OKLAHOMA BIORETENTION TECHNOLOGY DEMONSTRATION AND THE EFFECTS FILTER MEDIA HETEROGENEITY ON PERFORMANCE

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Abstract: Ten bioretention cells were constructed in Oklahoma as part of a full-scale technology project to demonstrate phosphorus reduction efficiency. The design used a sand/fly ash blend as the filter media, for enhanced phosphorus attenuation, and incorporated surface sand plugs for improved infiltration in poor draining soils. Engineering considerations, general design procedures, site parameters, construction and planting details and costs are documented.

A three-dimensional finite element model was developed to simulate flow through a bioretention cell and address some of the questions that arose during design and construction regarding the effects of soil amendment implementation, and sand plug size and placement on cell performance. Three general configurations were modeled for three different scenarios. A filter-only configuration was evaluated to assess the effect of filter media hydraulic conductivity heterogeneity on flow and transport. The second configuration added a top soil and sand plug layer with 6 sand plugs measuring 1.5 m by 1.5 m, which was similar to the constructed cells. The final configuration evaluated a top soil and sand plug layer with 14 smaller sand plugs measuring 1 m by 1 m. Three different scenarios were evaluated for each configuration that varied by size and distribution of the filter media heterogeneity. The first scenario used the measured scale and range variability, the second used the same scale with double the variation, and the third used the same variability, but increased the scale volume by a factor of 27.

Model results indicated that variability in fly ash content created complex flow through the filter medium, but did not result in significant preferential flow. Sand plugs created flow concentration but did not dominate flow within the cell, and the number of sand plugs was not significant provided that their total area was sufficient to maintain the desired drainage rate. Mean effluent concentration did not exceed the Oklahoma criterion for scenic rivers until after 22 years and 33 years for the filter only and sand plug configurations, respectively. Modeling predicted more than 144 years of P removal. All distributions show similar removal efficiencies indicating that reasonable mixing effort will enable proper cell performance.

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CHAPTER I

INTRODUCTION

Background Information

Grand Lake, located in northeastern Oklahoma, drains a total of 10,298 square miles from Kansas, Missouri, Arkansas and Oklahoma, with three major rivers contributing to the reservoir: the Neosho River, the Spring River, and the Elk River. Designated beneficial uses for the lake include: public and private water supply, agriculture, municipal and industrial uses, hydroelectric power generation, recreation, warm water fish habitat, and aesthetics. The area surrounding Grand Lake also supports a robust tourist industry, so the health of the lake is important to the economies of the local communities.

The Clean Lake Study by the Oklahoma Water Resources Board (1995) showed that the lake was eutrophic and metals contamination in sediments in the upper portion of the lake. At the time the proposal for the project was submitted, there were streams and rivers in the watershed listed on the U.S.E.P.A. 303(d) list of impaired and threatened waters in three of the four states the watershed resides in. There were 16 segments listed as Category V Waters, impaired and in need of a Total Maximum Daily Load standard (TMDL) in Oklahoma's 2002 integrated report, 303(d) list. Pollutants of concern listed for these stream and river segments were: low dissolved oxygen, chloride, lead, sulfates, pathogens, pH, total dissolved solids (TDS), and turbidity. The 2002 Kansas 303 (d) list included 45 stream/river segments. Pollutants of concern listed were: low dissolved oxygen, eutrophication, fecal coliforms, cadmium, zinc, beryllium, sulfate, lean, copper, siltation, and also failed bioassessments. The 2002 Missouri 303(d) list included 20 stream/river segments. Pollutants of concern listed were: zinc, nutrients, biological oxygen demand, fecal coliforms, algae, sediment, and ammonia.

In 2004, the Oklahoma Conservation Commission was awarded a 319 (h) grant from the U.S.E.P.A. to initiate a project to reduce nonpoint source pollution in the Oklahoma portion of the watershed. The Oklahoma Conservation Commission, in turn, teamed up with Oklahoma State University. The project was to focus on water quality problems associated with eutrophication including sediment, nutrients, and fecal bacteria through monitoring, planning, demonstration and education efforts. Some of the tasks for the project included reducing nutrient loss from lawns, gardens, parks, and golf courses; soil evaluation for accurate on-site residential septic system design; developing and implementing Total Phosphorus and Chlorophyll-a monitoring; supporting and expanding volunteer monitoring in the area through the Blue Thumb program; and design and implementation of 10 bioretention cells as part of the bioretention cell design, evaluation and technology demonstration task.

Scope and Objectives

Bioretention cells are an accepted stormwater management technology first developed in Prince George's County, Maryland in 1993. Though, a fairly young technology, they are one of the most common stormwater control measures used in the United States (Hunt et al., 2012). They are, in essence, "functional landscaping" and offer a range of potential benefits through physical, chemical and biological processes. Potential benefits include increased infiltration, reduced peak runoff, and contaminant attenuation. Over time, it is becoming apparent that a "one size fits all" to bioretention design is outdated and designs need to target specific contaminants based on need (Hunt et al., 2012). Considerable research has focused on phosphorus attenuation (Zhang et al., 2008; Roy-Poirier et al., 2010; Lucas and Greenway, 2011; Hunt et al., 2012; Komlos and Traver, 2012; Winston et al., 2013; Liu and Davis, 2014), thus, the use of bioretention for the Oklahoma demonstration project described above.

Ten bioretention cells were constructed in Oklahoma in 2007 and 2008 to demonstrate the effectiveness of the technology for phosphorus attenuation, one of the main contaminants in the Grand Lake watershed. Zhang et al. (2008) studied several potential soil amendments for enhanced P adsorption. A blend of sand and 5% fly ash by weight met the hydraulic conductivity of 2.54 cm/hr or greater recommended by Prince George's County (2002) and showed the most potential for phosphorus reduction efficiency in lab column and batch sorption studies. The design also inlcuded surface sand plugs for improved infiltration in local, poor draining soils.

Chapter 2 presents an overview of the design and construction of the ten bioretention cells implanted in Oklahoma as part of the 319(h) funded project. Bioretention cell design included soil amendments for enhanced phosphorus adsorption and surface sand plugs for improved infiltration. This chapter includes engineering considerations, general design procedures, site parameters, construction specifications, construction costs, planting success and costs, and lessons learned. Design and construction rasied the following questions that the author attempted to address in subsequent chapters:

- How do sand plugs interact with the filter media?
- How does the variability in fly ash content impact the flow and phosphorus transport through the filter?
- How does mixing effort impact performance? Degree and scale of variation?
- How does the construction design impact P transport?

- How does the variability of fly ash content impact the expected BRC life span?
- How can we use this information to improve cell design and construction practices?
- What does this mean in terms of long term planning?

Chapter 3 explores the questions raised during construction of the bioretention cells for the demonstration project. Samples collected from the filter media during construction exhibited heterogeneity in fly ash content, as well as the hydraulic conductivity of the filter media due to the pozzolanic nature of fly ash. A three-dimensional finite element model was developed using COMSOL Multiphysics to simulate saturated flow through bioretention cells to: determine the impact of flow within a bioretention cell due to spatial heterogeneity in the filter media hydraulic conductivity, evaluate the importance of size and placement of sand plugs on flow within the filter, establish how the scale of hydraulic conductivity heterogeneity affected flow through the cell, and determine the implications of mixing effort in filter media placement.

Chapter 4 builds on the model that was presented in the previous chapter by looking at the effects of spatial heterogeneity in the filter media on phosphorus attenuation. A linear isotherm was used to model transport where the isotherm coefficients were correlated to the heterogeneity of the fly ash contents to estimate cell life expectancy, determine the effects of variability due to soil amendment mixing effort on phosphorus transport, and to show how lack of long term monitoring data makes modelling necessary for long term planning.

Chapter 5 presents a summary of findings, engineering contributions and recommendations for future work.

Co-Authorship

Chapters 2 and 3 included in this dissertation have been published in peer-reviewed journals. The work presented was carried out by Rebecca Chavez, with the assistance of the following co-authors:

- Chapter 2: Glenn Brown, Reid Coffman, and Daniel Storm
    - Published in Applied Engineering in Agriculture, ASABE, in March 2015.
- Chapter 3: Glenn Brown and Dan Storm
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CHAPTER II

DESIGN, CONSTRUCTION AND LESSONS LEARNED FROM OKLAHOMA BIORETENTION CELL DEMONSTRATION PROJECT

Abstract

Ten bioretention cells were constructed in Oklahoma to demonstrate the effectiveness of the technology for stormwater runoff volume reduction and phosphorus attenuation. The cells embraced a variety of land uses including residential, public, and commercial and ranged in volume from 19 to 435 m^3. Designs featured sand plugs in the top soil layer for improved infiltration, and 1:1 side slopes for safety during construction. A blend of sand and 5% fly ash was used as the filter layer medium to enhance phosphorus attenuation. Of the ten cells, eight were installed by a contractor selected through a formal state bidding process during Summer 2007. The remaining two were constructed primarily by Oklahoma State University students and staff in Spring 2008. This article explores engineering considerations, general design procedures, site parameters, construction details, planting success and costs. Problems and successes encountered during the construction process are described and a comparison of contracted and in-house construction is presented.

Introduction

Bioretention cells (BRCs) are one piece in the battery of Low Impact Development (LID) technologies. They are popular, widely used throughout the country, and encouraged by government at many levels through ordinances and incentive programs. A BRC is in essence "functional landscaping." Its overall operating premise is that by mimicking nature, stormwater volumes will be reduced and water quality will be improved to predevelopment conditions, while maintaining an aesthetically pleasing appearance. While not a new technology, research on BRCs is ongoing, especially with regard to site and regional specific needs. Davis et al. (2012) stated that BRC design needs to reflect the needs of the geologic and climatic locations to improve hydrologic performance. Furthermore, Hunt et al. (2012) suggested that a "one size fits all" approach to BRC design is outdated and design needs to be focused on targeted treatment mechanisms based on need. Oklahoma has been experiencing water quality issues in streams and reservoirs due to nutrient overload, specifically phosphorus, especially in the northeastern corner of the state. Ten BRCs were constructed in Oklahoma, in a variety of suburban land uses, as part of an ongoing study to demonstrate the effective-ness of this technology on both hydrology and water quality. Eight are located in Grove, and two are located in Stillwater, in northeastern and north central Oklahoma, respectively. The climates at both locations are similar. Construction for eight of the BRCs was formally bid through the Oklahoma Department of Central Services, requiring a complete Plans, Specifications, and Estimate (PS&E) package. The two cells in Stillwater were constructed 'in-house' with only the excavation being contracted out. Of the ten BRCs, two are residential properties, six are public or municipal properties, and two are commercial properties. The drainage areas of the cells vary from parking lots, to roofs, to lawns. This article provides an overview of the engineering considerations, general design procedures, site parameters, construction specifications, construction costs, planting success and costs, and lessons learned during construction.

Site Parameters

Sites were chosen based on grade, location, drainage area, visibility, and access. Table 2-1 lists the sites chosen for BRC installation with approximate location, property type, land use, and drainage area. Of the sites listed, two are commercial properties, two are residential, and six are public. Land use includes both paved and grass. One site had a paved surface and grass surface that were approximately equal, and one had its runoff is intercepted primarily from a roof surface. Drainage areas vary from 0.045 to 0.77 ha, with all but one being less than 0.40 ha.

Elm Creek Plaza and Cherokee Queen Riverboats are commercial sites. The former is a busy shopping center, and the latter is a restaurant and entertainment venue. Both cells capture runoff from the parking lots at their respective sites, which would otherwise flow directly into a water body: a creek in the case of Elm Creek Plaza, and Grand Lake in the case of Cherokee Queen Riverboats.

Table 2- 1. List of sites designated for BRC installation in Grove and Stillwater, including approximate location, property type, land usage, and drainage area.

Site	Approximate Location	Property Type	Land Use	Drainage Area (Hectares)
Elm Creek Plaza	36˚34’47” N, 94˚46’08”W	Commercial	Paved	0.25
Lendonwood Gardens	36˚34’59” N, 94˚47’13”W	Public	Turf	0.22
Grove High School	36˚37’19” N, 94˚44’50”W	Public	Paved	0.65
Grand Lake Association	36˚36’39” N, 94˚48’14”W	Public	Paved/Turf	0.77
Cherokee Queen Riverboats	36˚38’05” N, 94˚48’54”W	Commercial	Paved	0.18
Early Childhood Development Center	36˚35’12” N, 94˚46’57”W	Public	Roof	0.04
Private Residence 1	36˚38’59” N, 94˚46’08”W	Residential	Turf	0.16
Private Residence 2	36˚35’18” N, 94˚49’36”W	Residential	Turf	0.07
OSU Botanic Gardens, Cell A	36˚07’00” N, 97˚06’01”W	Public	Paved	0.13
OSU Botanic Gardens, Cell B	36˚07’01” N, 97˚06’01”W	Public	Paved	0.36

Two other facilities are located adjacent to the lake. Private Residence 1 is a single family home with property extending to the lake. The cell was constructed in back in order to intercept runoff from the property before entering directly into the lake. The Grand Lake Association has the largest drainage area of the sites chosen for this project (0.77 ha). Runoff comes from both a parking lot and the lawn.

The cell at Lendonwood Gardens is located in front of the botanical gardens and receives runoff from the gardens themselves. Private Residence 2 is a single family home located adjacent to a golf course. The runoff intercepted by this cell is primarily from the lawn and roof, while a small quantity may be attributed to the golf cart path separating the residential property from the golf course.

Grove High School readily lent itself to BRC. There was an existing swale transporting runoff from the staff parking lot to the storm water drain in the city right-of-way. The cell was designed to fit inside the swale. The Early Childhood Development Center is a new pre-elementary facility, where the cell was placed near the main entrance and receives runoff only from the roof.

Two sites are part of an environmental research and education program in partnership with the Oklahoma State University Botanic Gardens in Stillwater, Oklahoma. Cell A and Cell B receive runoff from a short stretch of roadway serving as an entrance into the botanic gardens and a nearby parking lot, respectively. Both the roadway and parking lot were constructed in Spring 2009.

Cell Design

In general, the designs for this project are consistent with the BRC guidelines set by Prince George’s County (PGDER, 2002), Hunt et al. (2001 and 2005), and the LID Center (2003). Figure 2-1 depicts a typical section of the BRC design for this project. Variations from the references cited include a 1:1 side slope for improved safety during construction, sand plugs for adequate infiltration through the top soil layer, the addition of a blend of sand and fly ash as a filter medium, and vegetation criteria suitable for Oklahoma.

The design can be broken down into six steps: 1) site survey, 2) cell sizing, 3) inlet and overflow bypass design, 4) filter media selection, 5) cell drainage, and 6) top soil, sand plugs, and landscaping. Design specifics are provided in the following sections.

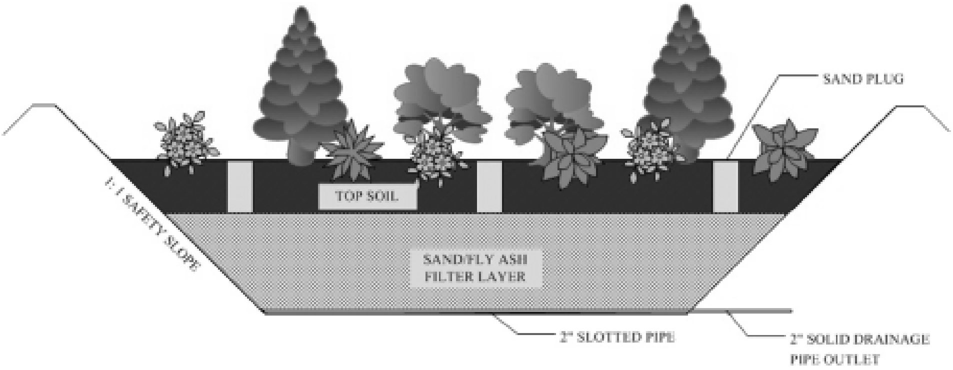

Figure 2- 1. Bioretention cell typical section.

Site Assessment

Site surveys for this project were conducted in three phases. An initial visit was used to evaluate the suitability of each potential site based on visibility for demonstration purposes, access for future sampling, drainage area, and overall cell operation. The second phase included a more thorough survey by collecting GPS data to measure drainage area and existing grade. Drainage areas were kept to less than three acres, 1.21 ha, (LID, 2003). Utility locates were also performed at this point to identify utilities in the vicinity and avoid potential conflicts and obstacles. Finally, soil surveys were conducted at each site using a Gidding's truck mounted hydraulic soil sampling and coring machine to determine soil conditions. The Grove sites had similar soils; thin silt loam top soil overlaying a clay loam with large rocks. The Stillwater site had a deep clay loam. Due to the low permeability of the subsoils ($< 10^{-8}$ m/s), drains were required on all BRCs.

Cell Sizing

BRC sizing is dictated by the selection of the volume of water to be treated. While there is an expectation that the majority of the pollutants will be present in the first flush, there are few supporting data for that assumption. In fact, the available data are highly variable (Lee et al., 2002; Hathaway et al., 2012). This is not unexpected, when one considers variations in watershed size, site conditions, antecedent moisture conditions, and in the definition of the first flush volume itself (Deletic, 1998; Taebi and Droste, 2004; Privette and Weeber, 2007; Batroney et al., 2010). It was arbitrarily decided that the BRCs for this project would catch, by surface ponding, the first 13 mm of runoff from any storm event, with the capacity for an additional 13 mm in the filter layer under dry conditions. Since the volume of the first flush is a function of the drainage area, it follows that the height of the berm and maximum ponding depth are dictated by the cell area and the volume of runoff to be accommodated.

The required filter media volume is usually defined in current practice based on stormwater storage volume (LID, 2003). Similarly, these cells were arbitrarily designed so that the filter porosity is equal to 13 mm of runoff. The filter layer consisted of a blend of sand and 5% fly ash by weight with a porosity of 0.30. Actual design filter depths for the irregular cells shapes were calculated by building a 3D model in Autodesk Inventor (2006). While filter performance was not explicitly considered, the BRC filter depths ranged from 0.85 to 1.5 m, which is consistent with the calculations by Zhang et al., (2008a,b).

The BRC at the Early Childhood Development Center, in Grove, was designed and subsequently constructed with a biozone, which is a saturated anaerobic layer to encourage denitrification. Kim et al. (2003) introduced the idea of an inverted siphon on the drain outlet to create a saturated zone at the cell bottom. Passeport, et al. (2009) and Brown and Hunt (2011) also found that the increased hydraulic retention time and anaerobic conditions, due to the inverted siphon drain configuration, resulted in reduced nitrate concentration in effluent. For the purposes of this project, the biozone consisted of clean sand with a specification that it contains no more than 5% fines. The volume of the biozone was again arbitrarily set to accommodate 13 mm of the runoff. Volume of this layer was calculated using a porosity of 0.39, which is a typical value for clean, uniform sand (Holtz and Kovacs, 1981).

Cell areas for BRCs using sandy soils generally range from 3% to 8% of the drainage area (Hunt and White, 2001). After conforming to landowner preferences, site limitations, the 1:1 side slope, and cell shaping for aesthetics, the final BRCs areas ranged from 1.1% to 11% of the drainage areas.

Inlet and Overflow Bypass

Inlet channel dimensions were calculated using a combination of the rational method for surface flow and Manning's equation. Since the drainage area size was limited to 1.21 ha or less, the rational method was an acceptable means of calculating the expected flowrate into the inlet channel. Intensity was obtained for a 50-year 1-h storm from the Rainfall Frequency Atlas of the United States (Hershfield, 1961). The dimensionless runoff coefficient, C, was assumed to be 0.95 for impermeable surfaces such as pavement and roofs (TXDOT, 2000).

Knowing the expected flow rate into the BRC, Manning's equation was employed to size inlet and outlet channels. Certain conditions were assumed for practicality. The depth of the channel, the slope, and Manning's coefficient, n, were held constant. The shape of the channel was assumed to be rectangular where the width was determined by setting the Manning's equation and the equation for the rational method equal to each other.

An overflow bypass was designed as a weir on the back end of the cell. Values for weir height and total head above the weir were held constant, and the length of the weir was sized using the equation for a broad-crested weir, as defined by Munson et al. (1994).

Filter Media Selection

Filter media selection was based on a series of laboratory experiments conducted by Zhang et al. (2008a,b) to find a cost-effective filter medium with a high capacity for phosphorus and heavy metal sorption, and an adequate hydraulic conductivity. Adequate hydraulic conductivity values were based on recommendations of PGDER (2002), which recommended a minimum value of 25 mm/h, and Hunt (2003) who suggested a desired range from 13 to 50 mm/h. Several materials were considered. However, it was determined that a blend of Dougherty Sand and 5% fly ash by weight best fulfilled the criteria with a distribution coefficient of 398 mL/g, and phosphorus removal of 94.2%, and a hydraulic conductivity, of 39 mm/h. Zhang et al. (2006) also found that hydraulic conductivity decreased exponentially with increasing fly ash content. A point of interest from Zhang et al. (2008b), desorption trials from this study showed negligible desorption of the sand / 5% fly ash blend, indicating that the sorption of phosphorus in a BRC using this filter medium may be irreversible.

Filter Media Installation

Installation of the filter medium consisted of 150 mm lifts to keep the mixture as consistent as possible and to prevent preferential flow through this layer of the BRC. The sand specified in the design was a clean sand with less than 5% fines. Fly ash utilized was class C, obtained from the Chouteau power plant (operated by the Grand River Dam Authority, GRDA, 2006, personal communication, Chouteau, Okla.) for the Grove sites and from the Sooner power plant for the Stillwater site. According to data from Zhang et al. (2008b) and GRDA (2006, personal communication), both plants are fueled with sub-bituminous coal from the Powder River Basin in Wyoming, and chemical analysis of the fly ash showed the materials to be similar.

Sand and fly ash were combined in the field by two means. The first method involved mixing with heavy equipment before placement in the cell. A load of sand was deposited near the cell site and the required amount of fly ash was then mixed into the sand by repeatedly filling the bucket of a front end loader and pouring it back over the pile containing the sand and fly ash, until an even blend was achieved (Figure 2-2). The second method used a roto-tiller to mix media in lifts inside the cell (Figure 2-3). A 150 mm lift of sand was placed into the cell. The appropriate amount of fly ash was then evenly distributed on top and tilled into the sand. While considerable effort was expended on both methods, sampling of the materials during placement showed considerable variation in fly ash content throughout the filter layer. Extensive analysis performed on the effects of the variability on hydraulics within the cells by Chavez et al. (2013) with a 3-D finite element model showed that variability in fly ash content, as relates to mixing method or effort, creates complex flow patterns but does not result in significant preferential flow. Additional analysis included the hydraulic testing of two cells in Grove, Oklahoma by Christianson et al. (2012). The data were then used to validate the ability of a 1-D model to simulate flow through a bioretention cell accounting for heterogeneity in the horizontal plane.

Figure 2- 2. Mixing fly ash into sand for filter layer using heavy machinery prior to placing into cells in 13 mm lifts.

Figure 2- 3. On the left, a Dingo was used to evenly spread out the appropriate amount of fly ash for a filter layer lift. On the right, a roto-tiller was used to mix the soil amendment into the designated lift.

Cell Drainage

Drainage pipes specified for this project were corrugated polyethylene pipes. Sizing for the drainage pipes was based on a modified version of the Darcy-Weisbach Equation, where the slope was assumed to be 1% and the Darcy coefficient was 0.75, to account for the roughness of the pipe. A 51 mm pipe has a capacity of 4.5 x 10^{-3} m^3/s, which is more than adequate for a cell with an area of 232.3 m^2 and a hydraulic conductivity of 36 mm/h. Drainage pipes were covered with filter fabric to prevent clogging and placed on a constant spacing ranging from 1.5 to 2.7 m over the entire cell, depending on the cell size to ensure adequate drainage while considering cost (Figure 2-4). There is also more head on the larger cells allowing for wider spacing between lateral drainage lines than for that of the smaller cells.

Figure 2- 4. Cell drainage pipe layout.

Top Soil, Sand Plug and Landscaping

The topsoil available in Grove, Oklahoma, is a silty loam, with a hydraulic conductivity much less than 25 mm/h. Even blending equal parts sand and topsoil did not provide adequate hydraulic conductivity to ensure infiltration into the filter layer. Sand plugs were introduced to increase infiltration into the cell, and were designed for ease of construction. Clean sand was placed in designated spaces to the specified areas and elevations (0.3 m above the surface of the filter media) to form the sand plugs. Topsoil was then backfilled around them, rendering forms unnecessary (Figure 2-5). The topsoil layer thickness of the BRC was specified as 0.30 m, based on communication with the landscape professional who did the vegetation design for the Grove Cells (Megan Perry, 2006, personal communication, Stillwater, Okla.). Sand plugs were arbitrarily placed, such that no two plugs touched each other (Figure 2-6). The size and number of the sand plugs were dependent on the dimensions of the cell. However, it was determined that the sand plugs should occupy approximately 25% of the topsoil layer. This combined area of the sand plugs was sized to drain the cell within two days, based on one half of sand's hydraulic conductivity, which would allow for clogging over time. The two-day limit on ponding was to prevent mosquito reproduction, since several of the cells were at schools and public locations. Analysis of the effects of sand plugs by Chavez et al. (2013) showed some flow concentration. However, the concentrated flow from the sand plugs did not dominate flow within the BRC, and the number and size of the sand plugs had minimal effect, provided their total area is appropriate to maintain the desired drainage rate. The arbitrary nature of the placement also provided flexibility for optimum placement of vegetation, since vegetation was not to be planted over sand plugs.

Figure 2- 5. Sand plug construction.

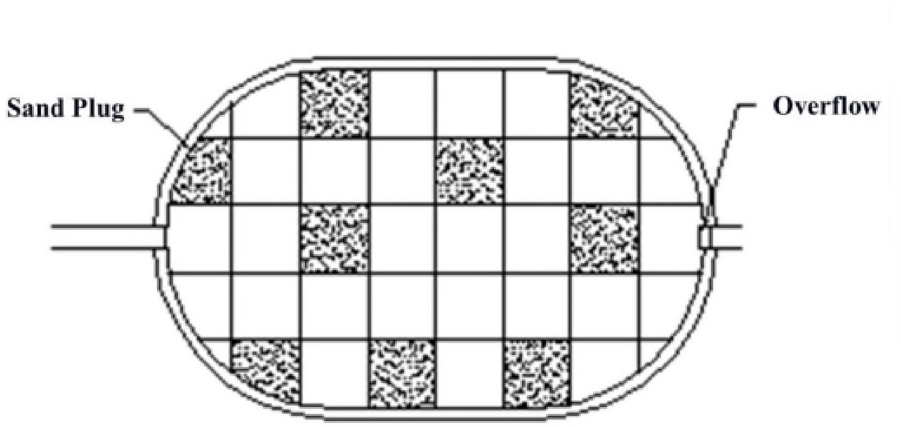

Figure 2- 6. Example of sand plug layout.

Table 2- 2. Target BRC vegetation and accent coverage

Plant Type	Surface Area%
Trees	8 to 10
Shrubs	15 to 20
Flowering Perennials	1 to 5
Ornamental Grasses	10 to 15
Rock Accents	1 to 5

Since BRCs are usually in landscaped areas, plantings should be aesthetically pleasing. With that requirement in mind, the horticultural planting list was developed using the following criteria. Plants had to be: wet and dry tolerant, not N fixers, noninvasive species, low-maintenance, offer color variety, easily attainable and replaceable, and include trees, shrubs, flowering perennials, ornamental grasses, and rock accents.

Native species were included in the list. However their use was limited, since many native plants can only be acquired from specialty nurseries, and the goal of the project was to make BRC technology readily accessible for homeowners and developers. Target vegetation quantities were based on the guidelines presented in table 2-2,as determined by Megan Perry, (2006, personal communication, Stillwater, Okla.) during the vegetation design. Plant species installed in the cells in Grove included: Heritage River Birch, Loblolly Pine Amur Red Maple, Red-Tip Photenia, Golden Euonymus, Dwarf Yaupon Holly, Virginia Sweetspire, American Holly, Fountain Grass, Purple Fountain Grass, Maiden Hair Grass, Great Blue Lobelia, Stella Daylilly, Knockout Rose, Chinese Sedum, Angelina Sedum, and Blue Chip Creeping Juniper. The sedums and juniper were used as ground cover between the large boulders surrounding the cell at Private Residence 1, and the juniper was planted as the vegetative cover on the outside of the berm at the same location. A total of 657 plants were installed at the eight cells in Grove, or approximately one plant per square meter with the large use of trees and shrubs. Installed plants varied in size from 10 cm to 19 L containers.

Construction Costs

The sites listed in table 2-3 were constructed by a contractor selected through a formal state bidding process. All eight sites are located in Grove, Oklahoma. Cost was bid on a volume basis and includes mulch but not vegetation. Cell cost ranged from \$7,368 to \$29,173. Bid costs ranged from \$7,368 at the Private Residence 2, which is the second smallest cell with a volume of 27 m^3, to \$29,173 at the Grand Lake Association, which had a volume of 435 m^3. Overall, the larger cost for the smaller cells is due to flat rates on material delivery and equipment mobilization. The cell at Lendonwood Gardens was the smallest, but cost more per volume, \$465/m^3, to construct because of site conditions requiring the removal of several large trees and traffic control in addition to the costs mentioned previously. Cost per volume of the cell at the Early Childhood Development Center was also on the higher end (\$153/m^3) of the range also, due to increased excavation and fill material costs for the biozone layer.

Final costs for all cells, with the exception of the Private Residence 1, were the same as the bid cost. Increased quanti-ties of sod and soil quantities due to changes in design were responsible for the \$1500 difference between bid cost and final cost for this cell.

Table 2- 3. BRC area, volume and cost as bid and constructed by a contractor in Grove, Oklahoma.

Location	Area (m^2)	Volume (m^3)	Final Cost
Lendonwood Gardens	23	19	\$8,847
Private Residence 2	30	27	\$7,368
Early Childhood Development Center	48	70	\$10,715
Elm Creek Plaza	63	128	\$12,496
Private Residence 1	101	93	\$13,271
Cherokee Queen Riverboats	116	108	\$13,796
Grove High School	149	161	\$17,071
Grand Lake Association	172	435	\$29,173

Table 2-4 lists the design parameters for the two BRCs constructed at the Oklahoma State University Botanic Gardens in Stillwater, Oklahoma. These cells were constructed primarily "in house," with labor from Oklahoma State University students and staff using two tractors, a Dingo TX 425, and a Troy Built Big Red Garden Roto-tiller. Excavation was professionally contracted, though not through a bidding process as were the cells listed in table 2-3. Final costs for both Cell A and Cell B were $4,753 and $11,479, respectively. This was more than the estimated costs due to increased soil stabilization costs (hydromulching in place of sod), an increase in scope for excavation to include the trenching for the drainage outlets, and increased costs for sand, hauling and labor.

A linear regression equation was fit to cell cost as a function of volume for both contractor and in-house constructed cells (Figure 2-7). A difference of approximately $6,000 separates contractor and in-house construction costs for cells of comparable sizes. However, the price difference may decrease as BRC technology becomes more common in the region and contractors learn more about what cell construction entails. Competition may also contribute to a decrease in the cost of contractor constructed projects.

Table 2- 4. BRC area, volume and cost as constructed by Oklahoma State University.

Location	Area (m^2)	Volume (m^3)	Estimated Cost	Final Cost
Cell A	28	66	$3,000	$4,753
Cell B	160	208	$7,000	$11,479

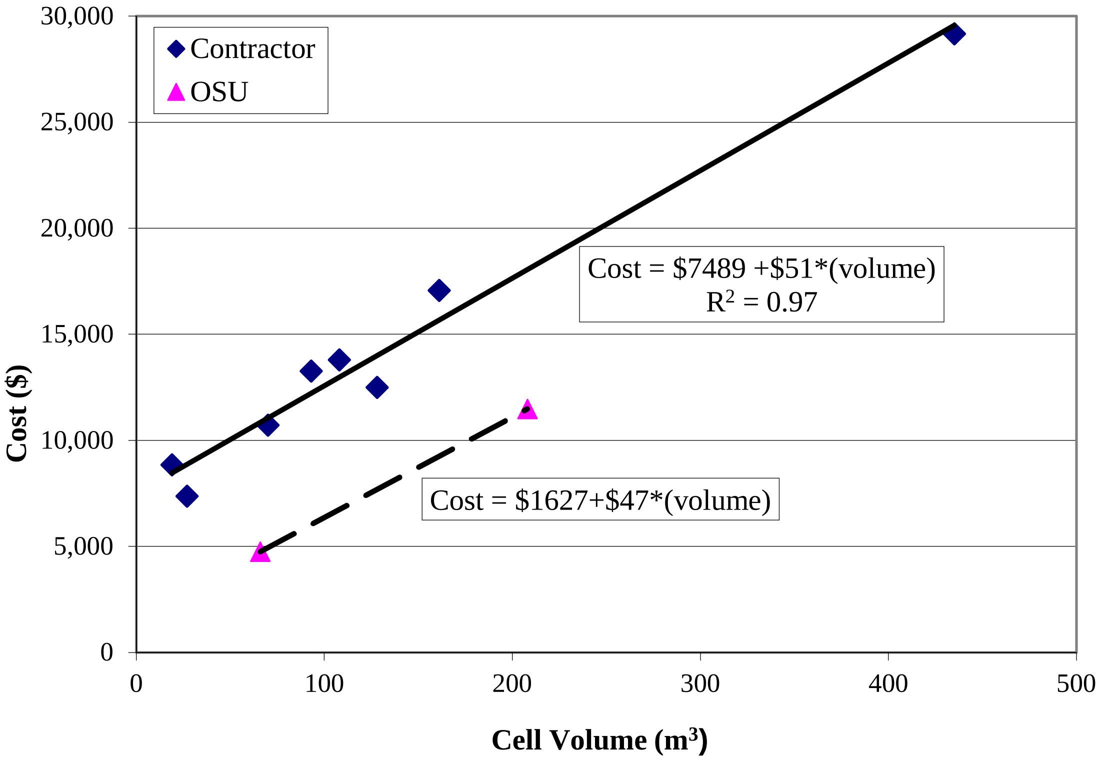

Figure 2- 7. Comparison of BRC cost in 2008.

Planting Costs

Planting was not part of the construction contract bid through the state. Eight of the cells were planted using materials provided through project funds (table 2-5). Material costs ranged from \$526 to \$3,025, depending on cell area and plant selection. Quantities were based on 65% surface coverage and varied as plants ranged in size from 10 cm to 19 L containers. Mulch was included in the construction costs. However, three cells required additional mulch at the time of planting due to losses from cell failure, inadequate mulch size, and submersion from extreme lake water elevations. Three of the cells were planted as volunteer opportunities: Lendonwood Gardens and both Private Residences. The cell at Private Residence 1 is shown in figure 2-8. The rest were contracted out to the Grove High School FFA as a fund-raising activity. Labor costs, as listed in table 2-6, were based upon total man-hours required per cell. Plant materials and labor for the two cells in Stillwater were provided at no cost to this project by the OSU Botanic Gardens as part of the above mentioned environmental research and education program.

Table 2- 5. List of BRC plant material, mulch, and labor costs in Grove, OK.

Location	Area (m^2)	Plant Cost ($)	Mulch Cost ($)	Labor Cost ($)	Total Cost ($)
Lendonwood Gardens[a],[b]	23	546	-	-	546
Private Residence 2[a],[b]	30	526	-	-	526
Early Childhood Development Center[a]	48	449	-	400	849
Elm Creek Plaza	63	796	144	750	1,690
Private Residence 1[b]	101	1,094	150	-	1,244
Cherokee Queen Riverboats[a]	116	870	-	500	1,370
Grove High School [a]	149	1,280	-	750	2,030
Grand Lake Association	172	3,025	456	1,000	4,481

[a] Mulch was included in the cost of construction and no extra was needed at the time of planting.

[b] Bioretention cell was planted by volunteers.

Figure 2- 8. Completed BRC at Private Residence 1.

Vegetation Assessment

To better understand the planting success, vegetative composition was assessed within the seven contractor-installed cells after four growing seasons. Total areas, sizes, and quantities of total vegetation were compared with the construction documentation, and vegetative cover by species (area) was recorded as area within each cell by full census using a centerline measurement wheel, rigid 1 m long rod and 1 m^2 plot. In the cases where no vegetation was growing on the surface within the cell, an area measurement was taken and labeled 'bare soil.' In addition, each species was examined to provide an indicator of general health across the scales of plant size, form, branch and foliage density, leaf shape and condition. This single point-in-time descriptive assessment provides information regarding plant survival, success, and weed establishment while showing the impact of maintenance practices.

Across all cells, horticultural plants covered the majority of the cell (48.6%) by a small margin over bare soil (34.3%), while volunteers covered the remainder (17.1%) (Figure 2-9). This finding is encouraging to nursery stock applications where individual plants specification is desired. However, the installation coverage of 48.6% for nursery stock indicates an overall decline in plant coverage for that group thus placing increased priority on plant species selection. The decline, or death, of nursery species gave way to volunteer species recruitment. Some gardens were managed with conventional practices of seasonal weeding in the form of in-line machine trimming. As a result, these gardens possessed larger contiguous areas of bare soil and were most similar or less than plan coverage amounts following installation. The largest was the High School site with 71.1% bare soil and the lowest was Private Residence 1 with 8.9%. In most cases, this was a combination of soil and remnant wood chip mulch from the original plant installation. The two sites void of seasonal weeding activity, Queen Cherokee and Elm Creek, possessed >92% vegetative cover from both horticulture plants as well as volunteer species. Cover of horticultural plants was highest in Private Residence 1 with 91.1%.

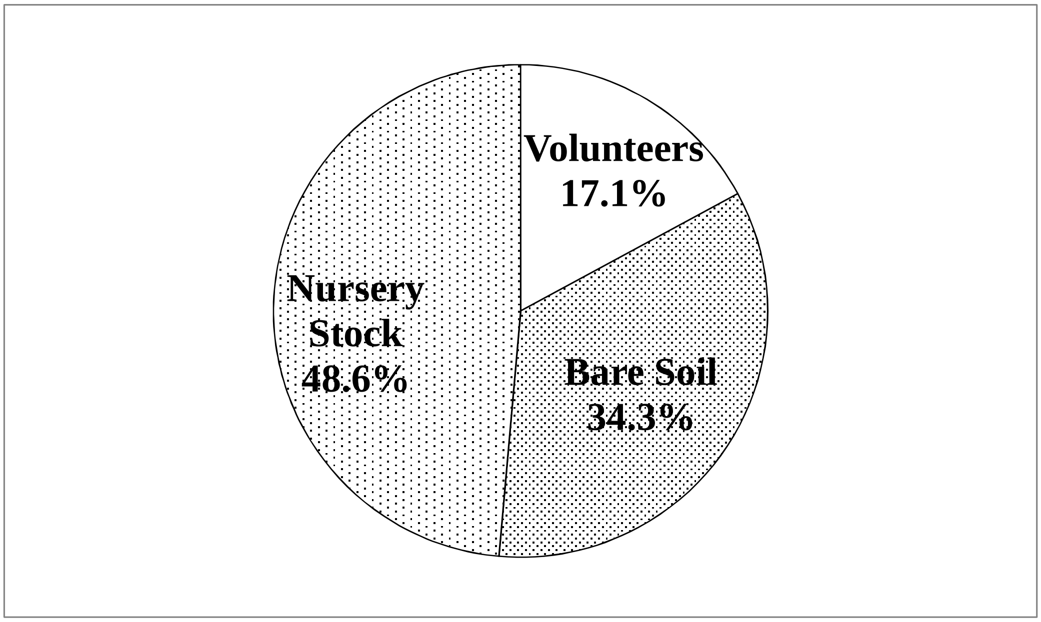

Figure 2- 9. Average plant coverage by type in the eight contractor installed BRCs in Grove, Okla.

The most commonly recorded plants were the Heritage River Birch (Betula nigra ‘Heritage’), Common Ragweed (Ambrosia artemisiifolia), Amur Red Maple (Acer ginnala), Stella Daylily (Hemerocallis ‘Stella d’Oro’) American Holly (Ilex opaca), and Loblolly Pine (Pinus taeda). These species were observed in 40% to 55% of the cells. Loblolly pine displayed highly balanced form, complete foliage, and true coloration. Growth rates in the Loblolly were positive and new growth was apparent. The Heritage River Birch also showed high growth rates, good form, and proper branching density, but only moderate canopy coverage. Upon inspection, leaf size was small. Species that were present but displayed compact forms and limited growth rate include Stella d’Oro daylily, Golden Euonymus (Euonymous japonicus spp.), American holly, and Dwarf Yaupon holly (Ilex vomitoria ‘Nana’). Only one species was absent in every cell where it was planted; Red-tipped Photinia (Photinia x fraseri).

Lessons Learned

Overall, the design process translated well to the construction of the BRCs for this project. Mixing fly ash in the field presented a challenge and was approached using the two previously described methods. The challenge arose in ensuring an adequately mixed medium on such a large scale, and neither method was considered adequate. Samples were taken during placement so that the variability could be quantified and analyzed using a 3D finite element model of BRC as designed for this project.

Fly ash storage is an issue that needs to be addressed. During the construction phase of this project, Oklahoma experienced significant rain. Fly ash exhibits pozzolanic characteristics when exposed to even small amounts of moisture. Clots of fly ash are formed, and it is difficult to sift through the large quantities of fly ash to effectively remove them. This poses many issues of concern such as effective sorption capacity, preferential flow within a non-uniform medium, and achieving an even blend of sand and fly ash. The contractor stored the fly ash underground in a pit and covered it with a tarp. A similar method was used for short-term storage at the Stillwater site. Under typical climate conditions this would be appropriate. However, a better solution would be to store the fly ash in a weather proof/resistant vessel such as a trailer.

Utilities presented another challenge. During the design phase of the project, every effort was made to avoid placing cells near utilities. We called the state call dig number (utility locator), worked with city employees, and studied as-builts. However, in an urban setting, good planning does not always mean that utilities will not be an issue. As a result, we were forced to work around utilities at a few sites during construction. We were fortunate that the Grove contractor was experienced working with utilities and was very careful about digging, even when we had received clearance at a site. Another point of interest is to observe the differences in capabilities and costs when comparing construction by a contractor versus construction “in-house.” On average, the contractor was able to complete a cell within four days, with three people, a Caterpillar 420D loader backhoe, and a Bobcat Turbo 863 skid steer loader. The cells constructed by OSU averaged six days, using five people, two tractors, a Dingo TX425, and a Troy Bilt Big Red Garden Roto Tiller. Most of the additional time required for the in-house construction was during the backfilling process. The contractor was able to use heavy equipment with a greater capacity for moving soil than the process employed by the in-house team, which relied more on man-power and smaller, more readily available equipment. It costs approximately $6,000 more to have a contractor build a cell. However, it takes half the time and considerably less man-power and equipment. Differences in cost and labor are attributed to the issues surrounding man versus machine and in-house versus contractor labor.

There were two cell failures. The first was at Elm Creek Plaza, where the cell receives runoff from a parking lot and sits directly next to a stream bank. Berm failure occurred due to fugitive water from a neighboring property during a 50-year storm, providing roughly twice the designflow. The flow destroyed the overflow weir that was poorly placed on the streambank. The cell was repaired and reinforced, and the overflow was moved to a different location to alleviate the possibility of a repeated failure. The property owner also had the channel between the two properties cleaned out and deepened. One positive outcome is that immediate benefits with regard to erosion were observed at this site. During construction the bank had to be rebuilt as it had eroded substantially in the time between the design and construction phases, and the cell would not have fit as designed.

The second failure was at Private Residence 1. The cell is located near the lakefront, above the GRDA take-line and the U.S. Army Corps of Engineer's regulation line. Excessive rains after a long period of drought caused the lake to rise to unusually high elevations, and the shore waves at the high lake elevations eroded the cell berm. Repairs commenced once the water receded. The berm was repaired and reinforced. High water levels around the lake area also delayed construction and submerged the Cherokee Queen cell, but caused no significant damage.

Summary and Conclusion

Ten Bioretention cells were constructed eight in Grove and two in Stillwater. Cells ranged in size from 19 to 435 m^3, and were incorporated into residential, commercial, and public sites. The cell filter media utilized fly ash to provide additional sorption and removal of phosphorus. However, mixing fly ash in the field proved to be a challenge, flow and transport patterns through the cells will be assessed using a 3D finite element model. Fly ash storage also needs to be more weather-proof to prevent clotting, and thus make field mixing easier and more uniform. Construction costs were higher using a contractor than those for the cells constructed by OSU. However, the contractor was able to complete a cell in less time with fewer people and less, although larger, equipment. Costs of contracted construction of BRC are also expected to decrease as local contractors have more experience and knowledge about what is entailed in cell construction over time. Assessment of vegetation within the BRCs revealed an overall decline in nursery stock plant coverage, but this decline gave way to volunteer species recruitment. Thus,bare soil in the cells, as a whole, was limited to 34.3% and within the guidelines for the original planting schedule of 45%. Loblolly pine did very well, while Red-tipped Photinia did not survive.

Overall, the cells appear to be functioning as designed, and a few added benefits such as erosion reduction and temperature attenuation of cell runoff have been observed. However, the only way to be sure that the soil amendment is indeed performing as expected is through monitoring, which is expected to begin soon with the start of a new project.

Disclaimer

The use of trade names is only for informational purposes and does not constitute endorsement by Oklahoma State University or the authors.

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CHAPTER III

IMPACT OF VARIABLE HYDRAULIC CONDUCTIVITY ON BIORETENTION CELL PERFORMANCE AND IMPLICATIONS FOR CONSTRUCTION STANDARDS

Abstract

Bioretention cells have become an accepted technology for stormwater management due to their potential benefits in runoff volume reduction and water quality improvement. Over the years, a considerable amount of research has been done to improve performance, whether by improved functionality or by introducing engineered filter media to target specific contaminants. The design for a full-scale demonstration project carried out in Oklahoma incorporated a sand and fly ash filter for enhanced phosphorus adsorption and surface sand plugs for improved infiltration. Samples taken from the filter media during construction exhibited heterogeneity in fly ash content, and therefore, hydraulic conductivity due to the pozzolanic property of fly ash. Maximizing contaminant attenuation will require achieving uniform flow through the cell to ensure use of the entire filter volume. Thus, it is important to understand how the small-scale filter heterogeneity and the large-scale sand plugs impact performance of this design. To do this, a three-dimensional finite element model was developed in COMSOL Multiphysics to simulate saturated flow through a bioretention cell.

Three general configurations were modeled for three different scenarios. A filter-only configuration was evaluated to assess the effect of filter media hydraulic conductivity heterogeneity on flow through the cell. The second configuration added a top soil and sand plugs

measuring 1.5 m by 1.5 m, which was similar to the constructed cells. The final configuration evaluated a top soil and sand plug layer with 14 smaller sand plugs only 1 m by 1 m. Three different scenarios were evaluated for each configuration that varied by size and distribution of the filter media heterogeneity. The first scenario used the measured scale and range variability, while the second used the same scale with double the variation, and the third used the same variability, but increased the scale volume by a factor of 27. Model results indicate that variability in fly ash content creates complex flow through the filter medium, but does not result in significant preferential flow. Sand plugs create some flow concentration but do not dominate flow within the cell, and the number of sand plugs is not significant provided that their total area is appropriate to maintain the desired drainage rate.

Introduction

Bioretention cells (BRCs) offer a range of potential benefits through physical, chemical, and biological processes including increased infiltration, reduced peak runoff, temperature mitigation and contaminant attenuation. Considerable research has been done on the technology over the past 15 years, especially with regard to hydrologic performance, water quality improvement (Brown and Hunt 2008; Brown and Hunt 2010; Li and Davis, 2008; Li and Davis 2009; Diblasi et al. 2009; Bedan and Clausen 2009; Sharkey and Hunt 2005; Passeport et al. 2009; Asleson et al. 2009) and soil media characterization (Carpenter et al. 2010; Zhang et al. 2008a, b; Thompson et al. 2008). While some modeling of BRCs has been done, few have focused on flow and solute transport within the cell, especially with regard to modified designs and soil amendments targeting specific pollutants. Aravena and Dussaillant (2009) used a two-dimensional model based on Richard’s equation to estimate infiltration and recharge of rain gardens, while He and Davis (2009) looked at fluid flow and the transport of naphthalene and pyrene with a two-dimensional, variable saturated flow model.

Ten BRCs were constructed in Oklahoma to demonstrate phosphorus reduction efficiency and overall performance. Figure 3-1 depicts a typical section of the design used for this project. Cell design included sand plugs for increased infiltration through the top soil layer to ensure that the cells do not pond water for more than one day (Chavez et al. 2006). In addition, fly ash was used as a filter media amendment to adsorb phosphorus and heavy metals (Zhang et al. 2008a, b). In this project, uniformly mixing the sand/fly ash blend for the filter media was an issue (Chavez et al. 2008). It was expected that the variability in fly ash content would induce variability in the hydraulic conductivity of the filter layer due to the pozzolanic nature of fly ash. Preliminary hydraulic testing of the BRCs showed signs of preferential flow. As treatment performance is largely a function of the uniformity of water and solute transport through the cell, it is important to understand the impact that any media variability has on the flow processes.

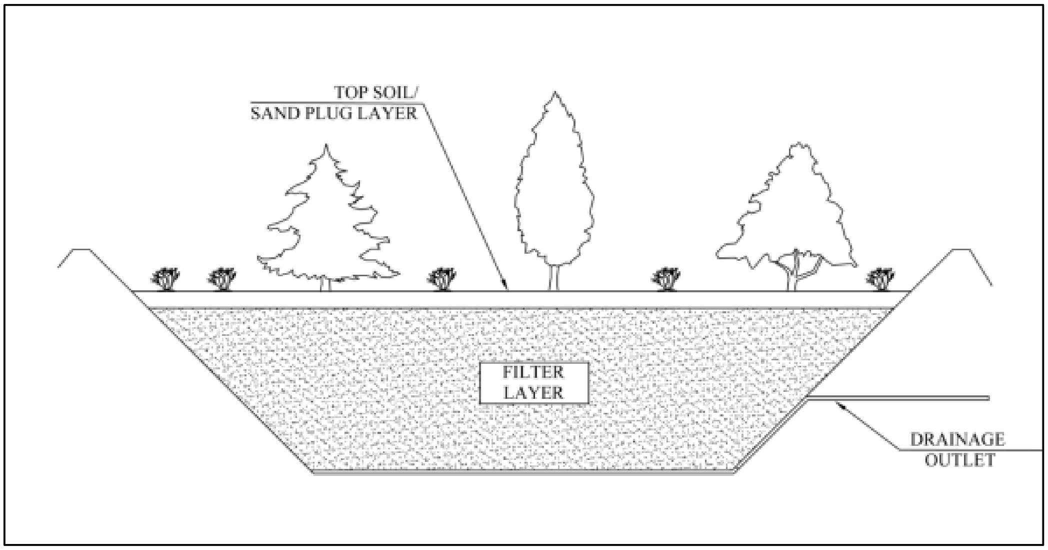

Figure 3- 1. Typical section of bioretention cell depicting layers and drainage.

The objectives of this paper were to, 1) determine the impact on flow within a BRC due to spatial heterogeneity in the filter media hydraulic conductivity, 2) evaluate the importance of sand plug size on flow within the filter, and 3) establish how the scale of the hydraulic conductivity heterogeneity affected flow through the cell, and its implications for requirements in mixing effort in filter media emplacement.

Conceptual Cell Design and Modeling

Cell Geometry

A three-dimensional finite element model was developed using the COMSOL Multiphysics Earth Science Module (2008) to simulate the effect of hydraulic conductivity variation on flow within a BRC. Dimensions for the model were 7.5 m wide by 7.5 m long by 1.5 m deep, where 1.2 m of depth represented the filter layer and 0.3 m comprised a top soil and sand plug layer as shown in Figure 3-2.

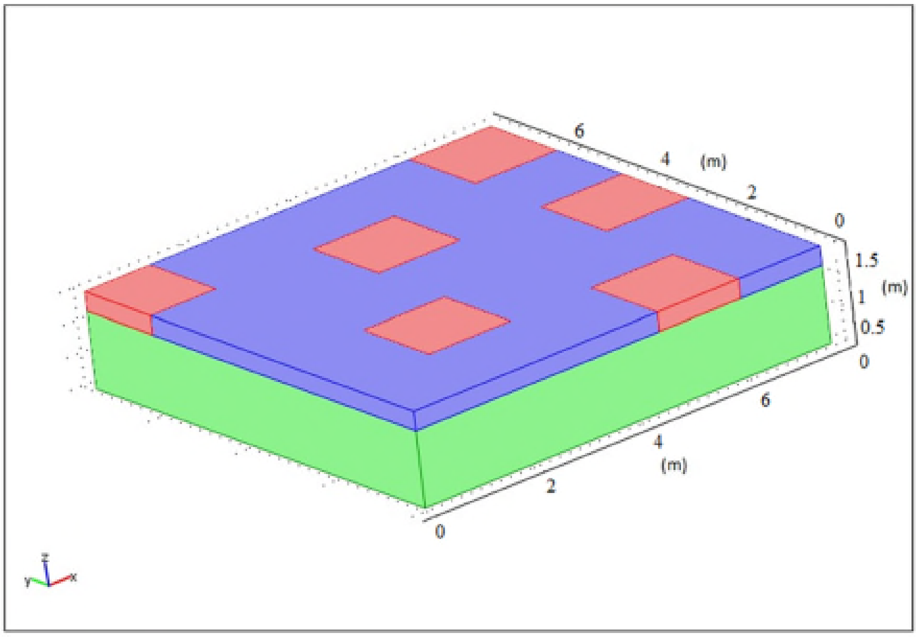

Figure 3- 2. Three-dimensional model geometry used for the configuration with six sand plugs.

Three configurations of the model were considered to determine the effect sand plug size and placement have on flow through the cell. The first configuration consisted of only the filter layer, neglecting the top soil and sand plug layer entirely. The second configuration contained a top soil and sand plug layer with 6 randomly placed sand plugs that were 1.5 m by 1.5 m, as shown in Figure 3-2. The third configuration contained a top soil and sand plug layer with 14 sand plugs that were 1 m by 1 m, as shown in Figure 3. Sand plugs were specified to cover approximately 25% of the cell surface to ensure complete water drainage within one day even after partial sealing from influent sediments (Chavez et al. 2007).

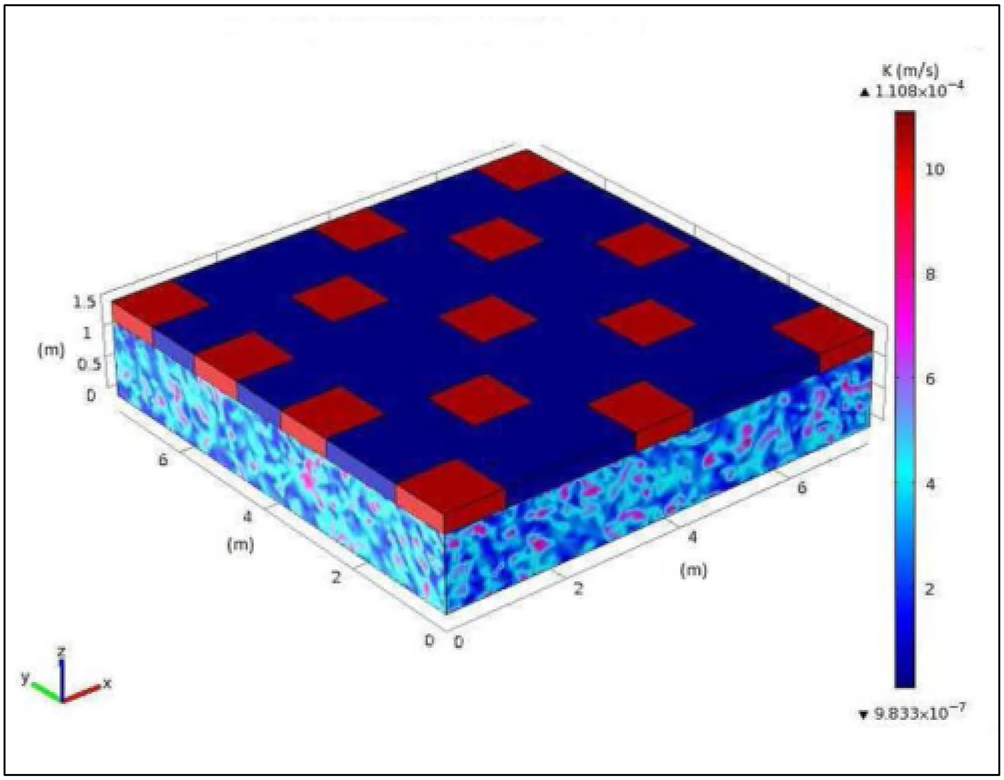

Figure 3- 3. Three-dimensional view of the model configuration with 14 sand plugs and the range of *K* values for the top soil, sand plugs, and the variation in the filter layer.

Initial wetting of the cells was neglected and only the saturated flow was modeled. Initial wetting may be ignored owing to the nature of BRC. The ratio of the watershed area to BRC surface area is typically 50:1. Even a rainfall event that produces an almost negligible 5 mm of runoff from the watershed will put 0.25 m of water on the BRC, while a 20 mm runoff event puts a meter of water on the cell. Remembering that the BRC also receives the rainfall, the BRC surface soils will be near saturation before the first influent arrives. In addition, except after long droughts, the deeper BRC media should have moderate to high initial water content, which will tend to reduce the potential for finger flow (Bauters et al., 2000). Thus, it is reasonable to assume that the initial wetting of the cells and unsaturated flow artifacts will only affect a small portion of the eight meters of water the BRC will receive in a typical year. This was demonstrated by the experiments of Christianson et al (2012), where these cells rapidly wetted and flow was fully saturated.

Laboratory measured hydraulic conductivities for the top soil and sand were 3 x 10^{-6} and 1 x 10^{-3} m/s, respectively. Since the focus here was the filter media, variations in the hydraulic properties of the top soil and sand plugs were beyond the scope of the study and not considered.

The hydraulic conductivity of the filter layer was randomly varied based on the distribution of samples taken from BRCs during construction, as discussed in more detail later. While there was variation in fly ash content, reasonable efforts were made during construction of the BRCs to ensure overall uniformity. Filter media was mixed on site by repeated scooping and overturning by front end loader. Then the filter was placed in 0.15 m vertical lifts to preclude any vertical structures. 75,088 hydraulic conductivity values were assigned to the filter layer in a 0.10 m grid and interpolated over the mesh built by the model, which consisted of over 400,000 elements. A typical distribution of hydraulic conductivity is depicted in Figure 3-3.

Boundary conditions at the surface and bottom of the cell were defined as atmospheric, as is appropriate for cells with bottom drains. A zero-flux boundary was imposed along the perimeter of the modeled cell such that all flow out of the system was directly through the bottom and that there were no losses through the sides. The boundary between the top soil and sand plug layer and the sand/fly ash filter layer was defined as a continuity condition.

Hydraulic Conductivity Variation

One hundred sixty two samples were collected during the construction of two BRCs in Stillwater, Oklahoma. Samples were analyzed for alkalinity, since fly ash content is difficult to measure directly. Fly ash content of each sample was calculated using the correlation between alkalinity and fly ash content presented in Figure 3-4. Hydraulic conductivity for each sample was then determined, based on the relationship established by Zhang et al. (2008a). They experimentally established a relationship between hydraulic conductivity, K (m/s) and fly ash content, X (%) for Dougherty sand,

$$K = 1.04 * 10^{-4} * e^{-0.454X} \tag{1}$$

Table 3-1 presents the basic sample statistics. K varies between 2.8 x 10-6 and 10-4 m/s with a mean of 3.5 x 10-5 m/s. The data also show a positive skew and a low kurtosis, indicating a non-normal distribution with a lower bound of zero.

Table 3- 1. Basic statistics on hydraulic conductivities of samples collected from the filter layers of the bioretention cells during construction.

N	Mean (m/s)	Standard Deviation (m/s)	Min (m/s)	Median (m/s)	Max (m/s)	Skew	Kurtosis
162	3.5 x 10^{-5}	2.5 x 10^{-5}	2.8 x 10^{-6}	3.2 x 10^{-5}	1.0 x 10^{-4}	0.98	0.54

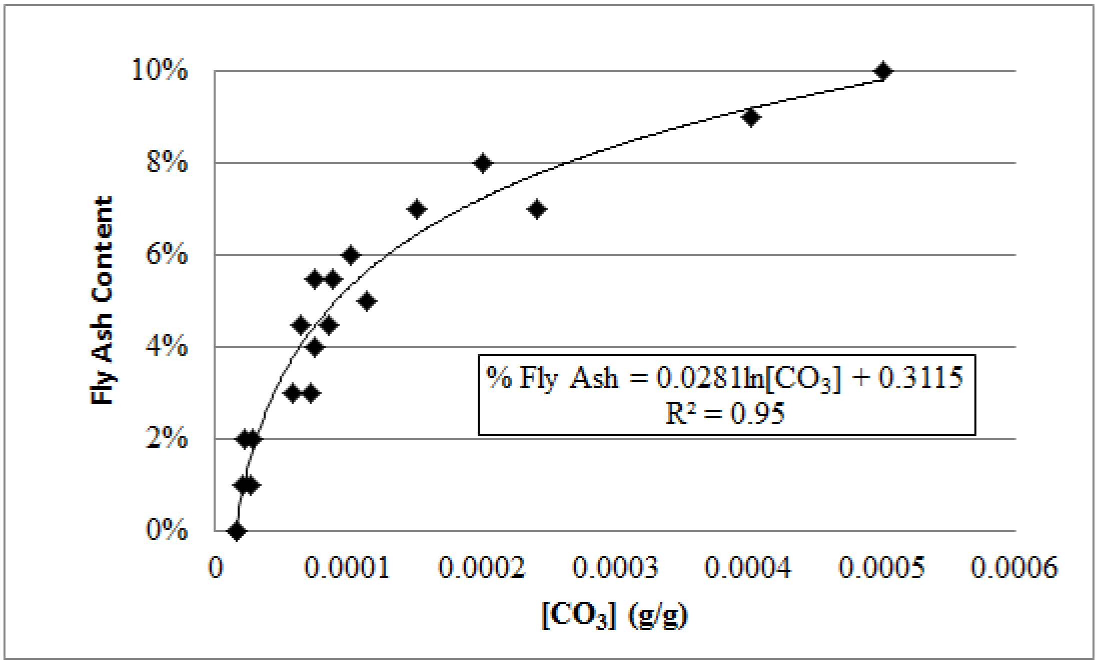

Figure 3- 4. Exponential relationship between fly ash content and alkalinity established by measuring the alkalinity of soil standards with known fly ash contents in the laboratory.

A distribution fitting was identified using Minitab 15 (2007). The Individual Distribution Identification function compared 16 distributions to the data including the Box-Cox transformation, Weibull distribution, Gamma distribution, and the Johnson transformation. All of these had relatively small Anderson-Darling values and p-values larger than 0.05, indicating goodness of fit and statistical significance. Ultimately, the data were fit to a normal distribution using the Johnson transform function, JT, since it had the smallest Anderson-Darling value (0.284) and the largest p-value (0.628). The relationship developed was,

$$JT = 1.272 + 0.9749 * \ln\left(\frac{K + 6.681*10^{-7}}{1.385*10^{-4} - K}\right) \qquad (2)$$

Figure 3-5 shows the fit of the transformed data to a normal distribution.

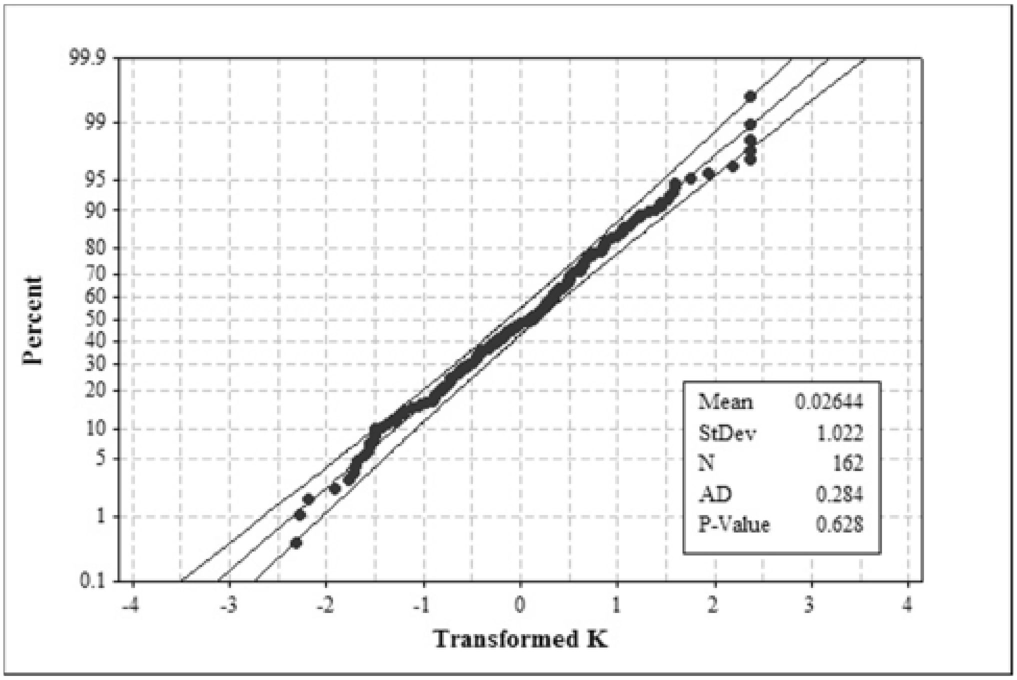

Figure 3- 5. Normal distribution plot of the transformed K values as derived from samples taken during construction of BRCs.

The fitted data were then used to generate a set of random K values to model the effect of variation on flow within the filter layer of a BRC. A set of 75,088 random JT values were generated in Minitab using the mean and standard deviation of the transformed data. These data were then transformed back in to K values by rearranging equation 2 such that,

$$K = \frac{1.385*10^{-4} e^{\frac{JT-1.272}{0.9749}} - 6.681*10^{-7}}{1+e^{\frac{JT-1.272}{0.9749}}} \qquad (3)$$

The K values were assigned to a 0.10 m grid within the filter volume and entered into the model. Twenty realizations of all three model configurations were run using different sets of K values generated using the conditions described above. The total number of realizations was chosen to achieve an asymptote on the moving average of the mean seepage velocity as calculated by the model.

Increased Heterogeneity in Filter Medium

One of the issues encountered during construction was trying to achieve homogeneity in the filter media mix of sand and fly ash. In order to gain a better understanding of how mixing of soil amendments in full-scale applications effects cell performance, the variance of the original data was increased to correlate with a more varied, less well mixed filter media. To do this, the variance from the Johnson Transform distribution of the samples collected during construction was doubled from 1.0455 to 2.0910. The transformed data was used to incorporate the variation because the original data was not normally distributed. Using the mean of the original JT values, 0.0264, and the standard deviation corresponding to the increased variance, 1.446, 20 new sets of JT values were randomly generated in Minitab. The new JT values were then transformed back into K values using Equation 3 and assigned to the 0.10 m grid. The output data from the 20 realizations was compared to that generated by the model using the original sample distribution to estimate the significance of mixing in the field on cell performance.

Increased Heterogeneity Scale

Another consideration was to determine how the scale of the hydraulic conductivity heterogeneity impacted the flow through the cell. The 0.10 m (on a side) grid used for the modeling in the previous sections was based on the approximate sample volumes collected during construction, and is considered the best representation for the mixing scale in the BRCs. However, less diligent mixing could produce larger scale heterogeneity and increased potential for preferential flow. To explore this concern, 20 new realizations of random K values were generated in Minitab using the same parameters from the collected samples. However, the random data were assigned to a larger grid, 0.30 m (on a side), in place of the 0.10 m grid previously used. A 0.30 m grid is the equivalent of a 27 liter sample size and is considered the minimal acceptable mixing effort. Twenty realizations were modeled and evaluated to discern any significant differences in the modeled flow. These simulations are considered a worst case for poor mixing effort, but would not represent deliberate shoddy construction.

Uniform Filter Media

Finally for comparison purposes, two simulations were performed for each of the three configurations with constant filter media conductivity. One simulation used the mean hydraulic conductivity, while the second used the median value of the samples taken from the cells during construction. Thus between the previously described variations and these, a total of 186 simulations were performed.

Results

Hydraulic Conductivity Variation

Table 3-2 presents the total BRC flow for each configuration assuming a constant hydraulic conductivity based on the mean and median values of the filter media samples as a control. As expected, Q increases proportionally with K.

Table 3- 2. Constant K input values and corresponding total BRC outflows, Q, for each configuration.

	***K* (m/s)**	***Q* (10^{-3} m^3/s)**		
		Filter Only	***6 Sand Plugs***	***14 Sand Plugs***
Mean	3.53×10^{-5}	2.04	1.33	1.48
Median	3.22×10^{-5}	1.86	1.24	1.38

Individual volume element fluxes computed by the model for the 20 realizations for each configuration with the measured hydraulic conductivity variation were exported to Minitab for analysis. Distribution identification was performed for each model configuration, but no distribution had a p-value greater than 0.05, indicating a lack of statistical significance for any attempted fit. This could be indicative of complex flow patterns for all three configurations.

The basic statistics of the 20 realizations of the filter-only configuration with variable K are presented in Table 3-3. The mean and median values for Q were 1.88 x 10-3 m3/s, which is comparable to those obtained by using the median value for K in the control model runs. Even with the complex flow patterns introduced by the heterogeneous K field, the overall effect is similar to discharge of a model with a constant K based on the median value for K of the samples collected during construction. Most importantly, the minimum and maximum of all realizations were within 1% of each other. This implies that the designers need not be concerned with anomalous rapid flow paths for filter media heterogeneity at this scale.

Table 3-4 presents the individual element statistics for the 20 realizations for each of the three configurations. The negative fluxes reported in Table 4 are due to boundary effects near the sand plugs. Even with sand plugs, the top soil reduces the mean downward flux by approximately 30%.

Table 3- 3. Basic statistics on total BRC outflow, Q, for 20 realizations of a variable K, filter-only configuration.

	Q (10^{-3} m^3/s)
Mean	1.88
Median	1.88
Standard Deviation	0.006
Minimum	1.87
Maximum	1.89

Table 3- 4. Basic statistics for the calculated individual finite element seepage flux for each of the three configurations.

	Flux (10^{-6} m/s)				
	Mean	**Standard Deviation**	**Min**	**Median**	**Max**
Filter-only	33	20	0	30	130
6 Plugs	23	20	-47	17	250
14 Plugs	24	19	-20	20	250

Table 3- 5. Summary of vertical seepage flux directly beneath the sand plugs and the ratio of vertical seepage below the sand plugs and vertical seepage for the entire cell for the configurations with 6 and 14 sand plugs.

	6 Plugs		**14 Plugs**	
	Flux (m/s)	**Flux Ratio**	**Flux (m/s)**	**Flux Ratio**
Sand Plug #1	0.00753	0.0575	0.0037	0.0261
Sand Plug #2	0.00689	0.0526	0.0035	0.0248
Sand Plug #3	0.00735	0.0561	0.0035	0.0250
Sand Plug #4	0.00805	0.0615	0.0035	0.0247
Sand Plug #5	0.00723	0.0552	0.0032	0.0225
Sand Plug #6	0.00817	0.0624	0.0030	0.0215
Sand Plug #7	-	-	0.0032	0.0230
Sand Plug #8	-	-	0.0032	0.0225
Sand Plug #9	-	-	0.0032	0.0227
Sand Plug #10	-	-	0.0031	0.0218
Sand Plug #11	-	-	0.0031	0.0217
Sand Plug #12	-	-	0.0036	0.0260
Sand Plug #13	-	-	0.0029	0.0209
Sand Plug #14	-	-	0.0036	0.0259
Total Flux for Bioretention Cell	0.131	-	0.1405	-

Table 3-5 lists the total outflow of the cell and the vertical seepage outflow of the cell directly beneath both of the 6 and 14 sand plugs configuration. In the six plug configuration, each plug is responsible for approximately 6% of the total outflow. On the whole, sand plugs make up approximately 25% of the cell surface and account for 34.5% of the vertical outflow from the cell, indicating a significant, but not dominating, influence on flow within the cell. Similar flux characteristics were observed for the 14-sand plug configuration. Each sand plug is responsible for a little more than 2% of the total outflow of the cell and together account for 33% of the vertical seepage from the cell, indicating little influence from the size and location of the sand plugs. However, there is little difference between six and fourteen sand plugs, which implies designers need not be too concerned with the number of plugs, as long as the total area of the sand plugs is appropriate to maintain the desired drainage time.

The vertical seepage velocities indicate a non-normal or irregular distribution as demonstrated in Figure 3-6. Complex flow paths are evident in all three scenarios, as shown in Figures 3-7 and 3-8 for two typical sand plug realizations. For the models with sand plugs, approximately 65% of the filter media volume has an advection flux of less than 10% of the maximum. When considering only the filter, approximately 40% of the filter volume has an advection flux of less than 10% of the maximum. Thus, the cell will undoubtedly exhibit dual porosity transport artifacts, regardless of size and location of the sand plugs. However, retardation will require diffusion from advective regions, effectively reducing contaminant attenuation in those regions further away from the sand plugs and in the cell overall. Sand plugs do create flow concentration, but size and location do not appear to have significant effect.

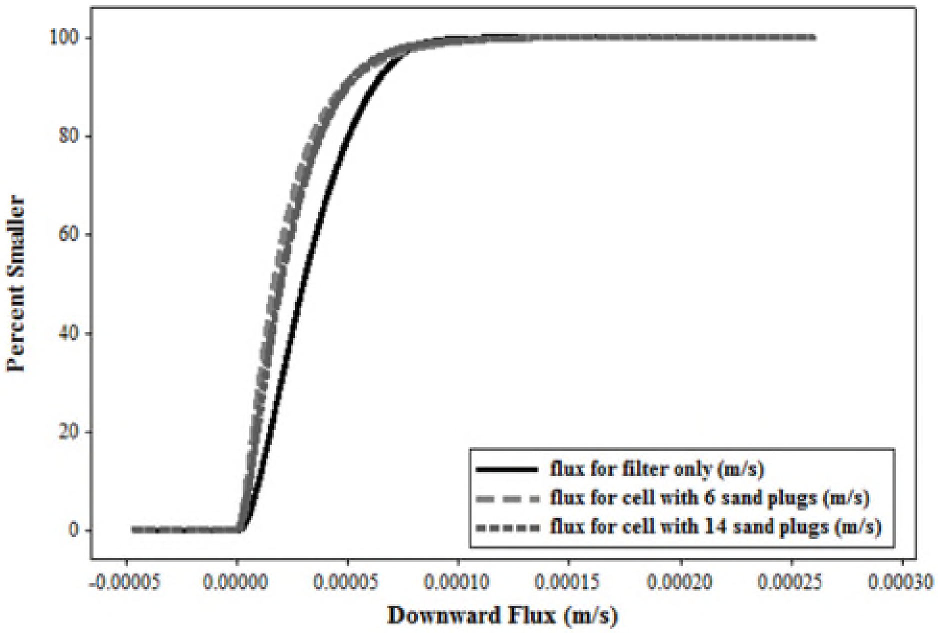

Figure 3- 6. Cumulative distribution of computed vertical flux values exported from the model for all three configurations.

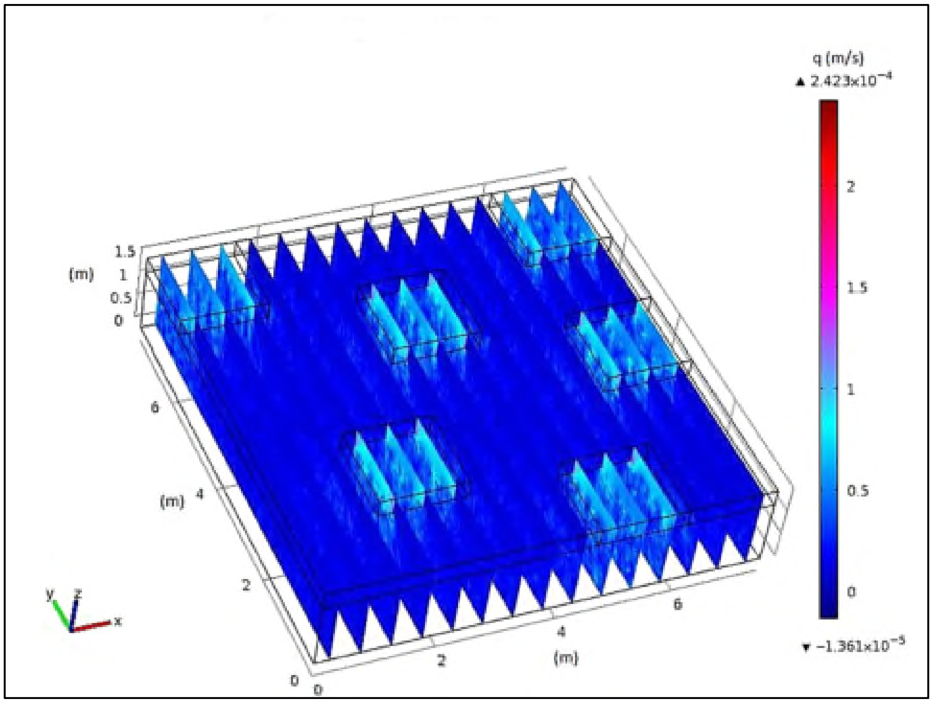

Figure 3- 7. Computed downward flux, *q*, within the bioretention cell with 6 sand plugs.

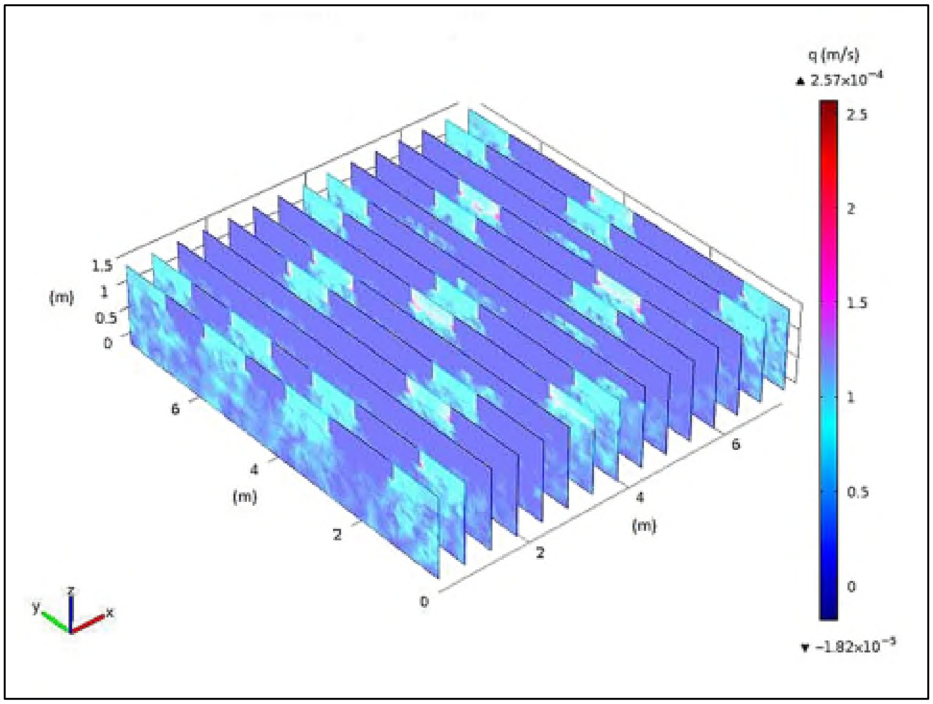

Figure 3- 8. Computed downward flux, q, within the bioretention cell with 14 sand plugs.

Increased Heterogeneity in Filter Medium

A practical concern for using amended soils in BRCs is the mixing of the amendments on the overall cell performance. As described above, the variance of the K distribution was increased to simulate a less thorough mixing process for a more heterogeneous filter medium within the cell. Table 3-6 shows that increasing the variance increased the discharge for all three configurations. When considering only the filter, increasing the variance of K from 5.95 x 10^{-10} m/s to 1.19 x1 0^{-9} m/s increased mean discharge for the entire cell 6.4% to 2.00 x 10^{-3} m^3/s as compared to the original sample distribution. This is the same general trend depicted in Figure 3-9 for all 20 realizations. The discharge for each realization of the original distribution ranged from 1.87 x 10^{-3} m^3/s to 1.89 x 10-3 m^3/s. Whereas, the discharge for each realization with the increased variance ranged from 1.98 x 10^{-3} m^3/s to 2.02 x 10^{-3} m^3/s. When considering the configuration with six sand plugs, the mean discharge increased by 4.8% to 1.32 x 10^{-3} m^3/s. As shown in

Figure 3-10, the discharge for each realization of the original distribution ranged from 1.25 x10^{-3} m^3/s to 1.31 x 10^{-3} m^3/s. Whereas, the discharge for each realization with increased variance ranged from 1.31 x 10^{-3} m^3/s to 1.34 x 10^{-3} m^3/s. For the configuration containing 14 sand plugs, the mean discharge increased by 4.1% to 1.46 x10^{-3} m^3/s as listed in Table 3-6 and depicted in Figure 3-11. From the model results presented in Table 3-6, it appears that the influence of the top soil and sand plug layer dampens the effect of the increased variance on the flow within the cells by 48% with 6 sand plugs and 43% with 14 sand plugs. The dampening effects of the uniform top soil and sand plug layer reduce the overall effects of possible preferential flow patterns within the cell as evidenced by the reduced discharge. Additionally, the small increases in discharge with increased variance are further evidence that, while it is recommended that mixing be as thorough as possible, mixing does not significantly impact cell hydrologic performance.

Table 3- 6.Comparison of calculated total flow, Q, for the three configurations with the original sample distribution, increased variance, and increased variation scale.

	Q (10^{-3} m^3/s)								
	Filter-only			**6 Sand Plugs**			**14 Sand Plugs**		
	Original Distribution	Increased Variance	Increased Scale	Original Distribution	Increased Variance	Increased Scale	Original Distribution	Increased Variance	Increased Scale
Mean	1.88	2.00	1.90	1.26	1.32	1.24	1.40	1.46	1.38
Median	1.88	1.99	1.90	1.26	1.32	1.25	1.40	1.46	1.38
Standard Deviation	0.006	0.01	0.02	0.01	0.01	0.02	0.006	0.006	0.01
Minimum	1.87	1.98	1.87	1.25	1.31	1.21	1.39	1.45	1.36
Maximum	1.89	2.02	1.96	1.31	1.34	1.28	1.41	1.48	1.41

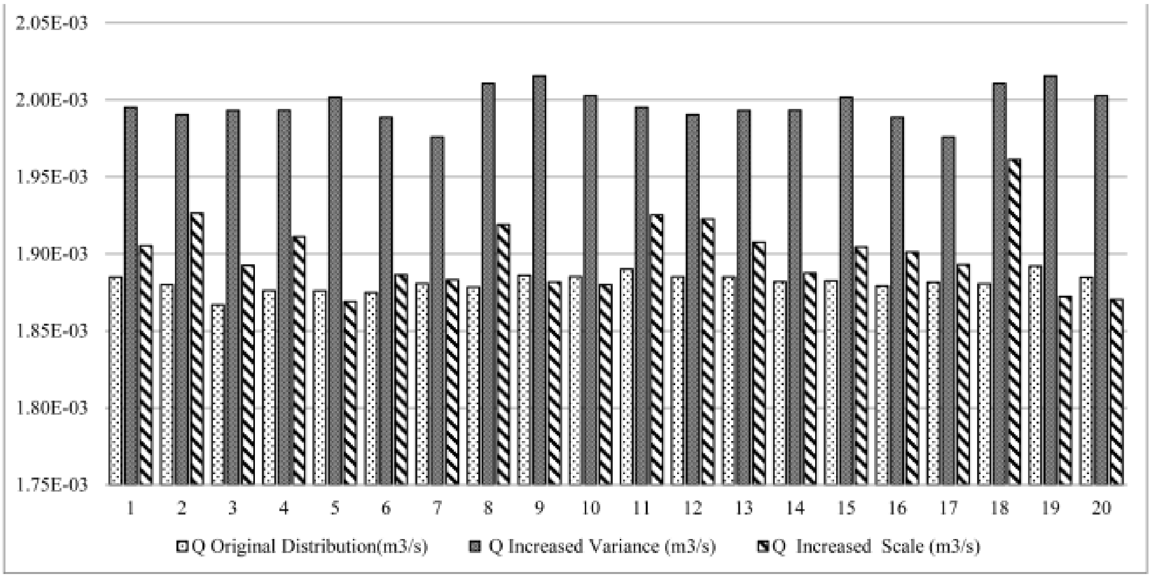

Figure 3- 9. Comparison of the total discharge, *Q* (m^3/s), for cell with only filter media for 20 realizations for each of the three scenarios.

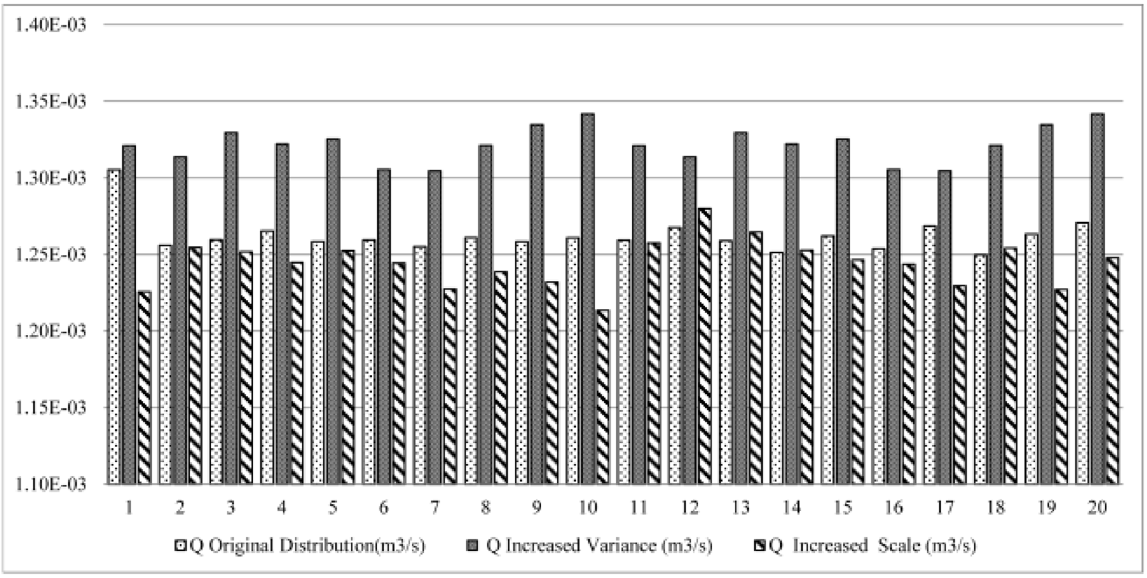

Figure 3- 10. Comparison of the total discharge, *Q* (m^3/s), for cell with six sand plugs for 20 realizations for each of the three scenarios.

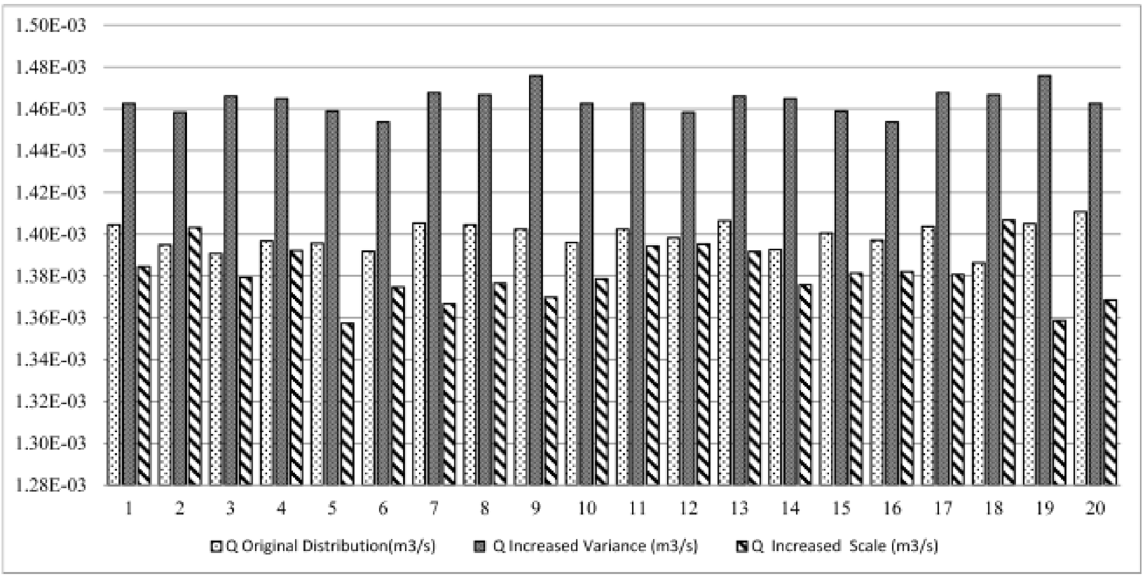

Figure 3- 11. Comparison of the total discharge, Q (m3/s), for cell with 14 sand plugs for 20 realizations for each of the scenarios.

Also considered was the effect of heterogeneity on the discharge directly below the sand plugs. For the configuration with six sand plugs, the mean percentage of discharge leaving the cell directly below the sand plugs increased slightly from 35.3% to 35.9% with the increase in heterogeneity, as shown in Table 3-7. This translates to an increase from 5.9% to 6.0% of the total discharge directly beneath each sand plug. The difference between the mean percentages of discharge directly below the sand plugs in the configuration with 14 sand plugs was approximately 0.01%. Table 3-7 lists the values compiled for 20 realizations of each configuration. The mean percent of discharge directly below the sand plugs was 33% for both the original distribution and the increased variance for the configuration with 14 sand plugs, or 2.4% per sand plug. While the overall discharge is increased with an increase in the heterogeneity of the filter medium, the percentage of seepage attributed to each sand plug is not significantly increased for either configuration containing sand plugs.

Table 3- 7. Comparison of percentage of total flow, Q, leaving the cell directly below the sand plugs for the control models with uniform K, the original distributions, the increased variance distributions, and the increased scale of heterogeneity distributions of cells containing 6 and 14 sand plugs.

	6 Sand Plugs				**14 Sand Plugs**			
% Discharge Directly Under Sand Plugs	Control Model Uniform K	Original Distribution	Increased Variance	Increased Scale	Control Model Uniform K	Original Distribution	Increased Variance	Increased Scale
Mean	35.5%	35.3%	35.9%	35.7%	33.1%	33.0%	33.0%	32.6%
Median	35.2%	35.1%	35.9%	35.7%	33.0%	33.0%	32.9%	32.6%
Standard Deviation	-	0.5%	0.4%	0.7%	-	0.3%	0.4%	0.5%
Minimum	-	34.6%	35.2%	34.4%	-	32.6%	32.2%	31.6%
Maximum	-	36.9%	36.4%	37.1%	-	33.6%	33.5%	33.9%

Increased Heterogeneity Scale

Increasing the representative sample volume was completed by reducing the number of grid points representing the K values within the filter layer of the cell. The grid size was increased from 0.10 m to 0.30 m to correlate with a larger representative sample volume, while the statistical distribution of K remained constant.

The mean discharge increased slightly from 1.88 x 10-3 m^3/s to 1.90 x 10-3 m^3/s when comparing the calculated discharge of the original sample distribution to that of the larger sample volume when considering only the filter, as shown in Table 3-6. Figure 3-9 depicts the same general trend for 19 of the 20 realizations. The standard deviation of the discharge quadrupled from 0.006×10^{-3} m^3/s to 0.02×10^{-3} m^3/s. Since the statistical distribution of the original sample data and the increased scale K values were equal, it follows that the increased standard deviation observed in the cell discharge is due to the increased scale.

The mean discharges for the configurations with sand plugs were reduced slightly, 1.4% and 1.3% for 6 and 14 sand plugs, respectively. For the configuration with 6 sand plugs, the discharge was decreased by 1.8 x 10^{-5} m^3/s from 1.26x10^{-3} m^3/s to 1.24x10^{-3} m^3/s. The configuration with 14 sand plugs was also decreased by 1.8 x 10^{-5} m^3/s from 1.40 x 10^{-3} m^3/s to 1.38 x 10^{-3} m^3/s. Again, the top soil and sand plug layer decreased the discharge by approximately 30% for the increased scale distribution. The difference between discharges for the original sample distribution and the increased scale distribution were the same for all 3 configurations, 1.8 x 10^{-5} m^3/s. However, for the configuration considering only the filter layer, the discharge increased by 1.8 x 10^{-5} m^3/s with the increased scale distribution. This is not wholly unexpected, since the larger scale would provide more variability within the cell as evidenced in the data for the filter-only configuration. However, the calculated discharges for the increased sample size are within 1% of the calculated discharges of the original sample distribution, indicating that the overall effect of mixing is minimal despite an increased scale of heterogeneity.

Previous sections have explored the effects of sand plug size and location on discharge patterns and have noted some concentration of flow beneath the sand plugs in general. As with the increased hydraulic conductivity variance, Table 3-7 shows that the percentage of discharge for the larger scale distribution that may be attributed to the sand plugs is within 1% of the percentages of those modeled with the original sample distribution. For the configuration containing 6 sand plugs, the percent of the total discharge attributed to the sand plugs was slightly higher for the larger scale distribution. It increased from 35.3% to 35.7%, which translates to 5.89% and 5.98% per sand plug for the original sample distribution and the larger scale distribution, respectively. For the configuration containing 14 sand plugs, the percent of total discharge attributed to the sand plugs was slightly lower for the larger scale distribution. The discharge decreased from 33.0% to 32.6%, which translates to 2.4% and 2.3% per sand plug for the original sample distribution and the larger scale distribution, respectively. While it is important to mix soil amendments into filter media as thoroughly as possible, the scale of heterogeneity does not appear to increase the overall potential for preferential flow within the cell for any of the configurations.

Uniform Filter Media

The control model run results for 6 sand plugs, also listed in Table 3-7 were similar to those for all three scenarios. For the K value based on the mean sample conductivity, 35.5% of the discharge was directly beneath the sand plugs, compared with 35.3% for the original distribution, 35.9% for the increased variance distribution, and 35.7% for the increased scale distribution. Whereas, 35.2% of the discharge was directly beneath the sand plugs for the model run with the uniform K value based on the median sample conductivity. When looking at the configuration with 14 sand plugs, again the control values were within 1% of those for the three scenarios. For the control run with the uniform K value based on the mean sample conductivity, 33.1% of the discharge was directly beneath the sand plugs compared to 33.0% for the original distribution and increased variance distributions, and 32.6% for the increased scale distribution. 33.0% of the discharge was directly beneath the sand plugs for the uniform K value based on the median sample conductivity. This is indicative that even though there are complex flow patterns due to the variability introduced in the filter media, that the overall differences between the control models run and the three variability scenarios are insignificant at this scale.

Conclusions

Based on the model results, variability in fly ash content creates complex flow through the filter medium, but does not result in significant preferential flow. Sand plugs do create some flow concentration, indicating a significant, but not dominant influence on flow within the cell.

Quantity and location of sand plugs do not appear to have any significant effect for the two conditions evaluated here. This implies that designers need not be overly concerned with the number of plugs, as long as the total area is appropriate to maintain the desired drainage time. The effects of fly ash uniformity on flow within the cells were minimal for all three configurations. Increasing the variance of K increased the mean discharge for all three configurations by 5% or less. The discharge increase was even less for the increased scale of heterogeneity; only 1%. However, the top soil and sand plug layer dampened the effect of increased variance by over 40% and by approximately 30% for the increased scale for both configurations with sand plugs. The measure of mixing efficiency also had very little effect on the amount of discharge below each sand plug. Therefore, while increased variance and scale of heterogeneity increase the potential for preferential flow pathways, a reasonable amount of mixing will enable proper cell performance with regard to flow.

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CHAPTER IV

THREE-DIMENSIONAL PHOSPHORUS TRANSPORT MODELING OF FLY ASH AMENDED BIORETENTION CELLS AND IMPLICATIONS FOR LONG TERM DESIGN

Abstract

Bioretention is an evolving technology that is becoming more site and contaminant specific as we continue to learn about the driving mechanisms within the cell and the characteristics of urban runoff. Modeling can be an invaluable tool for design and long term planning by making it possible to estimate cell performance under varied conditions and to estimate the effective cell life. Modeling is especially useful when there is little or no long term monitoring data available before considering financial investment. Ten bioretention cells were constructed in Oklahoma as part of a full-scale demonstration project. These cells utilized a blend of sand and fly ash as a filter medium to target phosphorus in stormwater runoff. A three-dimensional finite element model based on the design of the Oklahoma bioretention cells was used to simulate transport of phosphorus, accounting for the variability inherent in soil amendment applications. Effects of variable fly ash content and hydraulic conductivity on the performance of a bioretention cell and effective cell life were studied. The times for the mean effluent concentration to exceed the Oklahoma criterion for scenic rivers were approximately 22 years and 33 years for the filter only and six sand plug configurations, respectively. Modeling predicted more than 144 years of P removal for six sand plug configuration and greater than 95% removal after 20 years for both configurations. . .

Introduction

Bioretention cells (BRC) are an evolving technology that is becoming more site and contaminant specific. There are different designs for those targeting heavy metals (Davis et al., 2006; Li and Davis, 2008), organic contaminants such as petroleum hydrocarbons (Dibilasi et al., 2009; LeFevre et al., 2012), and nutrients such as phosphorus and nitrates (Davis et al., 2006;Hunt et al., 2012; Chavez et al., 2013). Designs consider site characteristics, such as sand plugs for improved infiltration or inverted drainage pipes for nitrate reduction (Brown and Hunt, 2011; Chavez et al., 2015). Whether it is through innovations to the physical design or by the incorporation of soil amendments, these changes affect the overall performance and expected design life. Construction of BRC can be a sizeable investment. Construction costs for Chavez et al. (2015) ranged from $4,700 to $29,000. Thus, it is important to study and understand the mechanisms at work within the cells, especially with regard to hydrology and contaminant attenuation, so that design and implementation of these structures becomes more efficient and effective in terms of both performance and cost.

Bioretention has been studied from many perspectives, including physical testing ranging over bench scale, pilot scale, and full-scale experiments. Mathematical modeling has addressed hydrologic, hydraulic and transport processes at one, two and three dimensions. However, one question that inevitably arises when discussing bioretention with stakeholders and the general public is: what happens when the cells exceed the design life? Should they be left in place? Should they be dug up and replaced? Is there a way to “recharge” them?

As we begin to consider the question of what happens after the fact, it becomes apparent that long-term monitoring would be ideal. The data provided from a long-term monitoring project would be the most accurate means of characterizing the processes occurring within the BRCs, as well as a good base of practical knowledge to figure out the next step. However, BRC is still a relatively young technology, and available monitoring data has yet to exceed the expected design life of a cell. Design has evolved significantly since the first BRCs were implemented in Prince George's County, Maryland, especially with regard to the filter media. Even if there were continuous monitoring data, it would not reflect current design practices. Additionally, BRCs have become increasingly popular as a stormwater best management practice (BMP). Thus, end of life issues and timing are more critical than they would otherwise be. Therefore, modeling is an invaluable, and perhaps only, tool for design and long-term planning.

Models can be used to improve cell design in general and for site specific conditions. They can be used to estimate effective cell life, to estimate performance under varied conditions, and to explore the viability of design innovations (Ackerman and Stein, 2008; He and Davis, 2009; Brown et al., 2010; Daly et al., 2012; Hurley and Forman, 2011; Christianson et al., 2012) Using available information from experiments or field studies, we can use modeling to assist with answering the questions associated with long-term planning. What happens if the cell is left in place after it has exceeded the design life? How much can we extend the life of the cell by 'recharging' the filter material sorption capacity? Which materials make the best candidates for sorption capacity recharge? What are the economic impacts for long-term alternatives?

The objectives of this paper are to demonstrate a method to estimate BRC life expectancy, determine how variability due to soil amendment mixing effort on phosphorus transport impact P retention, and to estimate the long-term expected performance of the Oklahoma BRCs.

Methods

Model Framework

Three-dimensional finite element models of bioretention cells were simulated using COMSOL Multiphysics 4.2 (COMSOL, 2013). The models assumed saturated flow with no unsaturated effects, linear reversible sorption, and no water losses to evapotranspiration or groundwater recharge. All stormwater passed through the BRCs and there was no overflow. All P was assumed soluble, and particulate P transport was neglected. The cell bottom was saturated at atmospheric pressure, and the geometry of the drainage pipes was ignored. It was assumed that there was no P removal by plant uptake or other processes. The relationships between fly ash content and hydraulic conductivity and between fly content and the distribution coefficient were based on sorption studies by Zhang (2006) and are described in more detail later.

Model Geometry

Consistent with the geometry of the full-sized cells constructed in Oklahoma as part of a technology demonstration project, the model cells were 7.5 m long by 7.5 m wide by 1.2 m deep, with an additional 0.3 m representing the top soil/sand plug layer depth.

Two configurations were modeled; a model where only the filter layer was considered, and one that included a top soil/sand plug layer. Only one configuration was modeled with a top soil/sand plug layer since Chavez et al. (2013) showed that there was little difference between configurations where the quantity and size of sand plugs varied, provided that they covered an appropriate area of the surface layer (top soil/sand plug). Therefore, the configuration with the top soil/sand plug layer contained 6 sand plugs 1.5 m by 1.5 m in size and comprising approximately 25% of the surface area of the cell.

Three scenarios were modeled, each representing a different mixing effort in the field as described by Chavez et al. (2013). The first scenario represents a very thorough mixing effort and is based on the distribution of fly ash content of soil samples collected from the filter layer of the bioretention cells during construction. The second scenario represents a less thorough mixing effort by doubling the variance of the original distribution. The third scenario represents the least thorough mixing effort by increasing the scale of variability from 1 L to 27 L. Twenty realizations for each combination of configurations and mixing effort scenarios were run for a total of 120 simulations.

Flow Parameters

Flow parameters for the models were consistent with those used by Chavez et al. (2013) with saturated conditions, the same geometry, and using the same variable hydraulic conductivity (*K*) sets based on variations found in samples taken from the filter layer lifts during construction. Hydraulic conductivity was based on the relationship established by Zhang et al. (2008a),

$$K = 1.04 * 10^{-4} * e^{-0.454X} \tag{1}$$

where *X* is the weight based fly ash content. The sets of random *K* values were generated using a Johnson Transform (*JT*) of the fly ash content distribution (Chavez et al., 2013),

$$K = \frac{1.385*10^{-4} e^{\frac{JT-1.272}{0.9749}} - 6.681*10^{-7}}{1+e^{\frac{(JT-1.272)}{0.9749}}} \tag{2}$$

As in Chavez et al. (2013), the sets of random *K* values in the filter layer were set in a 0.1 m x 0.1 m x 0.1 m grid for the original and increased variance distributions, and a 0.3 m x 0.3 m x 0.3 m for the increased scale distribution.

Transport Parameters

Building on the flow models, a linear, reversible P sorption isotherm was used to model transport through the BRC,

$$C_{solid} = K_d * C_{solute} \tag{3}$$

where C_{solid} is the mass of P sorbed per mass of solid, C_{solute} is the mass concentration of P in solution, and K_d is the distribution coefficient. The linear isotherm was chosen due to the narrow range of solution concentrations used and for computational efficiency. Top soil and sand plug materials were assumed to be homogeneous. Thus, distribution coefficient, K_d, values for top soil and sand plugs were constant.

In order to model the effects of variation on transport, the distribution coefficients for the filter layer used in the model corresponded to the varied fly ash content. Distribution coefficients were computed from the results of sorption studies reported in Zhang (2006).

$$K_d = 0.002 + 0.08712X \tag{4}$$

There was no extrapolation in the K_d calculations since the fly ash contents from the collected samples were within the range of 0-10% used in the Zhang (2006) sorption studies.

The model was run for continuous saturated flow, ignoring non-flow periods and assuming P degradation, uptake, unsaturated flow processes, and evaporation were negligible. Water loading on the BRCs was calculated by Zhang (2008) based on 50 years of precipitation data for the project location and land use. Assuming a 50/50 split of pavement and turf, the annual water loading is 8.05 m/yr. This is equivalent to 452.8 m^3/yr based on the cell geometry for the model. The model was run for a 1160 m^3/m^2 of influent, which is the equivalent of 144 years and well beyond the expected design life. Influent P concentration was assumed constant at 1 mg/L.

Results and Discussion

The effluent concentrations of phosphorus over time were used to determine cell life expectancy. The phosphorus loadings within the BRC over time were used to evaluate the impacts of heterogeneity and mixing effort on BRC performance. As previously mentioned, the models were evaluated for two configurations and three fly ash content distributions.

Cell Life Expectancy

Cell life expectancy was estimated using break through curves. The BRCs that the models were based on had drainage pipe systems in place as outlets. Therefore, it was reasonable to assume that the mean phosphorus concentrations in solution at the bottom layer of the filter layer grid (as defined by the variable hydraulic conductivities in the filter layer) was representative of the effluent concentration for each given time step. Data for each of the realizations modeled were analyzed at 31 times steps over a range of 0 to 144 equivalent years, or approximately every five equivalent years. Mean and median effluent concentration values were plotted versus equivalent time for 20 realizations for each of six scenarios (two configurations and three filter layer variability distributions). The "breakthrough" P concentration in the effluent was compared to the criterion for scenic rivers, 0.037 mg/L, established by the Oklahoma Water Resources Board (Tortorelli and Pickup, 2006).

Figures 4-1 and 4-2 are the breakthrough curves for the original fly ash distribution. All 20 realizations were plotted together to visualize any trends in the data. Figure 4-1 shows the effluent P concentrations based on the mean values for the P concentration in solution at the bottom plane of the model BRC for the filter only configuration. Figure 4-2 shows the effluent P concentrations based on the mean values for the P concentration in solution at the bottom plane of the model BRC for the six sand plug configuration. In both plots, the realizations are similar. They only start to diverge at the end of the curve for the six sand plug configuration. Although, the values are still within 2% for the mean values for all 20 realizations.

Figures 4-3 and 4-4 present the breakthrough curves for the increased variance distribution. All 20 realizations were plotted together. Figure 4-3 shows the effluent P concentrations based on the mean for the P concentration in solution at the bottom plane of the model BRC for the filter only configuration. Figure 4-4 shows the effluent P concentrations based on the mean values for P effluent concentration in solution at the bottom plane of the BRC model for the six sand plug configuration. Again, the realizations are similar, with no noticeable outliers. The realizations in the breakthrough curves for the six sand plug configuration start to diverge toward the end of the model run, as with they did for the original distribution plots. The mean effluent concentration values are within 2% at the end of the curve where it appears to spread out.

Figures 4-5 and 4-6 present the breakthrough curves for the increased scale distribution for the filter only and six sand plug configurations, respectively. All 20 realizations were plotted together. The realizations for the increased scale exhibit a more diverse range of values than the other two distributions. The mean effluent concentration values for the six sand plug configuration are within 7% at the end of the curve where it diverges, as compared with the 2% for the other two distributions.

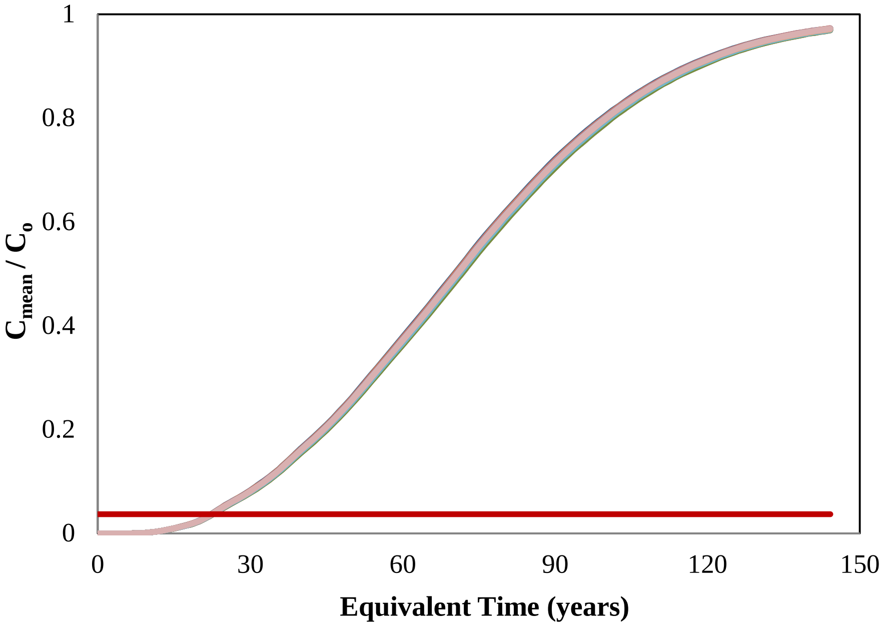

Figure 4-1. Phosphorus concentration in effluent over time for original distribution and the filter only configuration (C_{mean}). Water quality criterion of 0.037 mg/l in red.

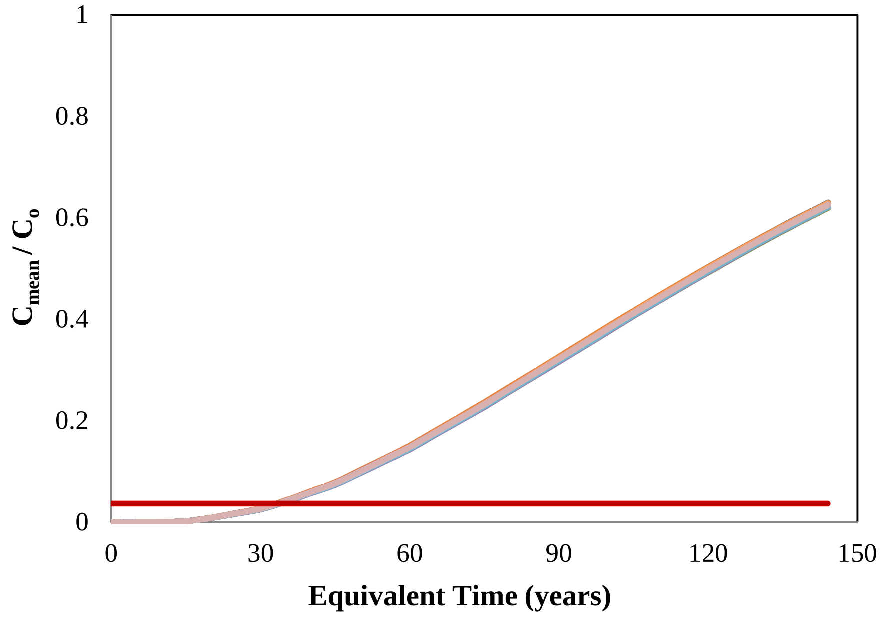

Figure 4-2. Phosphorus concentration in effluent over time for the original distribution and the six sand plug configuration (C_{mean}). Water quality criterion of 0.037 mg/l in red.

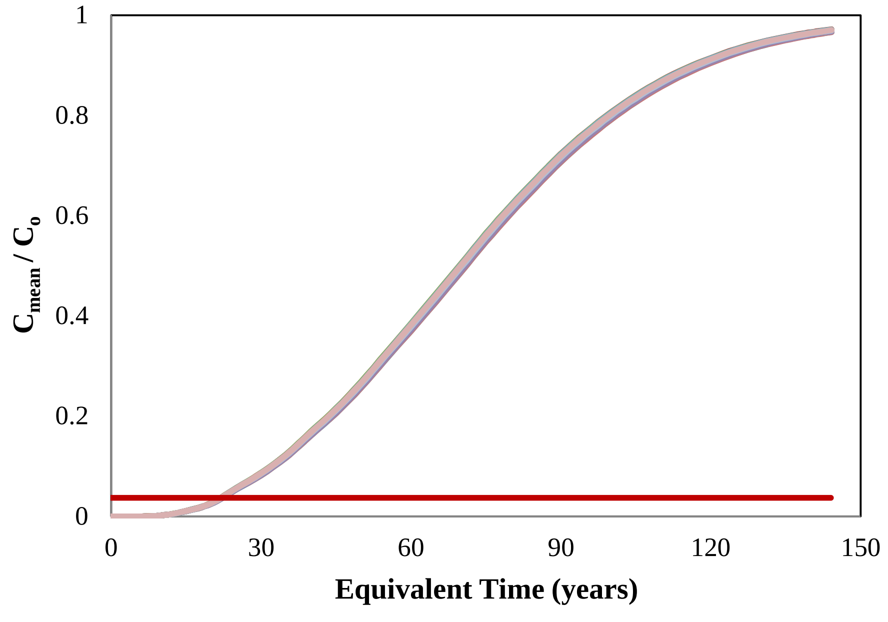

Figure 4-3. Phosphorus concentration in effluent over time for the increased variance distribution and the filter only configuration (C_{mean}). Water quality criterion of 0.037 mg/l in red.

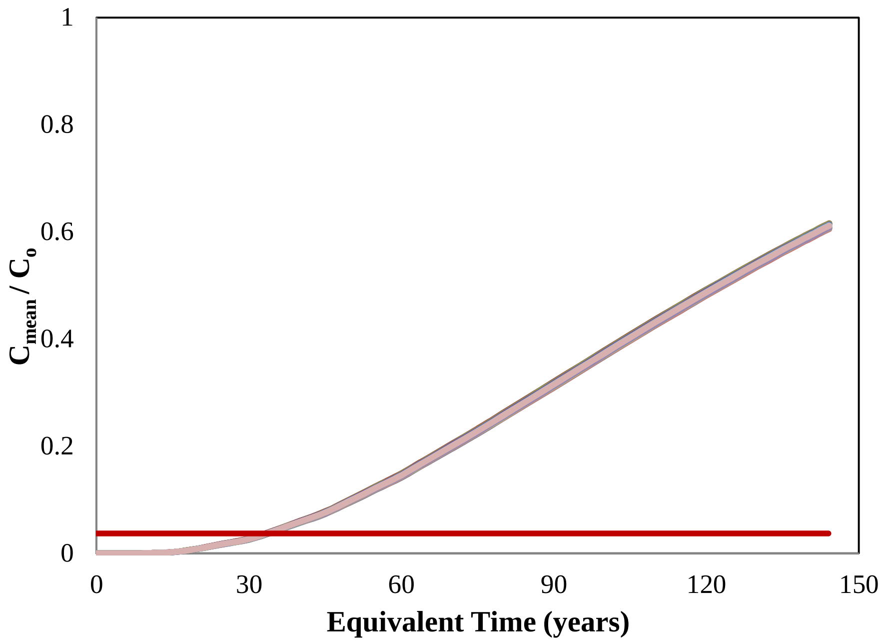

Figure 4-4. Phosphorus concentration in effluent over time for the increased variance distribution and the six sand plug configuration (C_{mean}). Water quality criterion of 0.037 mg/l in red.

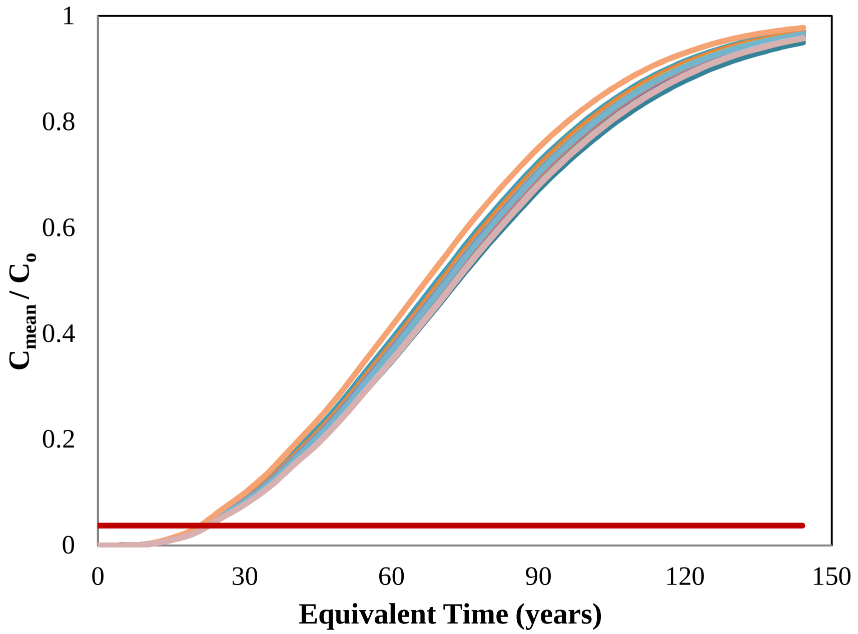

Figure 4-5. Phosphorus concentration in effluent over time for the increased scale distribution and the filter only configuration (C_{mean}). Water quality criterion of 0.037 mg/l in red.

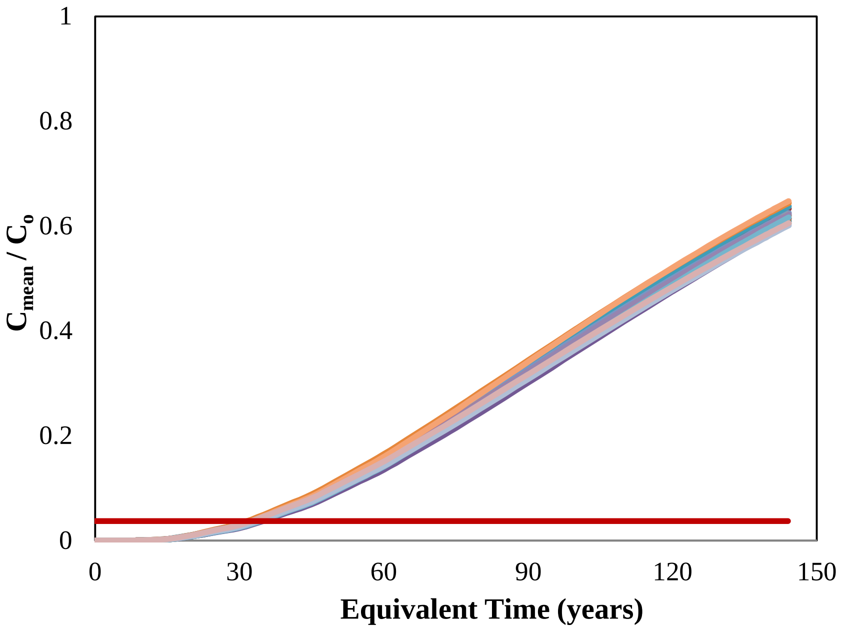

Figure 4-6. Phosphorus concentration in effluent over time for the increased scale distribution and the six sand plug configuration (C_{mean}). Water quality criterion of 0.037 mg/l in red.

Table 4-1 summarizes the time it takes for BRC effluent to exceed the Oklahoma standard for scenic rivers. For the configuration that considered only the filter layer, the time for the effluent to exceed 0.037 mg/L is approximately 22 years for both the mean and median concentration values and for all three distributions. For the configuration with the top soil and sand plug layer, the time for the effluent to exceed the 0.037 mg/L criterion is approximately 33 years and 37 years for the mean and median effluent concentrations, respectively. The addition of the top soil/sand plug increases the life expectancy of the BRCs by 10-15 years.

Table 4-1. Time for BRC effluent to exceed the Oklahoma criterion for P in scenic rivers of 0.037 mg/L.

	Distribution	Filter Only(years)	6 Plugs (years)
C_{mean}	Original	22.3	33.5
	Increased Variance	21.9	33.4
	Increased Scale	21.9	32.9
C_{median}	Original	22.3	37.0
	Increased Variance	21.9	37.1
	Increased Scale	22.1	36.7

Table 4-2. Phosphorus concentration in effluent after 144 equivalent years

	Distribution	Filter Only	6 Plugs	Difference (%)
C_{mean}	Original	0.974	0.625	35.8
	Increased Variance	0.969	0.611	36.9
	Increased Scale	0.964	0.619	35.8
C_{median}	Original	0.971	0.638	34.3
	Increased Variance	0.970	0.625	35.6
	Increased Scale	0.966	0.629	34.9

Table 4-2 shows the phosphorus concentration in the BRC effluent at the end of the model run, 144 equivalent years. For the configuration considering only the filter layer, the effluent P concentration is approximately 0.97 mg/L and close to meeting the 1.0 mg/L assumed influent P concentration. This is indicative of the filter media reaching saturation after 144 equivalent years. When the top soil and sand plug layer is considered as part of the BRC configuration, the effluent P concentration is approximately 0.62 mg/L after 144 equivalent years. This is a decrease of approximately 36% when compared with the filter only configuration and consistent with previous findings. In other words, there is still treatment occurring after 144 years in the configuration with the top soil/sand plug layer.

Table 4-3.Comparison of expected lifespan calculations Zhang (2006) and model results

Effluent P Concentration Exceeds	Expected Lifespan, yr							
	Zhang Calculations		Original		Increased Variance		Increased Scale	
	Pavement	Lawn	Filter Only	6 Sand Plug	Filter Only	6 Sand Plug	Filter Only	6 Sand Plug
0.037 mg/L	4	11	22	34	22	33	22	33
0.5 mg/L	12	35	71	120	70	122	71	121
0.95 mg/L	36	99	132	>144	133	>144	136	>144

Zhang (2006) estimated BRC lifespan based on column and batch sorption studies for sand and 5% fly ash filter media. They assumed a homogeneous filter media depth of 1 m, no top soil layer, a phosphorus concentration of 1 mg/L in the influent, a runoff loading rate of $5x10^{-4}$ m/s, and used the Freundlich isotherm to model sorption. The filter media for the BRCs modeled here assumed a 1.2 m filter media depth, a phosphorus concentration of 1 mg/L in the influent, the runoff loading rate varied due to heterogeneity based on mixing effort and a median fly ash content of 3% (Chavez et al., 2013). Table 4-3 shows a comparison of study Zhang et al. (2008) and the models presented here. The times for the effluent to exceed the 0.037 mg/L and 0.5 mg/L were approximately double those estimated for run off from lawns by Zhang et al. (2008). Adding the top soil/sand plug layer tripled the time for the effluent to exceed those same concentrations. As effluent concentration approaches the influent concentrations, the differences between the estimates decreases. The effluent from configuration with the six sand plugs is still only approximately 0.6 mg/L after 144 years as seen in Table 4-2, and the time it would take for the effluent to reach the 0.95 mg/L was beyond the time span modeled.

Figure 4-7 shows the phosphorus concentration in solution for a configuration with six sand plugs and the original distribution after 20 equivalent years. There is increased concentration directly beneath the sand plugs. Chavez et al. (2013) noted flow concentration beneath the sand plugs. However, it was not dominant or indicative of preferential flow, as is demonstrated in Figure 4-8. Figure 4-8 depicts the same modeled BRC after 144 equivalent years. There is still increased concentration beneath the sand plugs, but there is also sorption occurring in the rest of the BRC.

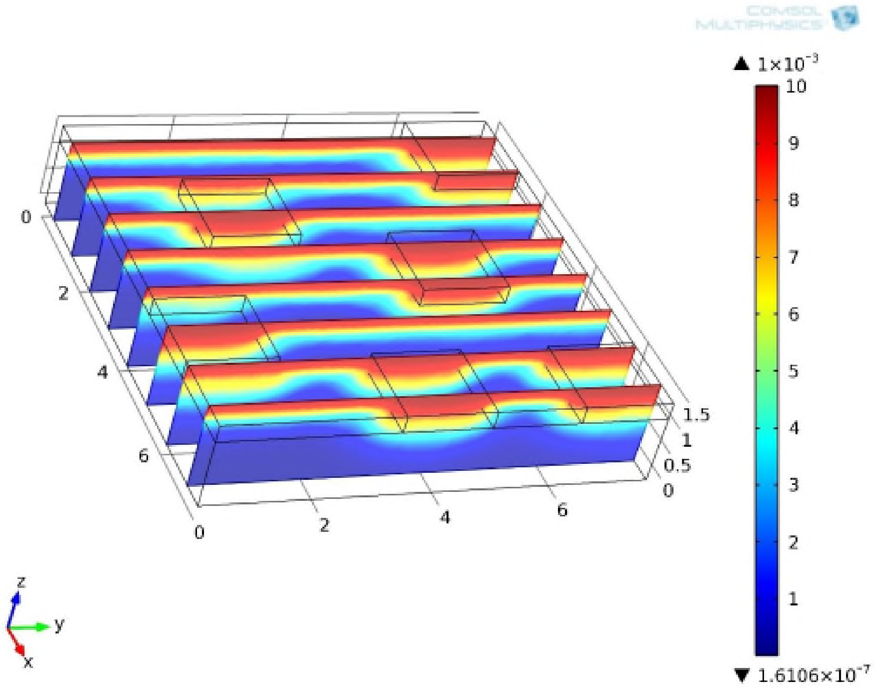

Figure 4-7. Phosphorus concentration in soil solution at 20 years (equivalent time) for a six sand plug configuration and using the original sample distribution.

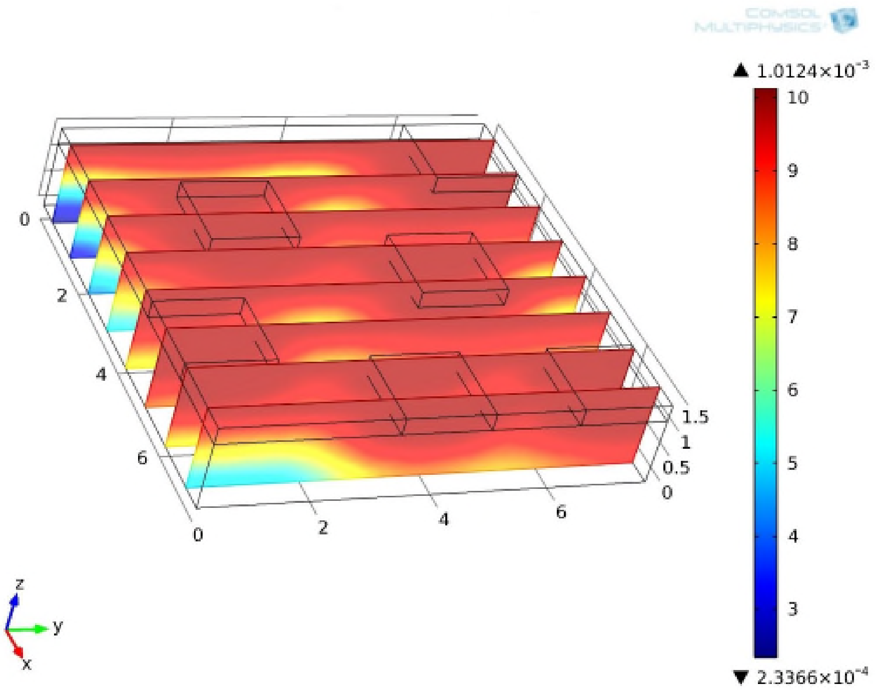

Figure 4-8. Phosphorus concentration in soil solution at 144 years (equivalent time) for a six sand plug configuration and using the original sample distribution.

Cell Performance Impacts

Impacts of heterogeneity within the filter media, and ultimately mixing effort, were evaluated by comparing the amount of P coming into the system to the amount of P being retained by the BRC over time for each of the six scenarios modeled. The mass of P coming into the BRC was calculated using the concentration of P in the runoff assumed in the model (1 mg/L) and the annual water loading for a BRC (Zhang, 2006), assuming a 50/50 split between pavement and lawn (8.05 m^3/m^2) over the area of the BRC footprint (56.25 m^2). The calculated influent loading was 0.45 kg/year. Annual mass of P retained in the BRC was calculated using the mean p concentration in the effluent for each scenario, and the annual water loading from the influent calculations. Tables 4 to 6 summarize the mass balance for the original distribution, the increased variance distribution, and the increased scale distribution, respectively.

Table 4-4. Summary of annual P retained in BRC for the original distribution.

Original	Filter Only		6 Sand Plugs	
Equivalent Time (years)	**Annual P Retained (kg)**	**% Removal**	**Annual P Retained (kg)**	**% Removal**
0	0.000	-	0.000	-
1	0.453	100	0.453	100
20	0.442	98	0.449	99
40	0.380	84	0.426	94
60	0.285	63	0.386	85
80	0.177	39	0.334	74
100	0.091	20	0.280	62
120	0.040	9	0.227	50
140	0.016	3	0.179	40
144	0.013	3	0.170	37

Table 4-5.Summary of annual P retained in BRC for the increased variance distribution.

Increased Variance	Filter Only		6 Sand Plugs	
Equivalent Time (years)	**Annual P Retained (kg)**	**% Removal**	**Annual P Retained (kg)**	**% Removal**
0	0.000	-	0.000	-
1	0.453	100	0.453	100
20	0.441	97	0.449	99
40	0.378	83	0.426	94
60	0.281	62	0.387	85
80	0.175	39	0.336	74
100	0.091	20	0.284	63
120	0.041	9	0.232	51
140	0.017	4	0.185	41
144	0.014	3	0.176	39

Table 4-6. Summary of Annual P retained in BRC for the increased scale distribution.

Increased Scale	Filter Only		6 Sand Plugs	
Equivalent Time (years)	Annual P Retained (kg)	% Removal	Annual P Retained (kg)	% Removal
0	0.000	-	0.000	-
1	0.453	100	0.453	100
20	0.441	97	0.449	99
40	0.379	84	0.425	94
60	0.286	63	0.385	85
80	0.181	40	0.334	74
100	0.097	21	0.281	62
120	0.045	10	0.229	51
140	0.019	4	0.182	40
144	0.016	4	0.173	38

Removal efficiencies decreased over time, but are consistent with the findings in the previous section. Treatment is still occurring after 144 nominal years in the six sand plug configuration, while the BRC appears to have reached P saturation for the filter only configuration. Filter only configuration removal efficiencies were 3% and 4%. Removal efficiencies for the original distribution (most thorough mixing effort) over the model time span ranged from 100% to 3% for the filter only configuration and from 100% to 37% for the six sand plug configuration. The increased variance distribution data, which represents the second level of mixing effort, had removal efficiencies over the model time span that ranged from 100% to 3% for the filter only configuration and 100% to 39% for the six sand plug configuration. The removal efficiencies for the increased scale distribution (least thorough mixing effort) over the model time ranged from 100% to 4% for the filter only configuration and from 100% to 38% for the six sand plug configuration. Also of note, comparison among the distributions show the removal efficiencies to be within 1% for the filter only configuration and within 2% for the six sand plug configuration, further emphasizing that mixing effort is not critical to cell performance, as reported by Chavez et al. (2013).

Figures 4-9 and 4-10 show that the modeled BRCs removal rates are above 95% for approximately 25 years for the filter only configuration and for approximately 37 years for the six sand plug configuration, for all three distributions. The removal efficiencies decrease to 50% at approximately 70 years for the filter only configuration and 120 years for the six sand plug configuration. This is indicative that BRCs may be viable longer than was previously expected.

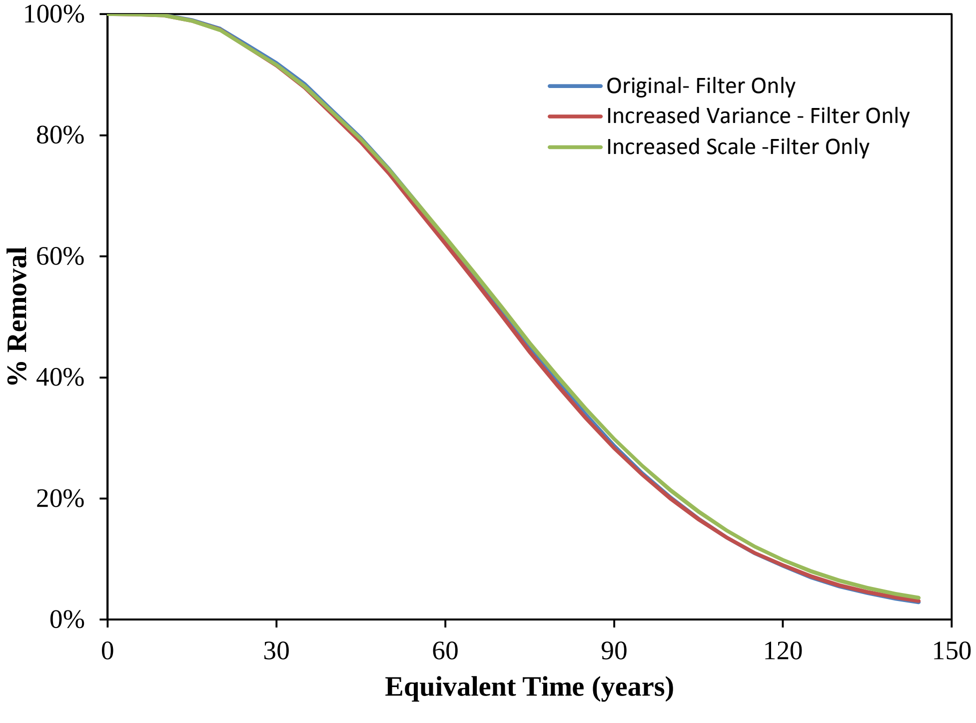

Figure 4-9. P removal efficiency over time for the filter only configuration.

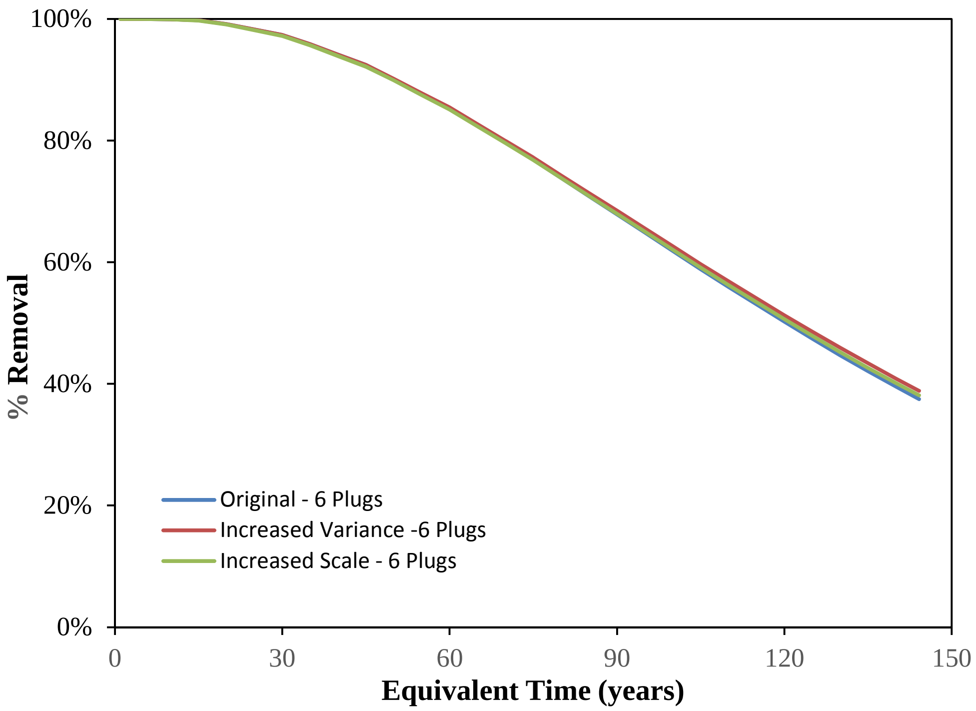

Figure 4-10. P removal efficiency over time for the six sand plug configuration.

The transport model did not account for acidity introduced to the system from particulates in the runoff, as it was beyond the scope of this study. It was assumed that desorption of phosphorus was negligible, based on studies by Zhang et al (2008). P precipitates out of solution when it reacts with the CaO in the fly ash. However, if enough acidity were introduced into the system, it could theoretically cause sorption of P to decrease. Zhang et al. (2008) did look at the effects of pH on phosphorus sorption of fly ash in a laboratory setting. At a pH of 8.6, the removal efficiency decreased from nearly 100% to 67.5%. However, they also found that as the pH approached 8.0, efficiencies increased again possibly due to the formation of oxide-phosphate complexes or precipitates with Fe and Al ions, as Al_2O_3 and F_2O_3 were both present in the fly ash used in the study and that used in this project. As the pH of the sand/fly ash blend of the filter media was approximately 11 when placed in the cells during construction, it is most likely that this would not happen over a reasonable lifespan for a cell, and would warrant further study.

Conclusions

From the results of this study, the expected life varies depending on the configuration. The time for the mean effluent concentration of filter only configuration to exceed the Oklahoma criterion for scenic rivers is approximately 22 years. The time for the mean effluent concentration of six sand plug configuration to exceed the Oklahoma criterion for scenic rivers is approximately 33 years. The addition of the top soil/sand plug layer increases the design life of the cell by 10-15 years, if the design life ends when the effluent concentration exceeds the water quality standard. At the end of the model time span, the equivalent of 144 years, the filter only configuration has reached P saturation. At the end of the model time span, the equivalent of 144 years, the six sand plug configuration is attenuating P. The three distributions/ mixing efforts show similar sorption patterns/ removal efficiencies for each configuration. The six sand plug configuration supports active treatment longer than the filter only configuration. The effects of the heterogeneity of the filter are consistent with previous findings (Chavez et al., 2013) that reasonable mixing effort will ensure proper performance.

Due to the life expectancy of 20 years or longer, it is recommended that future effluent sampling will be the best measure of cell performance. However, with increasing popularity of BRC as a stormwater BMP and the lack of available long-term monitoring data, modeling needs to be an integral part of design and long-term planning.

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CHAPTER V

ENGINEERING CONTRIBUTIONS AND RECOMMENDATIONS

Engineering Contributions

The objective of this research was to document design and construction efforts and to address some of the resulting questions from the bioretention technology demonstration project in Oklahoma. How do sand plugs interact with the filter media? How does the variability in fly ash content impact the flow and phosphorus transport through the filter? How does mixing effort impact performance? How does the construction design impact P transport? How does the variability of fly ash content impact the expected BRC life span? How can we use this information to improve cell design and construction practices? What does this mean in terms of long term planning?

The cell design implemented for this project included the use of a sand and fly ash blend for the filter media as a means to target phosphorus from surface runoff and also incorporated surface sand plugs for improved infiltration in areas with poorly draining local topsoils. A three dimensional finite element model was developed to explore the effects of heterogeneity introduced by soil amendments as well as sand plug size and location on cell performance and design life.

Overall, the cells appear to be functioning as designed, and a few added benefits such as erosion reduction and temperature attenuation of cell runoff have been observed. The sand plugs proved to be easy to construct and have been effective at allowing runoff to infiltrate the cell from observations. The model results show that sand plugs create flow concentration. However, it is not dominant. Model results also indicate that the quantity and location of sand plugs do not have an observable effect, provided that the total area is sufficient for the desired infiltration. In terms of application, implementation of sand plugs would allow the use of local top soils to support vegetation and still have adequate infiltration. By not being constrained by size and the number of sand plugs necessary, it is easier to work the sand plugs into open spaces in the garden design, allowing for more attractive structures and public buy-in. The addition of the sand plugs to the design, also makes using local top soils more practical, especially in areas where extremely low hydraulic conductivities are the limiting factor in whether to use a local top soil layer or to purchase commercial bioretention media and/or doing away with the layered approach to cell design. A layered design also makes it easier to vary soil amendments for targeting specific contaminant based on need. Model results show that the addition of top soil layer could possibly extend the design life of the bioretention cells by ten years or more. Use of local materials and longer design life would also affect construction costs. There is less material to transport to and from the site when local materials are used, and a longer design life makes it easier to justify the investment.

The model results show that variability in fly ash content creates complex flow through the filter, but show no evidence of significant preferential flow. In other words, while increased variance and scale of heterogeneity increase the potential for preferential flow pathways, a reasonable mixing effort will ensure proper cell performance. Mixing effort used for soil amendments would affect construction practices and unit costs due to labor associated with the different levels of effort.

The results from Chapter 4 showed that mean effluent concentration exceed the Oklahoma standard for scenic rivers after approximately 22 and 33 nominal years for the filter only and sand plug configurations, respectively, and that phosphorus removal continued after 144 nominal years. Evaluating performance over time and estimating design life of bioretention cells with the use of a model could have implications for more efficient cell design and the ability to target specific contaminants based on need, as well as long-term planning. If the design life of a cell is 30 years, it might be more economically feasible to invest additional time and money into a design, than it would if the design life were 10 years. The use of a model also makes it easier to estimate performance of several design variations before investing resources to implement full size structures. Ultimately, models can be an invaluable tool for a more efficient design process and a more efficient use of resources.

Recommendations for Future Work

The models presented in this dissertation depend largely on collected samples and laboratory experiments to simulate flow through a bioretention cell as well as estimate phosphorus removal efficiency. However, the models have not been validated, and monitoring is the next logical step to assess the accuracy of the models. Suggested monitoring would consist of measuring flow in and out of the cell after storm events, contaminant levels in influent and effluent samples, soil core samples, and temperature of influent and effluent. As the model assumed saturated and continuous flow conditions, flow monitoring data would provide insight to the effects of antecedent moisture conditions on cell performance. Monitoring the amount of phosphorus in the influent and effluent to assess the phosphorus attenuation and movement in the cells would be beneficial to gaining a better understanding of cell performance over time. Considering the high pH of the sand/fly ash filter media, metals would also be contaminants of interest. In addition to water samples, core samples taken from the cells periodically could provide data about pH levels, fly ash distribution and movement over time. During a hydraulic test of the bioretention cells in

Grove, it was observed that the effluent was noticeably cooler than the influent. Monitoring the temperature of the influent and effluent to quantify thermal attenuation would be interesting. Ideally, a long-term monitoring effort would provide invaluable data of cell performance over time.

In the discussion about soil amendment selection in Chapter 2, the results of desorption study by a previous graduate student suggested that sorption of phosphorus onto fly ash may be for all intents and purposes irreversible. The pH of the sand/fly ash filter media blend was approximately 11. The precipitation of phosphorus out of solution is highly dependent on pH. For the purposes of the model is was assumed that desorption of phosphorus was negligible. However, phosphorus sorption could theoretically be reduced if enough acidity were introduced to the system over time. As there are little data on the amount of acidity introduced into a bioretention cell for various land use types, and the mechanism for any soil amendment targeting phosphorus would be affected by pH, it would be interesting to study the how the acidity affects the expected lifespan of a cell and overall contaminant attenuation efficiency.

The model did not account for the possibility of preferential flow introduced by macropores caused the vegetation root systems and fauna. However, it would be helpful to understand how flora and fauna affect cell performance and to identify design features that may help mitigate to help prevent preferential flow due to unintentional macropores.

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