Evaluation of a parking lot bioretention cell for removal of stormwater pollutants

C. Glass & S. Bissouma
Department of Civil Engineering, Howard University, Washington D.C., U.S.A.

Abstract

Bioretention is used to retain and treat urban stormwater, which has been identified by the United States Environmental Protection Agency as one of the most significant forms of water pollution. In this study, the efficiency of a bioretention facility in terms of temperature, pH, dissolved oxygen, nutrients, and heavy metals removal over a period of 15 rain events was evaluated. This was performed by collecting representative samples of the stormwater runoff for laboratory analysis of both the influent to and the effluent from the bioretention cell. The bioretention was efficient in terms of pollutant removal in the following order: TSS (~ 98%) > Zn (~ 80%) > Cu (~ 75%) > Pb (~ 71%) > Cd (~ 70%) > NH$_3$-N (~65%) > Fe (~ 51%) > Cr (~ 42%) > NO$_2$-N (~ 27%) > Al (~ 17%) > PO$_4$-P (~3%). From the field results Cu (II), Zn (II) and Pb (II) were removed significantly at 81%, 79% and 75%. The field results indicate that bioretention facilities can be effective for the removal of heavy metals in the following order: Cu > Zn > Pb > Cd > Fe > Cr > Al. Although the removal efficiency for this actual field bioretention cell was not as high as previously reported laboratory and field evaluations, removal of pollutants was significant. Organic matter and plants were believed to be the dominant bioretention elements for the removal of heavy metals.

Keywords: bioretention, stormwater, heavy metals, adsorption.

1 Introduction

Combined sewer overflows (CSO) continue to occur throughout major cities in the Northeast, Great Lakes, and Northwest regions of the U.S., primarily as a result of rainwater that is diverted from roads, parking lots, and the roofs of buildings during storm events [1]. The rapid transport of water away from the
built environment to natural water bodies has dominated engineering for the past 130 years, since the recognition that pathogens in wastewater caused several human diseases. In older cities with combined sewers the continued replacement of natural surfaces with impervious ones leads to greater amounts of stormwater runoff. The contamination of natural water bodies leads to the destruction of habitat potentially leading to negative human health impacts (Griesel and Jagals [2]). Developing best management practices to prevent rain water contamination, remove pollutants before the runoff enters the combined sewer system, and retain or detain the movement of water in a decentralized fashion can potentially mitigate CSO events.

Urbanization creates impervious surfaces such as roads, sidewalks, highways, rooftops, and parking lots that result in an increase of stormwater runoff at the expense of infiltration. The stormwater runoff quickly flows over those impermeable surfaces and accumulates toxic pollutants such as heavy metals [3, 4, 5] generated by automobile use, weathering of building materials and atmospheric deposition (Davis et al [6]). A nationwide U.S. urban study showed that heavy metals were by far the most prevalent pollutant constituents of urban stormwater runoff (Cole et al [7]). Due to its toxic content, the storm water runoff when discharged to a stream, severely impacts the quality of natural water systems by causing a threat to aquatic life and human health, and also flooding and erosion. As a result, urban stormwater runoff has been identified as one of the most significant water pollution problems in the United States (Wiginton et al [8]).

To address the problem of surface water pollution from urban stormwater runoff, a number of engineered and managed natural systems have evolved and are being offered as “best management practices” (BMPs) for low impact development. They are part of the United States Environmental Protection Agency’s (USEPA) effort to regulate the release of pollutants into natural aquatic environments through water quality standards set forth by the National Pollutant Discharge Elimination System (NPDES). A stormwater BMP is a device, practice, or method used to remove, reduce, retard, or prevent targeted stormwater runoff pollutants from reaching receiving waters in the most cost-effective manner.

In the early 1990s, Prince George’s County, Maryland began developing and promoting a natural-based stormwater BMP system known as bioretention (or rain garden) [9]. Bioretention is a simple but effective way to improve the quality of stormwater runoff from developed areas such as parking lots, in order to minimize surface water impacts. Bioretention is a porous sand/soil media, supporting a vegetative layer, with a topping layer of hardwood mulch. Water quality enhancement occurs through the bioretention facility via biological, chemical and physical processes including phytoremediation, precipitation, adsorption, complexation, microbial activity, decomposition, sedimentation, filtration, and volatilization. In urban environments these systems are typically designed by filling a concrete box with gravel, sand, planting soil, a top layer of mulch, and various species of water loving plants. Currently little is known with regard to the field performance of bioretention cells. Few researchers have
evaluated the performance of best management practices with actual stormwater runoff (Davis et al. [10]).

The objective of this study was to evaluate the efficiency of a bioretention facility located at a parking lot of the Navy Yard, Washington, DC in terms of stormwater pollutants, with an emphasis on heavy metal removal due to their toxicity. Representative samples of the “first-flush” of stormwater runoff were collected at the inlet and outlet points of the bioretention cell and transported directly to the laboratory for analysis. Heavy metals were of particular concern due to their toxicity, possible accumulation in the bioretention facility, long-term fate, and persistence. Data was collected on the amount of rainfall and concentrations of heavy metals present in the influent and effluent runoff.

2 Materials and methods

Samples were collected from March 21, 2003 to June 20, 2003 (15 storm events), in accordance with the procedures outlined in Standard Methods for the Examination of Water and Wastewater, 20th Edition, section 1060 [11]. To monitor water quality and assess the efficiency of this bioretention facility to remove pollutants, composite samples were collected at the inlet and outlet points using two automatic samplers (3710 compact composite sampler, ISCO, Inc., NE), placed in protective shelters, and a rain gauge (674 rain gauge, ISCO, Inc., NE), placed on top of the inlet protective equipment shelter (Figure 1). The rain gauge initiates monitoring activity when there is a sufficient amount of rainfall.

At the inlet point, the sampler periodically collected the samples from the inflow stream into a collector plastic box placed at the end of the paved surface entrance. The sampler controller was programmed to initiate each collection sequence and to regulate the amount collected. The sequential composite samples were collected after a set volume of stormwater (volume needed to do the laboratory analysis, approximately 1.5 L) passed the monitoring point and by using continuous, constant sample pumping. The rain gauge’s rain collecting mechanism is triggered when the amount of rainfall reaches approximately 0.5 inches over 6 hours. At this point, a signal is then sent to the sampler.

The interest of the stormwater sampling at this site was to collect “first-flush” samples, typically during the first 30 minutes of a storm event. At the outlet point, depending on the intensity and the duration of the rain and also due to time the water takes to be infiltrated through the media (approximately 12 to 48 hours), the samples were collected by a manual activation of the sampler. No effluent was collected from the fifth storm event because of the low volume of the storm and the dry period that preceded it. During the eleventh storm event the collection device was tampered with resulting in no data collection for the influent.

2.1 Site characterization

The field site in this study was a 30-acre paved parking lot located at the Navy Yard, Washington, DC. Engineers of the Water Quality Division, D.C.
Department of Health, and experts at the Low Impact Development Center, MD, along with the authors selected this site because of its convenient location and its affinity to the monitoring equipment.

![30-acre parking lot (Navy Yard, Wash., D.C.).](image_url)

Figure 1: Bioretention cell.

The field study was conducted at a facility designed and constructed in 2001 by the Low Impact Development Center, MD. This facility is a 292-square-foot bioretention cell (Figure 1), part of a 0.27-acre watershed (area of the parking lot that drains along the stream to the outlet point). Curb cuts were placed around the cell to direct the stormwater runoff into the facility at the inlet entrance.

The bioretention media is a mixture of construction sand (50%), rocks and topsoil (30%) (with a modified clay content (~10%) and organic content (~20%)) hardwood mulch and plants (20%). The facility surface is dominated by approximately 6 cm of mulch, some selected plants such as *cephlantus occidentalis* and *aronia arbutifolia red chokeberry* and a few shrubs. A 6-inch (inside diameter) perforated PVC pipe, located at a depth of 30 inches, collected the infiltrated runoff. The outlet of this pipe opens into a 24-inch manhole, which feeds into a 12-inch storm sewer pipe. The outlet consisted of a concrete box with a rectangular opening in the side, set as an overflow for a water level exceeding the design ponding depth, with access to the effluent through a manhole cover.
2.2 Analytical methodology

Prior to metals analysis, the stored samples were filtered through 0.2 µm non-sterile syringe filters (Millipore millex, Fisher Scientific, Pittsburgh, PA) and placed into 2 mL plastic vials (Perkin-Elmer Corporation, Norwalk, CT). Heavy metal analysis was performed using an atomic absorption spectrometer (AAS) via the furnace module (800A Analyst, Perkin-Elmer Corporation, Norwalk, CT) following Standard Methods [11]. The collected filtrates were analyzed for the following dissolved heavy metals: Al, Cd, Cr, Cu, Fe, As, Pb, and Zn. Quality assurance and quality control procedures included triplicate and spiked samples for accuracy and confidence measurement.

Ammonia was analyzed using an ammonium selective electrode (Thermo Orion model 9318, Beverly, MA) with a detection limit of 0.07 mg/L NH₃, using a detection meter (Thermo Orion Model 920 A+). Nitrate, nitrite, and phosphate concentrations were determined using an ion chromatograph (Dionex, Model DX-120) equipped with a guard column (AG-14A) and separation column (AS-14A). Temperature and pH were determined using a portable dissolved oxygen meter with a thermocouple (Oakton, DO 100 Series 35640). Total Suspended Solids were determined following Standard Methods [11]. pH was measured using an Accumet pH probe and Accumet Research meter (AR20 pH/conductivity meter, Fisher Scientific).

Figure 2: Dissolved oxygen concentration for 15 storm events.
3 Results

This field study was conducted in order to evaluate the efficiency of the Navy Yard bioretention in terms of dissolved oxygen, temperature, pH, and heavy metals removal. In Figure 2 the dissolved oxygen concentration of influent and effluent to and from the bioretention are presented. Given the low temperature of the rain events 4-6, that marked the end of winter, the dissolved oxygen concentration was supersaturated leading to high dissolved oxygen concentrations. Even at supersaturated concentrations, the dissolved oxygen concentration was higher as the stormwater left the bioretention cell for all of the storm events.

The pH of rain water, influent, and effluent stormwater are presented in Figure 3. In Figure 3 the slightly acidic nature of rainfall in the Washington D.C. area can be seen with an average pH of 5.4 ± 0.2. The area of this study is known to have acid rain with a pH range as low as 4.2-4.4 [12]. Nevertheless the pH of the rain water increased as it created runoff into the system with an average pH of 7.5 ± 0.5 and did not significantly change as the stormwater passed through the system resulting in an effluent pH of 7.4 ± 0.4.

![Figure 3: pH of rain water, influent and effluent.](image)

3.1 Heavy metals removal

The summary of results for the average concentrations of heavy metals in the influent and effluent are presented in the Table 1. In addition, in Table 1 the drinking water maximum contaminant level required by the USEPA is listed as a...
reference for which parameter exceeded this regulated value. In this study only lead and cadmium concentrations in the influent exceeded the drinking water standard for these parameters. Nevertheless, the effluent metal concentrations were observed to be below the influent concentrations for all of the heavy metals displaying the successful adsorption of these compounds in the bioretention cell.

Table 1: Summary of heavy metal concentrations.

<table>
<thead>
<tr>
<th></th>
<th>Cu (µg/L)</th>
<th>Cd (µg/L)</th>
<th>Zn (µg/L)</th>
<th>Cr (µg/L)</th>
<th>Pb (µg/L)</th>
<th>Al (µg/L)</th>
<th>As (µg/L)</th>
<th>Fe (µg/L)</th>
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<tr>
<td>Cin</td>
<td>56.8</td>
<td>5.6</td>
<td>98.3</td>
<td>7.6</td>
<td>41.4</td>
<td>3.5</td>
<td>2</td>
<td>26.8</td>
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<tr>
<td>Cef</td>
<td>10.9</td>
<td>1.9</td>
<td>20.6</td>
<td>3.6</td>
<td>10.2</td>
<td>2.9</td>
<td>1.7</td>
<td>12.6</td>
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<tr>
<td>Removal %</td>
<td>81%</td>
<td>66%</td>
<td>79%</td>
<td>53%</td>
<td>75%</td>
<td>17%</td>
<td>11%</td>
<td>53%</td>
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<td>Maximum</td>
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<tr>
<td>Contaminant</td>
<td>1000</td>
<td>5</td>
<td>500</td>
<td>100</td>
<td>15</td>
<td>200</td>
<td>50</td>
<td>300</td>
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<td>Contaminant</td>
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<td>Level (µg/L)</td>
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<tr>
<td>Detection</td>
<td>0.85</td>
<td>0.065</td>
<td>0.05</td>
<td>0.35</td>
<td>1.5</td>
<td>1.55</td>
<td>2</td>
<td>0.6</td>
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<tr>
<td>Detection</td>
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<td>limit (µg/L)</td>
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In Figure 4 the removal of cadmium is depicted for the 15 storm events evaluated in this investigation. The bioretention performed well, removing cadmium to below the drinking water maximum contaminant level in all but two storm events, which happened to correspond to the events with the highest concentrations of cadmium. The percentage removal of cadmium based on concentration was 66% and 62% based on the load to the system. Figure 4 shows the drastic variation in the influent concentration in to the bioretention from storm to storm. This is largely dependent on the varying amounts of deposition in between storm events and was true for all of the heavy metals monitored in this study.

Lead was the only other heavy metal consistently present at influent concentrations that exceeded the drinking water maximum contaminant level. All of the storm events contained concentrations of lead in excess of the drinking water standard. The bioretention cell removed lead to concentrations below the drinking water standard for all storm events with an average removal rate of 75%.

Copper, zinc, iron, chromium, aluminium, and arsenic were removed from the stormwater at average percentage removal rates of 81%, 79%, 53%, 53%, 17%, and 11%, respectively. Due to space limitations the graphs that show the influent and effluent concentrations to and from the bioretention for all of these metals
are not shown, but there was a wide variation in the concentrations due to the nature of this field monitoring study. In addition, the concentrations vary based on the time period and the activity of the parking lot between storm events.

According to the field results, the bioretention is efficient in terms of heavy metal removal in the following order: Cu > Zn > Pb > Cd > Fe > Cr > Al > As.

![Cadmium concentration for 15 storm events.](image)

Figure 4: Cadmium concentration for 15 storm events.

Nutrient removal in the field study showed successful removal of nitrate, nitrite, ammonia, however none of these parameters were ever present at concentrations exceeding 1 mg/L. Soluble phosphorus as phosphate was never detected in the influent or effluent from the bioretention cell, with a detection limit of 0.1 mg/L. Ammonia was present in the influent at an average concentration of 0.5 mg/L and was never detected in the effluent. Nitrate was not detected in 8 of the 15 storm events and was only detected in the effluent of 4 events. Nutrients were not present at elevated concentrations in this parking lot.

### 4 Discussion

The metal removal efficiency results were less than those found in the literature for laboratory studies by Davis et al [6]. This is certainly due to the lack of maintenance of the bioretention mulch layer, which should retain metals at efficiencies from 88-99%. Laboratory and pilot studies have shown that the surface mulch layer is the most important component of the bioretention system for metal removal. In this study no special changes were made from the normal maintenance and operation of the bioretention area studied. During the early spring/late winter timeframe of this study the bioretention area contained a low
growth of plants and had not received new mulch. The facility was two years old and had not been replanted in that time prior to the study. The plant roots should have improved metal removal and the bioretention age should have provided more efficient metal uptake. However, in many of the prior studies a constant concentration higher concentration of synthetic water was utilized instead of the changing concentrations of actual stormwater.

5 Conclusions

In Washington D.C. approximately 1/3 (12,640 acres) of the city is served by a combined sewer system. Annually the 50 combined sewers expel over 3 billion gallons of combined sanitary wastewater and stormwater in an average year [13]. The majority of this water, approximately 2 billion gallons, enters into the Anacostia River which continues to be one of the most polluted rivers in the U.S. [14]. As a result of the continued CSO events in June 2003 a settlement was reached between the E.P.A. and the District of Columbia Water and Sewer Authority (WASA) to pay a fine of $250,000 and to provide $2 million to stormwater pollution prevention. A portion of the $2 million is to be used to promote Low Impact Development (LID) in the watersheds with CSO’s (E.P.A. 2003).

Although WASA established a long-term control plan in 2001, the cost to date, estimated at over $1 billion has been prohibitive to the initiation of the project. A more aggressive approach in the use of LID processes could yield important benefits. Of the many small drainage areas that lead to CSO’s in Washington D.C. the majority of them have a minimum rainfall of less than 1 inch to cause an overflow. Eighteen of the CSO’s overflow with less that ½ inch of rainfall. Although hundreds of rain barrels, bioretention cells, roof gardens, down spout disconnections, and other decentralized controls would have to be implemented to reduce the number of CSO events to zero, doubling or tripling the amount of rainfall required for an event would decrease the number of events significantly in a region that generally receives multiple small storms. The purpose of this project was to confirm the capability of bioretention cells to remove pollutants from stormwater lowering the load on the combined sewer system and the Anacostia River. Others have shown the capability of bioretention cells in the laboratory and with synthetic storm water in the field, but there are few studies that have evaluated the performance of bioretention cells with actual stormwater in a maintained field study.

The bioretention removed pollutants in the following order: TSS (~ 98%) > Zn (~ 80%) > Cu (~ 75%) > Pb (~ 71%) > Cd (~ 70%) > NH$_3$-N (~65%) > Fe (~ 51%) > Cr (~ 42%) > NO$_2$-N (~ 27%) > Al (~ 17%) > PO$_4^{3-}$-P (~3%). From the field results Cu (II), Zn (II) and Pb (II) were removed significantly at 81 ± 29%, 79 ± 14% and 75 ± 19%. The field results indicate that bioretention facilities can be effective for the removal of heavy metals, nutrients, and increase the dissolved oxygen content. In order to ensure removal of heavy metals to 90% the soil organic matter must be kept high and plants must be well maintained.
References