RESEARCH REPORT

Sustainable Design of
Urban Porous Landscape Detention Basin

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And
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The porous landscape detention basin (PLDB) is a constructed storm water quality enhancement facility intended to capture and filter runoff from micro rainfall events taking advantage of the intrinsic quality of plants to act as water treatment systems (Guo 2007). The current design consists of vegetation growiing on top of a filtration mix underlain with large aggregate and drains. This design shown in Figure 1 is specified in Drainage Criteria Manual, Volume 3, Chapter 5.6 (USWDCM 2001).

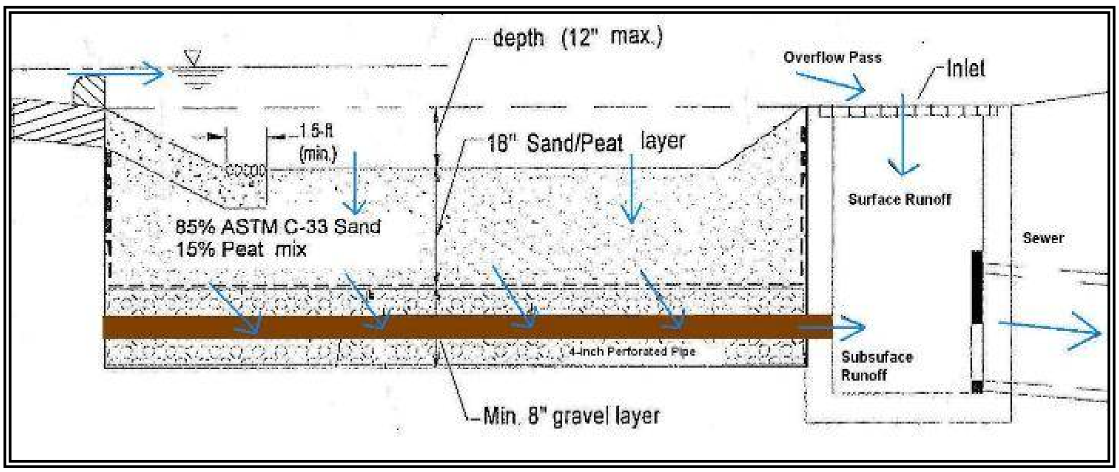


Figure 1 Illustration of PLDB

The current design recommendations leave opportunity for the incorporation of waste symbiosis and holistic design concepts. The current media mix design consists of peat, sand and gravel. Peat, which is imported, is very expensive and has associated environmental impacts. Local waste streams offer an opportunity for replacement of portions of the media. For example options for peat replacement include, compost, shredded paper and other organic waste stream materials (Tucker 2007). In addition the sub-layer may utilize waste stream materials such as recycled aggregate (McCambridge et al. 2004) and shredded tires (Tang et al. 2006).

The implications of changes to the current techniques must be evaluated in regards to sustainable design, ensuring
a) Local commercial products are identified and analyzed for quality

b) These waste streams do not release undesirable compounds, such as nutrients and heavy metals. There is also interest in enhancing metals, nutrients, sediment, and pathogen removal in PLDB.

1.1 Objectives and Phases of Work

The objectives of this research study are:

1) to select the best waste material reuse for sustainable PLDB sub-base system design,
2) to quantify the life-cycle environmental benefits of waste reuse for stormwater PLDB.
3) to investigate the impacts of waste materials and vegetation on performance of the PLDB addressing:
    3a) infiltration capacity for on-site stormwater volume disposal, and
    3b) effectiveness of contaminant removal for stormwater quality enhancement.

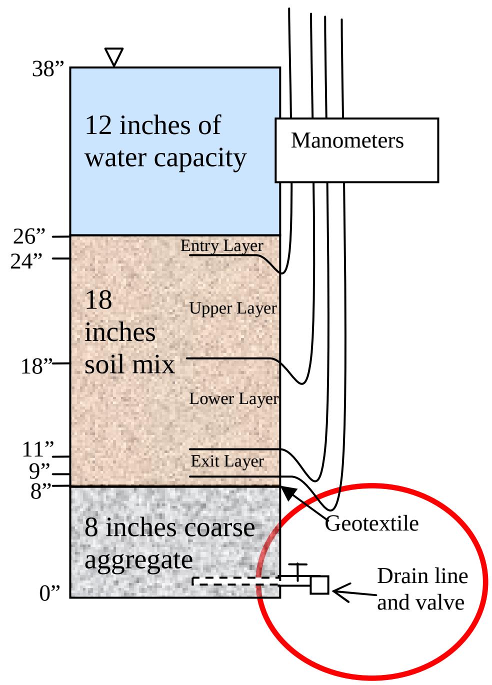
The objectives were completed through the following phases of work:

- Literature Review and Method Development
- Develop and Test Soil Column Design for the Bench Scale Test
- Model a 2-Layered PLDB Flow
- Waste Material Screening
- Environmental Life Cycle Analysis
- Bench Scale Test with Waste Materials and Bare Soil Conditions
- Bench Scale Test with Waste Materials both Bare Soil and Vegetated Conditions

1.2 Methodology

This report explores the possibility of increasing the sustainability of the current PLDB by incorporating waste steam materials. Waste materials were investigated and screened for use in a waste-incorporated PLDB. An environmental life cycle analysis (LCA) of the materials was conducted to assess the impact of waste-reuse. To test the performance of the waste-incorporated mixtures compared to the business-as-usual scenario a soil column infiltrometer for the bench scale lab tests was developed based on designs by various authors (Ames et al. 2001; Hunt 2003; Yang et al. 2004). Preliminary tests of the column design were completed and a 2-layered infiltration model was developed. Bench-scale testing was performed with three sub-base filtration mixtures and two surface conditions, bare soil and vegetated. The performance in terms of infiltration, clogging and contaminate removal was measured and assessed.

The infiltrometer designed for this study included a large diameter (38 cm, 15 inch) PVC column, pressure ports and a variable height outflow shown in Figures 2 and 3. Pressure ports and manometers were installed to measure changes in pressure through the filtration soil-mix. Each column was equipped with an overflow to maintain constant head of 30 cm (12 in) when necessary. The outflow at the bottom was designed to change depths from below the course aggregate to above the aggregate as in Figure 3. The elevated outflow served to saturate the filtration layers.



<u>Figure 2 Soil Column Design</u>

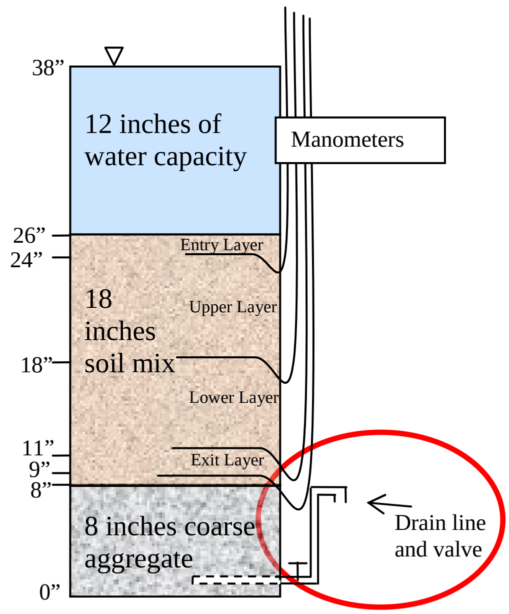


Figure 3 Soil Column Design with Elevated Out Flow

Model Development

Infiltration rate and hydraulic conductivity are important to the function of a PLDB. The PLDB is designed as a 2-layered system with an upper filtration layer of fine particles (sand-mix) and a lower layer composed of larger aggregate (gravel). The implication of overlaying media with lower porosity than the underlying layers can be observed in the lab. Data on infiltration rates and hydraulic conductivity were collected from lab tests. Based on the hydraulic conductivity and energy gradient, a model of the 2- layered flow was derived. The model predicted and laboratory tests confirmed an accelerated hydraulic gradient created from the large aggregate under-drain.

Waste Material Screening and Environmental Benefit

The incorporation of waste materials must include finding suitable waste materials and evaluating the environmental benefit (local and life cycle) of incorporating those materials. Through literature review possible waste materials were inventoried. Those materials were screened through performance tests (local availability, cost, leaching and infiltration rates) and confirmed by germination rate testing. Permissible waste-incorporated mixtures were defined and the environmental benefit was evaluated using greenhouse gas savings.

Local landscape suppliers were contacted for availability and cost of possible materials. The narrowed list of possible materials was subjected to leaching and flow rate testing. The testing began with replacement of one virgin material with one waste material e.g., replacing peat with compost only. Subsequent experiments included combining various waste materials e.g., compost and paper mixture for peat replacement. Small batches of approximately 4 liters of material were analyzed for flow rate and leaching of pH, total keldjal nitrogen (TKN), nitrate plus nitrate (NO2+NO3), total phosphorous (TP), and total metals. Figure 4 is a photograph of the experimental set-up for batch testing.

<u>Figure 4 Bacth Test Set-up for Collection of Leachate and Flow Rate</u>

After the completion of the flow rate and leaching tests, new batches of the passing mixtures were created for germination tests. As shown in Figure 5, the germination tests were conducted with a mixture of native grass seeds in small containers of approximately 200 square centimeters of bedding material. Grass seeds were counted in relative quantities recommended in Volume 3 Criteria Manual for the Denver Metropolitan area and mixed into the top 1/8 inch of media mix (USWDCM 2001). The containers were set near a sunny window, watered and monitored daily for germination and growth.

<u>Figure 5 Batch Test for Germination Rate</u>

The final results lead to a multi-criteria permissible range of mixtures for incorporation in PLDBs. Two sample mixtures in the mid-range of the permissible amounts were chosen and the environmental impact was evaluated. The EPA Waste Reduction Model (WaRM) and published GHG emissions specific to peat (EPA 2008, Cleary et al. 2005) and aggregate (Reiner, 2007) were combined to calculate the GHG savings. The boundaries considered for the calculation were extraction to installation and included transportation.

Bench Scale Testing

The bench scale testing of the various media-mixes was conducted in five steps divided into phases of bare soil conditions and with vegetation. The steps began with initial conditions for the new media mixtures without vegetation (bare soil) and ended with measuring the effects of vegetation on the systems. The descriptions of the steps are as follows:

Step 1- Initial Condition – Bare Soil- No Vegetation
First test with 72-hour elevated outflow and clean water to measure infiltration and calculate of hydraulic conductivity
Then lower the outflow and add stormwater for unsaturated field conditions until clogging occurs
Top layers were excavated and sieve analysis was performed
Step 2 – Duplicate Bare Soil Test
The top soil-mix layers were replaced.
Begin with 72-hour lowered outflow and measure infiltration rate
Then lower the outflow and add stormwater for unsaturated field conditions until clogging occurs
Step 3 – Effect of Vegetation
Germinate grass seeds on top of cake layer
Measure restoration of infiltration rate with 72-hour lowered outflow
Then lower the outflow and add stormwater for unsaturated field conditions
Step 4 – Dead Vegetation
Continue to add stormwater with sediment until the grass is choked and dies
Measure flow rates with dead grass
Step 5 – Replant Vegetation
Replant grass seeds on top of cake layer created in step 4
Then lower the outflow and add stormwater for unsaturated field conditions
Measure regeneration of flow rates

Triplicate columns were constructed for the control (1. peat and sand) and two treatment groups (2. compost, paper, sand and 3. compost, paper, sand, tires). A total of nine columns were set up in the lab as presented in Figure 6. As described in step 1, the initial saturated hydraulic conductivity was measured with tap water and an elevated outflow. Flow rates were recorded and water samples were collected for leaching. The outflow was lowered for the remainder of step 1 and all subsequent steps. Stormwater was added in 30 cm (12 inch) depths to represent the basin filling and emptying. The columns were monitored for sediment accumulation, outflow rates and water quality parameters. Two tests were conducted bare soil conditions (steps 1 and 2) until a cake layer was formed on the surface.

Figure 6 Soil Columns in Lab

Once the columns with waste materials were evaluated for performance criteria, vegetation was incorporated (steps 3, 4 and 5). Steps 3 and 5 included spreading seeds on top of the filtration mixture without disrupting the cake layer created in step 2. The seed mixture was the same mixture used in the batch test and recommended in Volume 3 Criteria Manual for the Denver Metropolitan area (USWDCM 2001). Grass seeds were spread on top of the cake layer, germinated and allowed to grow. The effect of the vegetation on the infiltration rate was measured by saturating the columns for 72 hours and then adding stormwater in the same method as the previous bare soil steps. The system was monitored for physical and chemical performance plus biological parameters of plant counts and qualitative growth rates.

The stormwater used throughout the study was collected from storm sewer outfall N-431E on the South Platte River draining from Denver (Figure 7). Urban runoff was collected from this outfall in 30 gallon plastic drums and transported to the lab.

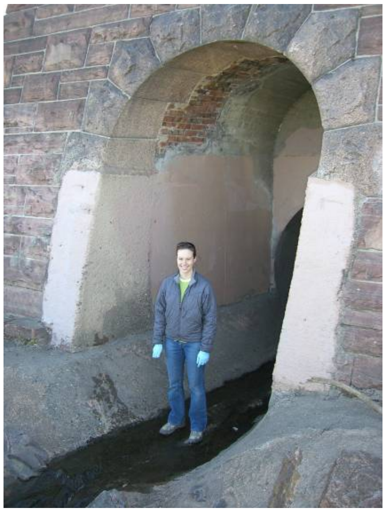


Figure 7 Outfall for Collecting Storm Water

Stormwater was applied with the same characteristics and equivalent volumes as urban runoff defined by Guo and Urbonas (2002). For the duration of the tests, the volume of stormwater applied and the accumulative sediment load were recorded and water quality samples were collected. The flow rate data were used to calculate infiltration decay due to clogging.

Water quality samples were collected and analyzed for total suspended solids (TSS), total dissolved solids (TDS), pathogens, total keldjal nitrogen (TKN), nitrate plus nitrate (NO2+NO3), total phosphorous (TP), and total metals. The nutrient and metals were analyzed at Metro Wastewater Reclamation District's laboratory. Total coliforms were measured as an indicator of concentration of pathogens and were both analyzed in-house and at Industrial Labs by the membrane filtration method (Clesceri et al. 1998). The pH, TS, TSS, TDS and pathogens were analyzed at the Auraria Campus laboratory following the *Standard Methodology for Examination of Water and Wastewater* guidelines (Clesceri et al. 1998). Soil samples were collected at the completion of the first test and analyzed for particle sized distribution by ASTM D-421 *Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants* (2009).

1.3 Results

Two-Layered Model Development

The filtering layers beneath a PLDB should be structured to completely consume the hydraulic head available in the system. The optimal dimension of the sub-base medium is found to be closely related to the design infiltration and seepage rates (Guo et al 2009).

Drain time controls the sediment removal rate. Based on the urban pollutant characteristics, a drain time for the PLDB is usually set to be between from 12 to 24 hours (USWDCM 2001). Figure 8 illustrates the flow through the two filtering layers including sand-mix and then gravel. Under a constant head, the steady flow condition is derived as:

$$f = V_1 = V_2 \quad \textbf{(1)}$$

In which f = infiltrating rate, and V= seepage flow velocity through each layer, The subscriptions "*1*" and "*2*" represent the variables associated with the sand-mix and gravel layers, respectively. A saturated seepage flow through a medium is proportional to the energy gradient as:

$$V_1 = K_1 \frac{dH_1}{H_1} \quad \textbf{(2)}$$

$$V_2 = K_2 \frac{dH_2}{H_2} \quad \textbf{(3)}$$

Where K = hydraulic conductivity, H = energy head, and dH = energy loss.

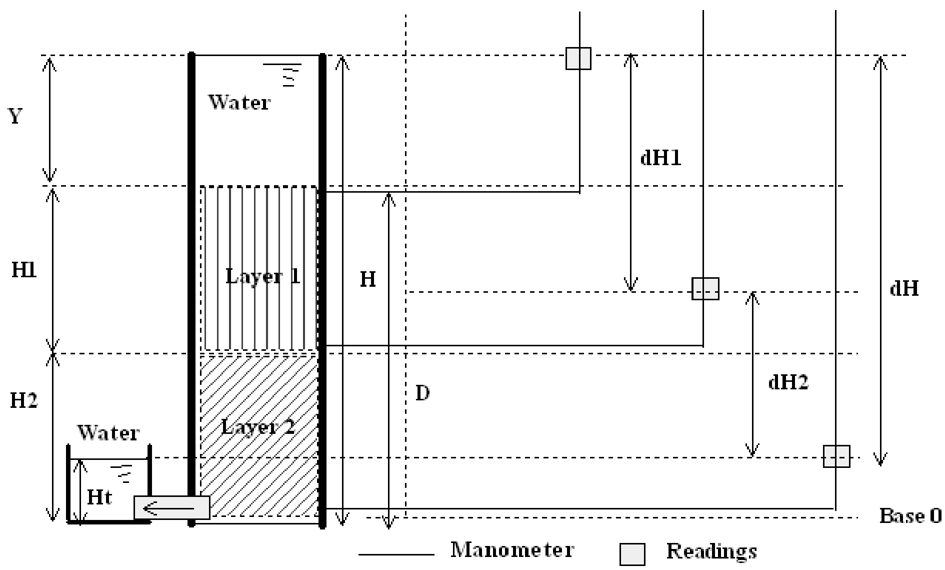


Figure 8 Illustration of Infiltrometer Operation

In practice, the design infiltrating rate depends on the drainage nature of the selected soil-mix. With a pre-selected design infiltrating rate, the total filtering thickness for the two filtering layers is calculated as:

$$D = f T_d \quad \textbf{(4)}$$

Where D= total thickness for two filtering layers, f = infiltration rate, and T_d = PLDB drain time. The fundamental challenge in PLDB design is how to divide the total thickness between the two filtering layers because the layer thickness is directly related to the hydraulic gradients for seepage flow through the system.

$$D = H_1 + H_2 \quad \textbf{(5)}$$

where H_1 = sand-mix thickness and H_2 = gravel layer thickness. As illustrated in Figure 7, the available hydraulic head for the PLDB system is

$$H = Y + D \quad \textbf{(6)}$$

where Y = water loading depth in PLDB. In this study, the optimal performance of a PLDB is defined by the infiltration flow and the subsurface thickness that allow the seepage flow to consume the hydraulic head available as:

$$H = dH_1 + dH_2 \quad \textbf{(7)}$$

Aided by equations 1, 2 and 3, the head losses through the two filtering layers are:

$$dH_1 = \frac{f}{K_1} H_1 \quad \textbf{(8)}$$

$$dH_2 = \frac{f}{K_2} H_2 \quad \textbf{(9)}$$

Aided by equations 6, 7, 8 and 9, the optimal performance of a PLDB is described as:

$$\frac{H_1}{D} + \frac{(\frac{f}{K_1} - 1) - \frac{Y}{D}}{(\frac{f}{K_1} - \frac{f}{K_2})} = 1 \quad \text{in which } f/K_1 > 1\text{, and } K_2 > K_1 \quad \textbf{(10)}$$

$$H_2 = D - H_1 \quad \textbf{(11)}$$

Equation 10 is valid when $f/K_1 > 1$ and $K_2 > K_1$. In other words, the infiltration rate is greater than the seepage rate and the sand-mix layer is above the gravel layer. Equations 10 and 11 are derived to be the guidance to divide the total required filtering thickness into two layers.

Equation 12 is numerically sensitive to f/K_1, but not to f/K_2 because the hydraulic conductivity coefficient of gravel is usually much higher than the infiltrating rate or the ratio, f/K_2, which is numerically close to zero. For simplicity, the thickness for the sand-mix layer is approximated as:

$$H_1 = (1 - \frac{K_1}{f})D + \frac{K_1}{f} Y \quad \textbf{(12)}$$

In this study, the infiltration rate for the peat and sand layer varies from 50 to 7.5 cm/hr (20 to 3 inch/hr). The final infiltration rate is approximately 7.5 to 12.5 cm/hr (5 to 3 inch/hr) after an operation of 72 hours. The hydraulic conductivity coefficient was varied within a small range through the soil-mix column. All these uncertainties are attributed to the residual pressure in the PLDB system. As a common practice, perforated pipes are installed in the subsurface system. A sub-drain pipe creates an accelerated hydraulic gradient to collect the excessive water and to alleviate the build-up pressure.

For example, the performance of a two-layered PLDB as shown in Figure 8 can be evaluated as:

(1) Given the Hydraulic Parameters for the Two-Layered PLDB				
Enter Design Infiltration Rate	*f=*	5.00	inch/hr	(Guess)
Constant Loading Water Depth	*Y=*	12.00	inches	(input)
Thickness of Upper Sand Layer	*H1=Hs=*	18.00	inches	(input)
Thickness of Lower Gravel Layer	*H2=Hg=*	8.00	inches	(input)
Conductivity of Upper Sand Layer	*K1=Ks=*	2.50	inch/hr	(input)
Conductivity of Lower Gravel Layer	*K2=Kg=*	25.00	inch/hr	(input)

(2) Hydraulic Performance of PLDB				
Hydraulic gradient in Upper Sand Layer	*Ss=f/Ks*	2.00		
Hydraulic gradient in Lower Gravel Layer	*Sg=f/Kg*	0.20		
Energy Loss through Upper Sand Layer	*dHs=Ss Hs*	36.00	inches	
Energy Loss through Lower Gravel Layer	*dHg=Sg Hg*	1.60	inches	
Total Energy Loss	*dH=dHs+dHg*	37.60	inches	
Total Head Available	*H=Y+Hs+Hg*	38.00	inches	
Residual Pressure Head on PLD's Bottom	*Hr=H-dH*	0.40	inches	**Close to Zero?**
Drain time	*Td=(Hs+Hg)/f*	5.20	hours	

(3) To adjustment infitlration rate until the residual pressure head = zero

(4) Is the drain time acceptable? If not, a Cap-Orifice is required on the subdrain pipe.

Waste Material Screening and Environmental Benefit

The possibility of a waste-incorporated upper filtration layer in the PLDB was investigated. The summary of the permissible bedding mixture is presented in Table 1 based on the three screening criteria, 1) cost/availability, 2) leaching, 3) flow rate, and confirmation germination tests. Results indicate that mixtures of compost, shredded paper, and shredded tires pass the screening criteria and confirmation tests. The three materials were locally available and cost effective. The relative amounts of compost, paper and tires in the mix were determined by the leaching and flow rate tests. The permissible amount of compost is between 6-10%, shredded paper between 5-9% and shredded tires less than 10% of the complete mixture.

Table 1 Permissible Bedding Mixtures

Virgin Material	Replacement Material	Permissible amount of material in the mixture based on the following criteria:				Permissible Amount of Material
		Cost/ Availability	Leaching	Flow Rate	Germination Test	
Peat	Compost	Pass	10% or less*	6-11%	5-10%	6-10% (5-8% if mixed with tires)
	Shredded paper	Pass	15% or less	4-9%	5-10%	5-8.5%
Sand	Tires	Pass	42% or less	<8%	42% or less	0-8%

Complete replacement of the organic portion (peat) is possible with a mixture of paper and certified compost. If the mixture contains only sand (not tires), a mixture of 6-10% compost and 5-9% shredded paper may be used. Due to leaching of metals, the amount of compost must fall between 5-8% of the total mix if tires are also incorporated. If tires are incorporated in the mix to offset some sand, equal amounts of paper (7.5%) and compost (7.5%) would fall within the permissible amounts for the compost, paper, sand tires scenario. A mixture of equal amounts of paper (7.5%) and compost (7.5%) falls within the permissible amount while obtaining benefit of each mixture and creating a buffer for error in measurement. The possible mixtures are shown in Figure 9.

15% Peat 85% Sand	7.5% Compost 7.5% Paper 85% Sand	7.5% Compost 7.5% Paper 77% Sand 8% Tires

Figure 9 Permissible Media Mixtures for PLDB

Two final mixtures were recommended for use in waste-incorporated media for a PLDB. The currently used 15% peat and 85% sand may be replaced by either of two mixtures. One option is to replace the peat with equal amounts of paper (7.5%) and compost (7.5%). Another option is a mixture replacing both the peat and sand portions which would consist of 7.5% paper, 7.5% compost, 77% sand and 8% tires. The greenhouse gas benefit of offsetting both peat and sand resulted in a total savings of 7.13 MTCO2E for an example PLDB of 3,450 square feet of basin surface area. Of the 7.13 MTCO2E, the greatest portion of the savings (6.63 MTCO2E) is realized from the replacement of the peat with compost and paper.

Bench Scale Test – Bare Soil

The control (peat and sand) and the two permissible waste-incorporated mixtures were further evaluated through bench scale testing. The bench scale tests consisted of five steps to compare bare soil and vegetative conditions. Steps 1 and 2 provided data for bare soil without vegetation. Step 3 began with germinating grass seeds on the cake layer created from the sediment buildup in step 2. Grass was allowed to grow and the same experimental procedures of adding stormwater, measuring flow rates and analyzing water quality parameters were followed. The vegetation eventually died leading to additional results with dead grass, step 4. Grass seeds were again planted on top of the clogged filtration layer with dead grass and additional information about the effect on infiltration rate was collected.

An initial saturated flow rate for the first bare soil test with new media-mixture was measured during 72 hours of elevated outflow. The infiltration rates over the 72 hour duration are plotted in Figure 10 and follow Horton's infiltration model stated in equation 13 (Horton 1933). As water is applied to the soil surface the infiltration rate reduces to infiltration capacity by an exponential decay function.

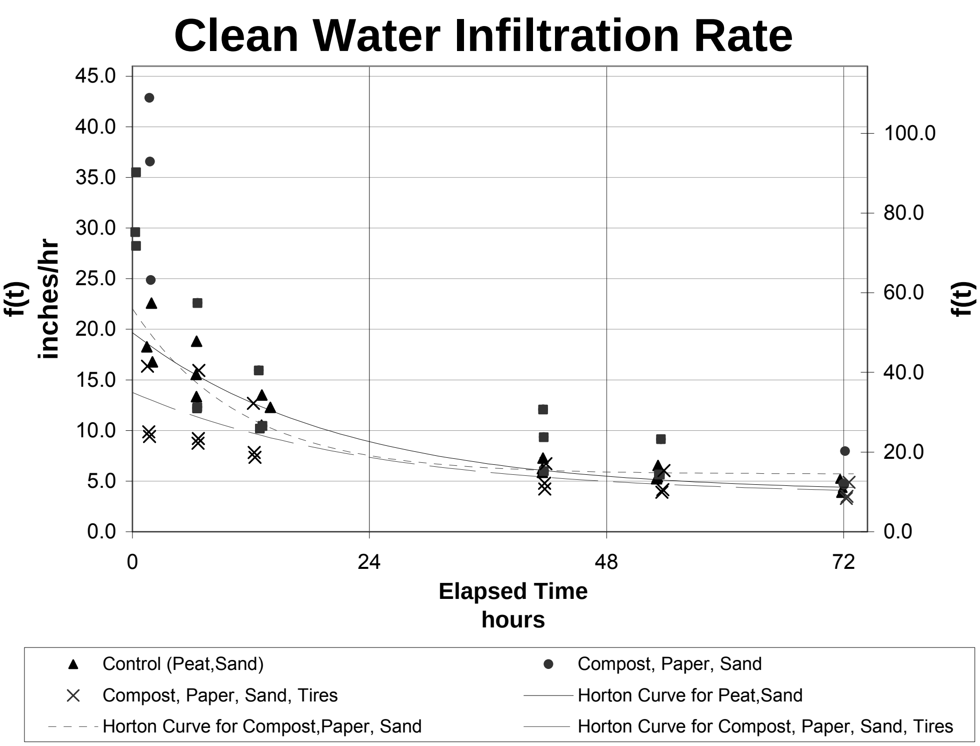


Figure 10 Infiltration Rate

Horton's estimate for infiltration rate over time is based on the equation:

$$f(t) = f_c + (f_o - f_c)e^{(-k)t} \quad \textbf{(13)}$$

Where *f (t)* is the infiltration rate at time *t*, f_o is the initial infiltration rate [L^3/t] and f_c is the infiltration rate at field capacity [L^3/t]. The *k* is a constant with units 1/time. The best fit equations for the infiltration rate of the three mixtures shown in Figure 10 are:

$$Peat\ and\ Sand:\ f_{control}(t) = 9.9 + (50 - 9.9)e^{(-0.0478)t} \quad \textbf{(14)}$$

$$Compost, Paper, Sand:\ f_{cps}(t) = 14.5 + (56 - 14.5)e^{(-0.0914)t} \quad \textbf{(15)}$$

$$Compost, Paper, Sand, Tires:\ f_{cpst}(t) = 9.1 + (35 - 9.1)e^{(-0.0415)t} \quad \textbf{(16)}$$

Where $f_{control}$ *(t)* is the infiltration rate [cm/hr] of the control (peat and sand) mixture at time *t*, f_{cps} *(t)* is the infiltration rate [cm/hr] at time *t* of the compost, paper and sand mixture and the f_{cpst} *(t)* is the infiltration rate [cm/hr] at time *t* of the compost, paper, sand and tires mixture. In equations 14, 15, and 16 f_o is expressed in cm/hr, f_c is the infiltration rate at field capacity expressed in cm/hr, and *t* is the elapsed time in hours. The *k* is a constant with units 1/hr.

After the initial saturated infiltration test, stormwater was applied in depths of 30 cm (12 in) in unsaturated conditions. As the stormwater was applied, the accumulation of sediment on the top layers caused a reduction in infiltration rates. The change of infiltration rate was measured throughout the continuous application of stormwater. For mathematic convenience, the reduced infiltration rate, f_s , is normalized by f_c and the accumulative sediment load, L_S, is expressed as weight of sediment per unit area in kg/m^2.

The decay of infiltration is plotted in Figure 11 for various sub-base mixtures. The relationship can be depicted by an exponential decay function between f_s/f_c and L_S [kg/m^2].

$$Peat\ and\ sand:\ \frac{f_s}{f_{c\ control}} = -4.449e^{-0.1361L_s} \quad \textbf{(17)}$$

$$Compost,\ paper\ and\ sand:\ \frac{f_s}{f_{c\ cps}} = 2.927e^{-0.1369L_s} \quad \textbf{(18)}$$

$$Compost,\ paper,\ sand\ and\ tires:\ \frac{f_s}{f_{c\ cpst}} = 2.8303e^{-0.0814L_s} \quad \textbf{(19)}$$

Where f_s is the infiltration rate [cm/hr] after accumulative unit-area sediment load L_s, [kg/m^2] and f_c is Horton's constant infiltration rate [cm/hr]. The subscripts, control, cps and cpst, indicate the media-mixture associated with each equation. *Where* $f_{c\ control}$ is the constant infiltration rate [cm/hr] of the control (peat and sand) mixture, $f_{c\ cps}$ is the infiltration rate [cm/hr] of the compost, paper and sand mixture and the $f_{c\ cpst}$ is the infiltration rate [cm/hr] of the compost, paper, sand and tires mixture

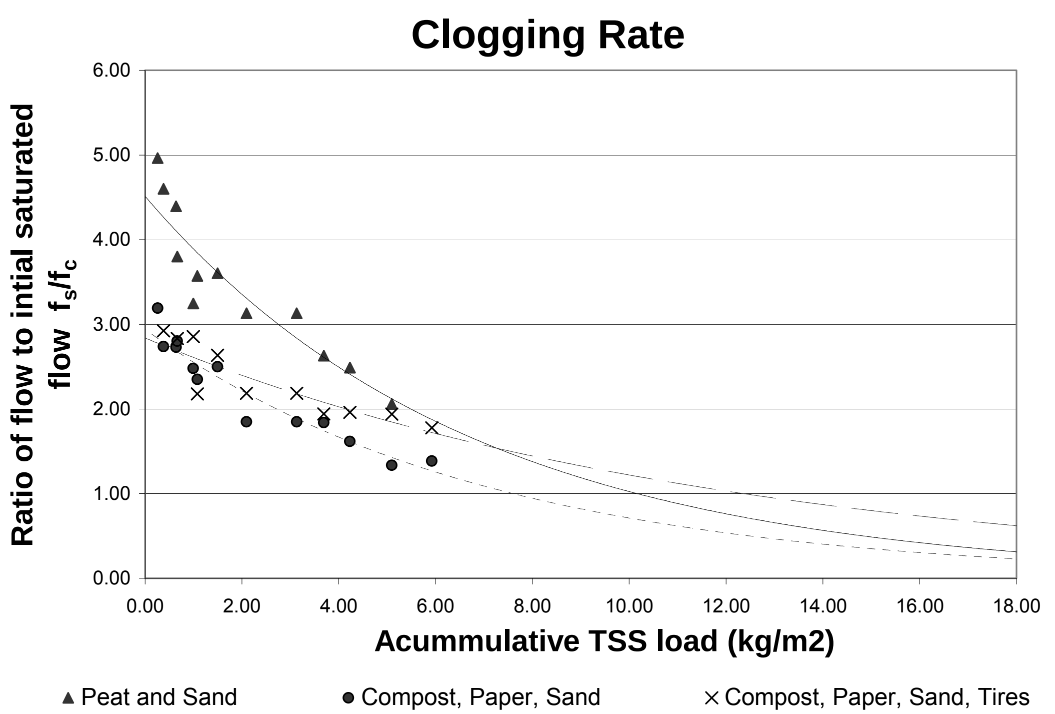


Figure 11 Reduction of Infiltration Rate with Accumulative Sediment Load

As indicated in Figure 11, clogging of the filtering layers is closely related to the accumulative amount of sediment loaded onto the infiltrating bed. The design example intends to illustrate how to interpret the accumulative sediment load into the basin's operation. The annual sediment yield generated from the tributary area can be estimated by the annual event mean concentration (EMC) of sediment and the annual runoff volume as:

$$V = CPA_{tributary} \quad \textbf{(20)}$$

$$W_S = C_S V \quad \textbf{(21)}$$

In which V= annual runoff volume in [L^3], C= runoff coefficient, P= annual rainfall depth in [L], $A_{tributary}$= tributary watershed area [L^2], C_S =sediment annual EMC [M/L^3], and W_S = annual amount of sediment eroded from the entire watershed [M]. In practice, the PLDB is designed to intercept the runoff from the tributary area. As a result, the annual unit-area sediment loading to the PLDB is estimated as:

$$\alpha = \frac{A_{tributary}}{A_{PLDB}} \tag{22}$$

$$B_S = C_S \alpha C P \tag{23}$$

In which α = the ratio of the tributary area intercepted by PLDB, A_{PLDB} = the surface area of the PLDB [L^2] and B_s = annual unit-area sediment load to the basin of the PLDB [M/L^2/year]. Figure 11 shows the decay of the infiltration rate with respect to the accumulative unit-area sediment load, Ls, which can be converted into the PLDB's service years as:

$$N = \frac{L_S}{B_S} \tag{24}$$

Where N = the number of PLDB's service years, L_S = accumulative sediment load [M/L^2] into the receiving PLDB and B_s = the annual unit-area sediment load in the receiving PLDB [M/L^2/year]. Equation 24 assists the engineer to convert Figure 11 into any PLDB's service years for an investigation of the life-cycle operation.

For example, a PLDB in Denver is designed based on the local requirements (USWDCM 2001) using the average annual rainfall in Denver, and average sediment concentration observed in Colorado (Doefer and Urbonas 1993). The example PLDB has a surface detention capacity up to a water depth of 0.305 m (12 inches). It will capture and treat runoff from a parking lot. The ratio, α, defined as the parking lot area to the PLDB, is 20 to 1 for this case. The TSS EMC , C_S, in runoff from commercial areas in Colorado is recorded as 240 mg/L. Annual precipitation (P) in Denver area is .4 meters (15.4 in). Aided by equation 23 with C_S = 240 mg/L, α=20, C=0.9 for parking lot, and P=0.4 m, the annual unit-area sediment load to the example PLDB is calculated as:

$$B_s = (240 mg/l)(20)(.9)(.4m) = 1.728 kg/m^2 \tag{25}$$

The accumulative sediment load (L_S) on the x-axis in Figure 11 can then be converted into years of service for the example PLDB. Figure 12 presents the reduction in infiltration over time for the example PLDB. The decay of infiltration capacity down to 2.5 cm/hr (1 in/hr) varies for each sub-base mixture based on the Horton's constant infiltration rate f_c. For this example, the PLDB is considered clogged at f_s/f_c=2.5/f_c.

As shown in Figure 10 and equations 17, 18 and 19, f_c is 9.9 cm/hr for the control (peat and sand), 14.5 cm/hr for the mix of compost, paper and sand and 9.1 cm/hr for the mix of compost, paper, sand and tires. Therefore the PLDB is considered clogged in Figure 12 where f_s/f_c is 2.5/9.9 for the control, 2.5/14.5 for compost, paper and sand and 2.5/9.1 for compost, paper, sand and tires.

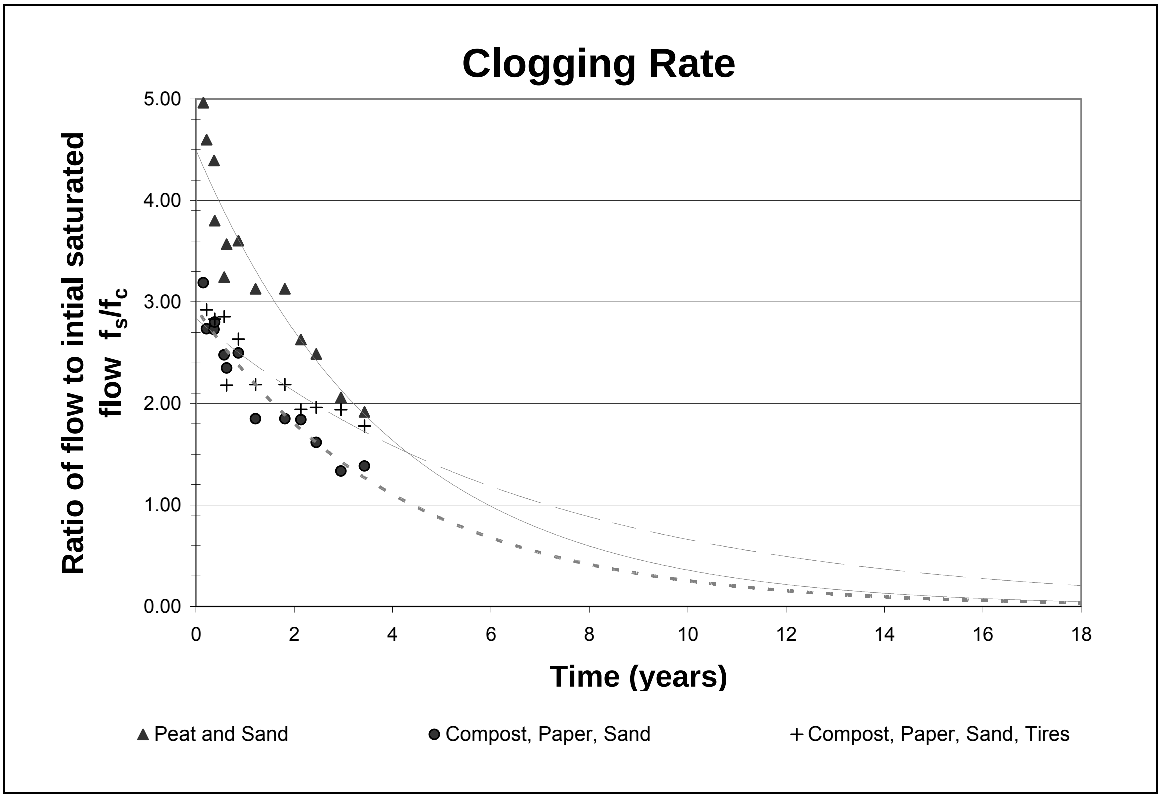


Figure 12 Reduction of Infiltration Rate for Example PLD

The infiltration tests indicated that improvements in water quality result in sediment accumulation on the PLDB's bottom, and clogging through the sub-base filtering media over time. All three mixtures filtered TKN, TP and copper from the system during the stormwater applications. Removal rates for TKN, TP, and Copper varied from 32% to 77%, 48% to 86%, and 48% to 95% respectively. The pathogen removal rates were between 88% and 99%. Sediment removal rates remained high throughout the two tests, 93% to 100%. Accumulation of sediment creates a cake layer on top of the filtration layer. Sieve analysis indicated the cake layer formed in all three treatments was on the top surface up to 1 cm. Additionally, the cake layer consists of both solids from storm water and floating particles from the PLDB's media mixture.

Bench Scale Test – Vegetation

The PLDB is designed to treat stormwater through a vegetated basin and soil-mix filtration layer. The previous section defined possible media-mixes for the filtration layer to achieve stormwater treatment goals with bare soil conditions. This phase evaluated those filtration mixes capacity to support plant growth and the possible water quality impacts due to the filtration mixture in the PLDB. The vegetation's effect on performance of the PLDB was assessed.

The three treatments (1. peat and sand, 2. compost, paper, sand and 3. compost, paper, sand and tires) supported germination and plant growth similarly when watered regularly. The waste-incorporated mixes (2. compost, paper, sand and 3. compost, paper, sand and tires) sustained the plant growth through a 2 month dry period. The growth of the vegetation was stunted in the control (peat and sand) mixture without water.

Vegetation did not reduce the contaminate removal rate in the PLDB and in some cases increased the removal rate as shown in Table 2. Vegetation benefited the nutrient removal capacity of the control mixture. The total metals (Cu, Pb, Zn) removal was consistently high (88% to 99%) with both bare soil and vegetated conditions. The average percent removal rates are presented in Table 2.

Table 2 Contaminate Removal Rate

	Test	Accumulative Sediment	Removal Rate Cin - Cout /Cout					
		kg/m^2	TKN	NO_2 $+NO_3$	Total P	Cu	Pb	Zn
Control	1 Bare Soil	.33	44%	0%	83%	45%	70%	87%
	2 Bare Soil	2.65	77%	76%	86%	95%	95%	98%
	3 Vegetation	7.00	87%	85%	98%	98%	97%	99%
	3 Vegetation	9.7	80%	69%	98%	92%	97%	98%
CPS	1 Bare Soil	.33	32%	-2%	48%	66%	70%	88%
	2 Bare Soil	2.65	71%	65%	80%	93%	95%	98%
	3 Vegetation	7.00	77%	57%	85%	95%	97%	99%
	3 Vegetation	9.7	81%	39%	91%	93%	97%	99%
CPST	1 Bare Soil	.33	35%	27%	61%	81%	70%	86%
	2 Bare Soil	2.65	71%	82%	85%	93%	95%	88%
	3 Vegetation	7.00	79%	76%	92%	97%	97%	95%
	3 Vegetation	9.7	74%	82%	92%	92%	97%	83%

Pathogen removal is of interest because pathogens in runoff water contaminate rivers and expose the public to health risks. Pathogens were removed from the stormwater with bare soil and vegetative conditions. As shown in Table 4 an average of 88% to 99% cfu were removed under bare soil conditions and from 87% to 99.8% pathogens were removed after vegetation. The two highest concentrations of pathogens in the inflow were 60,000 cfu with bare soil and 50,000 cfu with vegetation and the removal rate remained above 94%. The removal rate when the stormwater inflow was 5,700 cfu the removal rate varied between 88% ad 92%.

Table 4 Percent Removal of Pathogens

	Total Colony Forming Units (cfu)				
	5,700	26,000	60,000	20,000	50,000
	Percent Removal in Bare Soil			Percent Removal with Vegetation	
Control	92.0%	97.7%	99.0%	90.7%	99.8%
CPS	88.0%	98.6%	94.7%	97.5%	99.5%
CPST	90.1%	99.2%	98.4%	87.3%	99.2%

Both removal rates of contaminates as well as outflow concentrations are important to measure the filtering capacity of the PLDB system. The inflow and outflow concentrations can be compared to the EPA freshwater criteria for maximum allowable in-stream contaminate concentrations (EPA 2006). The concentrations of nutrients in the outflow water from the control were consistently lower than the other two treatments as shown in Table 3. Additionally, vegetation decreased the outflow concentration of TKN, NO_3+NO_2, and TP through the control (peat and sand). All inflow and outflow concentrations of NO_3+NO_2 were below the standard of 10 mg/L of NO_3. The TP concentration in the outflow from the control (peat and sand) mix with vegetation consistently met the EPA in-stream criteria of .06 mg/L. The outflow from the control (peat and sand) mix with bare soil conditions and all outflow samples from the other two mixes with bare soil and with vegetation were 3 to 6 times the EPA limit for TP.

With a few exceptions the systems continuously filtered metals from the stormwater to below EPA freshwater standards. The concentrations in the outflow met the EPA limits within one standard deviation, except for the last sample from the compost, paper, sand and tires mix. Although the highest inflow concentration of zinc was 2410 ug/L, only the last outflow from the compost, paper, sand and tire mix (412.7 ug/L) was above the standard of 120 ug/L of zinc.

Table 3 Contaminate Concentrations

	Test	Accumulative Sediment Load (kg/m^2)	TKN (mg/L)	Nitrate +Nitrite (mg/L)	Total P (mg/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)
Inflow	1 Bare Soil	0.33	1.70	3.56	0.63	21.1	16.7	169.0
	2 Bare Soil	2.65	2.60	4.43	1.30	113.0	100.0	955.0
	Tap Water	5.92	0.50	0.08	ND(.03)	9.7	ND(5)	ND(20)
	3 Vegetation	7.00	4.20	4.66	1.98	217.0	195.0	2380.0
	3 Vegetation	9.70	4.30	2.34	1.68	179.0	170.0	2410.0
EPA Freshwater Criteria (EPA 2006)			NR	10.00	0.06	13.0	65.0	120.0
Outflow Control	1 Bare Soil	0.33	0.95	3.58	0.11	11.65	ND(5)	22.3
	2 Bare Soil	2.65	0.60	1.08	0.19	6.10	ND(5)	ND(20)
	Tap Water	5.92	0.37	0.20	ND(.03)	ND (2)	ND(5)	ND(20)
	3 Vegetation	7.00	0.53	0.72	0.04	4.87	ND(5)	ND(20)
	3 Vegetation	9.70	0.87	0.73	0.04	14.00	ND(5)	40.0
Outflow CPS	1 Bare Soil	0.33	1.15	3.63	0.33	7.25	ND(5)	ND(20)
	2 Bare Soil	2.65	0.77	1.56	0.26	7.83	ND(5)	ND(20)
	Tap Water	5.92	0.45	0.23	0.09	ND(2)	ND(5)	ND(20)
	3 Vegetation	7.00	0.97	2.02	0.29	10.80	ND(5)	21.4
	3 Vegetation	9.70	0.83	1.43	0.15	13.23	ND(5)	ND(20)
Outflow CPST	1 Bare Soil	0.33	1.11	2.59	0.25	3.95	ND(5)	24.0
	2 Bare Soil	2.65	0.77	0.80	0.20	8.23	ND(5)	114.6
	Tap Water	5.92	0.37	0.24	0.07	2.13	ND(5)	50.9
	3 Vegetation	7.00	0.87	1.11	0.16	7.37	ND(5)	110.8
	3 Vegetation	9.70	1.10	0.42	0.14	14.07	ND(5)	412.7

Since contaminate removal is a goal of the PLDB, water quality from all outlets must be investigated. In the case of a large storm event the overflow becomes an outlet from the PLDB. Light particles from the filtration mixture such as organics and tires, were observed floating on the stormwater and in the overflow outlet as in Figure 13. Additionally, vegetation added un-germinated seeds and dead grass to the floating material. Large suspended solids in stormwater, such as leaves, twigs and cigarette butts, combine with the light materials in the filtration mix and may be carried downstream in the event of overflow or plug the outlet. Figure 14 shows trash which was combined with dead grass and overflowed a PLDB.

Figure 13 Floating Particles in Overflow in the Lab

Figure 14 Overflow of Light Particles in a PLDB

Total suspended solids samples collected in the lab indicate that the rainwater disrupting clean bare soil can float as much as 2,000 mg/L of suspended solids. Figure15 presents the concentration of floating particles, when tap water is added to the following conditions; 1. clean bare soil, 2. after the cake layer is formed and 3. after grass has been germinated in the cake layer.   The cake layer forms a crust which holds the floating particles in the filtration mix in place. When the cake layer has been disrupted by grass roots the light particles float again.

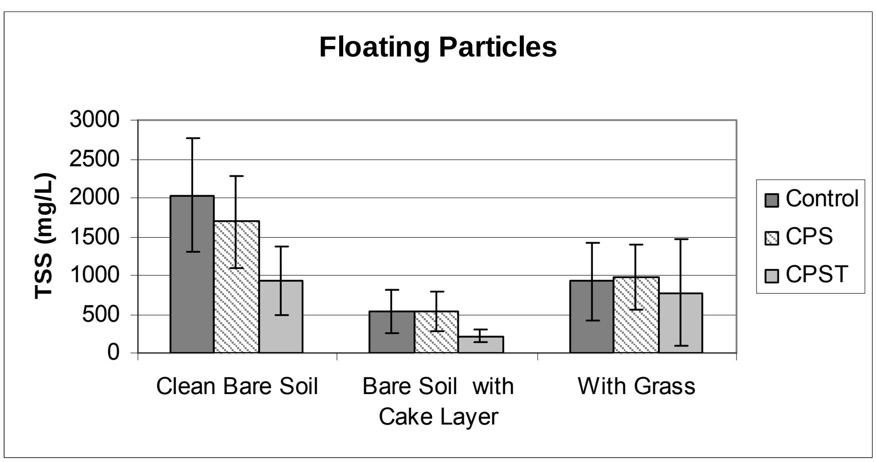


Figure 15 Amount of Floating Particles in Clean Water

Although the TSS concentration [mg/L] in the overflow from the three soil-mixes is statistically similar, the particles are different substances. The floating material is related to the nature of the filtration media and the vegetation growing in the PLDB. The overflow from each of the mixtures was filtered and photographs of the filtration paper are presented in Figure 16. The particles include light portions of the filtration mix (eg. peat, compost and shredded tires) plus un-germinated seeds and small pieces of dead grass.

Peat Sand	Compost Paper Sand	Compost Paper, Tires Sand

Figure 16 Overflow Particles after Grass was Growing

Vegetation positively affected the unsaturated infiltration rate as stormwater was applied depths of 30 cm (12 in)to the top of each column. In Figure 17 the infiltration rate f_s [cm/hr] after accumulative sediment load L_S,[kg/m^2] is normalized by Horton's constant infiltration rate f_c [cm/hr]. As stormwater was applied, the infiltration rate decayed as sediment is built up on the bare soil. After grass seeds were germinated on the cake layer, a greater infiltration rate is observed. A second reduction inflow rate is seen as the vegetation is choked and sediment builds up on bare soil.

The regeneration of infiltration rate after the first clogging and germination was measured as 54% (Control), 76% (compost, paper, sand) and 40% (compost, paper, sand, tires) increase in flow rate. After the grass was choked and system clogged, the second germination of grass seeds resulted in a 235% (Control), 96% (compost, paper, sand) and 8% (compost, paper, sand, tires) increase in flow rate from the infiltration rate. The regeneration of flow rate in Figure 17 equates to a longer time until the PLDB clogs. The vegetation had the greatest effect on the control (peat and sand) mixture and the least effect on the compost, paper, sand and tires mixture.

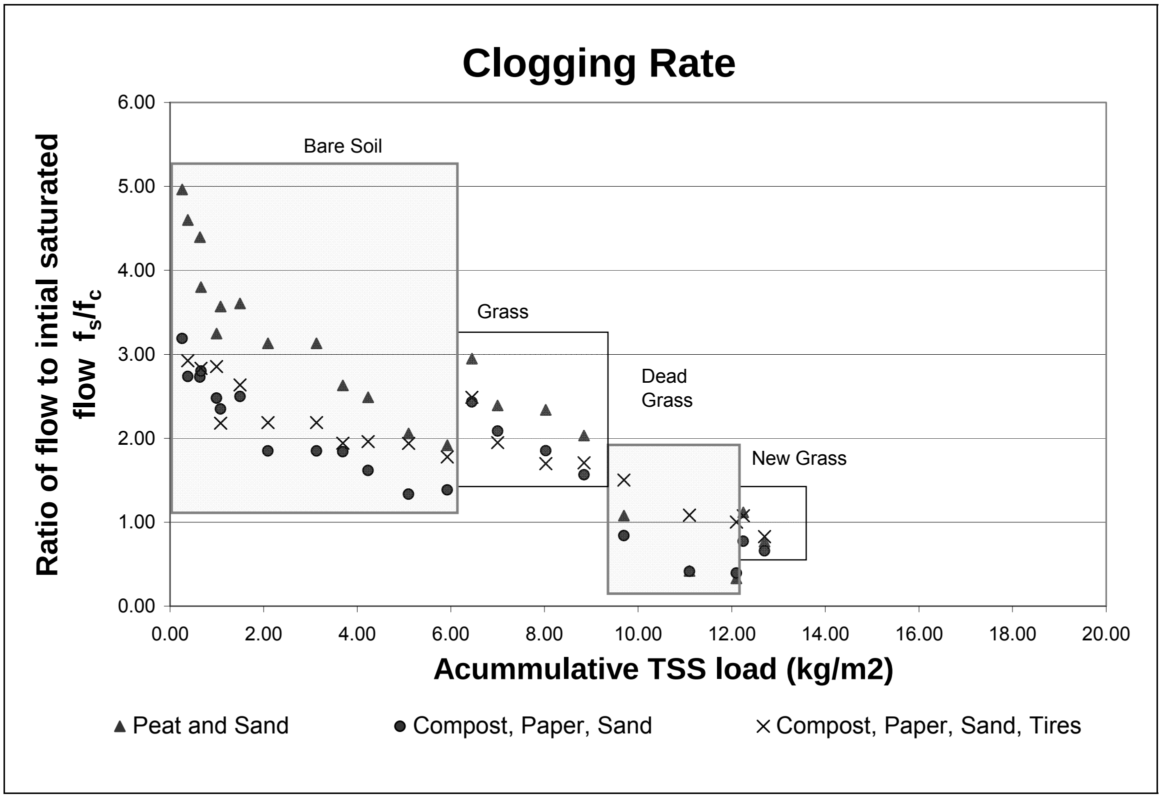


Figure 17 Effect of Vegetation on Flow Rate

1.4 Conclusions

This research evaluated the beneficial reuse of urban waste stream materials into sustainable substrate mixes for effective functioning of the PLDB. The best waste materials for the sustainable sub-base system design were screened and the environmental life cycle analysis (LCA) for a waste-incorporated design was completed. The impact of the waste materials and vegetation on the performance of the system was evaluated in bench scale tests with bare soil and vegetative conditions. The filtration mixes capacity to support plant growth the possible water quality impacts due to the filtration mixture in the PLDB and the vegetation were investigated. The vegetation's effect on performance of the PLDB was assessed.

A large diameter infiltrometer was designed and tested with a two-layered PLDB. A model for the optimal dimensions for the sub-base in the two layered design was created and confirmed with lab testing. The current recommendation a sand-mix filtration layer on top of a larger gravel layer, creates accelerated hydraulic gradient drawing water through the sand filtration layer.

The goal of the lab research was to find suitable waste replacements for these sub-base layers. Through screening and confirmation tests the currently recommended 15% peat and 85% sand mixture was compared to two waste-incorporated mixes 1) 7.5% compost, 7.5% paper, 85% sand and 2) 7.5% compost, 7.5% paper, 77% sand and 8% tires). Removal rates and outflow concentrations of nutrients, metal and pathogens was similar in all three treatments in the bare soil tests. TP was lowest in the control (peat and sand) mix with vegetation. Zinc had been a concern with the shredded tires and break through of zinc occurred after addition of 9 kg/m2 of accumulative sediment load.

The potential for the PLDB filtration media to become a source of water quality impact was investigated. In a large storm event the overflow may carry a mix of light particles in from the filtration mix (eg. peat, compost and tire particles), dead vegetation and grass seeds. Up to 2,000 mg/l TSS were found in the overflow which may clog the outlet or enter the downstream waterways.

The combination of filtration mix and vegetation were found to impact the water quality and the clogging over time. A mixture with tires increases the life span of the PLDB but has less filtering capacity for zinc. The compost and paper replacement for peat performs similarly to the control (peat and sand) in filtration capacity and clogging rate. A design example with bare soil conditions indicated that clogging occurs in 8 to 17 years at which point maintenance is required. The impact of vegetation was to extend the life of the PLDB by 3-6 years for the control (peat and sand) and the compost, paper and sand mixture. Results indicated that grass would not affect the clogging rate over time of the compost, paper, sand and tires mixture.

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