From Design to Construction: Lessons Learned about Bioretention Performance

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Background

Bioretention systems have become one of the most widely used stormwater best management practices (BMP) since its development in the early 1990's in Prince George's County, Maryland. Their implementation is critical for urban environments as studies have shown their effectiveness in stormwater and combined sewer overflow management (Patwardhan et al. 2005; Zhen et al. 2006). As such, they are encouraged by many state and local governments through incentives and are sometimes required through stormwater management ordinances. As bioretention systems increase visibility in the urban environment and become permanent urban infrastructure, proper procedure in maintaining visually appealing systems is necessary.

Research, both of field and laboratory studies, have shown the effectiveness of bioretention systems on reducing stormwater runoff quantity (Chapman and Horner 2010; Zimmer et al. 2007) and removal of heavy metals and pollutants (Davis et al. 2001; Davis et al. 2003). Further, research has highlighted the importance of vegetation and appropriate plant selection as a parameter in pollutant/nutrient removal (Lucas and Greenway 2008) and water absorbing capacity for runoff retention (Bratieres et al. 2008). Though research has shown the importance of vegetation on bioretention system performance, little research has been conducted on overall planting success. There remains limited literature available to designers regarding specific planting recommendations based on bioretention vegetation survivorship.

However, as bioretention systems become more widely used, poor and variable design, construction, and maintenance practices remain a concern. Improper soil mixture selection and placement have resulted in poor infiltration rates (Cosgrove and Bergstrom 2003) and unequal ponding (Carpenter and Hallam 2010). As maintenance practices evolve, researchers have called for an emphasis on maintenance recommendations (Davis et al. 2009).

In order for bioretention systems to be successful close coordination from design to construction to maintenance and monitoring needs to be practiced. Lack of communication between designers and contractors can lead to specifications that call for materials that are unavailable (e.g. filter media, plant species) and poor oversight of the installation process. Further, lack of coordination can lead to improper maintenance protocol and poor success of vegetation.

To understand the relationship between design, construction, and maintenance of bioretention systems, this study focused on bioretention cells designed and installed under Onondaga County's Save the Rain program in central New York. Save the Rain is a comprehensive stormwater program implemented to reduce pollution into Onondaga Lake and its tributaries. The program has implemented 175+ green infrastructure projects to reduce overflow of the combined sewer system during extreme rain events. Over 30 of the projects include bioretention as the focus of reducing stormwater runoff (Save the Rain).

Study Objectives

Save the Rain provided an opportunity to study the inconsistencies from design, construction, and maintenance of bioretention systems and how these variables impact vegetation success. This study was intended to specifically address the following questions: (1) Are soils installed accurate to the designer's original specifications?, (2) Do more detailed planting plans lead to more successful plantings?, and (3) Does a higher maintenance level positively impact vegetation performance?

Methods

Site Selection

Ten bioretention cells were surveyed in Syracuse, NY during June and July 2015. Save the Rain program requirements called for soils at all sites to follow the same specifications, so contractors were varied between sites to understand if soils were installed differently than specified. Sites were all constructed three to four years prior to this study and varying sizes and contexts were included to introduce variables in planting design and site conditions.

Field Data Collection and Analysis

To test the soils, all existing mulch and sediment was removed to gain access to the S1 (plant root growing medium) soil layer. The first six inches of the S1 soil was collected, using a core soil sampler at each site's inflow, emergency overflow, and two places near the center. At five sites there were several inflow points and/or emergency overflow locations, so it was assumed any single point would be characteristic of the drainage area. Soils were air-dried at room temperature.

Soil samples were analyzed for organic matter, pH, phosphorus, nitrogen, and texture (sand, silt, clay) at SUNY-College of Environmental Science and Forestry's Forest Soils Research Laboratory. Soil analyses were compared to the specified ranges provided by Onondaga County's Save the Rain technical documents.

Vegetation assessments were conducted visually at a single point in time for each species providing an indicator of overall vigor, branch and foliage density, leaf shape and condition. An additional metric, survivability, was needed for perennials and grasses to measure the planting success of groups. Survivability was assessed visually to compare observed establishment to what was intended from planting plans. Separate assessments were completed for species that had two or more separate and distinct planting groups at a site. Time of year observed, age of plantings, and initial planting size/age were taken into account for vegetation assessments. Original planting specifications were reviewed for base information. Trees and ground cover were not included in the analysis because of small sample sizes.

Maintenance

Maintenance was assessed using Save the Rain maintenance protocol and comparing the protocol to observable practices at each site. Discussing maintenance practices with Save the Rain personnel was an objective to understand specific maintenance concerns/successes at specific sites. Attempts to contact administration personnel responsible for overseeing maintenance was unsuccessful. Administration was willing to send maintenance technical documents but was unable to discuss specific maintenance practices.

Results

Site Parameters

Sites were constructed in 2011 (n=3) and 2012 (n=7), varied in area from 63 m² to 858 m², owned by City of Syracuse, and included five different contractors. Contextual land use included paved (n=6), grass (n=3), and paved/grass (n=1). Seven sites included detailed planting plans (i.e. single plant species identified to specific planting location) and three sites had nondetailed planting plans (i.e. two or more species assigned to a specific planting location via hatching) (Table 1). All sites had at least one runoff entry point (inflow) and one emergency overflow.

Table 1. Study sites and parameters including year completed, area, land use type, planting plan specifications, and contractor.

| Site	Year Completed	Area (sq. meters)	Land Use	Planting Plans	Contractor
Barker	2012	138	Grass	Non-detailed	John R. Dudley Construction
Genesee	Estimated 2011	49	Paved	Detailed	Barrett Paving Materials
Hazard 1	2012	72	Paved	Detailed	Davis Wallbridge
Hazard 2	2012	35	Paved	Detailed	Davis Wallbridge
Leavenworth 1	2012	63	Paved	Detailed	John R. Dudley Construction
Leavenworth 2	2012	59	Paved	Detailed	John R. Dudley Construction
Pass 1	2011	226	Grass	Detailed	Economy Paving
Pass 2	2011	858	Grass	Detailed	Economy Paving
South State	2012	43	Paved	Non-detailed	Davis Wallbridge
Sunnycrest	2012	533	Paved/Grass	Non-detailed	ACTS II Construction

Soil Analysis

Organic matter, pH, phosphorus, and texture were found to range from 1-3%, 7.9-8.7, 035ppm, and 83-88% (sand), 7-10% (silt), and 5-7% (clay), respectively; compared to specified ranges of 2-4%, 5.5-6.5, 20-100ppm, and 78-89% (sand), 6-12% (silt), and 3-6% (clay), respectively (Table 2).

Table 2. Study sites, original soil specifications, and analyzed soil ranges.

|	Organic Matter (%)	pH	Phosphorus (ppm)	Sand (%)	Silt (%)	Clay (%)
Specified Range	**2-4**	**5.5-6.5**	**20-100**	**83-88**	**6-12**	**3-6**
Barker	2	8.1	0.00	88	7	5
Genesee	3	8.0	34.51	85	9	6
Hazard 1	2	8.1	0.00	86	8	6
Hazard 2	2	8.1	0.00	86	8	6
Leavenworth 1	2	7.9	0.01	86	9	5
Leavenworth 2	2	8.1	0.00	86	8	6
Pass 1	1	8.1	6.29	86	8	7
Pass 2	2	8.1	11.88	87	7	7
South State	2	8.7	0.19	84	10	6
Sunnycrest	2	7.9	14.09	88	7	5

Vegetation Assessments

At the ten sites, a total of 49 nursery stock species were originally planted including six species of trees, 10 species of small trees/shrubs, 17 species of perennials, 12 species of grasses, and four species of groundcover. Vegetation vigor and survivability varied between sites (Figure 1, Figure 2, Figure 3). Of the originally planted nursery stock, six were not observed at the time of the study, due to either lack of surviving or not being planted. Total species per site ranged from two to 15. Two species were common among six sites, one common among five sites, four common among four sites, four common among three sites, 12 common among ten sites, and 26 found only at one site.
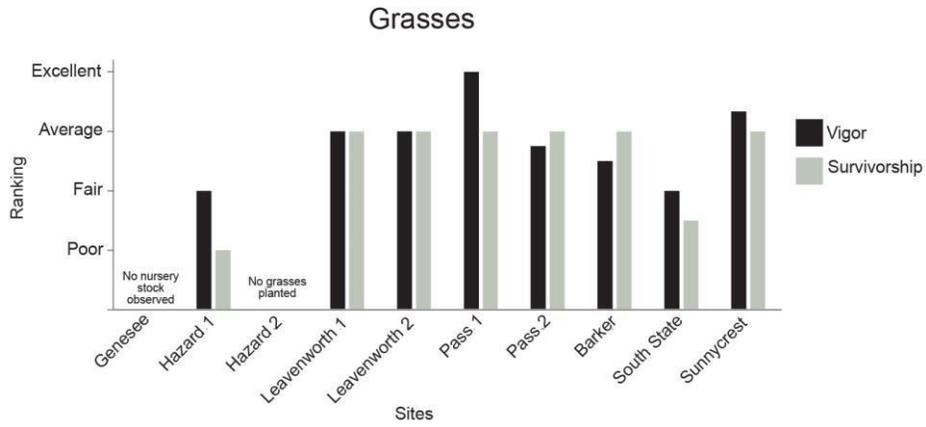
Figure 1. Average vigor and survivorship of grasses among sites.
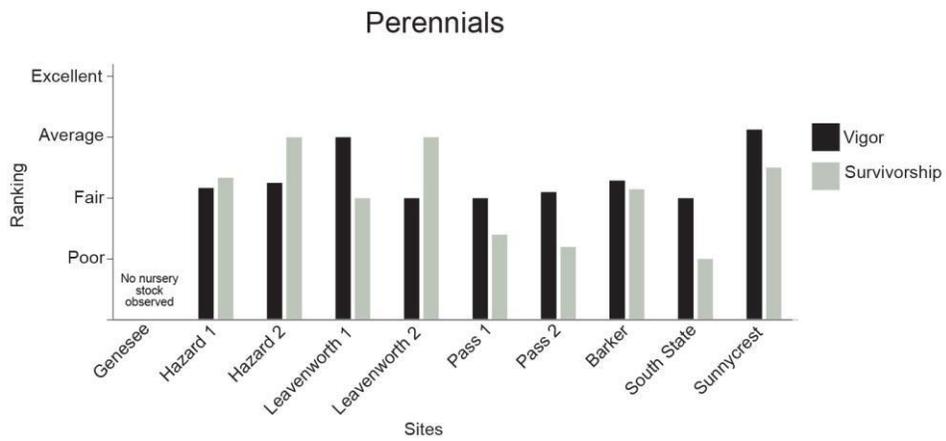
Figure 2. Average vigor and survivorship of perennials among sites.
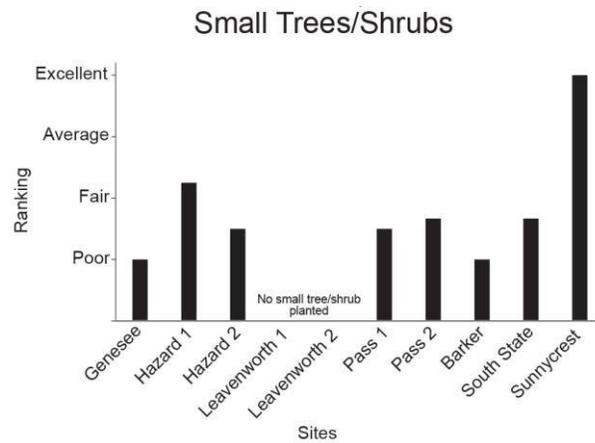
Figure 3. Average vigor small trees/shrubs among sites.

Discussion

Soils

      Installed soils were generally similar to original specifications. Clay content and organic matter differed from specified ranges by no more than 1%. Measured soil phosphorus ranged from 0.00 – 34.51 ppm, well below what was originally specified. It is assumed original phosphorus levels were higher. Soil pH also varied from original specifications, measuring from 7.9 to 8.7. There was a discrepancy between supplied soil and specific soil. Reviewing soil sign off sheets revealed that the soil supplied had considerably higher pH than specified.

      The planting design and species selection seems appropriate for the original soil specifications, though much variation in plant vigor and survivability was observed among sites. Variation in plant performance can be attributed, in part, to the original high soil pH as well as local conditions that exacerbate salt and pH issues.

Vegetation and maintenance/construction

      Vegetation survivability and vigor varied, with all sites exhibiting some poor performance, and with low survivability and vigor commonly associated with edge plantings at all sites, except Sunnycrest. Edge plantings, regardless of species, showed diminished growth, low branch/foliage density, and low group survivability when compared to inner region plantings. Poor performance of edge plantings may be attributed to higher stress environments related to heat, compaction, and salt, specifically when planted adjacent to hardscapes.

      Similar to Cosgrove and Bergstrom (2003) and Chavez et al. (2015), vegetation survivability varied in relation to maintenance and design specifications. Among sites with poor maintenance and inadequate site design, species survivability and distribution was low when compared to original planting specifications. East Genesee and South State showed a lack of post installation maintenance, specifically in regards to removal of sediment build up. Large amounts of sediment buildup were evident across the surface East Genesee and South State and around emergency overflows (Figure 4, Figure 5). Three of seven nursery stock species were observed at East Genesee including two woody plants (*V. angustifolium* 'Top Hat' and *C. caroliniana*), with

Figure 4. Lack of sediment removal from South State resulting in homogenous topography and sediment build-up around site emergency overflow.

Figure 5. Sediment build-up around the inlet of East Genesee, resulting in poor vegetation establishment and a compacted surface layer.

V. angustifolium 'Top Hat' standing but dead, and one grass (*S. scoparium*). *C. caroliniana* and *S. scoparium* were in very poor health and only one individual of *S. scoparium* was observed. The rest of East Genesee was established with volunteer species. Chavez et al. (2015) showed similar results when reviewing vegetation survivorshop within seven bioretention cells in Oklahoma. Their 2015 study showed an overall decline in nursery stock species which gave way to volunteer species recruitment. South State showed consistently low plant vigor and survivability, which can in part be attributed to sediment build up. South State shows evidence of

water transporting mulch and sediment throughout the site, specifically built up around the emergency overflow, which created a topographically homogenous site.

Pass 1 and Pass 2 showed low vegetation survivability around inlets and areas of high erosion. Both sites showed evidence of high water velocity entering the site through inlets and creating surface preferential flow paths and soil and mulch erosion around inlets (Figure 6, Figure 7). Pass 2 also exhibited erosion on banks (Figure 8). The cause of erosion was identifiable to water velocity near inlets, but the cause of erosion on the slopes was unclear. Due to a serious lack of vegetation and severe displacement of soil, erosion on the slopes was likely occurring well before the start of this study.

Figure 6. Erosion and preferential surface flow path from inlet at Pass 1, resulting in poor vegetation vigor and survivability.

Figure 7. Erosion surrounding inlet from Pass 2, resulting in poor vegetation vigor and survivability.

Figure 8. Erosion on bank of Pass 2, resulting in poor vegetation vigor and survivability.

Vegetation survivability and vigor was considerably higher at Sunnycrest than any other site. Most notably, *I. verticillata*, which was planted on a hillex in the center of the Sunnycrest cell, had excellent overall vigor while *I. verticillata* had poor vigor where found at four other sites. Vegetation success can in part be attributed to proper planting locations based on individual species needs.

Maintenance practices were assessed with limited available resources. Overall, maintenance was poor, specifically in regards to sediment removal, erosion management, and replacement of large swaths of dead vegetation.

Conclusion

Variable design, construction, and maintenance practices related to overall vegetative success. Specifically, poor practices were observed in regards to inlet design, vegetation placement, and removal of sediment. In the case of this study, initial vegetation survivability was poorly considered with installed soil pH considerably higher than species needs. The findings of this study call for increased coordination through the phases of design, construction, and maintenance. Further, concern of low maintenance resources calls for more consideration of less complex planting designs (fewer number of plant species, ease of maintenance). In regards to sedimentation, designs should consider more aggressive weir structures to capture inflow of sedimentation. Such structures will reduce sedimentation buildup in the cells while making sedimentation removal easier.

Overall, this study shows that lack of coordination between design, construction, and maintenance exists and negatively impacts the success of vegetation. There is a need for increased literature for designers regarding proper planting specifications in bioretention systems.

Further Studies

Further studies will be required to better establish bioretention design, construction, and maintenance recommendations. Specific studies should address dynamics of filter media chemistry/composition over time and its impact on vegetation performance, varying maintenance practices impacts on vegetation performance, and comparisons of vigor and survivorshop between types of plantings (e.g. grasses vs. perennials).

Acknowledgements

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