



Review

A unified look at phosphorus treatment using bioretention

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ARTICLE INFO

Article history:

Received 21 September 2015

Received in revised form

4 December 2015

Accepted 11 December 2015

Available online 15 December 2015

Keywords:

Stormwater management

Bioretention

Phosphorus

Mechanism

Model

Adsorption

Leaching

Water treatment residual

ABSTRACT

Phosphorus (P) is a water pollutant of significant concern as it limits the productivity of most freshwater systems, which can undergo eutrophication under heavy phosphorus inputs. Bioretention has shown great potential for stormwater quantity and quality control. However, phosphorus removal has been inconsistent in bioretention systems, with phosphorus leaching observed in some systems. This paper examines P removal mechanisms and performance in bioretention systems through published data. A temporal concept of P fate for different time-scales is proposed. A model is developed to predict effluent P concentrations (C_e) based on a media equilibrium concentration (C_{eq}) assumption, which is suitable for both short and long-term simulation. C_{eq} is well correlated with C_e for P data for different time-scales. C_{eq} varies less in media containing Al and Fe than in typical bioretention soil media. Although significant change in C_{eq} may occur during an event and long-term, C_{eq} variation in short-term is small. During the event and short terms, for high-P containing media, the concentration relationship is $C_{eq} > C_e > C_0$ (influent P concentrations); for low-P containing media, $C_{eq} < C_e < C_0$. During long-term, as media equilibrates with the influent runoff, $C_{eq} \approx C_e \approx C_0$. The model explains concentration changes of P with depth. With proper selection of media and amendments, C_{eq} can be driven towards zero for P in bioretention media.

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1. Introduction

With population growth and relocation, conversion of open land to urban infrastructure continues. Concomitant increases in impervious area drive the need to manage runoff volumes and compromised water quality derived from these surfaces. Increasingly, filtration/infiltration stormwater control measures (SCMs) such as bioretention are being employed to address urban stormwater challenges.

Phosphorus (P) is of particular interest in urban runoff because of the major concern for elevated levels of P in many natural waterways. Along with nitrogen, excessive P concentrations will promote eutrophication and the associated detrimental environmental impacts. To control eutrophication, the USEPA recommends a limit of 0.05 mg/L for total-P in streams that enter lakes and 0.1 mg/L in flowing waters (USEPA, 1986).

P treatment via bioretention has been shown to be highly variable. In a number of cases, effluent concentrations higher than influent concentrations have been reported (Dietz and Clausen, 2005, 2006; Hunt et al., 2006; Sharkey, 2006; TRCA, 2008; Li and Davis, 2009; Brown and Hunt, 2011a; Herrera Environmental Consultants, Inc, 2012; Palmer et al., 2013). In other studies, P concentration reductions have been found (Davis, 2007; Hunt et al., 2008; Brown et al., 2009; Passeport et al., 2009; Brown and Hunt, 2011b; Komlos and Traver, 2012; Liu and Davis, 2014). Additionally, the relative scatter of phosphorus monitoring data from several field-scale bioretention facilities has been reported (McNett et al., 2011). No discernable trend between input and output P concentrations (as EMCs, event mean concentrations) is apparent and simple regression models could not provide any acceptable description of the data.

P in urban runoff is distributed between dissolved forms (generally organic P and phosphate species) and P affiliated with particulate matter. Bioretention removal mechanisms will differ for each. Particulate P is generally well-removed via filtration mechanisms in bioretention systems, similar to particulate matter (Li and Davis, 2008a, 2008b, 2009; Liu and Davis, 2014). Although vegetative uptake and microbial immobilization are important, the critical dissolved P removal mechanism for bioretention is adsorption onto the media during transport through the media (Lucas and Greenway, 2008, 2011). Therefore, media selection and characteristics will play critical roles in the performance of bioretention SCMs in P management (Erickson et al., 2007; Lucas and Greenway, 2011; O'Neill and Davis, 2012a, 2012b). P uptake via adsorption will be controlled by the adsorption capacity of the media and the previous exposure history of the media to the adsorbate. With the accumulation and eventual saturation of P in the media, the media should gradually demonstrate P adsorption breakthrough and exhaustion.

Bioretention media generally consist of a mix of sand, topsoil, and an organic component (mulch, compost, peat, etc.). Each of these components will have an inherent background amount of P affiliated with it. This P may be held via an adsorption process, or likely in the case of the organic component, bound as inorganic or

organic P that can be released over time due to weathering and mineralization processes. Because of this background P, the bioretention media should not be thought of as a pristine treatment device that will have a large capacity for P uptake from urban runoff. A vast literature on P and soils is available, evaluating P leaching from soils, and soil parameters that control P sorption capacity. The use of amendments has been found to enhance the P sorption capacity, especially when the soils are exposed to readily available sources of supplemental P, such as manure and biosolids (Palmer et al., 2013). These studies indicate that soils have a very large range of P capacities and leaching capabilities.

The ability of a soil to sorb a significant amount of P can be related to the amorphous iron oxide + aluminum oxide contents ($(\text{Fe} + \text{Al})_{\text{am}}$) (Zhang et al., 2001; Bortoluzzi et al., 2015). The higher the $(\text{Fe} + \text{Al})_{\text{am}}$, the greater the capacity of the soil for P sorption. $(\text{Fe} + \text{Al})_{\text{am}}$ and previous exposure to P can be estimated with various leaching tests to evaluate P release. The oxalate ratio (OR) has been adopted as a measure of P adsorption/leaching potential. OR is the ratio between oxalate-extractable aluminum and iron content ($\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}}$, mmol/kg) and oxalate-extractable P (P_{ox} , mmol/kg). Following this logic, many studies have shown that amending soils with $(\text{Fe} + \text{Al})_{\text{am}}$ can lead to greater P sorption capacity of the soil and corresponding reduced leaching of P. The reciprocal of the OR is defined as the Phosphorus Saturation Index, PSI. Sources of $(\text{Fe} + \text{Al})_{\text{am}}$ have included iron (i.e., shavings and steel wool), water treatment residuals, and fly ash; these materials have been employed as amendments for enhanced removal of P from urban stormwater runoff in bioretention (Zhang et al., 2008; Lucas and Greenway, 2011; O'Neill and Davis, 2012a, 2012b) and other SCMs (Drizo, 2007; Erickson et al., 2007).

Because of the complexity of P fates in bioretention and its importance as a water quality parameter, a fundamental understanding of P treatment in bioretention (and related SCMs) is needed. The objectives of this work are: (i) To fundamentally examine the removal of P via bioretention as an urban SCM. Scientific linkages will be examined between bioretention media, P chemistry and P speciation, and behavior in urban stormwater. A simple mechanistic model is developed to describe the filtration of particulate P and the removal of dissolved P via adsorption onto bioretention media during the filtration/infiltration process. This model should also be applicable to sand filters and similar SCMs and to other adsorbing pollutants. The model will be used with published data on bioretention P performance to critically evaluate the mechanisms of P uptake and removal; (ii) To define and clarify the variation of P discharges and "equilibrium" concentrations during different time scales in different bioretention media; (iii) To quantify the influence of bioretention media depth on P removal and design optimization; and (iv) To offer recommendations for effective P removal in bioretention.

2. Background, fundamentals, and previous research

Urban stormwater total P concentrations based on NPDES data show a mean of 0.3 mg/L, with 10 and 90 percentiles of 0.03 and

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