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Capture of stormwater runoff and pollutants by three types of urban best management practices

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Abstract: Land cover changes associated with urbanization produce hydrological alterations, which often diminish infiltration, leading to increased runoff volumes, peak flows, and greater need for pollution control. A number of urban "green infrastructure" best management practices (BMPs) have been designed to capture and contain stormwater runoff near the source. Although implementation of such practices has slowly increased, lack of evidence about their effectiveness in reducing the quantity and improving the quality of stormwater runoff may still limit the degree to which they are implemented. The objectives of this study were to assess performance of three types of urban stormwater BMPs by measuring their soil characteristics, infiltration rates, runoff reduction, and water quality parameters compared to adjacent contributing areas. Three types of practices—bioretention cells, native landscaping (reconstructed prairie areas), and three-zone vegetated riparian buffers located in Ames and Ankeny, Iowa—were assessed by conducting infiltration tests and collecting soil and water samples. For the biocells in particular, practice surface areas were smaller in relation to their contributing areas than is recommended in current design criteria. On average, the bioretention cells and the buffers' wooded zones had significantly lower soil bulk densities, higher infiltration rates, and smaller runoff volumes than those of contributing areas. Time-to-runoff was particularly high for bioretention cells. Infiltration characteristics of the native landscapes (reconstructed prairie) and buffer prairie zones we studied were not significantly different from those of the contributing areas. Total extractable hydrocarbon concentrations were elevated in the bioretention cells, while metals such as chromium (Cr) had greater concentrations in the contributing areas. Based on these findings, we recommend careful attention to sizing, particularly for biocells, and suggest routine incorporation of soil amendments (such as compost) to improve the performance of reconstructed prairie areas. Our findings also suggest that more widespread implementation of these source-control measures in retrofit of existing developments and/or in the design of newly urbanizing areas will be effective for reducing stormwater runoff volumes and improving water quality.

Key words: bioretention cells—infiltration rates—infiltrometer—native landscaping—stormwater management—urban riparian buffers

The process of urbanization increases the proportion of impervious surfaces in the landscape and generally leads to increased stormwater runoff. Both increased runoff volumes and higher peak discharge rates can disrupt natural drainage patterns and exceed the infiltration capacity of remaining pervious surfaces, leading to changes in the overall hydrologic flow regime (Booth and Jackson 1997). Rapid flow of stormwater across urban surfaces can deliver high concentrations of nutrients, metals, and hydrocarbons into nearby streams and lakes, leading to cumulative downstream impacts that damage surface water ecosystems (Beasley and Kneale 2002; Paul and Meyer 2001; Schueler 2000; Walsh et al. 2004).

Historically, stormwater management was designed to attenuate flooding by removing water from the landscape quickly using "end of pipe" techniques in which impervious surfaces were directly connected to receiving waters via curbs, gutters, and storm drain pipes (Burns et al. 2012; Sage et al. 2015). Over time, a number of alternative practices have been developed aimed at retaining runoff water near the source and reducing pollutant loads before delivery to surface water systems (Prince George's County 1993; USEPA 2017). The enactment of Phase I (1990) and Phase II (2000) National Pollutant Discharge Elimination System (NPDES) rules created a legal mandate for many municipalities to incorporate structural management practices as one element in the "good housekeeping" permit requirement, although costs of doing so and lack of understanding limited early implementation of practices (Roy et al. 2008; USEPA 2000a). Currently, more is known about implementation of stormwater best management practices (BMPs), which can include cost-effective natural features that limit the quantity and treat the quality of stormwater runoff by capturing and processing it close to the area it is generated (Clar et al. 2004).

There is great potential for more use of these vegetated BMPs in both newly developing landscapes, such as Low Impact Development (LID) approaches (Dietz 2007), and for retrofitting in areas of existing infrastructure (Sansalone et al. 2013). However, adoption and implementation of these practices in urban watersheds is not yet widespread, due to a variety of possible factors (e.g., lack of "proof" that they work, continued concerns about cost, inadequate guidelines for design and installation, inadequate governmental capacity and coordination, and/or lack of legal or economic incentives [Roy et al. 2008]). There may also be real or perceived limitations related to space available for establishment of such practices (in the case of retrofitting) and urban residents' understanding of their role in the landscape (Page et al. 2015). Thus, there is great need for locally relevant data on practice effectiveness for a variety of BMPs to address these factors and perceived limitations.

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In this study, we examine the design criteria and efficacy of three vegetated stormwater management practices implemented in typical urban (residential, recreational, and commercial) settings in central Iowa. Our goal is to address some of the uncertainties about BMP designs and performance so that, if findings indicated it would be appropriate, they could be more widely adopted by both public and private entities and ultimately reduce stormwater impacts. Specifically, we examine the characteristics of bioretention cells, native (reconstructed prairie) landscaping, and riparian buffers, each of which is briefly described in the paragraphs that follow.

Bioretention cells (also called "biocells") are constructed depressions designed to infiltrate and temporarily store stormwater in order to decrease surface runoff, capture pollutants, and potentially recharge groundwater (Dietz 2007; LeFevre et al. 2015; Li and Davis 2009). Vegetation is included in these cells to promote evapotranspiration and maintain substrate porosity (Coffman et al. 1993). Design recommendations for biocells are regionally based, and vary in capacity, substrate media, and vegetation (Carpenter and Hallam 2008). Often biocells are installed in parking lot islands, road medians, and in urban locations with relatively high and often immediately adjacent impervious cover.

Native landscaping is a cost-effective alternative to traditional turf grass that uses plant communities indigenous to a particular region to promote the natural hydrologic processing of runoff (Nassauer et al. 2009; Peterson et al. 2012). In the Midwest United States, prairie plant communities have often been used in natural landscaping because seed and other propagules are readily available, restoration protocols are well understood, and the plant community is known to persist across a range of climatic conditions (e.g., thrive in both wet and dry years [Threlfall et al. 2017]). The aboveground density of perennial prairie plants has been found to trap sediment and reduce surface runoff velocity (Ghadiri et al. 2011). Belowground, prairie plant root systems are thought to contribute to nutrient retention, stabilize soil structure, lower soil bulk density, and increase infiltration rates (Baer et al. 2002; Perez-Suarez et al. 2014).

Riparian buffers contain perennial vegetation planted along streambanks and the adjacent landscape, and are designed to slow water movement and prevent sediment and other pollutants from entering a stream while also providing for streambank stabilization (Laub et al. 2013; Parkyn et al. 2003; Polyakov et al. 2005; Roy et al. 2005). These often include species of trees and shrubs that are thought to increase water infiltration into the soil before it reaches the stream itself (Roy et al. 2005; Smucker and Detenbeck 2014; Wahl et al. 2013). In practice, vegetated riparian buffers implemented in urban landscapes have often been confined to relatively narrow parallel strips of land along stream corridors because of space limitations.

Our specific research objectives were to answer the following questions: (1) are receiving areas of these BMPs sized such that they provide adequate capacity for the capture of stormwater based on their original design criteria; (2) do vegetated urban stormwater BMPs have greater infiltration rates and water absorption capacities than the surrounding contributing areas; and (3) are there differences in pollutant (nutrient, heavy metal, and hydrocarbon) concentrations between the receiving and contributing areas of these practices?

Materials and Methods

Study Area. The landscape of Iowa has been extensively altered to accommodate both agricultural and urban land uses. As urban areas in Iowa have expanded, changes in land cover include conversion of former agricultural land as well as forest and grassland to residential, commercial, and industrial land uses dominated by impervious surfaces (Bowman et al. 2012). Although overall population growth has been slow in Iowa, it has been concentrated and occurred rapidly in several municipalities in the central part of the state, causing dramatic localized increases in road surfaces, parking lots, and buildings (e.g., a 4.2% annual increase in total impervious surface from 2002 to 2011 in Ankeny [Wu and Thompson 2013]).

Several central Iowa cities with municipal separate storm sewer systems (MS-4) are permitted by the Iowa Department of Natural Resources through the US Environmental Protection Agency (USEPA)'s National Pollutant Discharge Elimination System (NPDES) under Phase I and II rules, which require them to address a number of measures, including municipal "pollution prevention and good housekeeping." As a part of their permit responses to address this measure, a number of these cities have participated in the Iowa Stormwater Education Partnership, which provides technical resources and support for municipal installation of stormwater BMPs. Among participants in that partnership, we chose to assess BMPs installed within the cities of Ames and Ankeny, Iowa, incorporated boundaries (figure 1).

Both cities are characterized by growing populations, which are estimated to have increased by 13% (Ames) and 37% (Ankeny) between 2010 and 2017. Current populations are estimated at 66,498 in Ames and 62,416 in Ankeny (US Census Bureau 2017a, 2017b). Population growth has led to rapid expansion of impervious surface coverage: recent studies indicate that the City of Ames has approximately 25% (city-wide average) impervious land cover (Jake Moore, personal communication, June 1, 2016) and the City of Ankeny has approximately 19% (in 2011) average impervious land cover (Wu and Thompson 2013).

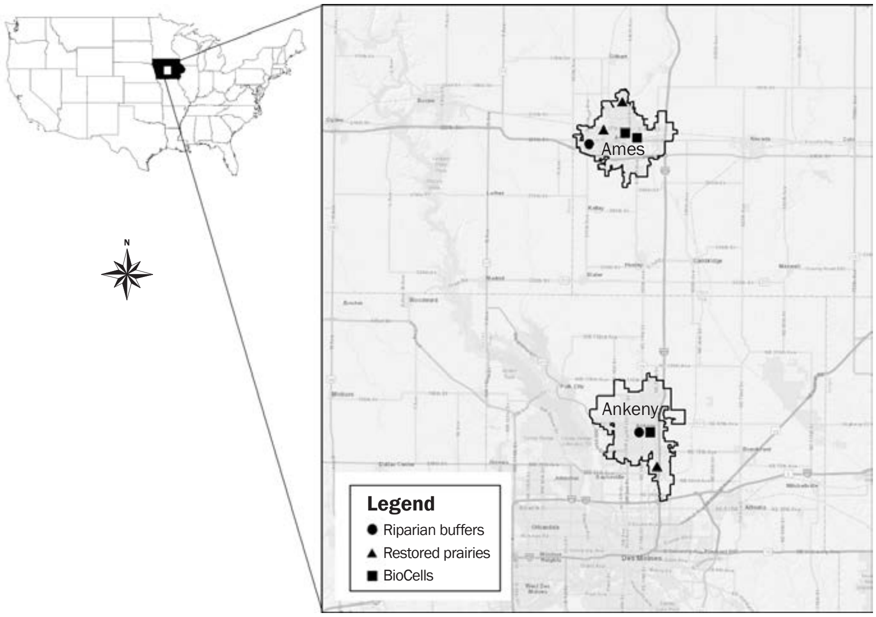
We chose eight study sites within these two municipalities, including three bioretention cells, three native landscaping (reconstructed prairie) areas, and two urban riparian buffers (figure 1). These BMPs were chosen to represent structural practices embedded in catchment areas that include a variety of urban land cover types—roads, sidewalks, parking lots, and parks. All BMPs were installed 5 to 15 years prior to this study and thus have had time for vegetative components to become established.

Study Sites: Bioretention Cells. The three biocells selected for study include one in Ankeny (Summerbrook Park) and two in Ames (Edison Street and City Hall) (table 1). All three biocells were set approximately 23 cm below the surrounding landscape, had a mulched and vegetated surface, a layer of engineered soil (between 30% and 60% sand, mixed with between 40% and 60% compost), and an aggregate rock layer enclosing a perforated drainage pipe. The Summerbrook Park biocell was located between a major road and a sidewalk. The two biocells in Ames both received stormwater from municipal parking lots; one (Edison) was established in 2011, and the City Hall biocell was established in 2009. The biocell in Ankeny was installed in 2001. All three bioretention cells were planted with mixtures of prairie grasses and forbs.

Study Sites: Native Landscaping (Reconstructed Prairies). The three reconstructed prairies were selected to represent urban areas converted to native landscap-

Figure 1

Generalized map of the United States with Iowa darkened, and insert with locations of stormwater management practice sites within the City of Ames and City of Ankeny (graphic developed by B. Marmur).



ing, including two areas in Ames (in Ada Hayden Heritage Park and on an Iowa State University site along Stange Road), and one in Ankeny (on the Iowa Association of Municipal Utilities [IAMU] grounds) (table 1). The Ada Hayden prairie area was surrounded by a parking lot associated with the main access to this heavily used city park, and was established by direct seeding in 2007. The IAMU prairie area was adjacent to the Carney Marsh Nature Preserve, and was first planted via direct seeding in 2001 (and reseeded in 2006 to enhance the species mix) on land that was previously used for row crop agriculture (Dave Hraha, personal communication, June 6, 2016). Both the Ada Hayden and IAMU prairie areas were predominantly comprised of native prairie grasses with admixtures of some forbs. The Stange Road prairie area was established in 2004 by 4-H youth with support from the Iowa Department of Transportation's Living Roadway Trust Fund (Chris Strawhacker, personal communication, June 10, 2016). The soil at this site was amended with a

Table 1

General characteristics of sites where three stormwater best management practices (BMP) were evaluated in central Iowa, United States. Surface areas of management practices on eight sites and their respective contributing areas (CA) by practice type, ratios of practice area to contributing area, and total impervious surface cover (roads, other pavement, roofs; by area and percentage) within each contributing area.

BMP type/site	Location	Surrounding land use	Year	Surface area (m²)	Practice area to CA ratio	Impervious cover (m²) (%)
Bioretention cells						
Summerbrook Park	Ankeny	City park	2011	35	1:28	
Contributing area				1,006		462 (46%)
Edison Street	Ames	Municipal parking lot	2011	143	1:14	
Contributing area				2,060		1,520 (74%)
City Hall parking lot	Ames	Municipal parking lot	2009	37	1:14	
Contributing area				515		458 (89%)
Reconstructed prairie areas						
Ada Hayden Heritage Park	Ames	City park	2007	3,279	1:1	
Contributing area				3,145		3,145 (100%)
Iowa Assoc. Municipal Utilities	Ankeny	Commercial area	2001	10,151	1:0.5	
Contributing area				5,478		2,592 (47%)
Stange Road	Ames	University grounds	2004	1,118	1:2	
Contributing area				2,630		1,757 (67%)
Urban riparian buffers						
Daley Park buffer prairie				4,200	1:9	
Daley Park buffer wooded	Ames	City park	2007	8,070	1:5	
Contributing area				38,740		8,236 (21%)
Summerbrook Park buffer prairie				1,490	1:10	
Summerbrook Park buffer wooded	Ankeny	City park	2011	2,400	1:6	
Contributing area				12,270		2,349 (19%)

compost mulch mixture just before planting. The Stange Road prairie area was planted primarily with native forbs to increase its aesthetic appeal.

Study Sites: Urban Riparian Buffers. Two urban riparian buffers were selected and include a vegetated buffer planted in 2007 in Ames (Daley Park; described in Herringshaw et al. 2010) and a similar buffer planted in 2011 in Ankeny (Summerbrook Park). Each riparian buffer contained a zone of native tree species planted closest to the stream, with an intermediate zone of native trees mixed with shrubs, and furthest from the stream a zone of native prairie grasses and forbs. These linear zones of vegetation ran parallel to the stream and perpendicular to nearby roadways, and vary in width throughout the reach of stream due to spatial constraints in each park. The Daley Park Buffer was located along a 310 m reach of College Creek in Ames, and the Summerbrook Park buffer was located along a 170 m stretch of an unnamed tributary in Ankeny. Both buffers were located in city parks located in residential neighborhoods.

Stormwater Management Practice Area Delineation. Practice areas and their contributing areas were delineated using a Geographic Information Systems (GIS) model. Light Detection and Ranging (LiDAR) data were used to generate digital elevation models (DEMs) at a 1 m resolution (Iowa LiDAR Mapping Project; GeoTREE 2016). These models were used to determine subwatershed boundaries and dimensions for the area draining to each of the stormwater management practice installations. Land cover data were extracted from the Natural Resources GIS Library in order to determine the area of impervious cover in each of the subwatersheds (NRGIS 2017).

Soil Bulk Density and Volumetric Water Content Measurements. Surface soil samples were collected adjacent to the location of three infiltrometer tests (described below) at each site to determine soil bulk density and soil water content. Soil samples were collected using an AMS Bulk Density Compact Slide Hammer to extract a 90.4 cm³ cylindrical sample from the first 7 cm of soil. Samples were sealed in plastic bags, chilled immediately, and transported in a cooler to the laboratory for further processing.

Soil bulk density samples were weighed, oven-dried at 70°C (to avoid soil nitrogen [N] loss and allow particle size analysis) for 48 hours, and weighed again to determine mass of water and soil in each sample. Bulk density was calculated as soil dry weight divided by sample volume. Volumetric water content ($\mathrm{cm^3\ cm^{-3}}$) was calculated using the following equation:

$$\text{Volumetric water content}\left(\frac{\mathrm{cm^3}}{\mathrm{cm^3}}\right) = \frac{m_{water} \div \rho_{water}}{m_{soil} \div \rho_{soil}} = \frac{\theta_{g} \times \rho_{soil}}{\rho_{water}} \ , \tag{1}$$

where $m_{water} \div \rho_{water}$ is the mass of the water in the soil over density of water, which is divided by $m_{soil} \div \rho_{soil}$, which is mass dry soil over the density of soil, or the gravimetric water content θ_g multiplied by bulk density over the density of water. Subsamples (40 g) were then mixed thoroughly with a sodium-hexametaphosphate solution (50 g $\mathrm{L^{-1}}$) and analyzed to determine particle size distribution using the hydrometer method (ASTM 1985; Gee and Bauder 1986).

Infiltration Measurements. A set of three infiltrometer tests were conducted in each practice area and in the surrounding contributing areas (managed turf areas) where possible (at three of the sites, those which were not dominated by pavement) between June and September of 2016. We used a portable single-ring Cornell Sprinkle Infiltrometer (van Es and Schindelbeck 2003) to determine field saturated infiltration rates, time-to-runoff, and sorptivity. When using a single-ring apparatus, infiltration rates are adjusted to account for three-dimensional flow at the bottom of the ring to calculate field saturated infiltration (0.95 adjustment rate used for 7.5 cm ring insertion depth, as recommended by Reynolds and Elrick [1990]). The cylindrical water reservoir of the infiltrometer has a perforated bottom, which delivers rainfall onto a 24.1 cm diameter area controlled by a 20.3 cm tall metal ring (van Es and Schindelbeck 2003). Rainfall rate was calibrated by adjusting a Mariotte tube, which also controlled for constant head. Rainfall rate was calibrated each day to deliver 0.6 cm $\mathrm{min^{-1}}$ using a two-minute test. Simulated rainfall rates were also determined directly to account for variation caused by field conditions (e.g., temperature variations). The reservoir was filled with deionized water transported from the laboratory, and the simulated rainfall rate was calculated by determining the difference in height of the water in the cylinder before and after the timed observation divided by the time elapsed.

A metal ring (17.8 cm height) fastened to the base of the reservoir was carefully inserted to be level with the soil surface to a depth of 7.5 cm. An outflow hole at 7.5 cm was set to be flush with the soil surface and was fitted with an effluent tube to allow water to run off once surface ponding occurred. We recorded rainfall rate, time-to-runoff, and volume of runoff water at three-minute intervals. The runoff rate (cm $\mathrm{min^{-1}}$) was calculated using the following equation (van Es and Schindlebeck 2003):

$$runoff\ rate = \frac{V_t}{457.30 \times t} \ , \tag{2}$$

where 457.30 (cm²) = area of the metal ring, t = time interval (min), and V_t = volume of water (mL) during time interval t. After reaching a steady state for runoff rate, the field-saturated infiltration rate was estimated by determining the difference between the applied rainfall rate and the rate of runoff, allowing direct comparisons among sites with different antecedent soil moisture contents (van Es and Schindlebeck 2003).

Determination of Practice Capacity and Potential Water Storage. Recommendations for practice design indicate that stormwater BMPs should be sized to capture/treat runoff from 90% of storms that occur in a typical year, which corresponds to a rainfall depth of 3.18 cm over a 24-hour period in central Iowa (Iowa DNR 2009). However, given near-future climate scenarios that include more frequent and much more intense rainfall events (at least an 18% increase in precipitation between year 2011 and 2040 [Wu and Thompson 2013]), we chose to estimate runoff generation for each site using a generalized 5.08 cm $\mathrm{h^{-1}}$ rainfall intensity. To estimate runoff for this hypothetical event, we subtracted the average infiltration rate (cm $\mathrm{h^{-1}}$) from this precipitation intensity and multiplied by the total surface area of each zone to determine the volume of water that would be generated (total runoff, indicated by a positive value) or infiltrated (total absorption, indicated by a negative value) by each BMP and contributing area.

Sample Collection and Analysis. All water samples were collected from the infiltrometer effluent tube at the time of initial runoff and were immediately chilled for transport and subsequent cold storage in the laboratory. Samples for measurement of nitrate (NO_3^-) concentration were collected in acid-washed (5% sulfuric acid; 2-hour rinse) and acidified (200 μg concentrated sulfuric acid) 125 mL bottles and analyzed using automated colorimetry (Method 353.2 [USEPA 1993a]). Acid-washed bottles treated in a phosphorus (P)-free soap bath (two-hour rinse) were acidified and used to collect 125 mL samples for analysis of total P concentrations using USEPA semiautomated colorimetry (Method 365.1 [USEPA 1993b]). Acid-washed bottles were also used to collect 75 mL samples for determination of chloride (Cl^-) concentrations using the low-level amperometric titration method (Method 4500-Cl E [APHA 2005]). Samples were analyzed in the Riparian Management Systems Laboratory in the Department of Natural Resource Ecology and Management (NO_3^-) or in the Water Quality Research Laboratory in the Department of Agricultural and Biosystems Engineering (total P and Cl^-) at Iowa State University.

Soil samples were also collected from the soil surface to a 7 cm depth at each site for determination of nutrient concentrations (NO_3^-, ammonium [NH_4^+], and total P). These samples were placed in plastic-lined soil sample bags, chilled, and delivered to the Iowa State University Soil and Plant Analysis Laboratory where they were analyzed using KCl extraction and cadmium (Cd) reduction detection methods for nitrate-nitrogen (NO_3^--N) and NH_4^+, and the Mehlich-3 extraction and ascorbic acid spectrophotometric detection method for total P (NCRR 2015). Samples for determination of soil metal concentrations (chromium [Cr] and zinc [Zn]) were placed in 250 mL wide-mouth glass jars, chilled immediately, and delivered to the Iowa State Hygienic Laboratory within five hours of collection. Samples were analyzed there using inductively coupled plasma mass spectrometry (Method 6020A and Method 6010C, respectively [USEPA 2000b]). Additional soil samples were collected at the three bioretention cells and reconstructed prairie sites (all located close to motor vehicle traffic areas) for determination of total extractable hydrocarbons using the flame ionization capillary gas chromatography method developed by the State Hygienic Laboratory for extractable petroleum products (Method Iowa OA-2 [UHL 1993]). These samples were collected in 250 mL wide-mouth amber glass jars, chilled immediately, and delivered within five hours to the State Hygienic Laboratory for processing.

Soil Cores from the Ames City Hall Bioretention Cell. We used a hydraulic drilling rig with a plastic-lined tube to extract six soil cores to a depth of 51 cm. We divided each core into four 13 cm segments. A portion of each core segment was placed in a prepared container (as previously described for other soil samples) and immediately chilled for transport to the laboratory within five hours of collection. Analyses of NO_3^-, NH_4^+, and total P were conducted at the Soil and Plant Analysis Laboratory, Iowa State University, using the previously described methods. Soil organic matter was estimated by determination of carbon (C) through dry combustion, and soil pH was measured potentiometrically using an electronic pH meter in a one-to-one soil:water slurry at this laboratory (NCRR 2015). Metals (Cd, Cr, and Zn) were analyzed at the State Hygienic Laboratory using the inductively coupled plasma mass spectrometry method for Cd and Cr (Method 6020A [USEPA 1998]) and the atomic emission spectrometry method for Zn (Method 6010C [USEPA 2000b]). Total extractable hydrocarbons and gasoline (as per previously cited methods) and *E. coli* using the multiple-tube fermentation technique (*Escherichia coli* procedure; Method 9221F [APHA 2005]) were also measured at the State Hygienic Laboratory.

Data and Statistical Analyses. We calculated means for characteristics (soil physical and chemical properties and infiltration tests) of biocells and reconstructed prairie areas using three samples from the three locations (means represent nine measurements; samples collected at random pattern). We calculated means for each buffer zone using three samples for each zone (prairie and wooded) at each site (means represent six measurements). We calculated means for contributing areas based on three samples from the three locations dominated by pervious surfaces surrounding one of the biocells and both urban riparian buffers (means represent nine measurements).

Mean values for BMPs were compared to those of contributing areas for soil bulk density and volumetric water content using Student's *t*-tests. To account for possible correlation among multiple tests/samples from each site, we used a linear mixed-effects model fit by restricted maximum likelihood to estimate and compare means for infiltration characteristics (average infiltration rate, time-to-runoff, and runoff volume) for the practices and contributing areas (the LMER function in the R statistical package [Cook 2014]). Estimates of time-to-runoff were converted to a log scale and were right-censored at 40 minutes (total test time) if 100% infiltration occurred. We used Student's *t*-tests for pairwise comparisons of means for water and soil chemical parameters for each practice type and the contributing areas. For detailed analyses of the City Hall biocell, means for soil physical and chemical characteristics were calculated using the six samples collected for each depth increment. We used Student's *t*-tests for pairwise comparisons among depth increments. For all statistical analyses, we set $p \leq 0.05$ to declare significance.

Results and Discussion

Characteristics of Stormwater Management Practices and their Contributing Areas. Subwatershed contributing areas of the three bioretention cells had surface areas of 515 m² to 2,060 m² (ratios from 1:14 to 1:28; table 1). The biocells were located in predominantly impervious landscapes—each of the three practices were surrounded by at least 46% impervious cover. The three reconstructed prairie landscape areas received stormwater from contributing areas ranging from 2,630 m² to 5,478 m² (ratios of 1:0.5 to 1:2.3), including between 47% and 100% impervious cover. Subwatershed contributing surface areas surrounding the two riparian buffers were between 12,270 m² and 38,740 m², areas 5 to 10 times larger than buffer zones themselves. These contributing areas were predominantly managed turf with some impervious cover (from 19% to 21%; table 1).

Bioretention cell surfaces were much smaller than their surrounding contributing areas, which were characterized by relatively high proportions of impervious surfaces. According to Iowa Stormwater Management Manual (ISWMM 2016) guidelines, biocell surface areas should be approximately 3% to 7% of the contributing impervious surface area. The bioretention cells we examined had surface areas that exceeded this criteria, representing between 7.5% and 9.5% of the surrounding impervious subwatershed. The bioretention cells also had practice area to contributing area ratios similar to those reported in other studies (Houdeshel and

Pomeroy 2014; Johnson and Hunt 2016). Although we studied only one biocell at each site, each of them were co-located with other biocells that likely increase overall capacity for source control treatment in these landscapes.

The three native landscaping (reconstructed prairie) areas had much larger surfaces relative to their contributing areas. Native landscaping is increasingly recommended for use in urban areas (Fischer et al. 2013; Reid and Oki 2008), although space available or urban dwellers' aesthetic preferences (Borgstrom et al. 2006; Lerman et al. 2012; Peterson et al. 2012) in many urban settings may limit its potential for application on private property. Native prairie landscaping in particular may be most appropriate at large scales, focusing on municipal or commercial properties, and using design plans that include specific maintenance methods and schedules.

The riparian buffers we examined had intermediate surface area to contributing area ratios (1:4 for combined prairie and wooded zones within each buffer) compared to the other two practices. Because of their purpose and landscape position as a linear feature along stream corridors, recommendations generally address buffer width rather than surface area—in Iowa, recommended width ranges from 4.5 to 7.6 m (ISWMM 2016). The riparian buffers we observed had variable widths ranging from 10 to 40 m, exceeding suggested design criteria. Similar to applications of native landscaping, the total area available for a riparian buffer may be quite constrained in urban settings, thus other reports of urban buffer widths vary greatly (from 5 to 60 m [Johnson and Buffler 2008; Schueler 1995]).

Soil Physical Properties and Practice Infiltration Characteristics. Surface soil cores from the three bioretention cells had lower soil bulk density than the contributing areas (p = 0.0117) (table 2). Soil bulk density in the reconstructed prairie areas and in the buffer prairie zones did not differ from their contributing areas (p = 0.6626 and 0.7610, respectively). The buffer wooded zones had lower soil bulk density than their respective contributing areas (p = 0.0285). Volumetric soil water content was not significantly different for bioretention cells, reconstructed prairie areas, or buffer prairie zones compared to their contributing areas, but for buffer wooded zones it was greater than that of their respective contributing areas (p = 0.0301) (table 2).

Average infiltration rates were greater for the bioretention cells ($p < 0.0001$) and buffer wooded zones ($p < 0.0001$), compared to their respective contributing areas (table 3). Average infiltration rates for the reconstructed prairie landscape areas and the buffer prairie zones were not significantly different from their contributing areas. Bioretention cells were also characterized by longer time-to-runoff compared to the contributing areas ($p < 0.0001$). There were no consistent differences in time-to-runoff for the other practices. The biocells (p = 0.0002) and buffer wooded zones (p = 0.0004) both produced smaller volumes of runoff than the contributing areas, although there were no differences between reconstructed prairie landscapes and buffer prairie zones compared to their contributing areas (table 3).

Infiltration rates were consistently high for the BMP areas, and were significantly greater for biocells and buffer wooded zones compared to the contributing areas. This is likely related to lower soil bulk density for substrate materials in these two practices leading to more pore space for water infiltration. The biocells were specifically created to have low substrate bulk density as per recommended guidelines using engineered soil mixtures (on average surface samples were 73% sand, ranging from sand to sandy loam textures based on particle size analysis). We also determined that soils in the buffer wooded zones ranged from sandy loam to loam textures with an average 45% sand content, likely enhancing their permeability.

We observed high variability in infiltration rates among the three reconstructed prairie landscape areas. Although thought to be a better alternative than managed turf lawns, several previous studies have revealed the potential for variable effects of prairie that are relevant to its potential for stormwater management. For example, Gish and Jury (1983) found that prairie plant roots created soil physical conditions leading to a narrow range of pore water velocities that actually reduced infiltration rates. The somewhat high soil bulk densities and low infiltration rates we observed for the reconstructed prairie areas could be related to those factors, or to conditions that existed or were created at the time of prairie establishment. For example, Ada Hayden Heritage Park is located at the site of a former gravel quarry, where initial soil bulk density may have been very high at the time of prairie installation (Joshua Thompson, personal communication, June 13, 2016). The prairie at the IAMU facility was planted on land previously used for row crop production, so soil physical properties at this site were also likely to have been altered by prior land use. The same may be true for the prairie zones associated with the two buffers, which were planted in urban landscapes that had been graded. In such situations, pretreatment of the area with soil amendments such as compost may be necessary to enhance soil properties before seeding

Table 2

Soil bulk density (g cm^{-3}) and volumetric water content (cm^3 cm^{-3}) for stormwater practices and their contributing areas (managed turf). Means for the same set of three contributing areas are used for comparison to all practices. Estimated mean differences between practices and the contributing areas, their standard errors, and p-values for comparisons using Student's t-tests.

		Soil bulk density (g cm^{-3})				Volumetric water content (cm^3 cm^{-3})			
Practice	n	Mean	Est. of diff.	Std. err.	p-value	Mean	Est. of diff.	Std. err.	p-value
Bioretention cells	9	1.16	0.24	0.09	0.012	0.25	0.01	0.05	0.822
Reconstructed prairie	9	1.35	0.04	0.10	0.663	0.27	0.01	0.05	0.825
Buffer prairie zones	6	1.36	0.03	0.10	0.761	0.27	0.01	0.05	0.894
Buffer wooded zones	6	1.18	0.23	0.09	0.029	0.38	0.11	0.05	0.030
Contributing areas	9	1.40				0.26			

Table 3

Means and estimates of average differences and their standard errors between stormwater management practices and contributing areas (managed turf). Means for the same set of three contributing areas are used for comparison to all practices. Parameters measured include average infiltration rate (cm h^{-1}), time-to-runoff (minutes, right-censored), and runoff volume (L).

Infiltration characteristic	*n*	Mean	Est. of difference	Std. err.	*p*-value
Average infiltration rate (cm h^{-1})					
Bioretention cell	9	33.79	31.77	4.57	<0.001
Reconstructed prairie	9	15.54	13.52	6.58	0.100
Buffer prairie zone	6	6.94	4.91	3.66	0.191
Buffer wooded zone	6	23.00	20.97	4.11	<0.001
Contributing areas	9	2.03			
Time-to-runoff (min)					
Bioretention cell	9	3.10	3.35	1.63	<0.001
Reconstructed prairie	9	2.12	2.37	9.13	0.130
Buffer prairie zone	6	1.15	1.40	1.26	0.089
Buffer wooded zone	6	0.95	1.21	1.34	0.290
Contributing areas	9	−0.25			
Runoff volume (L)					
Bioretention cell	9	2.13	−7.23	1.55	<0.001
Reconstructed prairie	9	4.93	−4.43	1.62	0.065
Buffer prairie zone	6	7.11	−2.25	1.36	0.111
Buffer wooded zone	6	3.13	−6.23	1.56	<0.001
Contributing areas	9	9.36			

to prairie (see for example, Singer et al. 2006) to achieve desired infiltration characteristics.

The buffer wooded zones that we sampled were characterized by relatively low soil bulk density values and generally high infiltration rates. This may be attributable to their position closest to the stream in areas less likely to have been disturbed by prior landscape alterations, in addition to the role of woody vegetation in creating large pores that increase water movement (Dexter 1991). Others have shown that soil bulk density in restored urban vegetated riparian buffers was intermediate between that of urban control sites (no treatment) and naturally forested streamside areas (Laub et al. 2013). We also measured significantly higher volumetric water content of soils in buffer wooded zones, which could be due to greater infiltration capacity as well as contributions from subsurface base flow based on their topographic position and proximity to the stream (Bosch et al. 1994; Sweeney and Newbold 2014).

Time-to-runoff was consistently high and runoff volume was consistently low for all three BMPs, although we detected significant differences only for the bioretention cells compared to contributing areas. The fact that we did not observe distinguishable responses in time-to-runoff for some practice areas relative to the contributing areas may be due to the more important role of rainfall intensity as a determinant of time-to-runoff (Bothma et al. 2012). The rainfall rate we used during infiltrometer tests (0.6 cm min^{-1}) may have uniformly caused surface ponding or slaking of soil aggregates regardless of substrate properties, affecting both the BMP areas and contributing areas. The lack of significant differences for BMPs compared to contributing areas could also be due to the high amount of variability in these parameters within the practices themselves and limitations on the number of tests we were able to conduct.

Practice Capacity and Potential Water Storage. One of the three reconstructed prairie areas and both riparian buffers including each of the buffer (wooded and prairie) zones had adequate capacity to infiltrate directly incident precipitation from a 5.08 cm h^{-1} event, as well as all of the runoff generated from their contributing areas (table 4). The three bioretention cells were unable to absorb the quantity of runoff generated by their surrounding contributing areas for this hypothetical event; for instance, the City Hall bioretention cell was estimated to absorb only 6.6 m^3 h^{-1} of the 26.2 m^3 h^{-1} runoff generated. One reconstructed prairie area was estimated to absorb even less than the direct incident precipitation that would be delivered to it by a rain event of this intensity (table 4).

Designed practice depths for the three bioretention cells ranged from 61 to 91 cm (table 5). Potential water storage depths in the bioretention cells were estimated to range from 11 to 30 cm. A uniform practice depth of 91 cm was assigned for the reconstructed prairie landscapes. Depths of potential water storage for these prairie areas ranged from 18 to 34 cm (table 5). Estimates of potential water storage for the buffer prairie zones ranged from 21 to 28 cm, and for the buffer wooded zones ranged from 26 to 44 cm (table 5).

Guidelines for stormwater control practices for Iowa are based on design criteria of 3.2 cm of rainfall delivered over 24 hours, which historically represented 90% of such events (Iowa SUDAS 2015; ISWMM 2016). However, based on current trends as well as climate change predictions, more frequent and intense rainfall events are very likely (Takle et al. 2010; Wu et al. 2013). Therefore, we tested whether these practices had the potential to mitigate runoff from a 5 cm rainfall event, representing a storm previously estimated to have a return period between 5 to 10 years (Iowa SUDAS 2015). For this storm intensity, the individual bioretention cells we studied are undersized for the quantity of stormwater production from their contributing areas (which include a predominance of impervious surface). Thus, it may be advisable to adjust design criteria to accommodate increased intensity of anticipated rainfall events. In addition, this underscores the necessity for establishing such practices in clusters to increase their effectiveness (as recommended, but not always complied with for practice installations). The reconstructed prairie areas generated runoff quantities similar to those of their surrounding contributing landscapes, again suggesting that soil amendments before prairie establishment (Singer et al. 2006) could enhance their performance.

Wooded zones of the riparian buffers we studied absorbed more stormwater runoff than their adjacent prairie zones. Suspended sediment has been observed to settle within the first 3 to 4.5 m of vegetated areas meant to intercept and treat runoff (Hunt and Lord 2006). The location of the prairie buffer zone at the outer edge of both vegetated buffers may lead to sediment accumulation in these prairie zones, which could fill pores, increase their bulk density, and decrease their infiltration capacity.

Water Sample Characteristics. There were no differences in NO_3^- concentrations of

Table 4

Determination of absorption capacity for each of three stormwater management practices and their contributing areas assessed at eight sites in central Iowa, based on average infiltrations rates and surface areas. Total runoff generation is indicated by a positive value and total absorption is indicated by a negative, calculated for each best management practice (BMP) and contributing area.

BMP type/site	Average infiltration rate (cm h^{-1})	Surface area (m^2)	Impervious cover (m^2) (%)	Runoff (+) or absorption (–) (m^3 h^{-1})
Bioretention cells				
Summerbrook Park	39.5	35		–12.0
Contributing area	1.9	1,006	462 (46%)	33.2
Edison Street	39.9	143		–49.8
Contributing area	—	2,060	1,520 (74%)	104.6
City Hall parking lot	22.2	37		–6.3
Contributing area	—	515	458 (89%)	26.2
Reconstructed prairie areas				
Ada Hayden Heritage Park	27.4	3,279		–731.3
Contributing area	—	3,145	3,145 (100%)	925.2
Iowa Assoc. Municipal Utilities	3.9	10,151		121.2
Contributing area	—	5,478	2,592 (47%)	278.3
Stange Road	17.2	1,118		–135.5
Contributing area	—	2,630	1,757 (67%)	133.6
Urban riparian buffers				
Daley Park prairie zone	6.2	4,198		–45.9
Daley Park wooded zone	29.9	6,149		–1,530.6
Contributing area	5.7	38,739	8,236 (21%)	–236.2
Summerbrook Park prairie zone	21.3	1,221		–198.2
Summerbrook Park wooded zone	9.9	1,871		–90.8
Contributing area	4.3	12,270	2,349 (19%)	90.4

effluent runoff water for any of the practice areas compared to their contributing areas. Total P concentrations in runoff were significantly lower for all practices (p-values ranging from 0.0013 to 0.0532) compared to those of the contributing areas (table 6). Chloride concentrations in runoff water were lower for reconstructed prairie areas ($p = 0.0129$) and buffer wooded zones ($p = 0.0443$) compared to contributing areas (table 6).

Phosphorus and N are primary nutrient pollutants found in stormwater runoff (USEPA 2009). Relatively low concentrations of NO_3^-, total P, and Cl^- in the effluent water samples we collected may have been a result of the short travel time/distance across the soil surface in our tests (maximum travel distance was 24 cm, the diameter of the infiltration ring). Consideration of NO_3^- in runoff water is essential for managing stormwater quality, but surface runoff is generally not seen as a dominant pathway for NO_3^- transport (Kleinman et al. 2006). Phosphorus concentrations in effluent water were significantly lower in all four practice types than the contributing areas, inconsistent with the P concentrations found in the soils of the practices. Although dissolved P concentration in surface runoff is likely to be related to soil P concentrations, some studies have observed that the relationship between soil and runoff P content depends on several site-specific factors (Kleinman et al. 2006; Nash et al. 2002; Sharpley et al. 1994), which we did not measure.

Higher Cl^- concentrations in contributing areas and somewhat elevated Cl^- concentrations in effluent runoff from bioretention cells and buffer prairie zones are probably due to residue from road salts used on adjacent impervious surfaces. These practice areas likely receive inputs of sodium chloride (NaCl) and calcium chloride ($CaCl_2$) that are used to treat snow and ice (Zhang et al. 2013). The reconstructed prairie areas and buffer wooded zones had lower Cl^- concentrations in their effluent water, likely because they are in landscape positions that are protected from salt inputs.

Soil Sample Characteristics. We did not detect differences for soil NO_3^-, NH_4^+, total P, Zn, or total extractable hydrocarbons in surface soil samples in practice areas compared to contributing areas (table 7). Soil Cr concentrations were significantly lower in bioretention cells than in contributing areas ($p = 0.0201$) (table 7). Although levels of extractable hydrocarbons are elevated in bioretention cells, variability within practice areas precluded detection of a significant difference between these practices and the contributing landscapes.

We did not detect differences in soil nutrient, metal, or hydrocarbon concentrations between the practices and contributing areas, which could be because there was high variability within each practice for the soil parameters we measured. For example, total extractable hydrocarbon concentrations were around 30 mg kg^{-1} for two of the bioretention cells (Summerbrook Park and Edison Street), but the third biocell (City Hall) had a concentration of 200 mg kg^{-1}. Although design guidelines that target specific pollutants have not been developed within the ISWMM standards, a target infiltration rate for capture of metals, total N, and total P between 2.54 to 15.24 cm h^{-1} for adequate soil absorption has been suggested (Hunt and Lord 2006). It is possible that the relatively low total P and Cr soil concentrations measured in the biocells and buffer wooded zones were due to their high infiltration rates. Although a number of researchers have documented removal rates for pollutants in stormwater control practices (Hatt et al. 2009; Wilkins et al. 2015), few have examined nutrient and metal concentrations retained within the practice substrates themselves. The data from our study are therefore helpful for understanding the capacity of these practices for pollutant retention/storage.

Detailed Analysis of City Hall Bioretention Cell. Mean NO_3^- concentrations were significantly greater in the surface two increments of the soil core samples ($p < 0.0001$) and decreased with depth (table 8). Ammonium and total P concentrations were significantly lower in the surface two core increments and increased with depth. Percentage organic matter was significantly greater in the surface core increment. Cadmium and Cr concentrations did not vary with depth. Zinc concentrations in the surface increment of soil cores were significantly higher than for deeper core increments ($p = 0.0001$). Soil pH was significantly lower at the surface compared to the other depth increments (table 8).

We were surprised to find that NH_4^+ concentrations increased with soil depth and NO_3^- concentrations decreased with depth in the City Hall bioretention cell. Typically NH_4^+ is oxidized through the nitrification process under aerobic conditions to form NO_3^- (Rittman and McCarthy 2001). However, anoxic conditions created by soil saturation would prevent nitrification, resulting in high retention of both NH_4^+ and NO_3^- (Baker and Vervier 2004; Dietz and Clausen 2006; Forshay and Stanley 2005). Dissimilatory NO_3^- reduction to NH_4^+ is another mechanism that could explain the increase of NH_4^+ in cores from greater depths in this biocell (Sgouridis et al. 2011). Lastly, higher concentrations of NH_4^+ with depth could simply be a result of leaching due to high sand content (55.5%) and high infiltration rates. Sandy soils, which have low ionic sorption capacities and provide more pore space for water percolation, would speed up movement of nutrients and limit opportunities for retention and more typical chemical transformations (McPharlin et al. 1994; Pathan et al. 2002).

Total P concentrations increased with depth in this biocell. This may be related to the substrate mixture (60% compost) releasing P that then accumulates at depth. For example, Paus et al. (2014) found that P was released at 203 ± 24 mg P kg^{-1} of soil media in the compost column of bioretention cells they studied. Other researchers have also found that bioretention cell soil media with high concentrations of organic matter can release both organic and inorganic P during decomposition, which could be transported to greater depths (Hatt et al. 2009; LeFevre et al. 2015).

Concentrations of Cd and Cr were generally low and did not vary with core increment depth. In previous research, Cd has been shown to accumulate in the surface layers of bioretention cells, thus the low and consistent concentrations we observed probably indicate low input from the surrounding contributing areas (Udom et al. 2004; Wang et al. 2016). Zinc concentrations were considerably higher in the surface core increments we tested, indicating contributions from the surrounding parking lot (due to residue from rubber tires, vehicle exhaust, and motor oil additives) and high adsorption/low mobility of this metal. Other studies have also shown that bioretention cells can effectively immobilize Zn from stormwater runoff (Davis et al. 2003; Li and Davis 2009). Levels of total extractable hydrocarbons, gasoline, and *E. coli* were also significantly greater at the surface and did not accumulate at greater depths. This suggests the bioretention cell is effectively retaining these pollutants, although further investigations of inflow and outflow water would be necessary to verify that function (Chapman and Horner 2010). Overall the pollutant removal per-

Table 5

Stormwater best management practice (BMP) water holding capacities prior to sampling based on practice dimensions (biocells) or estimated root depth in soil (prairie landscape areas and buffer prairie and wooded zones).

BMP type/site	Volumetric water content ($cm^3\,cm^{-3}$)	Practice depth (cm)	Depth of water held (cm)	Practice volume (m^3)	Volume of water held (m^3)
Bioretention cells					
Summerbrook Park	0.15	76.20	11.51	26.52	4.00
Edison Street	0.29	60.96	17.43	87.17	24.93
City Hall parking lot	0.33	91.44	29.72	33.80	10.99
Reconstructed prairie areas					
Ada Hayden Heritage Park	0.20	91.44	18.20	2,998.32	596.67
Iowa Assoc. Municipal Utilities	0.38	91.44	34.29	9,282.07	3,480.77
Stange Road	0.25	91.44	22.95	1,022.40	256.62
Urban riparian buffers					
Daley Park prairie zone	0.24	91.44	21.21	3,352.50	820.69
Daley Park wooded zone	0.30	91.44	25.97	1,949.88	581.84
Summerbrook Park prairie zone	0.33	91.44	28.44	3,202.02	1,065.95
Summerbrook Park wooded zone	0.53	91.44	43.89	2,862.63	1,506.88

Table 6

Means, difference of means, and standard errors for each stormwater management practice type for effluent runoff water nitrate (NO_3^-), total phosphorus (P), and chloride (Cl^-) concentrations. Means for the same set of three contributing areas are used for comparison to all practices using student's *t*-tests.

Effluent runoff concentration	*n*	Means	Difference of means	Std. err.	*p*-value
NO_3^- (mg kg^{-1})					
Bioretention cell	3	0.10	0.08	0.10	0.453
Reconstructed prairie	8	0.14	0.04	0.07	0.596
Buffer prairie zone	5	0.15	0.03	0.08	0.716
Buffer wooded zone	6	0.28	0.10	0.08	0.211
Contributing areas	9	0.18			
Total P (mg kg^{-1})					
Bioretention cell	3	0.34	0.28	0.14	0.053
Reconstructed prairie	8	0.25	0.36	0.10	0.001
Buffer prairie zone	5	0.34	0.27	0.11	0.027
Buffer wooded zone	6	0.30	0.31	0.11	0.008
Contributing areas	9	0.61			
Cl– (mg kg^{-1})					
Bioretention cell	3	0.96	1.49	0.89	0.108
Reconstructed prairie	8	0.70	1.74	0.65	0.013
Buffer prairie zone	5	1.66	0.79	0.75	0.301
Buffer wooded zone	6	0.95	1.49	0.71	0.044
Contributing areas	9	2.45			

Table 7

Means and difference of means for surface soil sample concentrations of nitrate (NO_3^-), ammonium (NH_4^+), total phosphorus (P), zinc (Zn), chromium (Cr), and total extractable hydrocarbons. *P*-values for comparisons between stormwater practices and their contributing areas are based on pairwise student's *t*-tests.

Soil nutrient or metal concentrations	*n*	Mean	Difference of means	Std. err.	*p*-value
NO_3^- (mg kg^{-1})					
Bioretention cells	9	7.2	4.5	3.2	0.195
Reconstructed prairies	9	1.3	1.5	3.2	0.654
Buffer prairie zones	6	7.2	4.4	3.5	0.243
Buffer wooded zones	6	2.1	0.7	3.5	0.844
Contributing areas	9	2.8			
NH_4^+ (mg kg^{-1})					
Bioretention cells	9	2.3	2.2	1.1	0.095
Reconstructed prairies	9	3.5	0.9	1.1	0.419
Buffer prairie zones	6	4.5	0.0	1.3	0.980
Buffer wooded zones	6	4.4	0.1	1.3	0.929
Contributing areas	9	4.5			
Total P (mg kg^{-1})					
Bioretention cells	9	88.0	17.3	33.8	0.622
Reconstructed prairies	9	91.7	21.0	33.8	0.552
Buffer prairie zones	6	100.5	29.8	37.8	0.453
Buffer wooded zones	6	49.5	21.2	37.8	0.591
Contributing areas	9	70.7			
Zn (mg kg^{-1})					
Bioretention cells	9	39.7	1.3	31.6	0.967
Reconstructed prairies	9	62.3	21.3	31.6	0.518
Buffer prairie zones	6	47.5	6.5	35.3	0.858
Buffer wooded zones	6	110.5	69.5	35.3	0.084
Contributing areas	9	41.0			
Cr (mg kg^{-1})					
Bioretention cells	9	7.1	8.2	2.8	0.020
Reconstructed prairies	9	19.0	3.6	2.8	0.232
Buffer prairie zones	6	14.5	0.8	3.2	0.799
Buffer wooded zones	6	9.3	6.0	3.2	0.093
Contributing areas	9	15.3			
Total extractable hydrocarbons (mg kg^{-1})					
Bioretention cells	9	88.0	30.0	82.2	0.734
Reconstructed prairies	9	41.7	16.3	82.2	0.852
Contributing areas	9	58.0			

formance lifetime of bioretention cells is relatively unknown due to the limited existing research. Predicting the bed life of a bioretention cell has been suggested to be challenging due to the variability in failure mechanisms (hydraulic, or loss of pollutant absorption capacity) and the variability over space and time (LeFevre 2015).

Summary and Conclusions

Uncertainties about performance, design guidelines, lack of public acceptance, and limitations on space available to install practices that control runoff generated in urban settings can be impediments to stormwater BMP implementation. We conducted this research to provide locally derived data on the effectiveness of a set of BMPs under current and anticipated future precipitation regimes. All practices observed in this study were characterized by relatively high infiltration rates and demonstrated capacity to contain water and pollutants compared to contributing areas, strongly supporting increased use of such BMPs to capture and process stormwater. Further, these practices were successfully retrofitted into a variety of existing land uses under the purview of either municipal governments or a commercial entity, indicating that the application of BMPs does not have to be limited by urban land use or space constraints.

The physical properties of the substrates used in the bioretention cells we examined contributed to high infiltration rates, longer time-to-runoff, and greater pollutant accumulation compared to contributing areas. Additional design adaptations could include expansion of practice surface areas to enhance their performance during anticipated frequent intense storm events, and by customization of substrate amendments for removal, absorption, and transformation of the specific pollutants expected in the landscapes where biocells are to be installed. For greatest effectiveness, biocell installation should include placement of curb cuts for street-side stormwater entry, as well as installation of forebays at the point(s) of entry to capture sediment and prevent surface clogging.

Benefits of native (reconstructed prairie) landscaping include ease of integration in a variety of urban settings, reduced need for maintenance (e.g., regular irrigation and/or mowing), and creation of habitat that could support other forms of native biodiversity. Based on the sites we studied, application of soil amendments prior to establishment of native plants is probably necessary to increase infiltration rates and capacities of these features by decreasing bulk density and through increasing plant density (Singer et al. 2006).

The three-zone buffers observed in this study provided surfaces that stormwater could flow over or through. Buffer wooded zones closest to the streambanks performed very well for infiltration and absorption. Further, although full-stream-length buffers are known to be most effective, urban riparian buffers (including those observed in this study) function adequately even when implemented on a more limited reach-scale to accommodate existing infrastructure or fit within space under direct municipal management (e.g., public parks).

We determined that even though most of the BMPs we assessed are somewhat undersized, they do have greater infiltration rates and absorption capacities than their surrounding contributing areas and likely provide adequate source control for frequent low-intensity rain events. We observed some pollutant accumulation in the BMPs

Table 8

Detailed analysis of City Hall bioretention cell. Six soil cores were extracted to a depth of 50.8 cm and divided into four, 12.7 cm segments. Depth increments are labeled as follows: A = 0 to 12.7 cm, B = 12.7 to 25.4 cm, C = 25.4 to 38.1 cm, and D = 38.1 to 50.8 cm. *P*-values are based on comparisons using student's *t*-tests. Means within a column with the same letter are not different at $p = 0.05$.

Depth Increment	Mean	Mean difference	*p*-value
Nitrate (mg kg^{-1})			
A	3.35a		
B	1.23b	2.12	0.0001
C	0.76b	2.58	0.0001
D	0.30b	3.05	0.0001
Ammonium (mg kg^{-1})			
A	1.85a		
B	2.83a	0.98	0.6308
C	9.77b	7.92	0.0008
D	15.85b	14.0	0.0001
Total phosphorus (mg kg^{-1})			
A	114.7a		
B	120.3a	5.67	0.7244
C	130.2a	15.50	0.3397
D	158.8b	44.16	0.0114
Organic matter (%)			
A	7.23a		
B	3.55b	3.63	0.0001
C	2.88b	4.35	0.0001
D	3.43b	3.80	0.0001
Cadmium (mg kg^{-1})			
A	2.02a		
B	2.00a	0.02	0.1727
C	2.00a	0.02	0.1727
D	2.00a	0.02	0.1727
Chromium (mg kg^{-1})			
A	6.30a		
B	6.16a	0.13	0.7969
C	6.62a	0.32	0.5426
D	6.53a	0.23	0.6529
Zinc (mg kg^{-1})			
A	65.33a		
B	30.83b	34.50	0.0001
C	30.33b	35.00	0.0001
D	29.66b	35.66	0.0001
pH			
A	8.08a		
B	8.31b	0.22	0.0449
C	8.30a	0.22	0.0527
D	8.38b	0.30	0.0098
Total extractable hydrocarbons			
A	200a		
B	28.2b	171.8	0.0040
C	14.8b	185.2	0.0022
D	90.0a	110.0	0.0504
Gasoline (mg kg^{-1})			
A	45.5a		
B	3.0b	42.5	0.0001
C	3.0b	42.5	0.0001
D	3.0b	42.5	0.0001
E. coli (mg kg^{-1})			
A	30.4a		
B	3.1b	27.3	0.0030
C	3.1b	27.3	0.0031
D	3.0b	27.4	0.0030

we studied, and suggest that future research could more intensively investigate this aspect of BMP performance. Because our findings clearly indicate these features are effective from a biophysical perspective, we also suggest that additional research on the social aspects of practice adoption (e.g., design, governance, and cost) may be helpful to support increased implementation of stormwater BMPs.

The conservation implications of this study are that vegetated source-control BMPs are effective, that increased implementation of these practices is warranted, and that modifications to design criteria for such practices could provide additional protection for surface water systems (streams, rivers, and lakes). Such modifications would enhance the performance of BMPs to protect surface waters from impacts of peak runoff flows and the pollutants they often carry in urban areas, particularly under predicted future climate scenarios.

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