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Assessment of clogging phenomena in granular filter media used for stormwater treatment

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SUMMARY

Hydraulic performance of granular filter media and its evolution over time is a key design parameter for stormwater filtration and infiltration systems that are now widely used in management of polluted urban runoff. In fact, clogging of filter media is recognised as the main limiting factor of these stormwater treatment systems. This paper focuses on the effect of physical characteristics of filter media and flow-through rates on the clogging of stormwater filters. Five replicate experimental columns were constructed using zeolite, scoria, riversand and polymeric glass beads, and different flow-through rates were achieved using restricted outlets. The systems were dosed with semi-synthetic stormwater and the evolution of hydraulic performance and sediment removal rate was observed (for four filter media and across four flow rates) to investigate impacts of media type and flow rate. It was found that shape and smoothness of filter media grains had limited effect on clogging and sediment removal rate. All media except scoria clogged after similar volumes of stormwater but scoria-based filters were found to be highly variable in performance, most likely due to breakdown of its particles. Conversely, flow-through rate significantly affected clogging and sediment removal rate. For instance, in the case of zeolite filters, the systems with the lowest flow rate clogged after application of over 30 m of stormwater, while the unrestricted zeolite columns (with 200 times the flow rate) clogged after only 10 m of applied stormwater. At the same time, the zeolite filters with the lowest flow rate had an overall treatment efficiency of 88% compared with the unrestricted design's efficiency of 59%. Further work is needed to analyse the influence of filter bed design, stormwater inflow characteristics and drying and wetting regimes on clogging and to understand the location of the clogged material in these filters.

1. Introduction

Techniques such as filtration and infiltration have been recognised as effective for managing the increased volumes of urban runoff and mitigating pollution of receiving waters (e.g. Geldof et al., 1994; Barraud et al., 1999; Braune and Wood, 1999). Treated stormwater also offers promise as an alternative source of supply for non-potable water use. Unfortunately, clogging of most of these treatment systems, which rely on filtration media, is a significant problem that impacts their performance (e.g. Rice, 1974; Lindsey et al., 1992; Dechesne et al., 2004). Clogging is the reduction in infiltration rate (also called hydraulic conductivity/permeability) and leads to increased overflows and long periods of ponding. This results in a range of problems that span from public safety to aesthetics, flooding and pollution of receiving water bodies (Le Coustumer et al., 2008, 2012; Knowles et al., 2011; Hatt et al., 2012).

Clogging processes have been studied in civil engineering, soil science, membrane research and other disciplines for many years and the findings are typically very discipline specific (Schubert, 2002; Mays and Hunt, 2005; Mays, 2010). For example, it has been shown that the evolution of hydraulic conductivity over time is specific to the shape and size of both sediment grains and suspended particles in the influent (Suthaker et al., 1995; Evans et al., 2002; Knowles et al., 2011); the nature of filter bed (McIsaac and Rowe, 2007; Knowles et al., 2011); the characteristics of inflows (Gautier et al., 1999; Raimbault et al., 1999; Perez-Paricio, 2001; Mays and Hunt, 2005); infiltration rate and fluid velocity (Changhong, 2008; Mays, 2010); suspension viscosity (Herzig et al., 1970; Skolasinska, 2006); antecedent moisture conditions in the filter media and the nature and extent of clogged material within filter bed (Herzig et al., 1970; Mays and Hunt, 2005).

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However, very limited studies have been undertaken to understand clogging processes in the context of stormwater treatment systems (e.g. Siriwardene et al., 2007; Le Coustumer et al., 2007, 2008; Hatt et al., 2008; Li and Davis, 2008a; Bratieres et al., 2012; Yong et al., 2013). Given the importance of clogging in stormwater filtration systems, and the specific nature of stormwater pollution, it is necessary to understand clogging processes in order to ultimately improve the design and performance of stormwater filtration media with high infiltration rates.

Filter media differ from each other on the basis of material, shape (angularity and surface texture) and this may be of consequence for the hydraulic and treatment performance of granular media. For instance, Hatt et al. (2008) compared six different types of filter media (fine sand, sandy loam and its different combinations with hydrocell, vermiculite, perlite, compost and mulch) for stormwater application and observed a difference in their hydraulic performance. Similarly, Knowles et al. (2011) recognised that significant differences exist between sand filters and bio-retention facilities because of the difference in media used in these facilities. The shape and size of filter grains has also been found to affect the overall performance of the system. For instance, improved performance of crushed grains (jagged and angular, collected from the crushing of larger pieces of rock) over spherical grains (rounded and smooth, collected from river beds or glacial outwash) has also been demonstrated for drinking water filtration (Suthaker et al., 1995; Evans et al., 2002). Knowles et al. (2011), while reviewing clogging phenomena in vertical and horizontal subsurface flow treatment wetlands for wastewater treatment, found that the hydraulic conductivity of porous media was very sensitive to media shape and size. Non-spherical or angular media aggravate clogging as it reduces porosity and increases the specific surface area available for bio-film growth. Similarly, the size of filter media has also been found to impact the infiltration rate of the system as it controls the flow through rates. For instance, McIsaac and Rowe (2007) compared clogging performance of different sized gravel media for leachate collection systems. The coarse gravel bed (38 mm) performed much better than the 19 mm gravel and maintained a hydraulic conductivity that was higher than the 19 mm gravel even after operating for twice as long. These findings reinforce the need to compare commonly used stormwater filtration media for their hydraulic and treatment performances over time.

Unfortunately, current clogging studies in stormwater treatment systems have been limited to fine filter media (e.g. Hatt et al., 2008) or very coarse media (e.g. Siriwardene et al., 2007). Clogging of filter media of particle size range between 1 and 5 mm has not been studied, even though some commonly used stormwater filters use coarse filter media (Clark and Pitt, 1999; Bratieres et al., 2012). Mays and Hunt (2005) analysed clogging data collected from a number of experimental and modelling studies for different types of influents in fine media, and found that flow rate has a significant impact on hydraulic performance, with clogging rate inversely related to flow rate. Given that the size of filter media (and hence the infiltration rate of the system) could be a key factor affecting clogging, it is important to study the overall performance of filter media of this size range for stormwater treatment.

Furthermore, research also suggests that the most critical factor that determines straining processes (prevalent in stormwater filtration applications) is the ratio between the diameter of media particles and that of the suspended sediments (Herzig et al., 1970; McDowell-Boyer et al., 1986; Li and Davis, 2008b). Given the diverse range of particle sizes in stormwater, which varies depending on the type of catchment, level of pre-treatment etc. (Lloyd et al., 1998), it is necessary to understand the nature of clogging specific to filters with high infiltration rates so as to inform a better design with low maintenance needs.

The main purpose of this research is therefore to understand the process of clogging in filter media with high infiltration rates that are typical of stormwater infiltration and treatment systems. This article focuses on impacts of filter media type and flow operational conditions (i.e. filtration or flow-through rate). It also discusses the interplay between clogging and sediment removal performance. Effects of intermittent loading (i.e. the wetting and drying) regime have not been included in this paper (they will be presented in consequent publications).

Based on a review of the literature, the following hypotheses have been identified for investigation in context of stormwater treatment:

1. physical characteristics of the media material such as its structural strength, shape (angularity) and smoothness have a significant impact on the rate of clogging and treatment performance;
2. flow-through rate has a significant impact on filter clogging and treatment performance for a specific particle size of filtration media.

2. Methods

2.1. Experimental setup

Four granular filter media were tested (Fig. 1): zeolite, scoria, riversand and glass beads (made from a polymer material). These media were specifically selected to address the first hypothesis and cover a range of particle shapes (angularity), porosity, roughness, and structural strength (as shown in magnified picture of these media in Fig. 2). These media are also representative of typically-used materials in filtration (Clark and Pitt, 1999; Kele, 2004; Bratieres et al., 2012; River Sands Pty Ltd.). Zeolite was chosen because of its cage like structure and its wide acceptability in the water treatment industry. Scoria particles were selected because they are the most uneven and have the lowest structural strength. Riversand was chosen because of its angular shape and also because it is one of the most widely available media. Glass beads were chosen as a theoretical material as they are the most spherical, impermeable and smooth.

A uniform filter media particle size of 2 mm (passing 2.36 mm sieve and retained on 2 mm sieve) was selected for all media. Sieving has been done to prepare a filter bed with particles sized between 2 and 2.36 mm as a preventative measure against a mixed filter bed with diverse set of particle sizes (which could create a new variable affecting performance of compared systems). Systems with a filter particle size lower than this size (such as 0.5 mm) were found to have a lower filtration rate, in a series of prior pilot experiments and Kandra et al., 2014, whereas bigger particle sizes (such as 10 mm) had lower treatment performance. Therefore, the selected particle size range is something of a trade-off between the hydraulic and treatment performance. Further clogging of non-vegetated stormwater filter media that is made from particles sized between 1 mm and 5 mm has not been investigated even though they are often used in proprietary stormwater systems (Clark and Pitt, 1999; Bratieres et al., 2012).

Using the selected materials, 95 experimental columns of 150 mm diameter were constructed. The ratio of experimental column diameter to filter particle diameter was more than 50, as recommended for filtration studies (Lang et al., 1993). Table 1 and Fig. 3 show the characteristics of the experimental column design wherein 300 mm of filter material was placed between a 50 mm layer of coarse gravel at the top (that protected the filter from the energy of water applied) and a 50 mm gravel layer at the bottom that prevented migration of the media out of the filter. A