determinants of their levels, than wash-off and transport processes during wet weather, since the most influential factors for event mean concentrations (EMC) of *E. coli* were antecedent catchment conditions and nutrient levels in stormwater, described by ammonium, total phosphorus (TP), and total nitrogen (TN).

Finally, stormwater quality varies not only in space, but also during and between the events, and is likely to differ seasonally, when comparing rain and snowmelt runoff events occurring in cold climate regions. Large parts of Scandinavia lie in the subarctic region above the 60° latitude, where seasonal snowpacks last 4 to 6 months during the year and about 40% of the total annual precipitation occurs as snow (Bergström, 1993). Thus, snowmelt contributes a high percentage of the annual runoff, the quality of which differs from that of rainfall runoff. In particular, snowmelt runoff may carry elevated amounts of solids released during short periods of time (Westerlund et al., 2003) and those solids contain such adsorbed contaminants as heavy metals, bacteria, and trace organics originating from anthropogenic activities (Schillinger and Gannon, 1985; Hvitved-Jacobsen and Yousef, 1991; Viklander, 1998; Marsalek et al., 2008). However, large quantities of mineral-origin solids on the catchment surface, their scouring by snowmelt runoff, and low air/runoff temperatures are likely to produce different relationships between indicator bacteria, solids and nutrients than those typical for rainfall runoff during warmer conditions (Bogosian et al., 1996).

The main objectives of the study presented herein were to assess the magnitude of indicator bacteria concentrations in stormwater runoff from urban catchments in central Sweden, and to investigate the influential factors, including catchment and climatic characteristics, affecting indicator bacteria populations. A secondary objective was to expand the published information on indicator bacteria in urban stormwater in climates with seasonal snowpacks.

2. Methods

2.1. Sampling sites

The field study of indicator bacteria in stormwater was conducted in four urban catchments, which were selected for study in the City of Östersund, Sweden. Östersund has a population of about 44,000 inhabitants and is located in the central part of Sweden, at latitude 63°11′N and longitude 14°30′E, at elevations ranging from 300 to 380 m above sea level. The study catchments were selected for their locations in the vicinity of the drinking water plant (two to the south and two to the north) and recreational beach areas. All four catchments (designated A–D) are drained by separate storm sewers, with outfalls discharging into Lake Storsjön, the fifth largest lake in Sweden (surface area 464 km^2, Fig. 1). Two catchments (B and D) convey baseflow during dry weather. The mixed catchment (C) is divided in two parts; a less developed subcatchment with large infiltration areas upstream from a flow divider conveying some of the stormwater to an adjacent catchment and a highly urbanized subcatchment downstream from the flow divider. The downstream subcatchment of 12 ha is contributing permanently with runoff to the measurement point during all events whereas some parts of the upstream subcatchment of 27 ha are contributing to the runoff in addition depending on rain amount and intensity.