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A STUDY OF HYDRAULIC DYNAMICS IN VEGETATED AND NON-VEGETATED BIORETENTION MESOCOSMS

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ABSTRACT

Bioretention systems are stormwater treatment devices installed to remove both dissolved and particulate pollutants. As stormwater percolates through the bioretention system, dissolved pollutants are removed from solution by chemical and biological processes. In our study, 20 bioretention mesocosms (10 with loamy sand and 10 with sandy loam, half with and half without vegetation) were used to investigate hydraulic behavior. The mesocosms were dosed with 120L to 160L synthetic stormwater over 3h to 5h. The infiltration and percolation rates in the sand was rapid ($>15 \text{ cm-h}^{-1}$), while rates in the loam were much less ($2\text{-}3 \text{ cm-h}^{-1}$). Retention time in the sand was 1.5h while that in the loam was well over 10h. Vegetated systems had better percolation rates than the non-vegetated systems. Constriction of outlets rapidly affected infiltration rates. The infiltration and percolation response of the bioretention systems was evaluated in terms of the Green-Ampt equation, as affected by soil properties and vegetation. Implications for the design of bioretention facilities are then discussed.

KEYWORDS: Bioretention, Hydraulics, Green-Ampt Equation

INTRODUCTION

Bioretention systems are better management practices (BMPs) which typically consist of an excavated basin filled with porous media and planted with vegetation. The media in most bioretention systems ranges from loamy sands to sandy loams. As the stormwater passes through the bioretention system, particulates are removed by filtration. Dissolved pollutants are removed from solution by chemical adsorption/precipitation processes largely affected by the media as well as biological processes of the system such as vegetative and microbial biomass uptake. Small scale bioretention systems used to treat runoff from small areas such as roofs and driveways are called rain gardens.

Initial studies of bioretention systems documented that they offer considerable potential to retain TSS and metals, while providing encouraging results for nutrient retention (Davis et al, 2001). Henderson et al (2006) compared retention in vegetated mesocosms to those without vegetation (barren). The dosing results indicated that the presence of vegetation had a pronounced effect to promote N and P retention. After 12 months establishment, Orthophosphate ($\text{PO}_4\text{-P}$) removal approached 100% in the vegetated treatments and sand media; but only 75% in the loam media. The vegetated treatments also removed 77% of TN from

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synthetic stormwater, compared to retention of only 10% in barren sand and 25% in barren loam treatments (Henderson et al 2006).

However, there is a substantial lack of published data on the hydraulic performance of bioretention systems. While many studies may list runoff volumes or mass loads on an annual basis (eg. Hunt et al, 2005), we are aware of only few published studies reporting hydrographs and/or lag time coefficients for bioretention systems (Muthanna et al, 2005, 2006; Dietz and Clausen, 2005).

Since the interaction of runoff capture volumes and treatment efficiencies of captured runoff are central to determining overall BMP performance on a mass load basis, this most basic aspect of hydraulic performance needs to be addressed. Our study is intended to partially address some of the gaps in our knowledge of hydraulic performance of bioretention BMPs.

METHODS

The experiments were conducted from May to August 2006 in Brisbane, Australia using the existing bioretention mesocosms of Henderson et al (2006). These bioretention mesocosms were constructed in June 2003 in 240L containers (105cm by 53cm by 53cm, tapering to 42cm by 42 cm) using 2 media types, a loamy sand (2% silt) and a sandy loam (3% clay and 8% silt). The media depth is approximately 85cm, with 20 cm of freeboard, and a 5cm gravel underdrain layer. The media is separated from the underdrain layer by coarse screening. Effluent is drained by means of a valve at the bottom of the gravel underdrain layer.

For each media type, five mesocosms were planted with native vegetation, with the remaining five being non-vegetated, providing 5 replicates for each treatment. Unplanted (barren) mesocosms were covered by a gravel mulch 2.5 cm deep. The plant species were: Swamp Foxtail Grass (*Pennisetum alopecurioides*), a tufted grass, interplanted with Banksia (*Banksia integrifolia*) – a shrub/tree, Bottlebrush (*Callistemon pachyphyllus*) – a shrub/tree, and Flax Lily (*Dianella brevipedunculata*) – a tufted small lily. At the time of our experiments, the vegetation had been established for 3 years.

The initial leaching experiments involved saturating the mesocosms with 50L to 70L tap water, and collecting grab samples of the resulting effluent. For the dosing experiments, synthetic stormwater was mixed in a 5,000L tank and applied at a uniform rate of 36 L-hr⁻¹ through 18 mm tubing by use of parallel 12- and 24 L-hr⁻¹ irrigation drippers. The dosing experiments involved up to 180L of synthetic runoff. At a typical 15:1 ratio of catchment to treatment area (0.27 m²), this represents a rainfall depth over 40 mm over 2 hours, a fairly typical event in terms of annual rainfall distribution.

The entire effluent volume was collected in 150L cylindrical PVC chambers (300cm x 250mm diameter) for 24h from the sand mesocosms, and for 48h from the loam mesocosms. Applications were interrupted in loam mesocosms with lower infiltration rates to avoid overflows, while continuing in the sand mesocosms which had greater infiltration rates. Applications were extended in the loam mesocosms to provide as much influent as possible. Even so, the influent volumes were lower in the loam systems, ranging from 107 to 138 L.

During the leaching experiments, the average infiltration rate was measured as the total inflow volume less ponded volume, divided by inflow time. During dosing, water levels of the

ponded mesocosms were recorded at regular intervals. By accounting for the influent volumes during each time step, the average infiltration rate for each interval was computed as the difference between inflow and storage increase.

Once effluent began to flow, the flow rate was measured by recording the weights on scales placed under each end of the collection chambers. The difference in weights between each interval divided by the interval time thus provided the average outflow rate for each interval. In this manner, it was possible to develop the outflow hydrographs.

The leaching runs were conducted in May and June of 2006. Two dosing runs were made at the end of July, 2006, separated by an interval of a week. As an experimental treatment, controllable outlets were placed in the sand mesocosms to restrict outflows in the second run, thus increasing retention time. These outlets were constricted to $12 \text{ L}\cdot\text{h}^{-1}$ when the mesocosms were full, resulting in an effective outflow rate of $5\text{cm}\cdot\text{h}^{-1}$.

RESULTS

The hydraulic experiments involved measurements of the infiltration into, and percolation rates through, the mesocosms. Mean results are displayed for the mesocosms, with parametric box plots of the quartiles, maxima and minima. The average free pore space in the media was 46 to 52 L, or approximately 25 % of the total media volume. As such, the percolation rate within the media would be four times the infiltration rates. No ponding was observed in the sand mesocosms during the first run, so the infiltration rate into the sand media was at least the inflow rate of $15 \text{ cm}\cdot\text{hr}^{-1}$ at all times. The average infiltration rate in the loam mesocosms observed during the leaching experiments was $11.9 \text{ cm}\cdot\text{h}^{-1}$.

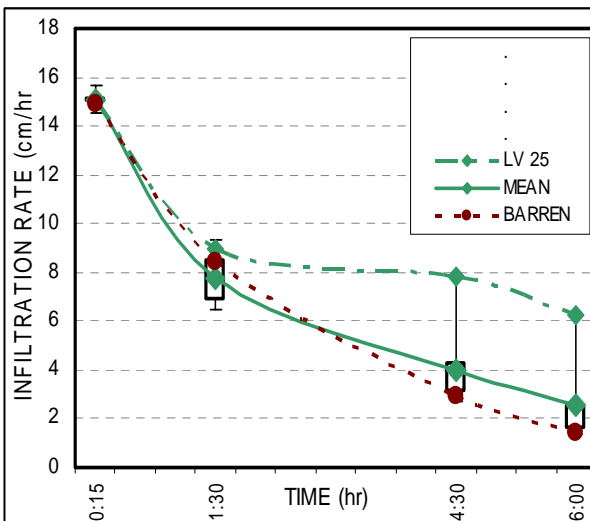


Figure 1: Infiltration, Loam Mesocosms

Data from the second run is not displayed, since most of the barren loam mesocosms discharged at rates below $1 \text{ cm}\cdot\text{h}^{-1}$ by then.

Figure 2 displays the second run outflow hydrographs from the vegetated loam mesocosms. The peak percolation rate of $2.8 \text{ cm}\cdot\text{hr}^{-1}$ closely corresponds to the stabilized infiltration rate. There was a decline in percolation rates from the first run to the second run.

Figure 1 displays the first run infiltration hydrograph for the loam mesocosms. The initial rate of $15 \text{ cm}\cdot\text{h}^{-1}$ is some 6 times higher than the stabilized range of $2.5 \text{ cm}\cdot\text{h}^{-1}$. The volume under the curve above $2.5 \text{ cm}\cdot\text{hr}^{-1}$ suggests an average infiltration rate of some $6 \text{ cm}\cdot\text{h}^{-1}$ for 6 h, or an inflow volume of 36 cm (90 L). This average rate is substantially lower than the free discharge rates observed in the leaching experiments. A residual volume of 10 to 17 cm (25 to 45 L) remained as surface ponding in the mesocosms, which eventually percolated through the media. There was no appreciable effect of vegetation upon infiltration rates, except in the case of LV 25, which had a much higher infiltration rate.

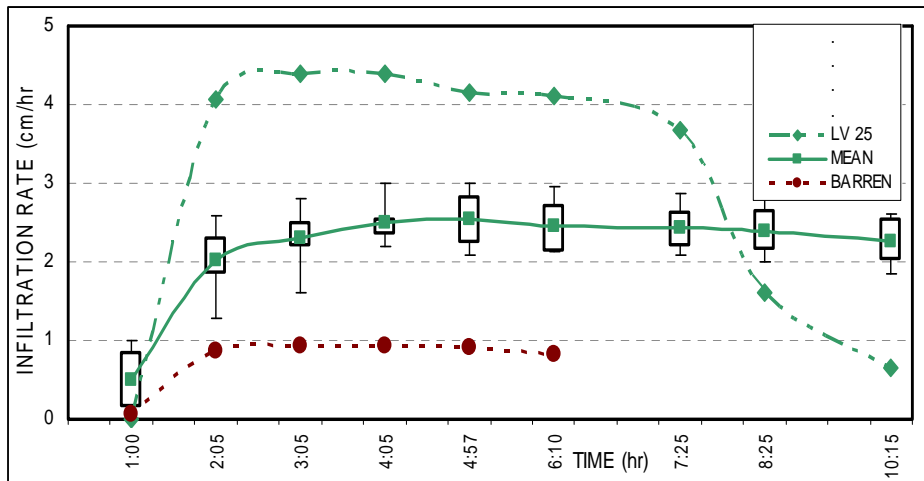


Figure 2: Outflow Hydrograph, Loam Mesocosms

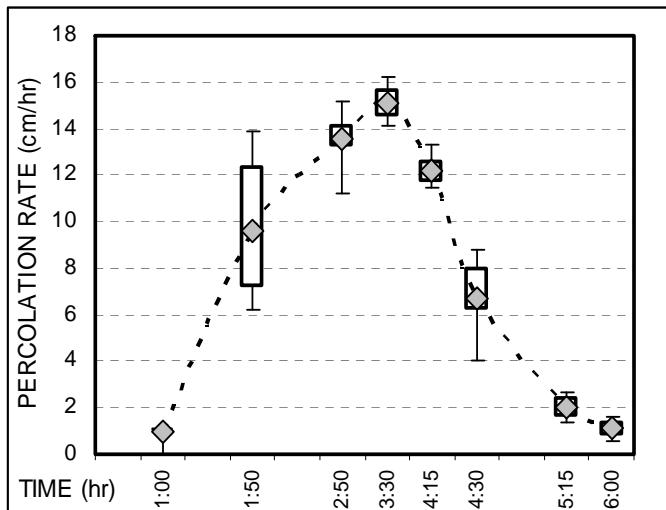


Figure 3: Outflow Hydrograph, Sand Mesocosms

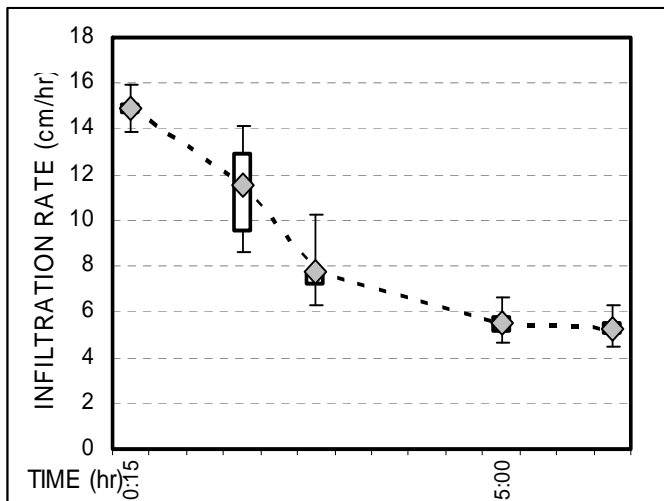


Figure 4: Infiltration, Restricted Sand Mesocosms

These declines in the infiltration and percolation rates suggest that the underdrain gravel became clogged by migration of the fines in the loam, restricting its effective discharge rate. Characteristics of such constriction are reflected in a linear decline in percolation rates for a period of 28 hours in the recession limb of the hydrographs of all but the LV 25 vegetated mesocosm. This resulted in an average retention time in the range of 10 hours. Note the low percolation rate from the few barren loams that still percolated, shown with the dotted line. Clogging eventually obstructed the rest of the barren loam mesocosms, as the coarse screen proved ineffective in preventing the migration of fines into the gravel underdrain layer under the hydraulic loads of this experiment. An exception was the LV 25 mesocosm shown with the dot-dashed line, which remained unobstructed, and discharged most of its volume within 8 hours, resulting in an average retention time of 4 hours.

Compared to the loam mesocosms, the outflow hydrograph from the first run of the sand mesocosms is much faster, as displayed

in Figure 3. Note how the peak percolation rate of 15 cm-h^{-1} approaches the peak inflow rate. Even though there was appreciable flow after 2 hours, it still took 3.5 hours for flows to peak, after which drainage was very rapid, with minimal outflow after 5 hours. This resulted in an average retention time of roughly 1.5 hours. This is equivalent to a percolation rate through the sand of 60 cm-h^{-1} passing through 85 cm of media..

In the second run of the sand mesocosms, the outlets were constricted with valves so as to provide an average flow rate of 5 cm-h^{-1} . Figure 4 displays the resulting effect upon the infiltration hydrographs. In this case, ponding was observed at the surface within 15 minutes, long before the media was saturated. However, the infiltration rate remained quite high over the first 1.5 hours, exceeding 12 cm-h^{-1} , then declining much more rapidly in the next hour as the media became saturated. A similar response to outlet constriction was observed during the leaching experiments in June, where initial runs with the outlets closed resulted in an average infiltration rate of 8.0 cm-h^{-1} . Opening up the outlets increased the effective infiltration rate to 11.9 cm-h^{-1} , nearly a 50% increase.

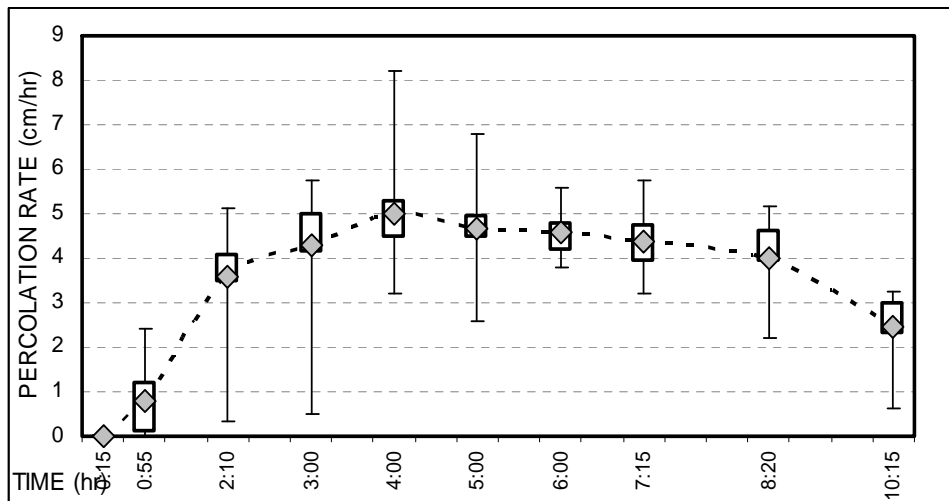


Figure 5: Outflow Hydrograph, Restricted Sand Mesocosms

Figure 5 displays the resulting outflow hydrograph, where it can be seen that the retention time in the sand media is at least 4 hours. This reflects the percolation rate of 5.0 cm-h^{-1} (or 20.0 cm-h^{-1} through the 85cm of media). The lower error bars in the earlier intervals reflect outlets that were too tight, which were then loosened in the next two hours to make up the missing volume, as reflected in the subsequent higher error bars. Comparison with Figure 2 shows that this response closely mimics the longer retention time for the LV 25 mesocosm.

DISCUSSION

A key factor in the operation of bioretention systems is the infiltration rate into the system, as it is this rate that establishes the resulting volume of runoff that can be treated from a given area at a given surcharge depth. Systems that infiltrate faster will treat more runoff than systems with lesser rates. Since infiltration rates vary over time as a function of moisture status and head, this aspect of bioretention systems needs to be better understood. Figure 1 documents how the majority of the infiltrated volume infiltrates at rates higher than the stabilized range of 2.5 cm-h^{-1} .

The infiltration response of the loam mesocosms in Figure 1 displays the characteristic decline in infiltration rates as a function of soil saturation, as expressed in both the Green-Ampt and Horton's equations. Soil infiltration can be described by Horton's formula as follows (Bedient and Huber, 1988):

$$f(t) = f_c + (f_o - f_c)e^{-kt} \quad (1),$$

where $f(t)$ is infiltration rate at time t , f_c is final infiltration rate, f_o is initial infiltration rate, k is an empirical coefficient, and t is time in hours since rain begins. This expression means that infiltration is most rapid at the beginning, and decreases to f_c as t increases. The initial infiltration rate is higher due to the capillary suction at the wetting front as water is "pulled" into the soil. Infiltration can also be described by the Green-Ampt equation as follows:

$$f(t) = K_{sat} \frac{F(t) + S_{av} M_d}{F(t)} \quad (2),$$

where K_{sat} is saturated hydraulic conductivity, $F(t)$ is volume infiltrated at time t , S_{av} is the average capillary suction head at the wetting front, and M_d is available water storage at surface saturation. This term is defined as soil porosity n , less is initial soil moisture content θ_i , which would usually be a value intermediate between saturated and completely dry conditions.

In the relatively uniform moisture regime at the wetting front, S_{av} remains constant as follows:

$$S_{av} \cong -\psi_0 / 2, \quad (3),$$

where ψ_0 is the matric potential at the wetting front. Matric potential is highest when the soils are dry at the beginning of the event, declining to 0 under saturated conditions when the wetting front meets the water table. In the moist conditions typically found in the vadose zone, ψ_0 also would have a value intermediate between completely wet or dry conditions.

$F(t)$ can be defined as a function of depth of the wetting front $L(t)$ as follows:

$$F(t) = L(t) \times M_d \quad (4)$$

Substituting (4) into (2):

$$f(t) = K_{sat} \frac{L(t) + S_{av}}{L(t)} \quad (5)$$

To apply the Horton formula, it is necessary estimate the value of three parameters, f_o , f_c , and k . On the other hand, since n and θ_i are easily quantified, only two parameters are needed for the Green-Ampt equation: K_{sat} and ψ_0 , which are analogous to f_c and f_o , respectively. As such, equation (2) does not depend upon the empirical constant k , which is difficult to properly quantify. Instead, $f(t)$ is now becomes a function of $L(t)$, which can be readily computed. To account for the effect of pressure head created by surface ponding within the bioretention systems, groundwater flow at time t is expressed by Darcy's Law:

$$v(t) = K_{sat} \frac{H(t)}{L(t)} \quad (6)$$

where $v(t)$ is Darcy's velocity (analogous to infiltration rate from the surface pond), $H(t)$ is the head, and $L(t)$ is the distance between measurements. Note that Darcy's law has the same form as the Green-Ampt equation. Combining the analogous terms in Darcy's Law with the Green-Ampt equation, the effective infiltration rate under detention conditions is:

$$f(t) = K_{sat} \frac{H(t) + L(t) + S_{av}}{L(t)} \quad (7)$$

$L(t)$ is determined by (4), knowing the value of $F(t)$. $H(t)$ is simultaneously determined by the routing of the hydrograph into the pools created by bioretention systems, while routing infiltration losses as a function of $f(t)$ and the wetted area, and routing outflows through the check dams at each time step. These values for $L(t)$ and $H(t)$ are then substituted into (7) at each time step to determine $f(t)$ for the following time step.

This equation is an approach to projecting infiltration rates in isotropic media that is responsive to the effects of head and saturations status. Note that the higher infiltration rates estimated by this equation accounts seem to account for well over half the total infiltrated volume (Figure 1), suggesting that the typical design approach of using a uniform saturated infiltration rate could substantially understate infiltration performance, and the resulting interception volume.

In this manner, the infiltration parameters dynamically reflect the hydraulic response of the bioretention system to its inflow hydrograph, pool routing and physical design parameters. This is a far more realistic approach than "estimating" the k term in the Horton formula, which bears no explicit relationship to either H or L .

Further confounding the analysis, there seems to be a rapid "back-pressure" effect when a constricted orifice is used, as shown in Figure 3. In contrast to the lack of ponding when unobstructed, the effect of the outlet constriction occurs almost immediately, well before the media can be saturated. There then follows a steady initial decline in infiltration rates. This decline then accelerates as the media saturates, and then stabilizes at the orifice controlled rate of 5 cm-hr⁻¹. This discontinuous three-phase response suggests a complex interaction between the outlet orifice dynamics and the storage available in the media, such that infiltration into the media is affected by the outflow hydraulics, even under unsaturated conditions. This effect is also likely to occur with the presence of a constricting layer, as proposed by Hsieh and Davis (2005).

It is possible to estimate K_{sat} and ψ_0 as a function of soils series, as is typically done in continuous simulation models. There are many published relationships of K_{sat} and ψ_0 to soil types; however, since soil properties can vary substantially within a soil series, there often can be unacceptable error using this method to determine the value of these parameters, particularly in the case of K_{sat} . For this reason, field measurements are preferable.

On the other hand, the suitable value of K_{sat} is difficult to measure in the field. To properly evaluate the results of infiltrometer tests, the effect of capillary suction must be addressed. Capillary suction can be expressed as the water-entry value h_{we} , (a term analogous to f_o or ψ_0). Values range from -5 for sands to below -100 for clays. This effect increases tested infiltration rates over the final equilibrium rates depending upon the ratio of h_{we} and

diameter (in cm) of the testing apparatus. When the ratio is below -1, tested rates are close to equilibrium rates; as the ratio approaches -6, the tested rates can exceed the final equilibrium rates by a factor of roughly 12 (Bouwer *et al*, 1999). Therefore, infiltrometer tests typically overstate the actual values of K_{sat} in clayey soils, unless methods are taken to incorporate the depth of the wetting front $L(t)$ in adjusting the results (see Bouwer *et al*, 1999).

As an alternative, Massman and Butchart (2000) investigated saturated hydraulic conductivity as a function of soil textural properties, using the pedotransfer function (PDF) equation of Rawls and Brakensiek (1985), in which K_{sat} is determined according to the percent clay, sand, and porosity. Results from this method generated K_{sat} values that corresponded to observations of infiltration rates using infiltrometer tests and pilot field tests (Massman and Butchart, 2000), suggesting that it is a reasonably conservative method.

Recently, Saxton and Rawls (2006) have derived a PDF that includes terms for silt, bulk density, salinity, and organic matter (OM). This series of 24 different equations has been used to project K_{sat} , ψ_0 , and available water capacity (AWC) parameters. This PDF was found to match a great proportion of field observations (R^2 ranged from 58 to 94), thus providing considerable utility to this approach. It has been incorporated into the SPAW model (Saxton, 2005). It has the advantage of addressing the effects of compaction and organic matter, which can substantially affect soil properties. Data on the soils textural class can be initially estimated from soil surveys. For more accurate estimates, field samples at each BMP site should be analyzed to get the proper values for soil texture, OM and bulk density parameters.

K_{sat} is greatly decreased by compaction (OCSCD *et al*, 2001; Pitt, 2003). This is explicitly addressed in the PDF function of Saxton and Rawls (2006) as the bulk density parameter. Furthermore, bioretention systems are more complex due to the presence of vegetation, as well as the development of soil aggregates. It is only recently that the literature has begun to address how media parameters such as texture and organic matter interact with soil structure and vegetation to affect the matrix infiltration and percolation response (e.g., Sharma *et al*, 2006). In addition to matrix properties, infiltration is also strongly affected by the presence of macropores. Plants roots promote the formation of macropores, which can lead to substantial increases in effective infiltration rates. Our observations show that breakthrough in sandy media seem to occur much faster than K_{sat} , even adjusted for the increased rates found under wetting conditions, thus implying macropore flow.

There are many processes associated with vegetation that are remarkably effective in restoring and/or enhancing infiltration rates. Vegetation roots penetrate confining layers, opening up soil structure (Gilker *et al*, 2002). Root turnover promotes the formation of macropores. Field infiltration rates in native grass hedges are much higher than found in adjacent croplands (Rachman *et al*, 2004; Blanco-Canqui *et al*, 2004a, 2004b; Seobi *et al*, 2005). Much of this increase is attributed to the formation of macropores (Rachman *et al*, 2004, Udawatta *et al*, 2006). The beneficial effects of native plants on infiltration rates persist even in depositional situations where sediments accumulate (Rachman *et al*, 2004). In bioretention columns, Culbertson and Hutchinson (2004) have documented that switchgrass (*Panicum virgatum*.) increased infiltration rates in bare soils from 0.5 cm-h^{-1} to 128 cm-h^{-1} , an increase well over two orders of magnitude. These authors noted that switchgrass was well adapted to the hydraulic regime, and the dense root system reached 90cm depth after a single

growing season. In contrast, facultative shrubs such as Yellow-twig dogwood (*Cornus stolonifera*) died under the high hydraulic loads.

In light of these findings, the response displayed in Figure 2 is quite characteristic, with plants either preventing clogging, or still performing much better than barren mesocosms when clogged. However, even though plants seemed to improve the percolation response, there was no appreciable effect upon infiltration rates. It seems likely that the lack of any response due to vegetation is due to the clogging, creating the “back-pressure” effect on infiltration discussed above.

It is now recognized vegetative factors can alter the underlying soil properties by up to several orders of magnitude, so they often play a much more important role in determining surface infiltration rates than the underlying soil texture composition. This discussion highlights the importance of plants in media infiltration response. Achieving a better understanding of the complex interactions involved between plants and the media will enable the science to be optimally combined with the engineering design to improve stormwater bioretention technologies.

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