Evaluation of a New Storm Water BMP- a Filtration Basin

THESIS

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By

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Abstract

Present methods to increase quality and reduce rate and quantity of urban storm water runoff between developed land and receiving streams exhibit limitations, often resulting in a failure to achieve US Environmental Protection Agency (EPA) targets. A new BMP is proposed which combines proven methods in a new configuration designed to increase pollutant removal and reduce peak flows using an aesthetically acceptable design. Named a filtration basin, it uses a wide infiltration zone composed of turfgrass and native soil to capture contaminants and a storage and transmission zone to reduce peak flows.

A 6 m long (approximately 1/10 scale) lab model was designed and constructed that enabled testing of certain factors including its ability to remove dissolved reactive phosphorus (DRP) and sediments (total suspended solids-TSS) while resisting clogging of the filter media.

The filtration basin provided load and concentration reductions of 36% DRP and over 90% TSS. Infiltration and hydraulic conductivity rates did not decrease during 40 trials lasting six months and adsorption capacity analysis of the soil indicated potential for a 75 year life span. The results give some indication that this method of filtration merits further evaluation. Based on these results, more in-depth study is anticipated.

Dedicated to
Penny

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Chapter 1: Introduction- Characterization of Storm Water Effects and Remediation Solutions

Urban storm water runoff has caused serious hydrologic, environmental and economic damage downstream from developed land (Verstraeten and Poesen, 1999). The increase in impervious surfaces, often exceeding 50% of a drainage area (Weinstein *et al.*, 2008) means greater rainfall runoff and higher peak flows, reduced base flow (Hancock and Holley, 2010) and increased flow velocity and erosion (Schueler, 2000). Runoff also delivers contaminants, reducing stream water quality (Alberti, 2005; Bryan, 1972; Makepeace *et al.*, 1995).

The USEPA enacted storm water regulations, especially Phase II, finalized in 1999, to control storm water runoff pollutants "to the maximum extent practicable" (USEPA, 1999a). Phosphorus (P) is a contaminant of particular concern since concentrations as low as 0.03 mg/L in lakes and 0.075 mg/L in streams can cause eutrophication or excessive algae growth (Dodds *et al.*, 1998). Index of Biological Integrity scores associated with total phosphorus (TP) concentrations less than the median (0.12 mg/L in wadeable streams) were significantly higher than those associated with TP concentrations above the median (Miltner and Rankin, 1998). The US EPA 2008-2009 National Rivers and Streams Assessment found that 40% have high levels of TP and only 34.2% are in good condition (US EPA, 2009).

Results from the Nationwide Urban Runoff Program (USEPA, 1999a) show urban runoff concentrations range from 0.02 – 4.3 mg TP/L with a median concentration of 0.38 mg/L and median soluble phosphorus (DRP) concentrations of 0.14 mg/L under urban residential land use. Loads range from 0.04 to 1 kg TP/ha/yr.

Many states have established target levels of TP for water bodies ranging from 0.01 mg/L TP in Vermont to 0.1 mg/L in several states (Ohio EPA, 2004). Targets also vary depending on size of contributing area such as 0.05 mg/L in headwaters(<20 mi^2) to 0.12 mg/L in small rivers (200-1000 mi^2) (Ohio EPA, 2004).

Solutions or best management practices (BMP's) presently used to achieve these targets include storm water basins, wetlands, storm water filters, bioretention and storm water infiltration (Center for Watershed Protection, 2007). Many of the systems were originally designed to address water quantity issues, (peak flows, short detention time, low base flows and stream erosion) produced by storm events (Makepeace *et al.*, 1995). More recently, efforts have been made to provide pollutant removal capabilities as well but few studies have been performed to evaluate the results of these changes. Target removal efficiencies have been published for some BMP's. For example, constructed wetlands have a target of 30% TP reduction, which is low due to uncertainty associated with their long term viability (USEPA, 1999b).

While each BMP provides some level of contaminant removal and peak flow reduction (Table 1), limitations remain. The limitations (Table 2) include: inadequate removal of pollutants (Ballantine and Tanner, 2010; Rosenzweig *et al.*, 2011), excessive maintenance (Thompson, 2009; Westerbeek-Vopicka, 2009), sediment build-up and clogging (Bratieres *et al.*, 2008; Claytor and Schueler, 1996; Dechesne and Barraud, 2005; Egemose *et al.*, 2009), increased water temperature (USEPA, 1999a) and inadequate peak flow reduction (Booth and Hartley, 2002; Fennessey *et al.*, 2001) among others.

Table 1: Mean removal rates (%) from multiple studies of six BMP's

Basin Type or Treatment	TSS Removal			Total N Removal			Total P Removal			Soluble P removal		
	max	med	min	max	med	min	max	med	min	max	med	min
Dry ret. pond	90	49	-1	43	24	-19	48	20	0	87	-3	-12
Wet ret. Pond	99	80	-33	76	31	-12	91	52	12	92	64	-64
Wetlands	100	72	-100	76	24	-49	100	48	-55	82	25	-100
Filtering	98	86	8	71	32	17	88	59	-79	78	3	-37
Bioretention	98	59	-100	61	46	-2	65	5	-100	69	-9	-100
Infiltration	97	89	0	85	42	0	100	65	0	100	85	10

(Center for Watershed Protection, 2007)

Table 2: Summary of common limitations of BMP's

Limitation	Bioretention	Retention ponds	Wetlands	Filtration	Infiltration
high cost/space requirements	1		5,6	9	4,9
low N or P removal		2,9	7	3,9	4
high maintenance	1		5	3,9	4,9
limited peak flow reduction		2	5	3	
clogging/sediment buildup	1	2	5	3,8	4
warm water discharge		2,9	3,6,9		
problematic aesthetics			5, 6		9

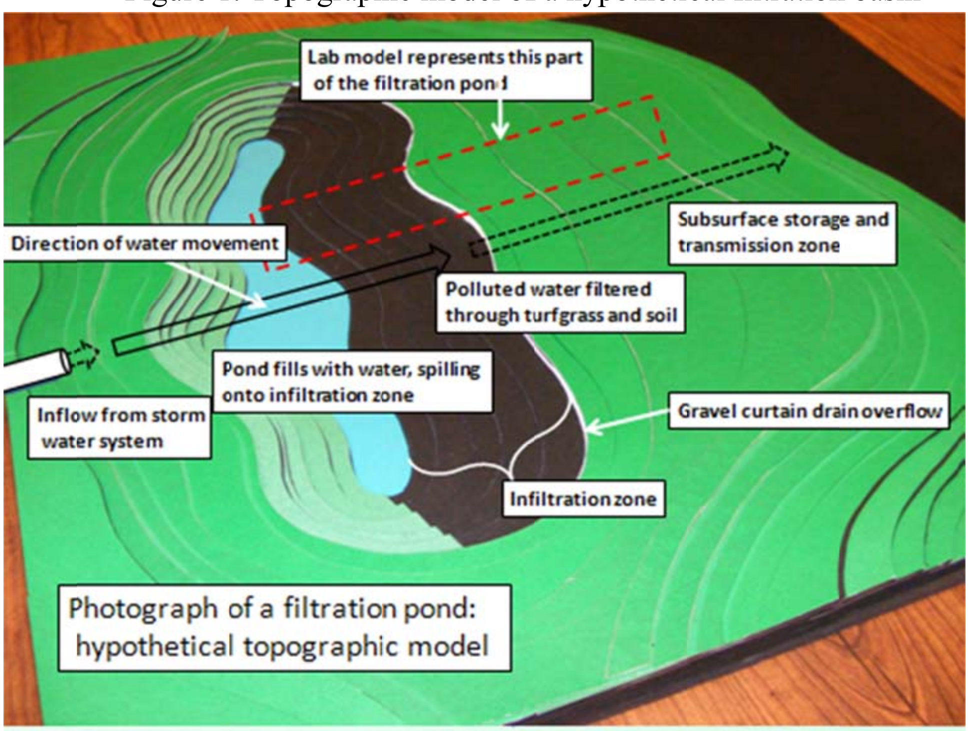
Numbers indicate a limitation noted by the following sources-
1: (USEPA, 1999c); 2: (USEPA, 1999d); 3: (USEPA, 1999e); 4: (USEPA, 1999f); 5: (USEPA, 1999b); 6: (USEPA, 1999g); 7: (Center for Watershed Protection, 2007); 8: (Brown, 2011); 9: (Claytor and Schueler, 1996)

Research attempting to address these limitations has focused on making improvements to existing systems. These include: adding forebays to reduce sedimentation in the main basin (Claytor and Schueler, 1996; Thompson, 2009), methods to assist particulate settling (including prevention of short circuiting) (Braskerud, 1994), and various filters to increase removal rates (Kim *et al.*, 2010; Ryan *et al.*, 2009). The success rates of these methods have been mixed since downstream surface water TP concentrations frequently don't reach targets (Booth and Hartley, 2002; Brush, 2008; Rosenzweig *et al.*, 2011). For example, based on a typical storm water concentration of 0.4 mg/L and 50% removal rate, the resulting concentration, approximately 0.2 mg/L, is still above the target level for most states.

A new method- Filtration Basin

This research will test the performance of a promising new technology called a filtration basin (Figure 1).

Figure 1: Topographic model of a hypothetical filtration basin



While reviewing the design and effectiveness of existing BMP's, the author conceived of a new BMP that may have potential to overcome some existing limitations by using a new design that includes the use of native subsoil to remove DRP. Based on his concept, he designed and constructed a working lab model to begin evaluation of its potential.

The filtration basin incorporates proven methods into a new configuration. Some key features are: an infiltration zone of turfgrass over native subsoil (modified as needed), promotion of sediment and pollutant filtration through a larger surface area, a woodchip bioreactor for nitrate-nitrogen removal, elimination of primary (pipe) spillway and a subsurface storage/transmission zone.

The filtration basin is composed of a permanent basin bordered by an infiltration area on one side. The infiltration area consists of sloped land with turfgrass over native subsoil which has been amended to facilitate infiltration. Directly below the infiltration area is a sand/gravel storage and transmission zone (Fig. 1). A dam on the infiltration side of the basin separates it from the infiltration area. Water rises in the permanent basin as a result of storm water runoff from the drainage area. As the water level rises it moves across the turfgrass infiltration area and seeps through the turfgrass into the soil where the bulk of contaminant filtration occurs. Next, the partially filtered water passes through the sand/gravel transmission/storage zone and finally through a woodchip bioreactor (Chun *et al.*, 2009) to remove nitrate, before exiting the system. The gravel zone can be reduced in thickness (10-20 cm) if the only purpose is transmission, or expanded (50-100 cm+ if ample head is available) if water will be stored for irrigation. At the top edge of the infiltration area, a gravel curtain drain overflow catches runoff from large rain events that exceed the capacity of the infiltration area.

The overall hypothesis is that this system will increase removal rates of pollutants compared to other BMP's, will require less maintenance, have a longer lifespan, moderate elevated water temperatures, be more acceptable to homeowners and store water below ground for irrigation using the filtered water, a concept that is gaining acceptance (Younos, 2011).

Comparison to existing BMP's and justification based on proven methods.

Soil

Soil is the main filtration component and is critical as it determines the infiltration rate and P adsorption capacity of the filtration basin. The objective is to use native subsoil and other materials, such as sand, may be added to ensure an appropriate infiltration rate.

Many recent studies have evaluated materials such as byproducts of steelmaking and contaminants scrubbed from powerplant emissions to determine their capacity to remove DRP (Ballantine and Tanner, 2010)(Cui *et al.*, 2008; Drizo *et al.*, 1999; Pratt *et al.*, 2007). Some have shown considerable promise but are often expensive to transport.

Subsoil, low in organic matter and often with a significant clay fraction, may have a large capacity for P removal. Clays (especially amorphous types), due to large surface area, exhibit significant P sorption capacity (Ballantine and Tanner, 2010). For example, allophane, an amorphous clay, was capable of binding 16 g P/kg of allophane (Ballantine and Tanner, 2010; Gibbs, 2008), potentially enough to adsorb over 500 years' worth of P under the following circumstances (storm water DRP concentration of 0.4 mg/L, 30% runoff, rainfall of 1 m/yr, filtration area 2.5% of drainage area, 1 m soil depth, 1 mg/kg adsorption capacity and 50% P removal rate). Another study found that an Australian soil could potentially adsorb P for 28.4 years from an effluent concentration of 1 mg/L P and a soil depth of 70 cm (Sakadevan and Bavor, 1998), a concentration 2.5x that of typical storm water. Another study indicated a sorption capacity of 1.4 g/kg from topsoil (Cui *et al.*, 2008). Phosphorus adsorption analysis can determine the theoretical capacity of a soil to adsorb P; Phosphorus fixation in soil involves both adsorption and precipitation reactions, although the former appears to be dominant over a short time period. Different substrates are responsible for these reactions with precipitation being more permanent (Sakadevan and Bavor, 1998). An important advantage of using subsoil is its low cost due to on-site availability. A goal of the filtration basin is to use a soil containing a percentage of clay that will enable maximum P adsorption while facilitating an adequate infiltration rate. The soil should be low in organic matter to reduce the likelihood of P leaching (Ballantine and Tanner, 2010; Bratieres *et al.*, 2008; Roy-Poirier *et al.*, 2010).

Research has shown that filtration through similar media is effective at removing particulate matter (Hatt *et al.*, 2009), meaning this system may also remove a significant percentage of heavy metals, volatile organic compounds and other contaminants that readily attach to particulate matter (Dechesne and Barraud, 2005). Investigations of several different substrate materials have shown that grain-size distribution, specific surface area and the Al, Fe and Ca ions present are particularly important properties for P sorption (Ballantine and Tanner, 2010; Cui *et al.*, 2008).

Some have stated that soil is an inappropriate filtration media due to clay swelling upon saturation but acknowledged that it could be used as a (minor) part of the substrate (Cui *et al.*, 2008). A goal of this research was to test the validity of that concern.

Since soils vary significantly depending on morphology, geography, topography, climate and location, they may vary greatly in their adsorption capacity. Even with this information, all soils being considered for a filtration basin need to be analyzed chemically and physically to determine if the soil will be suitable for the removal of phosphorus and other contaminants, and whether additional amendments must be added to ensure suitability. The clay mineral components may be key to the success of this system. Amorphous allophane has a higher adsorption capacity than other clay minerals so soils high in allophane, assuming suitable infiltration rates, may remove more P than soils with large concentrations of 2:1 non-expanding minerals such as illite.

Increased filtration surface area

Many BMP's place the filtration zone at the bottom of a depression where stormwater collects before passing through. The filtration basin incorporates a filtration zone along one side of the permanent basin to allow for increased filtration surface area compared to the aggregation method used with filtration BMP's. The lifespan of the filtration basin may be increased in proportion to the increase in filtration area since clogging shortens the life of most filtering BMP's. This will better distribute pollutants, facilitating natural incorporation and decomposition. In addition, storm water enters at the opposite side of the basin, which can act as a forebay, reducing sediment deposition onto the filtration zone. Although this system is intended for use in locations where high sediment loads over prolonged periods are unlikely, it may be more effective at sediment removal than most BMP's due to the larger area of filtration.

Turfgrass

The infiltration zone is covered by turfgrass, providing 100% soil surface coverage and reducing erosion potential, especially if sod is used rather than seed. Plant coverage of an infiltration zone resists clogging and reduction in infiltration rate (Bratieres *et al.*, 2008; Hatt *et al.*, 2009). The turfgrass also acts as a filter to remove total suspended solids (TSS) and will grow through sediment deposit depths commonly associated with storm water runoff. The nitrogen (N) and P from storm water will fertilize the turf and the clippings can be harvested to remove N and P (Davis *et al.*, 2006). Compared to other forms of vegetation, turfgrass is more easily maintained and accepted by homeowners in residential settings (USEPA, 1999b) and establishes faster. Maintenance of turf at 15 cm may discourage geese and their droppings since they tend to avoid taller vegetation (USEPA, 1999b). Turfgrass also survives drought by entering dormancy. Many wetland plants are less tolerant of these fluctuations (USEPA, 1999b)

Pipes

Retention basins and some other systems use pipes to evacuate storm water, carrying with it dissolved and suspended pollutants. The filtration basin is designed so that all water filters through the turf and soil, minimizing and sometimes preventing pollutant bypass or short-circuiting. As a result, basins can be built deeper, increasing capacity, because sediment deposition is no longer dependent on shallow water to accelerate settling. (re-suspension is no longer an issue) (Braskerud, 1994).

Subsurface storage and transmission zone

Below the infiltration zone a layer of gravel receives the filtered water and stores it for reuse (turfgrass irrigation) if desired. This moderates the temperature of water entering streams. Underground storage enables reduced basin area and the land can be used as a park which may enhance property values (Weinstein *et al.*, 2008). The storage zone allows for peak flow reduction and increased detention time. Water stored underground reduces stagnation and mosquito breeding. This zone can also be built using additional P filtering materials such as shale, limestone or light expanded clay aggregates (Drizo *et* *al.*, 1999). An exfiltration zone can be incorporated beneath the storage zone assuming the subsoil is not impervious and groundwater doesn't enter a dedicated drinking water supply.

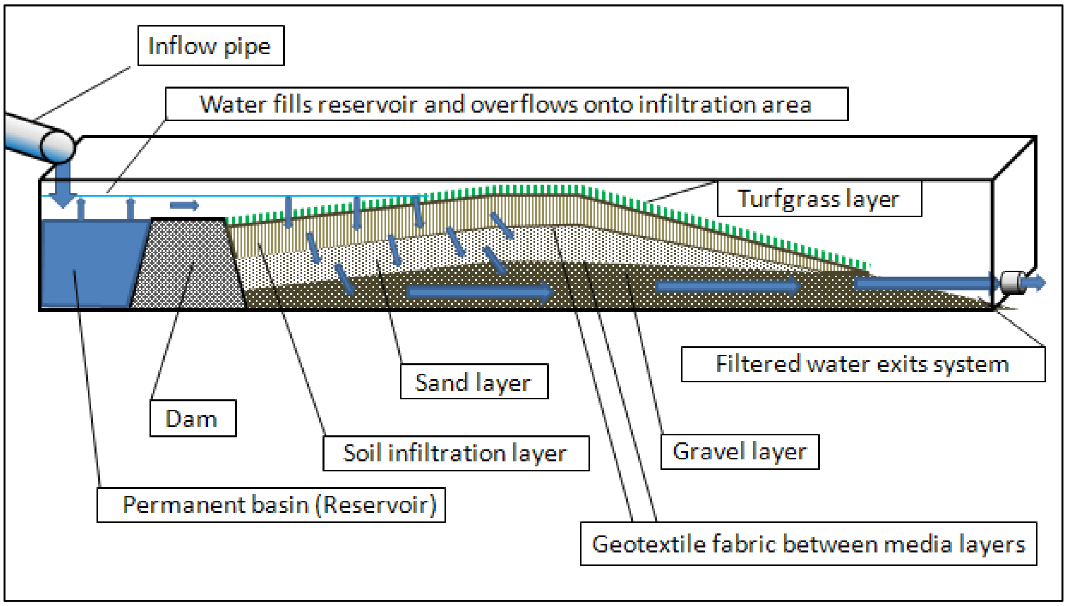
While the total footprint of this system may be similar to retention basins, the permanent basin area is smaller, providing more green space than a retention basin.

A carbon source (woodchip) bioreactor could be placed at the end of the system to remove nitrate (Chun *et al.*, 2009). It is placed after the storage zone so that some nitrate remains in the water for irrigation. A bioreactor was not incorporated into the present research.

Purpose and Objectives

A proof-of -concept model was built to test the ability of this system to reduce TP concentrations to near target surface water concentrations of 0.15 mg/L TP (primarily phosphate) (Makepeace *et al.*, 1995), reduce TSS and enable sustained water infiltration without clogging. This proof-of-concept is a lab scale longitudinal "slice" of a full scale system (Fig. 2).

Figure 2: Longitudinal cross-section of lab scale filtration basin



The lab scale filtration basin model was used to perform multiple research trials in which a known amount of artificial storm water with a known concentration of DRP and sediment was applied at a known inflow rate. Nitrate was also evaluated although no removal was expected. Water from the inlet and outlet, and soil and grass samples were analyzed to determine fate and transport of the contaminants.

The main objective of this research was to test the ability of this system to remove TP and TSS under various conditions with minimal reduction of infiltration rate and hydraulic conductivity. Other factors, the capacity to remove N, heavy metals, volatile organic compounds (VOC's) and polycyclic aromatic hydrocarbons (PAH's) and to reduce peak flows, can be evaluated during future lab or field trials.

The results will help determine if the filtration basin concept deserves further consideration. The desired results include: the ability to resist clogging, indicated by a consistent infiltration rate, DRP and TSS removal rates higher than existing BMP's, and the ability to retain healthy turfgrass despite frequent inundation.

Chapter 2: Materials and Methods

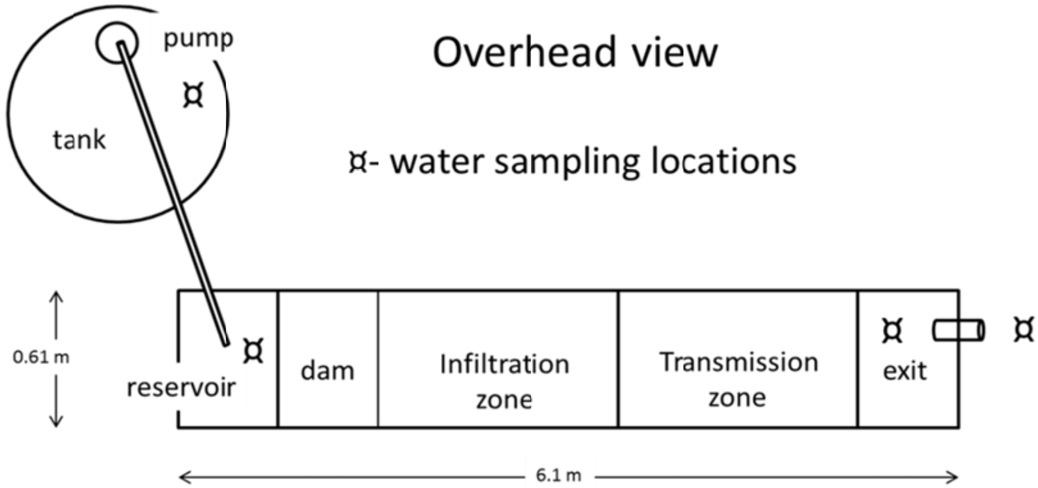
Construction of the lab model

The lab scale filtration basin was established at The Ohio State University and constructed in the roofed, fenced-in area of the Agricultural Engineering Building near its southern edge so that it received no natural rain but did receive sunlight, as much as 5 hrs spring and fall, decreasing to 1 hr in mid-summer. Based on a basin size of 2.5% of the impervious surface drainage area (Bäckström *et al.*, 2006) the lab model drainage area was determined to be 150 m^2 (1600 ft^2). A waterproof trough with dimensions 6.1 m long x 0.61 m wide x 0.76 m high (20 ft x 2 ft x 2.5 ft) was constructed from wood, acrylic (polymethyl methacrylate**)** sheets, polyethelene plastic and a rubber membrane (synthetic rubber ethylene-propylene-diene terpolymer) (Fig. 3). All materials that came in contact with water are inert. The trough was constructed with wood framing then covered with plywood and rubber lining on the bottom, ends and the north side. Clear, rigid acrylic sheets, 6.3 cm thick, were attached vertically to the south side of the trough to allow visual inspection of the filtration media and sunlight to reach the grass. A 0.5 m tall wood dam, covered with rubber and plastic was constructed inside the trough approximately 0.6 m from the inlet. The dam separates the reservoir (capacity 155 L), where water enters the system, from the filtration zone. Wood brackets were placed on top of the trough to secure the sides and prevent them from displacing outward under pressure.

The reservoir holds 13.6% of the water volume added during each trial and water remaining in the reservoir was not removed after a trial. Therefore, the concentration of each trial was potentially affected by the previous trial, or 13.6% of the difference in concentrations. For this reason, samples were taken from both tank and reservoir to evaluate the significance of this potential influence. A 5 cm diameter outlet was placed at the end of the trough at the bottom of the end wall. The structure was built to slope on a 1% grade toward the outlet.

Figure 3: Views of the filtration basin lab model

Figure 4: Overhead view of filtration basin model layout and sampling locations



A 15-30 cm layer of gravel (granite, round, 2-4 cm) was placed on the bottom of the trough and covered by a sheet of geotextile filter fabric (polypropylene), followed by a 15 cm layer of mason sand (particle size - 98% between 0.07 and 0.6 mm), another layer of filter fabric, then a 15 cm layer of clay loam soil and finally a turfgrass cover (Figure 2). Approximately half the length of the turf surface (200 cm) was available for inundation and filtration as it sloped up away from the basin/reservoir at a 7% slope. When filled to the crest of the filtration area the reservoir has a water holding capacity above permanent basin level of approximately 200 L (50 g) with a maximum head of 15 cm.

The overall weight of the system when full of water was over 3000 kg. The height of 75 cm maximized the water holding capacity while keeping the system low enough to be accessible to researchers and allowing as much sunlight as possible to reach the turfgrass. The 15 cm thick soil layer provided the minimum depth for turf root growth. Visual inspection of water movement through the sand and gravel layers was facilitated with the use of plexiglass on the south wall.

Components of the filtration basin lab scale model

Soil

The soil used for the first two sets of trials was obtained from the Waterman Agricultural and Natural Resources Lab at The Ohio State University. This subsoil had no fertilizers or pesticides applied to it for several years and was composed of 60% sand, 20% silt and 20% clay. P content was not tested. Because subsoil is often characterized by a slow infiltration rate, column infiltration tests were performed to produce a suitable soil mix. Mason sand was added to the soil in nine different proportions in 10% increments from 0% to 90% sand. Each blend was placed in a 10 cm dia by 30 cm long plastic tube to within 15 cm of the top, and the bottom opening of the tube was covered with filter fabric to retain the soil. Each tube was held vertically, filled to the top with water, allowed to infiltrate, and timed to measure infiltration rate two times, first with dry soil then with saturated soil. A soil mix moderately high in sand was chosen to test whether adequate adsorption could occur in such a short time, resist clogging and to ensure adequate drainage of the system. Because P adsorption reactions occur quickly, a relatively high infiltration rate soil was desired, 25 cm/hr was achieved by a soil/sand mix of 55/45% (Table 3).

Table 3: Soil column tests to determine target infiltration rate

% Soil	Infiltration rate, cm/hr	
	unsaturated soil	saturated soil
10	197.4	136.5
20	155.0	80.7
30	85.9	44.9
40	63.8	42.6
50	44.3	31.4
60	32.4	20.5
70	24.6	14.2
80	23.5	12.5
90	19.8	9.9

When this subsoil mix was used in the research trials, the infiltration rate observed was closer to 45 cm/hr. After 30 trials (sets 1 and 2), the original soil was replaced with a 45 cm thick layer of subsoil from a different location at the Waterman Lab. This subsoil consisted of 40% sand, 25% silt and 35% clay with a TP content of 0.021 mg/g. In spite of the higher clay content, the infiltration rate continued to be fast (40 cm/hr). The observed infiltration rate was most likely related to flow through large pore spaces from soil aggregation and bypassing along the soil-plastic interface. The soil had been placed in the trough carefully during installation to avoid excess compaction /aggregate destruction. Before trial set 4, the turfgrass was lifted from the infiltration area, the soil was compacted, and turfgrass placed back. This reduced the infiltration rate to 15 cm/hr which was similar to other studies using clay loam (Hsieh *et al.*, 2007)

Turfgrass

The turfgrass was a bluegrass (*poa pratensis*) blend sod (varieties Blues Blaze, Hampton, Courtyard, Midnight II and Avalanche), grown on a field consisting primarily of Warsaw and Eldean loam soil (42% sand, 38% silt, 20% clay) approximately 1.5 cm thick. After installation, the sod was flushed approximately 10 times with 1000 *l* of water to try to remove residual soluble nutrients. No fertilizer was applied during the research trials and the grass was cut with scissors as needed, leaving the clippings on the surface to decompose. The trough was under roof, so between April and September began to thin out and die due to inadequate sunlight. The sod was installed in August 2012 and replaced in October when 95% of grass blades were dead. The new sod stayed healthy and green through April of 2013. It began to thin in May and was very thin (<10% green blades) by late June. However, no change was observed in P removal due to time of year or growth rate of turf. Turf was watered as needed.

Water

All water used for the trials was from the City of Columbus water supply and had a DRP concentration range of 0.36 to 0.45 mg/L and pH range of 7.6 to 7.9. This phosphorus was from zinc phosphate added at the water treatment plant to reduce pipe corrosion. 1135 L (300 g) of water for each trial was initially added to a 2080 L (550 g) polypropylene tank placed beside the trough. A 1/3 hp pump mixed the pollutants by recirculation and pumped the artificial storm water through pvc pipes into the filtration basin reservoir. A Rain Bird flow meter (Azusa, CA) measured flow rate. Water volume was equivalent to runoff from a 4.5 cm (1.75 in) rainfall event with a return period of 2.5 years. Water was pumped into the trough until the tank was emptied, a duration of two hours; an equivalent rainfall intensity of 2.25 cm/hr. With the lower infiltration rate during set 4, only 378 L of water was used, so that these trials took the same amount of time as previous trials.

Sediment

Sediment used for Set 1 trials was from the same soil as was used in the filtration zone. It was air-dried and ground so as to pass through a 2 mm sieve. The target amount for each trial was poured into a container with water and stirred by hand for several minutes before being added to the tank. The sediment solution in the tank was mixed continuously. During each Set 1 trial, 800 ml water samples were taken at the trough outlet every fifteen minutes to determine sediment removal.

Each 800 ml sample sat for 48 hours to allow settling. Then 700 ml of water was removed from the top by pipette, leaving a 100 ml solution containing sediment on the bottom which was dried at 103°C and weighed. Sediment removal was calculated by measuring the weight of the dried sample using the following equation:

1135 L/trial*1000 ml/L*X mg sediment/800 ml = X mg/trial

A mean of all sediment weights from each trial was obtained. Total sediment added – mean sediment at outlet = sediment removed. Sediment removed/total sediment x 100 = % removal.

Phosphorus

Phosphorus used to for the P solution was obtained from Santa Cruz Biotechnology, Inc. (Santa Cruz, CA), in the form of KH_2PO_4 (potassium phosphate monobasic), 22.78% elemental P which dissolves in water to form a phosphate ion ($H_2PO_4^-$ or HPO_4^{2-}). This DRP was added to trials in various concentrations (Tables 4-6) by stirring the appropriate mass into a liter of water, then pouring the solution into the tank of recirculating water to ensure thorough mixing. Tank and reservoir concentrations were analyzed and compared to verify that background P levels from city water plus the amount added to the tank were essentially equal to the amount detected by lab analysis.

Research trials and sets

Four sets of trials were performed with a different focus for each (Table 4). For all trials, water samples were taken every fifteen minutes. Inlet samples were combined to form one composite per trial. Outlet samples from sets 1 and 2 were composited by hour, resulting in 3 or 4 samples per trial. Since no substantial difference in removal rate was observed from hour to hour during set 2, outlet samples from sets 3 and 4 were composited by trial, resulting in 1 sample per trial. Duplicate trials were used during sets 1 and 2; these were not true replicates because P concentrations from each trial affected the subsequent trial. Duplicate trials were not used during sets 3 and 4.

Table 4: Trial sets with purpose of each set

set	dates	# of trials	purpose
1	8/7-8/15/12	7	increasing sediment concentrations-% removal
2	8/16-10/25/12	22	increasing DRP concentrations- % removal
3	11/13-2/14/12	12	alternating high and low DRP concentrations- % removal
4	4/27-5/17/13	5	time between trials- % DRP removal

Set 1

The first set of trials was performed to evaluate the ability of the filtration basin to remove sediment without a reduction in infiltration rate due to clogging. TSS concentrations in storm water have been reported between 4 and 1223 mg/L (Makepeace *et al.*, 1995) and typical concentrations for developed urban areas are generally below 100 mg/L (USEPA, 1999a). Two trials of each sediment concentration (100, 200 and 400 mg/L) (Table 5) were run with 400 mg/L, the highest concentration attempted because the pump and meter clogged. Also, values above 400 mg/L are not typical for urban storm water in established developments (Bratieres *et al.*, 2008; Bryan, 1972; Ohio EPA, 1999). No P was added during Set 1.

Table 5: Sediment concentration inputs (Set 1)

trial #	days since previous trial	sediment added (ppm)
1	x	0
2	1	100
3	1	100
4	1	200
5	3	200
6	1	400
7	1	400

Set 2

The second set (Table 6) tested the effect of increasing DRP concentrations on removal rate. The purpose of this set was to determine the relationship between increasing concentrations and removal efficiency and the overall capacity of the system to remove DRP given large runoff events and relatively high DRP concentrations.

Table 6: DRP concentrations of trials (Set 2)

Trial #	days since previous trial	DRP added (g)	DRP concentration inlet (mg/L)
1	x[1]	0.04	0.441
2	1	0.04	0.437
3	3	0.07	0.502
4	2	0.00	0.405
5	x[1]	0.07	0.462
6	1	0.11	0.493
7	3	0.11	1.38
8	1	0.18	0.539
9	1	0.18	0.532
10	1	0.37	0.67
11[2]	1	0.37	0.703
12	4	0.74	0.982
13	1	0.74	1.02
14	5	1.85	1.81
15	2	1.85	1.71
16	5	2.77	2.52
17	3	2.77	2.53
18	4	0.00	0.41
19	23	0.00	2.33
20	2	0.00	0.351
21	3	0.18	0.496
22	3	1.85	1.88

[1] new soil used

[2]400 ppm sediment added to trial 11 to test effect on P adsorption

Set 3

The third set of trials (Table 7) evaluated the effect of residual adsorbed P on subsequent trials by varying high and low concentrations. In addition, the subsoil in the lab model was replaced following set 2 to compare DRP removal efficiency of two subsoils with different clay content and infiltration rates.

Table 7: DRP concentrations of trials (Set 3)

trial #	days since previous trial	DRP added (g)	DRP concentration inlet (mg/L)
1	x	0.00	0.38
2	3	0.07	0.55
3	3	0.18	0.68
4	1	0.37	0.66
5	1	0.74	0.87
6	2	0.74	0.99
7[1]	5	1.48	2.35
8	1	1.48	1.52
9	1	0.00	0.51
10	10	0.74	0.72
11	1	0.00	0.31
12	3	0.74	0.93

[1]Trial 7 yielded extremely high DRP concentrations at the inlet and is considered unreliable.

Set 4 trials (Table 8) evaluated the effect of length of time between trials on removal efficiency. Time lapse varied from two to eight days. Additional soil

-

compaction resulted in a slower infiltration rate for this set of trials. Therefore, 1/3 as much water (380 L) as for previous trials was used to maintain consistent trial duration.

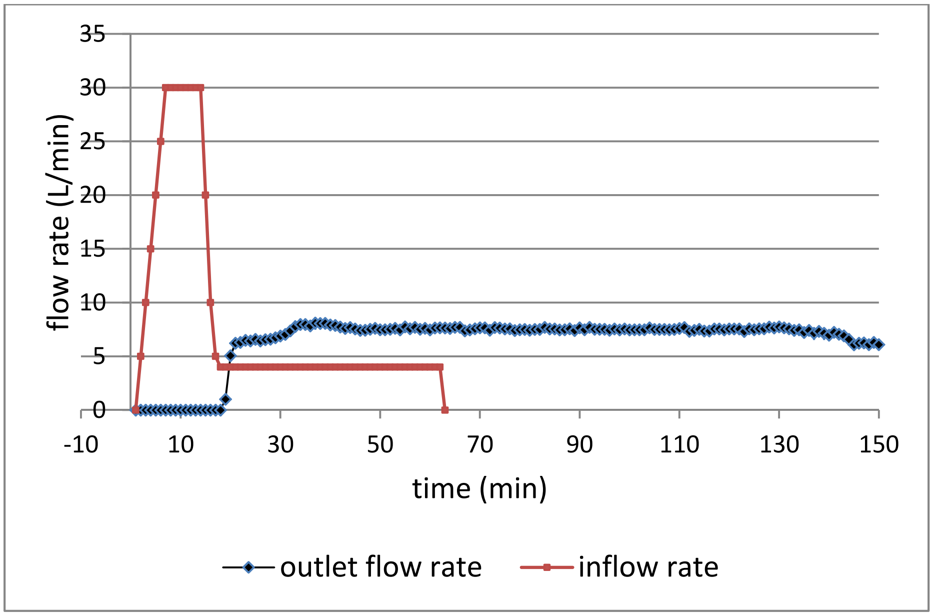
Table 8: DRP concentrations of trials (Set 4)

trial #	days since previous trial	DRP added (mg)	DRP concentration inlet (mg/L)
1	x	0	0.355
2	2	0	0.384
3	4	0	0.401
4	6	0	0.405
5	8	0	0.422

Trial procedures

Trials were performed by pumping the storm water from the tank into the trough's reservoir at a flow rate of 25-35 L/min until the water level in the trough reached a maximum height of 14 cm above dam level. Flow was then reduced to approximately 4 L/min to maintain a constant head until 1135 L was delivered and the pump was then turned off (Figure 5). The purpose of adjusting the pumping rate was to maximize filtration through the entire filtration zone surface while minimizing water loss by overland flow. The duration of most trials was between 2-3 hrs. Each trial was terminated when outflow was reduced to a trickle. A valve at the outlet end was opened during a trial and closed once the trial was finished. This allowed a small amount (less than 5%) of residual drainage to collect in the bottom of the trough until the next trial. Immediately before the next trial, the valve was opened to allow residual water to drain and be sampled. Since the time chosen to terminate a trial was subjective, this water volume was measured to ensure that all water from each trial was accounted for and trials were consistently timed.

Figure 5: Typical hydrographs of inlet and outlets[1]



[1] Inflow data are from estimates based on meter readings following pump flow rate adjustments. Outflow data points are from 1 min interval pressure transducer readings.

Outlet water drained through a 5 cm dia pipe to a bucket containing a cube shaped acrylic v-notch weir with a 5 cm dia hole at the bottom. As water filled the bucket it passed through the v-notch then exited through the hole in the bottom. A pressure transducer (or PT) (HOBO U20, Onset Corp. Cape Cod, MA) was placed in the bucket to measure water height stage and temperature every minute during a trial. A second PT was placed next to the trough to measure air temperature and atmospheric pressure and, when combined with data from the first PT, water flow rate was estimated.

Water samples were taken from four locations - the tank, reservoir, end of trough and v-notch weir. Tank samples were taken to compare to reservoir samples and trough samples were taken to compare against weir samples. Sampling containers were 60 ml polystyrene bottles that were acid washed then rinsed. Water samples were stored at 5°C, then sent to the OARDC STAR Labs in Wooster OH, and analyzed for PO_4-P, NO_3-N and, NH_3-N using flow injection analysis (4500P – G and 4500NO_3 – I Standard Methods for the Examination of Water and Wastewater). Samples from two trials were also analyzed for TP to verify that all P remained in the phosphate form.

Every trial was given a serial number and although 49 trials were completed, trials 30, 43 and 44 were not analyzed and do not show in any lists of data but were performed to determine if all parts of the system were working properly. The first seven trials were analyzed for sediment (TSS) and the next 39 were analyzed for DRP.

Statistical method

Statistical analyses were performed using Microsoft Excel 2010 for Windows. Statistical hypotheses were tested using t-tests where $\alpha = 0.05$.

Chapter 3: Results and Discussion

Total suspended solids (TSS)

Mean removal of TSS across the six sediment trials was 91% (Table 9).

Table 9: Mean sediment removal, Set 1

trials	ppm sediment	sediment (TSS) removal
2,3	100	87%
4,5	200	92%
6,7	400	95%

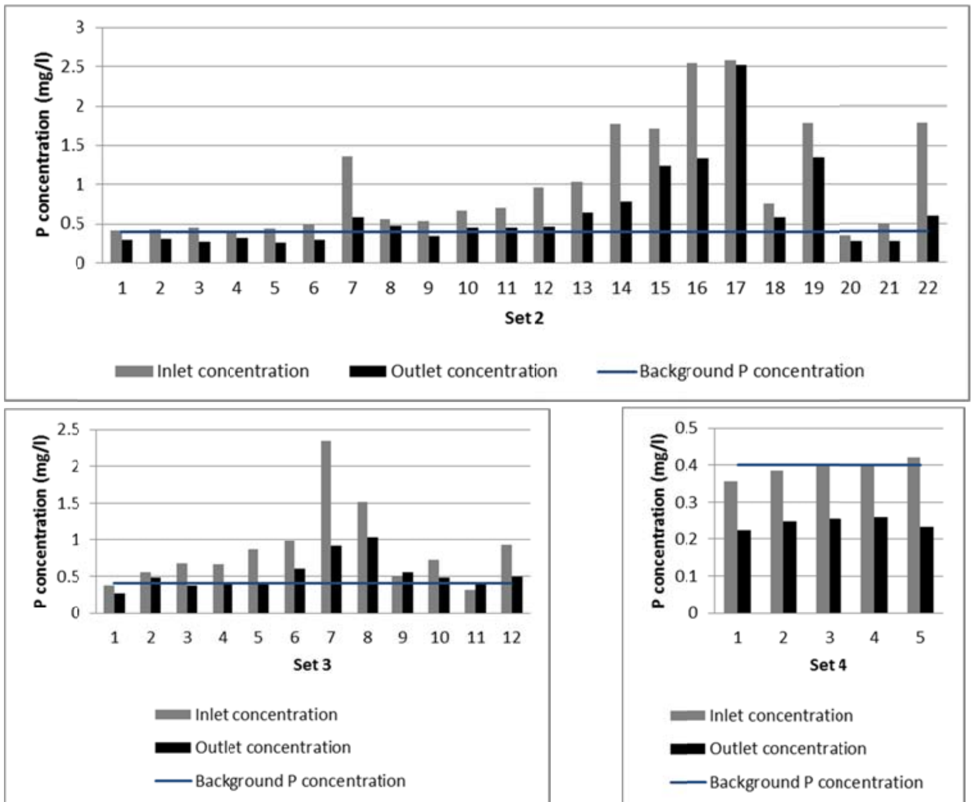
At the beginning of each trial, regardless of sediment addition, the first flush of water stirred up sediment at the outlet, producing several minutes of cloudy water which dissipated after a few minutes. Thus, the first outlet sample from each trial was not included in calculations of sediment removal.

Sediment removal rates are similar to other filtration BMP's. For example, Bratieres observed 95-99% TSS removal in bioretention column studies (Bratieres *et al.*, 2008). Hatt observed 76% and 93% mean TSS reductions from two different biofiltration basins (Hatt *et al.*, 2009)

Phosphorus

Mean and median removal rates of phosphorus (as PO_4-P) across three sets with 39 trials of various treatment effects and concentrations, ranging from 0.4 to 2.5 mg/L PO_4-P (Figure 6), were 36% (Tables 10-12) with a total load reduction of 34% or 14.2 g from an input of 42.3 g (Figure 6). This resulted in a mean concentration reduction from 0.87 mg/L at the inlet to 0.56 mg/L at the outlet. Of the 39 trials, 37 achieved positive P removal.

Figure 6: DRP concentrations by set, inlet vs. outlet[1]



[1] Horizontal blue line indicates background P concentration from city water supply

Table 10: Percent DRP removal from set 2 with means and days between trials

trial	days since last trial	inlet conc. (mg/L)[1]	outlet conc. (mg/L)	% removal
1	1	0.42	0.30	28.7%
2	1	0.44	0.31	28.3%
3	3	0.46	0.28	39.9%
4	2	0.40[2]	0.33	18.9%
5	1	0.45	0.26	42.0%
6	1	0.49	0.30	39.8%
7	3	1.36[3]	0.59	56.6%
8	1	0.56	0.48	15.6%
9	1	0.54	0.35	34.9%
10	1	0.67	0.46	31.6%
11	1	0.71	0.46	34.9%
12	4	0.96	0.47	51.2%
13	1	1.03	0.65	37.3%
14	5	1.78	0.78	56.2%
15	2	1.72	1.24	28.1%
16	5	2.55	1.33	47.7%
17	3	2.58	2.52	2.5%
18	4	0.76	0.58	23.2%
19	23	1.79	1.34	25.0%
20	2	0.35	0.27	22.0%
21	3	0.50	0.28	44.9%
22	3	1.79	0.61	66.2%
mean		1.03	0.64	37.3%

[1]Includes background DRP concentration of approximately 0.4 mg/L from city water
[2]No DRP was added
[3]A mistake in weighing the amount of DRP resulted in excess DRP concentration

Table 11: Percent DRP removal (set 3 trials) with means and days between trials

trial	days since last trial	inlet conc. (mg/L)	outlet conc. (mg/L)	% removal
1	19	0.38	0.27	28.9%
2	3	0.55	0.48	12.7%
3	3	0.68	0.38	44.1%
4	1	0.66	0.40	39.4%
5	1	0.87	0.40	54.0%
6	2	0.99	0.60	39.4%
7	5	2.35	0.92	60.9%
8	1	1.52	1.04	31.6%
9	1	0.51	0.55	-7.8%
10	10	0.72	0.48	33.3%
11	1	0.31	0.42	-35.5%
12	3	0.93	0.50	46.6%
mean		0.87	0.54	38.52%

Table 12: Percent DRP removal from set 4 trials with means and days between trials and mean of sets 2-4.

trial	days since last trial	inlet conc. (mg/L)	outlet conc. (mg/L)	% removal
1	x	0.36	0.23	36.6%
2	2	0.38	0.25	35.2%
3	4	0.40	0.25	36.6%
4	6	0.41	0.26	36.0%
5	8	0.42	0.23	44.9%
mean		0.39	0.24	38.0%
mean of sets 2-4		**0.87**	**0.56**	**36.0%**

The TP removal rate from the filtration basin was less than that of some other BMP's. For example, a wetland removed 49% of dissolved reactive phosphorus (DRP) and 68% of TP (Liikanen *et al.*, 1994). A bioretention BMP removed 67% of TP (Brown, 2011). A column experiment removed 80-85% of TP using 70 cm soil depth (Bratieres *et al.*, 2008). Sand filters removed 60% of TP (Claytor and Schueler, 1996). Gravel filters exhibited a range of removal from 44 to 89% TP. A detention basin removed 24% TP, 33% particulate P (PP) and 25% phosphate P (Stanley, 1994).

Whereas all P used in these trials was soluble, a typical phosphorus ratio in storm water runoff is 30-40% soluble and 60-70% adsorbed to particulate matter (Bratieres *et al.*, 2008; Li *et al.*, 2011). PP is easier to remove than DRP (Ballantine and Tanner, 2010). Based on a typical PP removal of 95% by filtration BMP's (Bratieres *et al.*, 2008), the filtration basin may potentially remove over 70% of TP, a rate higher than the mean of other BMP's (Ballantine and Tanner, 2010; Bratieres *et al.*, 2008; Claytor and Schueler, 1996; Mitsch *et al.*, 2013; Reddy *et al.*, 1999; Roy-Poirier *et al.*, 2010). Also, since trial infiltration rates were faster than column infiltration tests, some bypass evidently occurred and may have reduced the P removal rate. Finally, 15cm of soil was used for this research but 30-100 cm or more would be used for a field scale filtration basin. Other studies using lab scale column or box models have used 60-80 cm or more (Davis *et al.*, 2006; Scholz and Lee, 2005). Greater soil depth provides more removal capacity and possibly a higher removal rate (Davis *et al.*, 2006).

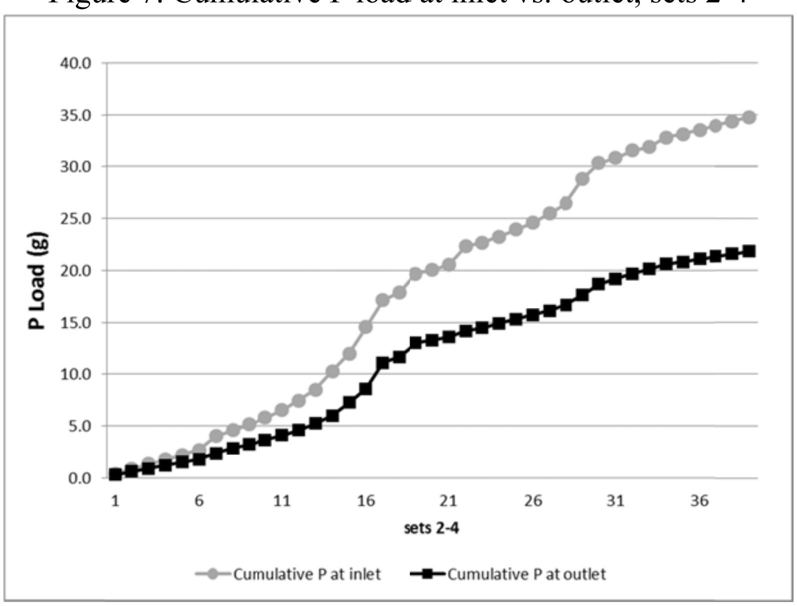
The reservoir contained 13.6% of the water used each trial. It was not drained between trials so could potentially contain residual DRP concentrations that would affect the results of the proceeding trial. For this reason, samples were taken from both reservoir and tank each trial during set 2. Analysis showed that concentration differences were insignificant ($p = .67$; $\alpha = .05$), indicating no residual effect from DRP remaining in the reservoir from the preceding trial.

Cumulative DRP load

Accounting for all concentrations, time between trials and infiltration rates, cumulative DRP load reduction was 14.2 g, or 0.36 g per trial (Figure 7). This is equivalent to 0.27 g/m^2 of infiltration zone surface area per trial or 1.8 g DRP/m^3 soil per trial. Another study found the in situ removal of P by sediment varied from 0.03 to 2.6 mg P/ m^2/day for DRP and from 0.03 to 66.7 mg for TP (Liikanen *et al.*, 1994).   Accounting for all trials, the filtration basin removed 54 mg DRP/kg soil. Hsieh obtained removal rates of 28 and 66 mg P/kg for two clay loam soils using a concentration of 0.35 mg P/L (Hsieh *et al.*, 2007). A study by Cui found that soil adsorption ranged from 200 to 700 mg/kg in topsoil at concentrations of 100 to 500 mg DRP/L (Cui *et al.*, 2008).

The water passing through the system was equivalent to 1.7 years of rainfall in the Columbus area. The mean P concentration of the water was 2.2 times the typical P concentration of storm water. The soil depth was one sixth the expected soil depth (16 cm vs 80-100 cm) of a field scale filtration basin. Based on these numbers, the life expectancy of the soil used in this study could approach 75 years.

Figure 7: Cumulative P load at inlet vs. outlet, sets 2-4



Increasing P concentrations

Set 2 tested two duplicates of 8 different increasing DRP concentrations and shows some increase in removal rate as inlet concentration increased except for the highest inlet concentration (Fig. 8). This is similar to what other research has shown (Idris and Ahmed, 2012). Most trials were performed 1 or 2 days apart and some residual DRP is likely to have reduced removal rates, especially for trials with larger concentrations.

Figure 8: Effect of increasing phosphorus concentration on % removal (sets 2-4)

target DRP inlet concentration mg/L	removal rate
0	22.2%
0.03	28.5%
0.06	30.3%
0.1	39.8%
0.16	35.1%
0.32	35.3%
0.64	46.1%
1.6	50.4%
2.4	25.0%

Differences due to sample time within trial

Removal rates of DRP differed by hour during set 2, but the differences were not significant (Table 10) ($p>0.4$; $\alpha = .01$). Because the hourly difference was insignificant, hourly outlet samples from sets 3 and 4 were composited. The first hour removal rate varied more than hours 2 or 3, which may indicate a residual effect from the previous trial. The consistency of removal rate may indicate that the chemical adsorption reactions occur quickly and long residence times are not required. It is also likely that the soil was capable of removing the studied concentrations of DRP and adsorption sites were not overwhelmed (Oh *et al.*, 1999).

Table 13: Mean removal rate by hour (set 2)

	inlet	outlet		
		hour 1	hour 2	hour 3
mean P load mg/L	1.0012	0.654	0.673	0.696
mean P removal %		36.2%	32.5%	30.2%
standard dev.		26.1%	9.6%	11.1%
coefficient of variation		0.72	0.30	0.37

Infiltration rate vs. removal

The three infiltration rates studied (45, 40 and 15 cm/hr) did not significantly affect removal rates. This is reasonable because the reactions involved in the adsorption of P by clay particles occur quickly, mainly phosphate replacing hydroxyl groups and attaching to Fe and Al on the edges of clay minerals.

Time between trials

Increasing the time between trials increased removal rate (all sets) by 10% (N.S.) (from 30 to 40%) as days between trials increased from 1 to >7 (Fig. 9). Other studies have shown that filtering media, including soil, does have an increased ability to remove P as time between events increases (Cui *et al.*, 2008). This is believed to be because some P moves from outer sphere weak bonds to inner sphere bonds over time. Because the initial adsorption bond is relatively weak, trials close together in time often leach some of this adsorbed P, causing a lower removal rate.

When set 4 trials were run specifically for effect of time between trials, no effect was observed until more than 7 days had elapsed (Fig. 10).

Unfortunately, no time was available for additional trials involving longer periods of time between trials.

Figure 9: Days between trials vs. removal rate

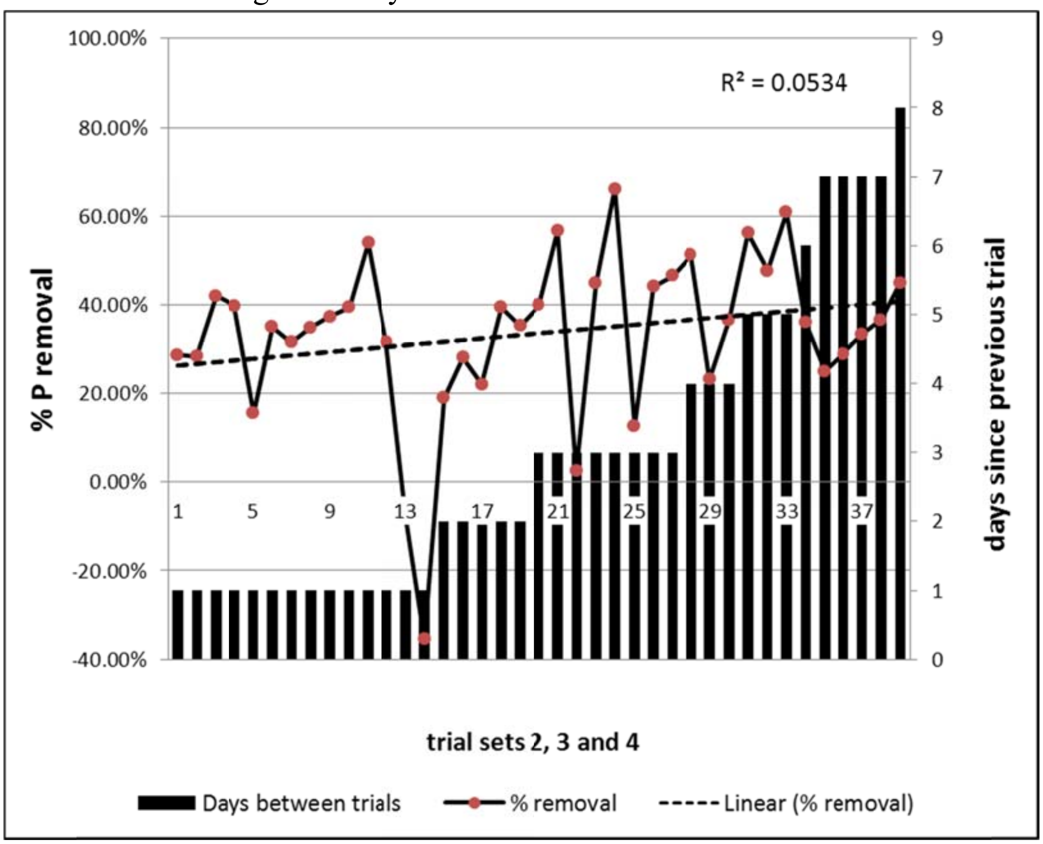
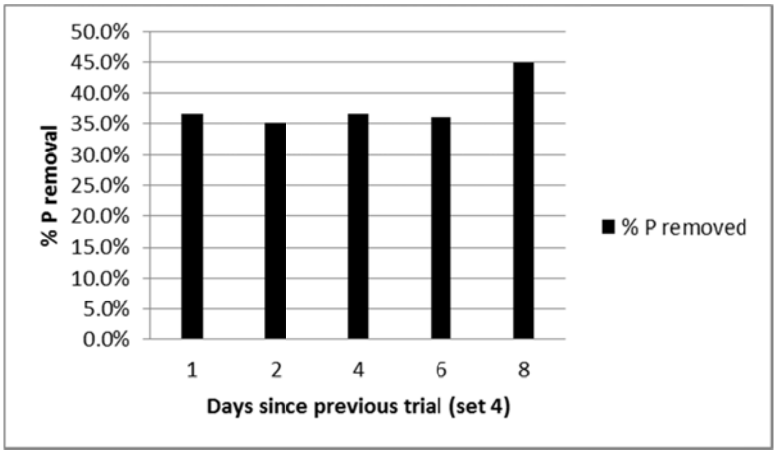


Figure 10: Effect on removal rate of increasing days between trials.



Analysis of the data, specifically set 2, revealed that dosing the system twice in a short period of time (less than 4 days apart) with concentrations over 1 mg/L DRP resulted in a smaller removal rate the 2nd trial compared to the first (51.7% vs. 22.6%) (Table 14). Although there is not enough data to prove significance, this supports the concept that adsorbed P is initially held by weak bonds and some P becomes more tightly bound over time (Cui *et al.*, 2008; Idris and Ahmed, 2012). Due to time constraints, it was not possible to regularly perform trials farther apart in time, even though such data would be valuable and such a time gap between rainfall events is common.

Table 14: Comparison of removal rates of consecutive trials (set 2)

first of two			second of two			
trial #	inlet concentration mg/l P	% removal	days since previous trial	trial #	inlet concentration mg/l P	% removal
12	0.98	51.2%	1	13	1.02	37.3%
14	1.72	56.2%	2	15	1.78	28.1%
16	2.55	47.7%	3	17	2.58	2.5%
	mean	51.7%			mean	22.6%
standard dev.		0.043		standard dev.		0.181

Plant uptake and removal

Grass clippings were sampled from one cutting on May 20, 2013 when 10 cm of leaf tissue was removed and analyzed for TP. The sample contained a TP concentration of 0.09% (wet basis) and 0.47% (dry basis). This was extrapolated to 8% TP removal per year. Although it was only one sample, the removal rate was within the expected range of 6-10% (Harper *et al.*, 1933) or 500- 850 mg P/m^2.

Some BMP's use wetland plants to remove P from the water column. However, while removal takes place during the life of the plant, once it dies and decays, P re-enters the water (Reddy *et al.*, 1999). Harvesting of these plants to permanently remove P may be costly . On the other hand, grass harvesting is a normal maintenance procedure resulting in ease of maintenance for the filtration basin.

Soil P

Soil from the infiltration area taken at the end of the study was analyzed for P content and compared with pretreatment soil data to evaluate the change in adsorption load along the length of the trough resulting from treatment (Table 14). The only sample that contained a significantly higher concentration of P (outside 2 standard deviations) was that of the soil closest to the dam and which filtered the largest volume of runoff water. All other samples contained concentrations similar to those of the original soil. This suggests that the part of the infiltration zone closest to the dam received significantly more P load than the rest of the infiltration area. Reducing the slope will enable a more even spread of storm water and adsorption of P (and sediment) across the entire infiltration area.

Soil was also analyzed for pH, CEC, Ca, Mg and K concentrations and base saturation for pre and post treatment soil. CEC was inversely proportional and pH proportional to P adsorption. Cations showed no correlation. Regular inundations with storm water tended to raise pH and lower CEC especially for soil nearest the dam.

Two soil samples, one pre and the other post treatment, were used to develop P adsorption isotherms and maximums. Using the Langmuir equation, the adsorption maximum for the pretreated soil was 0.32 g P/kg soil and 0.40 g P/kg soil for post treatment soil. Using 25% of the post treatment soil value the lifetime P removal capacity of this soil is estimated to be 75 years based on the following conditions:

- 1 meter rainfall/year
- 0.4 mg/L soluble P in storm water runoff
- 30% runoff
- BMP sized at 2.5% of impervious surface of drainage area
- 1 meter BMP soil infiltration zone depth
- 36% P removal rate

Table 15: Phosphorus concentrations, pH and CEC of soil and sample location

	distance from dam (m)	elevation above dam surface (cm)	DRP concentration (mg/L)	pH	CEC
original soil			21.3	6.28	13.4
post treatment soil	0.2	3	33.2	6.81	11.4
	0.6	4	18.2	6.63	13.0
	1.0	6	21.4	5.93	13.4
	1.4	9	17.4	5.57	14.0
	1.8	14	22.4	6.06	13.9
	2.2	17	18.8	5.7	15.0
	2.6	13	18.7	5.83	14.4
	3.0	8	20.5	5.96	15.5
	3.5	3	15.3	5.55	16.9
		mean	20.66	6.00	14.2
		standard deviation	5.17	0.44	1.56

Chapter 4: Summary and Conclusion

Soluble phosphorus concentrations of artificial storm water runoff were substantially reduced using the infiltration basin lab scale system and proposed changes are likely to further improve DRP removal performance. The hydraulic conductivity of the filtration media is critical to the success of the filtration basin. Clay based media has been avoided in filtration BMP's because of low hydraulic conductivity and potential for clogging (Cui *et al.*, 2008). This study suggests that soil with a significant clay component (20-35%) has potential to be successfully used to remove DRP from storm water runoff without significant danger of clogging. Because soils vary greatly, obtaining a soil that will perform appropriately will require thorough testing before implementation to ensure successful operation in a field scale filtration pond.

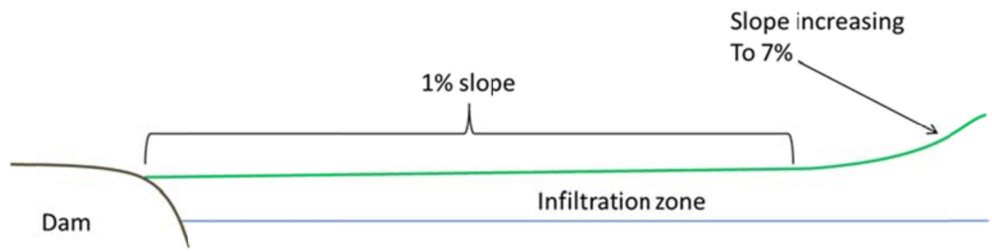
In the short term, turfgrass survived repeated inundations suggesting it can be incorporated into the infiltration basin and provide additional benefits of erosion and clogging prevention, lower maintenance, ease of public acceptance and nutrient harvesting.

This was a new concept conceived, designed and built by the author; the lab scale trials were the first attempts and based on what has been learned so far, the results are encouraging.

The following improvements to the filtration basin and trial procedure are suggested and future trials involving a field scale system will:

- Incorporate a smaller infiltration area slope (1% and increasing to 7% near the top of the infiltration area (Fig. 7).

Figure 11: Longitudinal cross section view of suggested filtration basin design change



- Provide for the compaction of infiltration zone soil to more closely approximate field conditions for infiltration and saturated hydraulic conductivity.
- Use a thicker soil infiltration zone (30 cm or more) and less sand and gravel. Others have used 60-90 cm in lab trials (Davis *et al.*, 2006; Henderson *et al.*, 2007)

- Perform additional tests of time-between-rainfall-events.
- Test smaller rainfall events with lower “rainfall intensity”
- Test artificial storm water containing particulate as well as soluble P.

. Further testing with various clay soils is recommended to determine if adequate P adsorption is common to most soils.

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