Defining Rain Garden Filter Bed Substrates Based on Saturated Hydraulic Conductivity

H. Kraus[a], R. Pledger, E. Riley,
W.C. Fonteno and B.E. Jackson
Department of Horticultural Science
North Carolina State University
Campus Box 7609
Raleigh, North Carolina
27695-7609
USA

T. Bilderback[b]
J.C. Raulston Arboretum
Department of Horticultural Science
North Carolina State University
Campus Box 7522
Raleigh, North Carolina
27695-7522
USA

Keywords: urban stormwater, biofiltration, stormwater BMP

Abstract

Water is one of the planet's most precious non-renewable resources, yet it has become one of the most polluted and neglected. The number one cause of water pollution in many watersheds originates from non-point sources, such as storm water runoff. Rain gardens trap storm water runoff and remove pollutants. To effectively remove pollutants, storm water runoff must be held in the rain garden substrate as long as possible. Since a substrate's water retention characteristics are defined by it particle size distribution, rain garden filter bed substrates are best classified as horticultural substrates. Filter bed substrates sand and slate were tested with composts (biosolids, food, and yard wastes) added. All composts increased course and decreased fine particles when added to sand. Sixty percent amendments of all composts gave the greatest increase in medium particles in sand. For slate, food and yard composts decreased fines, biosolids increased fines, and enzyme had no impact on fines. All composts had no or little impact on medium and coarse particles when added to slate. A 20% addition of all composts resulted in optimal saturated hydraulic flow and greater retention of simulated stormwater runoff in both the sand and slate based substrates. Sand with an initial particle size distribution of 83% fine, 17% medium and 0.25% coarse particles should be amended to achieve a final particle size distribution of 67% fine, 30% medium, and 2% coarse. The coarser textured slate (31% fine, 44% medium, and 24% coarse) should have a final particle size distribution of 30% fine, 48% medium, and 22% coarse particles.

INTRODUCTION

Urban storm water runoff (a non-point source of pollution) is still listed in the top 10 causes of US river, stream, lake, pond, reservoir, bay and estuary impairments (EPA, 2009). Arnold and Gibbons (1996) feel this is in a great part due to the large increase in impermeable surfaces which correlates with increases in population. Rainfall that lands on urban impervious surfaces is not available for infiltration into soil systems and transference to underground water reserves. The Center for Watershed Protection (CWP, 2003) reports that when as little as 5% of land in a watershed is paved, stream water quality decreases. Stormwater generates two threats to water quality – volume of runoff and pollutant load in the runoff.

Rain gardens which are positioned in the landscapes to capture stormwater runoff are widely accepted mechanisms of stormwater runoff treatment in the urbanized areas of the US and worldwide. Construction of a rain garden generally involves excavation of the native soil and filling this depression with a filter bed substrate that is composed of both inorganic and organic constituents. Rain garden aesthetics, in unison with water pollution

[a] E-mail: Helen_Kraus@ncsu.edu.
[b] E-mail: Ted_Bilderback@ncsu.edu.

remediation potential and return of clean water to the water supply, drives interest in rain gardens by landscape designers and contractors, urban designers and engineers, and environmentally conscious laypersons. Sustainable landscaping includes installation of stormwater treatment components, such as rain gardens which are accepted as Low Impact Development (LID) in the United States, Water Sensitive Urban Drainage Systems (WSUD) in Australia, and Sustainable Urban Drainage Systems (SUDS) in Europe (Davis et al., 2009; Dietz and Claussen, 2005; Hunt, AG-588-3; Lucas and Greenway, 2008). Depending on design parameters, size of storm event, and substrate composition; rain gardens are effective in remediating nitrogen, phosphorus, metals (zinc, copper, and lead specifically), total suspended solids, and pathogens to safe levels (Davis et al., 2009; Dietz and Claussen, 2005; Hunt, AG-588-3). These are non-irrigated landscape features that experience both flooding and drought. Therefore, plants selected for rain gardens must be tolerant of short-term flooding and long-term drought.

Rain gardens remove pollutants through several physical (filtration and sedimentation), chemical (absorption and adsorption), and biological (uptake and fixation) processes (Davis et al., 2009; Dietz and Claussen, 2005; Hunt, AG-588-3). Intrinsic to the success of all these remediation processes is the slow drainage (Ksat) of stormwater runoff through the rain garden filter bed. Low rates of Ksat increase water retention time and remediation of pollutants (Davis et al., 2009; Dietz and Claussen, 2005; Hunt, AG-588-3). An individual substrate component's particle size, shape and ratio within the substrate will determine the blended substrate's Ksat, moisture retention, and re-aeration rates (Bunt, 1983; Drzal, 1999). However, rain garden substrates are more often described using soil textural classification terms. As an example, a substrate composed of 80% sand, 7% silt, 5% clay and 0.5% fine gravel and one composed of 80% sand, 15% clay/silt, and 5% pine bark by volume are sold as sand based filter bed substrates.

Soil textural classification may be too general of a description to apply to rain garden filter bed substrates, especially since these substrates are engineered blends of both soil based and non-soil based components. Non-soil based filter bed substrates (such as those composed of expanded slate) and sand:soil:pine bark mixtures are easily defined and blended to achieve predictable drainage rates. Thus, rain garden filter bed substrates may be better classified as horticultural substrates, by particle size distributions and Ksat. Drzal et al.'s (1999) work focused on designing and defining particle size clusters for container substrates. He described particle size of substrates within three different categories: coarse (>6.3-1.99 mm), medium (2.0-0.5 mm) and fine particles (0.49-<0.11 mm). Each of these categories affects and alters the water holding capacities of substrates. Furthermore, Bilderback and Lorscheider (1995) reported that substrates with uniform particle size (less difference in the amount of coarse and fine particles) had greater total porosity. Relations between Ksat values and rain garden particle size groups will be evaluated in this paper.

MATERIALS AND METHODS

An experiment was designed as a randomized complete block design with three replications to evaluate the effect of substrate on the saturated hydraulic flow (Ksat), particle size distribution, plant growth, and volume, pH, and electrical conductivity of effluent (EC). Substrates included a factorial combination of substrate base component and organic amendment. Two substrate bases were evaluated: sand and slate. The sand base was a blend (v/v/v/v) of 80% sand, 7% silt, 5% clay and 0.5% fine gravel (donated by Bradsher Landscape Supplies, Raleigh, NC). This substrate was chosen to represent a commonly used rain garden filter bed substrate for North Carolina. The slate was 100% expanded slate (donated by PermaTill, Carolina Stalite Company, Salisbury, NC). The slate substrate was chosen because it has become a popular commercial rain garden filter bed substrate in North Carolina and is locally produced.

Organic amendments included a food waste compost (donated by Brooks Contractor, Goldston, NC) (referred to as food) and a biosolids compost including residuals and byproducts from industrial, municipal, commercial and agribusiness sources (donated by McGill Environmental Systems, New Hill, NC) (referred to as biosolids). Food waste and biosolids composts were fine in texture. Two coarse textured composts were also evaluated – a composted blend of enzyme production residuals and yard waste (referred to as enzyme) (donated by Novozymes North America, Franklinton, NC) and a yard waste compost (City of Raleigh, NC) (referred to as yard). These organic constituents were added to each base at 0, 20, 40, 60, or 80% by volume using hand-filled cubic foot box.

On 11 June 2012 *Callicarpa americana* was planted into 23 L Pecan King containers (Haviland Plastics, Haviland, Ohio 45851) filled with each substrate and grown for 48 weeks (16 May 2013). The plants were watered daily without fertilizer for the first two weeks to allow them to become established. After this plants were fertigated with 2 mg/L of P (supplied by diammonium phosphate, 18-46-0) and 11 mg/L of N (supplied by ammonium sulfate 21-0-0-24) to simulate polluted stormwater runoff. One inch of fertigated water was applied once a week (June-October), once a month (November-March), and every two weeks (April-May) using a low-volume spray stake (PC Spray Stake, Netafim, Ltd., Tel Aviv, Israel) to mimic rainfall for Raleigh, NC. Planted containers were set into an 18.9 L bucket with a hole drilled in the bottom and supported above the surface of the ground by two bricks. A tray was placed under the bucket's drainage hole during simulated rainfall events to collect the effluent that drained from the container. Volume of the effluent was measured and pH and EC were measured using a Hanna pH/EC meter (HI 8424, Hannah Instruments, Ann Arbor, MI).

Particle size and saturated hydraulic conductivity (Ksat) were measured for three replications of each substrate. Particle size was determined by shaking a 350 g oven dried sample for five minutes using a Rotap shaker fitted with thirteen sieve plates; 6.3 mm (0.25 in), 4.0 mm (0.16 in), 2.8 mm (0.11 in), 2.0 mm (0.08 in), 1.4 mm (0.06 in), 1.0 mm (0.04 in), 0.71 mm (0.03 in), 0.5 mm (0.02 in), 0.36 mm (0.01 in), 0.25 mm (0.009 in), 0.18 mm (0.007 in) and 0.106 mm (0.004 in). The portion of the sample collected on each sieve plate was weighed and expressed as a percentage of the total weight of the sample. Percentages of total sample were then grouped into fine, medium and coarse fractions as described by Drzal et al. (1999) for statistical analyses. Saturated hydraulic conductivity was determined by packing each substrate into 1,029 cm^3 cylindrical polyvinyl chloride (PVC) columns (5.08 cm diameter, 50.8 cm height). Columns were slowly saturated from the bottom and allowed to remain at saturation for two hr. After this saturation period, water flow was resumed through the columns, flow out of an elbow fitting was caught for five min, measured and used to calculate Ksat using Darcy's Law.

The study consisted of 34 substrates and was conducted at the Horticulture Field Laboratories, Raleigh, NC (longitude: 35°47'29.57"N; latitude: 78°41'56.71"W; elevation: 136 m). SAS 9.2 was used to test all variables for differences using analysis of variance procedures and regression analyses ($p \geq 0.05$) where appropriate (SAS Institute, 2001).

RESULTS AND DISCUSSION

For the sand based substrate, food and yard composts decreased fine particles linearly while there were quadratic responses with biosolid and enzyme composts having the lowest amounts of fine particles with 60% (Table 1). There were quadratic responses in the medium fraction to adding compost to sand for biosolids with the minimum at 40% and enzyme and food with minimum at 20%. Yard compost resulted in a linear increase in the medium fractions when added to sand. All composts resulted in a linear increase in coarse particles when added to the sand based substrate which was finer in texture than any of the composts.

With slate, food and yard composts decreased fine particles linearly while biosolids increased fine particles linearly (Table 2). There was no impact on the the medium particle fraction to the addition of any of the composts when added to slate. Food compost resulted in a linear increase in the coarse fraction. This response was surprising due to the fact that food compost was generally finer in texture than the slate. Biosolids resulted in a quadratic response in the coarse fraction with the minimum found with the 80% biosolid addition. Enzyme and yard composts did not alter the coarse particle fraction in the slate based substrate. Furthermore, enzyme compost did not alter the fine, medium, or coarse particle fractions in slate.

All composts increased course particles when added to sand. The coarse particles in a substrate create large pores within the substrate and therefore establish the pore network that conducts water through the substrate (Bunt, 1983; Drzal et al., 1999). All composts also decreased fine particles in the sand substrate. The fine particles nest into larger pores and retain water against leaching (Bunt, 1983; Drzal et al., 1999). Sixty percent amendments of all composts gave the greatest increase in medium particles in sand. The medium particles retain large amounts of water and contribute to increased total porosity (Drzal et al., 1999). For slate, food and yard composts decreased fines, biosolids increased fines, and enzyme had no impact on fines. All composts had no or little impact on medium and coarse particles when added to slate.

When composts were added to sand, Ksat increased linearly for biosolids, food, and yard composts (Fig. 1A) due to the increase in large pores created by course particles. Sand amended with 60% enzyme compost resulted in the greatest Ksat. Since rain garden substrates require maximum contact time with stormwater pollutants, Ksat needs to be as low as possible. It appears that no more than 20-40% enzyme, food, and yard composts should be added to sand. With slate, there was a linear increase in Ksat for biosolids, food, and yard composts and a quadratic response with enzyme compost (Fig. 1B). Compost additions as high as 40% kept Ksat low in slate. Ksat began to increase more sharply as greater than 40% food and yard composts were added to slate. Another method of assessing water retention by the substrates is through the measurement of the volume of effluent that leaves the rain garden. For both sand and slate 20% additions of all composts resulted in greater water retention in (lower water loss from) the rain gardens (data not shown).

Shoot dry weight was not affected by compost addition to either sand or slate based substrate (data not shown). However, substantial plant death occurred in this study possibly due to high EC levels (data not shown). Additions of biosolids, enzyme, and yard composts greater than 20% resulted in 50% mortality of plants. At the beginning of the experiment, EC levels greater than 6 mS were measured for all the compost additions greater than 20% except yard compost. Electrical conductivity decreased linearly for all compost additions to both sand and slate and reached levels below 2.0 mS with biosolids, enzyme, and food composts by 30 days after initiation (5 simulated rain events). Electrical conductivity levels of yard waste began slightly above 2.0 mS and fell to below 2.0 mS within four simulated rain events (18 days after initiation).

In conclusion, a 20% addition of all composts resulted in optimal saturated hydraulic flow and greater retention of simulated stormwater runoff in both the sand and slate based substrates. Sand with an initial particle size distribution of 83% fine, 17% medium and 0.25% coarse particles should be amended to achieve a final particle size distribution of 67% fine, 30% medium, and 2% coarse. The coarser textured slate (31% fine, 44% medium, and 24% coarse) should have a final particle size distribution of 30% fine, 48% medium, and 22% coarse particles.

Literature Cited

Arnold, C.L. and Gibbons, C.J. 1996. Impervious surface coverage: the emergence of a key environmental indicator. J. of the American Planning Association 62(2)243-258.

Bilderback, T.E. and Lorscheider, M.R. 1995. Physical properties of double-processed pine bark: Effects on rooting. Acta Horticulturae 401:77-83.

Bunt, A.C. 1983. Physical properties of mixtures of peats and minerals of different particle size and bulk density for potting substrates. Acta Horticulturae 150:143-153.

Center for Watershed Protection (CWP). 2003. Site planning for urban stream protection: Chapter 2, The importance of imperviousness. http://www.cwp.org, Accessed February 2, 2012.

Davis, A.P., Hunt, W.F., Traver, R.G. and Clar, M.E. 2009. Bioretention technology: An overview of current practice and future needs. Journal of Environmental Engineering 135(3):109-117.
Dietz, M.E. and Claussen, J.C. 2005. A field evaluation of rain garden flow and pollutant treatment. Water, Air and Soil Pollut. 167(1-4):123-138.
Drzal, M.S., Fonteno, W.C. and Keith Cassel, D. 1999. Pore fraction analysis: A new tool for substrate testing. Acta Hort. 481:43-54.
Environmental Protection Agency (EPA). 2009. National Water Quality Inventory: Report to Congress. EPA-841-R-08-001.
Hunt, W. AG-588-3. Designing rain gardens (bio-retention areas). http://www.bae.ncsu.edu/stormwater/PublicationFiles/DesigningRainGardens2001.pdf accessed 6/17/13.
Lucas, W.C. and Greenway, M. 2008. Nutrient retention in vegetated and nonvegetated bioretention mesocosms. J. Irrig. Drain. Eng. 134(5):613-623.
SAS Institute, Inc. 2001. SAS/STAT User's Guide, Release 9.3 Edition, SAS Inst., Inc., Cary, NC.

Tables

Table 1. Effect of compost on fine (<0.5 mm), medium (0.5-2.0 mm), and coarse (>2.0 mm) particles of a sand based rain garden substrate.

		Particle size		
Compost[z]	Amendment %[y]	Fine	Medium	Coarse
Biosolids	20	68	30	2
Biosolids	40	52	45	4
Biosolids	60	50	45	5
Biosolids	80	66	28	7
Regression[x]		Q – 0.0001	Q – 0.0001	L – 0.0001
Enzyme	20	74	19	1
Enzyme	40	66	28	2
Enzyme	60	42	46	10
Enzyme	80	67	26	11
Regression		Q – 0.02	Q – 0.004	L – 0.0001
Food	20	64	34	2
Food	40	49	48	4
Food	60	30	57	13
Food	80	28	44	29
Regression		L – 0.0001	Q – 0.0001	L – 0.0001
Yard	20	63	35	2
Yard	40	71	27	2
Yard	60	47	45	8
Yard	80	44	45	11
Regression		L – 0.002	L – 0.01	L – 0.0001
Sand[w]	0	83	17	0.25

[z] Composts included a biosolids compost including residuals and byproducts from industrial, municipal, commercial and agribusiness sources (biosolids), enzyme production residuals compost (enzyme), food waste compost (food), and a yard waste compost (yard).

[y] Composts were added to each base at 0, 20, 40, 60, or 80% by volume.

[x] Regression analyses. L = linear, Q = quadratic. P-value given.

[w] The sand base was a blend (v/v/v/v) of 80% sand, 7% silt, 5% clay and 0.5% fine gravel.

Table 2. Effect of compost on fine (<0.5 mm), medium (0.5-2.0 mm), and coarse (>2.0 mm) particles of a slate based rain garden substrate.

		Particle size		
Compost[z]	Amendment %[y]	Fine	Medium	Coarse
Biosolids	20	32	48	20
Biosolids	40	34	65	32
Biosolids	60	35	44	21
Biosolids	80	44	39	17
Regression[x]		L – 0.01	Q – 0.003	Q – 0.0001
Enzyme	20	33	43	21
Enzyme	40	34	38	22
Enzyme	60	35	42	22
Enzyme	80	31	46	24
Regression		NS	NS	NS
Food	20	26	52	21
Food	40	24	55	20
Food	60	15	50	35
Food	80	11	61	28
Regression		L – 0.0001	NS	L – 0.04
Yard	20	27	47	26
Yard	40	26	51	25
Yard	60	19	50	31
Yard	80	15	48	37
Regression		L – 0.0001	NS	NS
Slate[w]	0	31	44	24

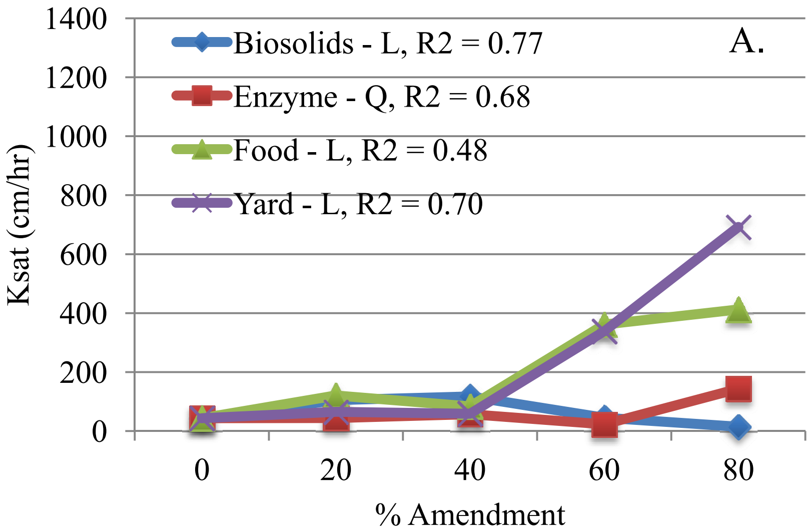
[z] Composts included a biosolids compost including residuals and byproducts from industrial, municipal, commercial and agribusiness sources (biosolids), enzyme production residuals compost (enzyme), food waste compost (food), and a yard waste compost (yard).

[y] Composts were added to each base at 0, 20, 40, 60, or 80% by volume.

[x] Regression analyses. L = linear, Q = quadratic. P-value given.

[w] The slate base was a 100% expanded slate.

Figures



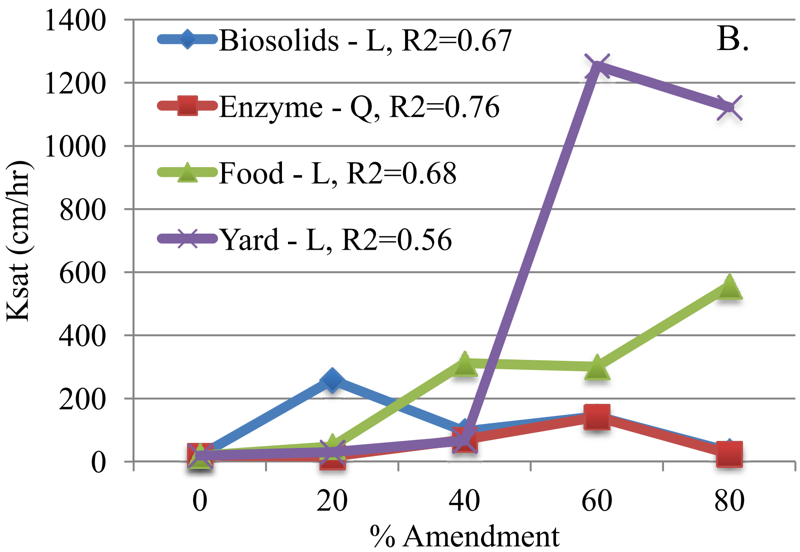


Fig. 1. Effect of compost addition on saturated hydraulic flow of a sand based (A) and slate based (B) rain garden substrate. The sand base was a blend (v/v/v/v) of 80% sand, 7% silt, 5% clay and 0.5% fine gravel. The slate base was a 100% expanded slate. Composts included a biosolids compost including residuals and byproducts from industrial, municipal, commercial and agribusiness sources (biosolids), enzyme production residuals compost (enzyme), food waste compost (food), and a yard waste compost (yard). Composts were added to each base at 0, 20, 40, 60, or 80% by volume. Regression analyses. L = linear, Q = quadratic. P-value and R^2 given.