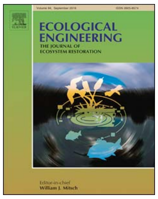
Ecological Engineering 112 (2018) 116–131

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Effects of different soil media, vegetation, and hydrologic treatments on nutrient and sediment removal in roadside bioretention systems

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ARTICLE INFO

Keywords:
Bioretention
Urban road runoff
Sediment
Nitrogen
Phosphorus
Stormwater management

ABSTRACT

Water quality performance of eight roadside bioretention cells in their third and fourth years of implementation were evaluated in Burlington, Vermont. Bioretention cells received varying treatments: (1) vegetation with high-diversity (7 species) and low-diversity plant mix (2 species); (2) proprietary SorbtiveMedia™ (SM) containing iron and aluminum oxide granules to enhance sorption capacity for phosphorus; and (3) enhanced rainfall and runoff (RR) to certain cells (including one with SM treatment) at three levels (15%, 20%, 60% more than their control counterparts), mimicking anticipated precipitation increases associated with climate change. A total of 121 storms across all cells were evaluated in 2015 and 2016 for total suspended solids (TSS), nitrate/nitrite-nitrogen (NO_x), ortho-phosphorus (Ortho-P), total nitrogen (TN) and total phosphorus (TP). Heavy metals were also measured for a few storms, but in 2014 and 2015 only. Simultaneous measurements of flow rates and volumes allowed for evaluation of the cells' hydraulic performances and estimation of pollutant load removal efficiencies and EMC reductions. Significant average reductions in effluent stormwater volumes (75%; range: 48–96%) and peak flows (91%; range: 86–96%) was reported, with 31% of the storms events (all less than 25.4 mm (1 in.), and one 39.4 mm (1.55 in.)) depth completely captured by bioretention cells. Influent TSS concentrations and event mean concentrations (EMCs) was mostly significantly reduced, and TSS loads were well retained by all bioretention cells (94%; range: 89–99%) irrespective of treatments, storm characteristics or seasonality. In contrast, nutrient removal was treatment-dependent, where the SM treatments consistently removed P concentrations, loads and EMCs, and sometimes N as well. The vegetation and RR treatments mostly exported nutrients to the effluent for those three metrics with varying significance. We attribute observed nutrient exports to the presence of excess compost in the soil media. Rainfall depth and peak inflow rate had consistently negative effects on all nutrient removal efficiencies from the bioretention cells likely by increasing pollutant mobilization. Seasonality followed by soil media presence, and antecedent dry period were other predictors significantly influencing removal efficiencies for some nutrient types. Results from the analysis will be useful to make bioretention designers aware of the hydrologic and other design factors that will be the most critical to the performance of the bioretention systems in response to interactive effects of climate change.

1. Introduction

Urban waters are widely impaired by excess nutrients and sediments in the input stormwater, despite substantial efforts spent in stormwater management and control in the surrounding watersheds (Hobbie et al., 2017). Urban stormwater is a major contributor to nonpoint source pollution in surface waters nationwide. As diffused nonpoint source pollution is much more difficult to regulate than point source pollution, stormwater is considered one of the most pressing water quality challenges of today (Wang et al., 2000; Hsieh and Davis, 2005; NRC, 2008). Among many pollutants of concern, those commonly detected in urban storm runoff are nutrients (nitrogen; N and phosphorus; P), which are major culprits of eutrophication nationwide (Erickson et al., 2013), suspended solids, heavy metals, and organics (Porcella and Sorensen, 1980).

As cities are expanding rapidly, proliferating the impervious footprint, natural hydrological flow paths resulting in absorption, filtering and treatment of stormwater through soils is bypassed (Cook, 2007). During high flow events, urban storm infrastructures can show failure, leading to harmful combined sewer-storm-water overflows, contaminating surface waters by nutrients and pathogens (Kaye et al., 2006) intended to be kept out of those very waters. Thus, newer

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https://doi.org/10.1016/j.ecoleng.2017.12.004
Received 22 August 2017; Accepted 5 December 2017

strategies to address urban stormwater management are becoming increasingly necessary to improve surface water quality. Low impact development (LID) approach was therefore introduced in the 1990s in Prince George's County, Maryland as an alternative to conventional stormwater management approach (LID Center, 2007). LID, more broadly termed Green Stormwater Infrastructure (GSI), comprises landscape design strategies that promote infiltration, filtration, soil storage, evapotranspiration, groundwater recharge and/or re-use of stormwater, while minimizing impervious cover and runoff (Davis, 2007; Roy et al., 2008; County, 1999; Hinman 2012).

Bioretention, a prominent type of green infrastructure, is increasingly being used as a sustainable stormwater control measure in urbanized watersheds within the U.S. and abroad (Davis et al., 2009; Roy-Poirier et al., 2010; Liao et al., 2017). The technology is an aesthetically pleasing, sunken (approx. < 1.3 m deep) planted basin filled with porous media that intercepts, filters, stores, and treats pollutant-laden runoff conveyed as sheet flow from impervious surfaces (Cook, 2007). Bioretention design allows for stormwater runoff to be treated for water quality on-site, close to the source of origination (Hurley and Forman, 2011), via different physical (filtration, evaporation), chemical (sorption, ion exchange, precipitation), and biological (phytoremediation, microbial-mediated transformation, transpiration) mechanisms, facilitated by the filter media (Davis, 2007; Feng et al., 2012; Liu et al., 2014; Lucas and Greenway, 2007). Runoff is also detained and stored temporarily in the bioretention media, and aboveground in the ponding zone, and is released slowly to the surrounding soil via infiltration or an existing storm sewer system. Integrating bioretention systems throughout urban spaces (most commonly in roadsides, parking lots, and streets) offer more opportunities to restore natural hydrologic functions. Bioretention's storage of stormwater in the landscape can alleviate pressure on existing storm infrastructure by decreasing storm flow velocities, and reducing peak discharge and downstream erosion and flooding. Furthermore, ancillary benefits from bioretention include wildlife and pollinator habitat, and enhanced urban biodiversity, and aesthetics (County, 1999).

A growing body of literature has shown that bioretention systems are effective water quality treatment devices with good removal capacities for total suspended solids (Hsieh and Davis, 2005; Bratieres et al., 2008; Hatt et al., 2009a), heavy metals (Davis et al., 2003, 2001; Hunt et al., 2006), fecal coliform (Hunt et al., 2008; Passeport et al., 2009), hydrocarbons and oil and grease (Hong et al., 2006). However, nutrient removal performance (specifically for N and P) is more variable (Davis, 2007). Field studies have shown successful removal of ammonium (NH_4^+) and Total Kjeldahl Nitrogen (TKN) from runoff (Davis et al., 2003; Birch et al., 2006; Dietz and Clausen, 2006; Hunt et al., 2006; Hatt et al., 2009b; Passeport et al., 2009), but removal of nitrate + nitrite (NO_x), total nitrogen (TN), total phosphorus (TP), and ortho-P have been shown in both lab and field studies to be highly variable, and sometimes negative removals (or exports) of these nutrient forms have been reported (Davis et al., 2001; Hsieh and Davis, 2005; Birch et al., 2006; Davis et al., 2006; Dietz and Clausen, 2006; Hunt et al., 2006; Van Seters et al., 2006; Bratieres et al., 2008; Hatt et al., 2009b; Passeport et al., 2009).

This research evaluates water quality performances of seven roadside bioretention cells receiving different vegetation, soil media, and hydrologic (enhanced rainfall + runoff (RR)) treatments in Burlington, Vermont in the northeastern USA. The experimental design and its treatment variables were informed particularly by concerns regarding the elevated levels of P in the Lake Champlain Basin attributed to watershed inputs and internal cycling of phosphorus (P) from lake sediment bottoms, which causes algal and toxic cyanobacterial blooms in the summer. The hydrologic treatment is informed by climate change projections associated with frequent and intense rainfall events for Vermont and other Northeastern states (Frumhoff et al., 2006; Pealer, 2012). Average daily precipitation is projected to increase between 5 and 10% (10% being an increase of 4 inches yr^{-1}) by midcentury (Hayhoe et al., 2007; Guilbert et al., 2014), and extreme precipitation events (amount of precipitation that falls over five consecutive days) are also likely to progressively increase over the century, i.e., 8% by mid-century, and 12–13% by late century (Frumhoff et al., 2006).

Field studies such as the following are valuable as there is insufficient number of field-performance data in the bioretention literature. Bioretention performance needs to be robust and responsive to various physical site conditions/constraints, variability in storm sizes, volumes and pollutant levels, plant survival, and non-steady environmental conditions. Monitoring results from our study will be important to understand how small-scale bioretention retrofits implemented under constrained field conditions can provide stormwater controls, and how their performance may vary based on different design attributes, hydrologic conditions, and other environmental factors.

The specific objectives of the study were:

1) to characterize the composition of N and P species in bioretention inflows and outflows in a roadside field study;
2) to characterize (A) stormwater volume and (B) pollutant retention capacities of bioretention cells across various storm sizes;
3) to evaluate and compare bioretention cells (A) hydraulic performances, (B) pollutant mass removal efficiencies (MRE), and (B) event mean concentrations (EMCs) among vegetation, soil media, and hydrologic treatments; and
4) to investigate whether environmental factors (precipitation depth, antecedent dry period (ADP), seasonality), hydrological factors (inflow volumes, inflow mass, peak flow, hydraulic loading ratio), and treatments (vegetation, soil media, hydrologic), are significant predictors of pollutant mass removal efficiencies.

2. Methods

2.1. Study site description

The study site consists of eight bioretention cells (Fig. 1) located on both sides of a medium-traffic campus roadway at University of Vermont (Burlington, USA). Monitoring of the bioretention cells was carried out from May to November in the years 2015 and 2016. The cells were constructed in November 2012 (Cording et al., 2017). Vegetation was planted in May 2013 and was well established by the time this study commenced in Spring 2015. Table 1 describes the design parameters of the bioretention cells. Each cell collects stormwater runoff from road watersheds of varying sizes (30–120 m^2). Curb cuts along the road route the runoff to a shallow rock-lined swale, which then directs it to each bioretention cell's "inflow" where water samples are collected. The cells are rectangular with identical size (1.22 m wide by 3.05 m long by 0.91 m deep) and drainage configurations. From top to bottom, the bioretention soil media is layered with two layers each 30.5 cm deep: the upper layer is a 60:40 sand compost mix (compost derived from cow manure, food scraps, and wood shavings); below is a pure sand layer (Fig. 2a). Below the sand media is a 7.6 cm-layer of pea stone, and the bottom 23 cm of the cell is occupied by 5-cm diameter stones or gravel. Two of the cells contain a soil additive treatment, where the bottom 7.6 cm of the pure sand layer is replaced by SortiveMedia™ (SM; Fig. 2b), described later in detail. The entire cell (sides and bottom) is lined using an impermeable ethylene propylene diene monomer (EPDM) liner to isolate the cell and prevent water exchange with the underlying native soil and cross contamination of the water quality. The liner also accounts for all the water volume and pollutant loads for mass balance calculations. The bioretention cells are drained using an underdrain pipe at one end of the cell, a 26-cm long, 15.24 cm-diameter perforated PVC pipe that is placed 2.5 cm from the bottom of the cell within the gravel layer. The underdrain is connected to a solid PVC pipe outside the soil media where the effluent is sampled for water quality analysis. The pipes are connected to the existing storm sewer system. Additional details about construction of the bioretention cells