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Research article

A novel test method to determine the filter material service life of decentralized systems treating runoff from traffic areas

Maximilian Huber [a], Antje Welker [b], Martina Dierschke [b], Jörg E. Drewes [a], Brigitte Helmreich [a, *]

[a] Chair of Urban Water Systems Engineering, Technical University of Munich, Am Coulombwall 3, 85748 Garching, Germany
[b] Fachgebiet Siedlungswasserwirtschaft und Hydromechanik, Frankfurt University of Applied Sciences, Nibelungenplatz 1, 60318 Frankfurt am Main, Germany

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ABSTRACT

In recent years, there has been a significant increase in the development and application of technical decentralized filter systems for the treatment of runoff from traffic areas. However, there are still many uncertainties regarding the service life and the performance of filter materials that are employed in decentralized treatment systems. These filter media are designed to prevent the transport of pollutants into the environment. A novel pilot-scale test method was developed to determine – within a few days – the service lives and long-term removal efficiencies for dissolved heavy metals in stormwater treatment systems. The proposed method consists of several steps including preloading the filter media in a pilot-scale model with copper and zinc by a load of n-1 years of the estimated service life (n). Subsequently, three representative rain events are simulated to evaluate the long-term performance by dissolved copper and zinc during the last year of application. The presented results, which verified the applicability of this method, were obtained for three filter channel systems and six filter shaft systems. The performance of the evaluated systems varied largely for both tested heavy metals and during all three simulated rain events. A validation of the pilot-scale assessment method with field measurements was also performed for two systems. Findings of this study suggest that this novel method does provide a standardized and accurate estimation of service intervals of decentralized treatment systems employing various filter materials. The method also provides regulatory authorities, designers, and operators with an objective basis for performance assessment and supports stormwater managers to make decisions for the installation of such decentralized treatment systems.

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1. Introduction

Parameters commonly monitored in runoff from traffic areas include organic substances, heavy metals, and compounds of deicing salts (Eriksson et al., 2007; Folkeson et al., 2009; Fraga et al., 2016). Heavy metals such as cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), and zinc (Zn) are highly relevant pollutants because of their toxicity, non-degradability, and their increasing presence in the environment as a consequence of their widespread industrial use (Roeva et al., 1996; Tiefenthaler et al., 2001). Among these heavy metals, Cu, Pb, and Zn commonly occur in highest concentrations in runoff from highways and other traffic areas (Kayhanian et al., 2012; Revitt et al., 2014; Huber et al., 2016a). However, Pb concentrations have decreased significantly in traffic area runoff in the last few decades because of the phase-out of leaded gasoline and the substitution of Pb in other traffic-related sources (Kayhanian, 2012; Huber et al., 2016a). In addition, Pb occurs mostly particle-bound, while Cu and Zn are usually more present in the dissolved phase (Timperley et al., 2005; Wilson, 2006; Kayhanian et al., 2007). Helmreich et al. (2010) concluded that the fractionation of these heavy metals is not affected by seasonal variations but remarkable fluctuations can occur between different rain events with dissolved fractions higher than 90%. Therefore, Cu and Zn are relevant dissolved substances in runoff from traffic areas during all seasons because of their total concentrations, fractionation behavior, and toxicity.

To retain these heavy metals from traffic area runoff, decentralized stormwater treatment systems are used, which can be

* Corresponding author.
E-mail address: b.helmreich@tum.de (B. Helmreich).

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designed as an integral part of existing urban infrastructure for stormwater management and rainwater harvesting (Scholes et al., 2008; Inamdar et al., 2013; Scholz, 2015). In a first step of these treatment systems, sedimentation and filtration are the predominant retention mechanisms used to remove particle-bound substances. Subsequently, dissolved heavy metals are retained on filter materials by sorption, ion exchange, or precipitation (Liu et al., 2005). Thus, a second treatment step with a filter material is necessary to reduce the total concentrations of all metals (Hilliges et al., 2013; Maniquiz-Redillas and Kim, 2014). In recent years, various technical decentralized stormwater treatment systems have been developed to treat the runoff of traffic areas when space is limited (Sample et al., 2012; Dierkes et al., 2015a). Three categories of these urban drainage systems are: permeable pavement, filter channel system (FCS), and filter shaft system (FSS). These systems are commonly used as conforming products in order to treat stormwater runoff at the source before it infiltrates into the subsurface or is discharged to surface water. Permeable pavements are similar to those of traditional concrete block pavements. They are specifically designed for infiltration of stormwater through the pores of the pavers and/or the joints between the pavers, which are filled with filter media to retain pollutants, into the various pavement layers and subsequently into the soil (Dierkes et al., 2015a). A FCS consists of a typical drainage channel (concrete or polypropylene) that is filled by filter materials (mixture, layers, or only one material). Each FCS has a specific retention volume between the grate and the filter media and the stormwater runoff percolates (down-flow mode) through the filter media and the treated water is subsequently drained by holes in the bottom of the channel or by a pipe. The pollutants are retained by sedimentation on top of the filter and within the filter media by filtration and (bio-)chemical processes. Some FCS have a sedimentation box/trap (polypropylene or steel) ahead of the filter. FSS usually consist of a sedimentation unit and a subsequent filter, which is integrated either into the system or in another shaft (concrete or polypropylene). The stormwater can be treated by the filter vertically in both up-flow and down-flow mode, or in a radial direction. Some FSS are permanently submerged and others run dry after each rainfall event (Dierkes et al., 2015a). In Germany, the Deutsches Institut für Bautechnik (DIBt, German Center of Competence for Construction) can approve these decentralized systems for the infiltration of runoff from traffic areas after performing several tests (e.g., removal of fine particles, total petroleum hydrocarbons, and heavy metals; remobilization of Cu and Zn under application of sodium chloride) (DIBt, 2012; DIBt, 2015). In the United States, several methods have been developed to test decentralized systems. In the State of Washington, the Technology Assessment Protocol-Ecology (TAPE) of the Washington State Department of Ecology is used to evaluate and classify decentralized stormwater treatment systems by lab- and field-scale experiments (e.g., removal of total suspended solids, Cu, Zn, phosphor, and petroleum hydrocarbons) (Department of Ecology (2011)). In New Jersey, a procedure for obtaining verifications of stormwater treatment systems was implemented by the New Jersey Department of Environmental Protection to assess the removal of total suspended solids in the laboratory (NJDEP, 2013). As an amendment to the TARP (Technology Acceptance Reciprocity Partnership) Protocol, a field testing for the removal of total suspended solids can also be performed for final certification (NJDEP, 2009). However, there is no standardized method available to quickly determine the filter material service life of decentralized stormwater treatment systems.

In general, two factors influence the determination of the service life of decentralized systems treating runoff from traffic areas:

- The service interval is limited because of a hydraulic failure of the plant (i.e., clogging of the filter material because of sediment accumulation and deposition) (Mercado et al., 2015). This is often related to an increased solids load in combination with site-specific factors that enhance clogging (e.g., mineral substances such as grit and construction site dust, or organic loads of pollen and leaf litter) (CH2MHILL, 1998).
- The service life is limited because of the substance removal efficiency (i.e., a reduced retention of substances). In most cases, the capacity of the filter material for heavy metal removal is exhausted.

Clogging phenomena of the filter material can be simulated in the laboratory by using a full-scale system but realistic particle size distributions and site-specific factors of the system's catchment area cannot be considered. Therefore, this factor needs to be determined by extensive and comparable field measurements that might take several years. The terminal service life of the filter material (e.g., breakthrough of heavy metals) is rarely noticeable by the operator although this has a crucial effect on the receiving water. However, this effect can be simulated reproducibly at pilot-scale for decentralized systems. Nevertheless, a standardized test method for the determination of the service life and long-term performance of different types of filter systems is currently not published by other researchers. This lack regards the complete procedure (e.g., input parameters such as estimated service lives and metal loads, rainfall events, breaks, and effluent requirements) and the performing of an experimental study.

Since the treatment of traffic area runoff is a serious issue, the evaluation of decentralized filter systems for the removal of heavy metals is very important. An appropriate experimental setup is necessary to evaluate the removal of dissolved substances as the use of filter systems for stormwater treatment is increasing worldwide and keeping track of the filter usability and performance is currently a difficult task because of the multitude of manufacturers of filter systems. Such a method is also needed because, depending on the type of the system, field experience of 5–20 years is often missing for existing systems. Because of the missing experience and information concerning their long-term performance and service lives, it is currently difficult to guarantee a sustainable and cost efficient stormwater management by decentralized systems. The determination of the service life is also essential for a sustainable management of urban infrastructure because maintenance and the exchange of filter material have an effect on life-cycle costs of decentralized treatment systems (O'Sullivan et al., 2015). In addition, the benefit of using a novel method, which must consist of several well defined steps that represent the real conditions realistically, for testing new product developments and existing decentralized systems must also be based on a rapid performance assessment within a few days for toxic dissolved substances.

The hypothesis of this study is that a novel test method can be developed and implemented to evaluate the long-term performance of new and already operational decentralized systems. This novel assessment method can provide a simulation of the service lives of the filter materials and their long-term performances within a few days prior to field applications. The objectives of this study are the development of a pilot-scale test method, the evaluation of nine channel and shaft systems to determine their service lives and efficiencies to remove dissolved heavy metals, validation of results, and the delivery of stormwater treatment guidelines of authorities for the assessment of heavy metal retention

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