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A large-scale lysimeter study of stormwater biofiltration under cold climatic conditions

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ABSTRACT

Stormwater biofiltration was studied at a large-scale lysimeter facility in southern Finland. Biofiltration systems, constructed within eight lysimeters, consisted of an organic topsoil, a sand layer and three gravel layers of varying gravel size underneath. Six of the lysimeter systems were vegetated with *Phalaris arundinacea, Salix glauca var. callicarpaea* and *Lythrum salicaria*, and two systems were left unplanted. The effect of vegetation on the functioning of the systems was studied by comparing the vegetated with the non-vegetated systems. The systems were irrigated during three seasons with artificial stormwater containing nitrate, phosphate, zinc, copper and aluminium to study pollutant retention and water infiltration during warm and cold temperatures. Half of the systems also received road salt (NaCl) to study its effect on the functioning of the systems. Phosphate, zinc and copper were well retained (81–98%) during each season in each system. Nitrate retention improved (from 0 to 47%) with time in the vegetated system but negative retention was also observed during some irrigation events, indicating that nitrate also leached from the parent soil. The retention of aluminium in the unsalted biofilters decreased (from ca. 80 to 0%) during the snowmelt season in spring and was highly negative in the salted systems during spring and summer. Salt also slightly diminished (ca. 8%) the retention of Cu. Vegetation only improved the retention of nitrate. However, the non-vegetated systems infiltrated water poorly while the vegetated systems infiltrated large volumes and intensities of water one year after biofilter establishment. Hence, vegetation was necessary for operational infiltration. The study showed positive results for stormwater biofiltration in cold climates. Nonetheless, long-term studies with varying soil types and pollutants are recommended.

1. Introduction

Sustainable stormwater management, including the use of stormwater biofiltration systems, is widely used to reduce stormwater quantity and to improve its quality within urbanised catchments (Coffman and Clar, 2003). Such biofiltration systems are composed of soil layers with a top layer consisting of vegetation, also known as a rain garden (Le coustumer et al., 2012; Barrett et al., 2013; Lim et al., 2015). Previous studies have generally shown efficient phosphorus removal, whereas the retention of nitrogen has been poorer owing to the leaching of nitrate from biofiltration systems (Bratieres et al., 2008). For instance, retention rates of 80–99% have been reported for phosphorus (Coffman and Clar, 2003; Blecken et al., 2009, 2011; Barrett et al., 2013) as well as for metals (Coffman and Clar, 2003; Blecken et al., 2009, 2011), but the retention rates of nitrogen have clearly been less, 40–80% (Coffman and Clar, 2003; Blecken et al., 2009, 2011; Barrett et al., 2013). However, most of these studies have been conducted in the laboratory as small scale column (diameter 100–400 mm) studies and at temperatures above zero (Bratieres et al., 2008; Blecken et al., 2009, 2011; Le coustumer et al., 2012; Barrett et al., 2013; Lim et al., 2015). Therefore, more stormwater biofiltration studies at a mesocosm scale need to be conducted (Liu et al., 2014).

Despite the good water treatment capacity of stormwater biofilters in general, the pollutant retention efficiency and hydraulic conductivity of biofilters depend, e.g. on the selection of plant species (Henderson, 2008; Barrett et al., 2013) and soil type/filter media (Barrett et al., 2013; Lim et al., 2015). As for pollutant removal, vegetation plays a critical role, particularly for the uptake of nitrogen (Pitt et al., 1994; Bratieres et al., 2008; Hatt et al., 2009). In addition, some plant species are efficient in the extraction of

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Fig. 1. The lysimeter facility in Lahti, southern Finland, with the eight lysimeters used in this study. The soil systems in the lysimeters were either vegetated or non-vegetated (left panel). The right panel illustrates the lysimeters as seen from below where each lysimeter rests on a set of three scales. The average mass of soil in a lysimeter was 2400 kg.

heavy metals from soils (Kumar et al., 1995). Vegetation and in particular the root zone is also important in improving the infiltration capacity of biofiltration soils, even at cold temperatures (Muthanna, 2007; Moghadas et al., 2015). Even though several soil types can retain common stormwater pollutants, such as metals and nutrients (Muthanna, 2007; Coffman and Clar, 2003; Blecken et al., 2009, 2011; Hatt et al., 2009; Feng et al., 2012), retention can be increased by selecting a suitable soil medium (Hatt et al., 2009; Feng et al., 2012). Also, conditions in the soil – such as saturated, anoxic conditions that increase denitrification (Barrett et al., 2013) and the optimal nutrient content that supports plant growth but not nutrient leaching (Liu et al., 2014; Hatt et al., 2009) – are important in the pollutant removal processes.

Apart from the construction materials of biofilters, weather conditions affect the functioning of the systems (Muthanna, 2007; Blecken et al., 2011; Mangangka et al., 2013). Under cold climatic conditions in particular, the functioning of biofiltration systems is questionable due to frozen soils and inactivity of the biological component within the systems for a substantial part of the year (Muthanna, 2007; Moghadas et al., 2015). For example, retention rates of some heavy metals (Bäckström, 2003) and nitrogen (Blecken et al., 2010) diminish at low temperatures in biofilters. In addition to cold weather, cold season pollutants such as deicing chemicals used for slipperiness control (Amrhein et al., 1992) and increased metal and nutrient emissions (Oberts, 1994; Brezonik and Stadelmann, 2002; Marsalek, 2003; Reinosdotter, 2007) may cause challenges for the treatment of stormwater (Moghadas et al., 2015). Road salt mobilizes heavy metals in stormwater infiltration systems (Nelson et al., 2009) due to several mechanisms, such as cation exchange and colloid dispersion (Amrhein and Strong, 1990; Amrhein et al., 1992). However, previous biofiltration studies investigating the effects of salt on the functioning of the soil have not included an unsalted control biofilter (Amrhein et al., 1992; Nelson et al., 2009).

Due to uncertainty in the proper functioning of stormwater biofiltration systems, they are not yet a common practice in Nordic countries and have, thus, rarely been studied (Muthanna, 2007). Since urban stormwater is one of the most important surface water pollution sources (Fletcher et al., 2013), there is a need for practical runoff water treatment plans at northern latitudes where, e.g. lakes abound. This requires detailed knowledge of the ability of local soil types and vegetation to retain stormwater pollutants in the biofilter during cold months (Muthanna, 2007). In addition, the impact of deicing salts on stormwater biolfiltration needs to be studied to improve the functionality of biofilters under cold climates (Muthanna, 2007; Blecken et al., 2011). Most of the above-mentioned studies have been conducted in small-scale laboratory columns. Laboratory experiments enable the investigation of several factors affecting the performance of biofilter systems. Yet, the use of small columns, laboratory "weather conditions" and an emphasis on summer rainfall conditions do not necessarily provide information on how biofiltration systems work under field conditions at a larger scale.

The aim of this study was to explore how biofiltration systems, consisting of soils and vegetation typical of local urbanised settings, retain metals and nutrients, and infiltrate water during different seasons. Specifically, our objective was to investigate how vegetation and road salts influence the efficacy of biofiltration systems under cold climatic conditions. We hypothesized that i) pollutants are retained more efficiently during warm seasons than during cold ones due to dormant vegetation and the freezing of soils during the latter, ii) vegetation improves the retention of pollutants due to plant uptake and modification of the soil by roots, and iii) road salts boost the leaching of stormwater pollutants, especially metals, from biofiltration systems. The study was conducted in large scale lysimeters located at a field station experiencing real local weather conditions at the top of the mesocosms.

2. Methods

2.1. Experimental setup

The study was conducted during 2009–2010 at a large-scale lysimeter facility in Lahti, southern Finland (60°59′00″N, 25°39′20″E). As shown in Fig. 1, the open-air lysimeters are located in an underground bunker with their tops exposed to local weather. In the bunker, air temperature is kept as close as possible to the natural temperature of the surrounding soil.

In June 2009, eight lysimeters (diameter ca. 1 m, depth 2 m) were filled with the following soil layers from top to bottom: organic soil layer, sand filter layer, transition layer of fine gravel, drainage layer of coarse gravel and saturated layer of coarse gravel (Fig. 2). During the filling of the lysimeters, all soil layers, except the topmost organic layer, were carefully compressed by irrigating the soils with water, which at the same time washed away some organic debris and fine mineral particles. Two of the lysimeters were left unplanted while the rest included three plant species (*Phalaris arundinacea, Salix glauca var. callicarpaea, Lythrum salicaria*) common in Finland and known for their tolerance to drought and excessive soil moisture.

2.2. Irrigation

The biofiltration experiment was conducted using artificial stormwater. Irrigation volumes (Table 1) for each season were calculated based on a theoretical catchment area and typical rainfall