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Pollutant Deposition in Stormwater Management Green Infrastructure

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ABSTRACT

Green infrastructure (G-I) systems are used to mitigate and manage non-point source pollutants in stormwater and typically consist of a series of gently sloped and vegetated areas to provide friction and infiltration, reducing runoff flow rate and volume. The reduction of flow rate and volume provides time for pollutants to deposit, preventing contaminant transport to streams or other water bodies. For this study suspended and dissolved solids deposition in an urban G-I system near Atlanta, Georgia, U.S. was observed to analyze the interaction of the runoff and its constituents to estimate the G-I system's efficiency. Deposition of suspended solids was observed by collecting soil samples at varying depths and lengths of a vegetative slope. The top 2.5 cm was used to analyze deposited sediments, while the deeper collection was analyzed for site characterization. Infiltration characteristics were determined using a Modified Philip Dunne Infiltrometer. Sensitivity analyses determined the flow rate for varying slopes and vegetation, infiltration capabilities in the first hour of a storm for varying soil types, and sedimentation of varying pollutant types for different flow rates and lengths of flow paths. Overall, the infiltration capabilities of the observed G-I system were 32.6% of runoff infiltrated in the first five minutes of experiencing runoff, which dropped to 5.6% after the first hour. The G-I system also showed to remove nearly 97% of the sediments observed from the soil samples. The sensitivity analyses help predict the efficiency of this GI system but are adaptable to suit G-I systems with highly variable properties.

Keywords: Green Infrastructure, sedimentation, pollutant transport, stormwater runoff

1 INTRODUCTION

Solid pollutants in stormwater can be classified as either suspended or dissolved, and they are typically collected and transported as nonpoint pollutants by runoff. Dissolved solids either remain dissolved in the runoff or bind to suspended solids through flocculation (Munoz-Carpena et al., 1999). Suspended and dissolved solids that have bound in the runoff get deposited through sedimentation, and unbound dissolved solids are also deposited via dispersion as runoff infiltrates the ground (Deletic, 2005). In urban areas, pollutant loads are heightened due to higher population, more construction activities, and greater wear from traffic. Stormwater runoff also flows faster and is more abundant due to the impervious surfaces (roads, roofs, cleared and compacted land, sidewalks, etc.).

Stormwater management plans have been established to limit or eliminate the harmful results of pollutant transport from runoff and typically consist of extensive underground retention and detention systems. As storm intensities increase due to changes in the climate these systems have proven to be inadequate (Berland et al., 2017). To provide relief to current stormwater management infrastructure and to prevent other adversities caused by stormwater runoff, the implementation of green infrastructure (G-I) systems has become widely considered. The design of G-I systems typically consists of specific topography, utilizes soil or other infiltration-promoting media, and encourages native-plant growth with three goals in mind: minimize the flow rate of runoff, maximize pollutant filtration, and increase watershed capacity potential. To optimize G-I systems and understand the pollutant filtration capabilities of vegetation it is essential to interpret how and where pollutants are deposited. This study includes observations of a G-I system consisting of roadside vegetative slopes to observe where pollutants are being deposited and show how efficiency can be modeled to improve design efforts.

2 LITERATURE REVIEW

There have been many studies done that monitor pollutant types, loads, and transport in stormwater (Barrett et al., 2004; Deletic & Fletcher, 2006; Li & Davis, 2014). The most common method is to collect stormwater runoff samples at inlet and outlet locations and perform mass balance to observe the efficiency of various stormwater management practices (Strecker et al., 2001). Barrett et al. (2004) showed that most suspended solids can be removed in just the first few feet of a vegetative slope. In addition, Barrett observed that a satisfactory reduction of heavy metals in stormwater best management practices (>76%) could be found in the first 12 feet of a vegetative slope. The rate of reduction slowed however with longer lengths; a 99% removal was not achieved until slopes stretched over 40 feet. From Deletic & Fletcher (2006), it was found that most suspended solids settled in the first part of a series of vegetative slopes, but that most solids below 5.8 μm in diameter were not removed at all. Dissolved nutrients (total phosphorous and nitrogen) were shown to decrease over the length of the slopes, but that emphasis should be focused on removing finer-grain suspended solids due to the high nutrient-sorption capabilities of the soil. Li & Davis (2014) observed nitrogen removal in a bioretention cell which showed poor removal of total nitrogen with composition primarily being dissolved organic nitrogen and nitrate suggesting that denitrification-promoting processes should be considered for design.

Previous studies have been done on modeling the removal of suspended solids in roadside vegetated structures. Deletic (2001 & 2005) developed different models that predict trapping efficiency in roadside slopes, solids buildup on impervious surfaces, and solids wash from impervious surfaces using Stoke's Law and a modified Kentucky Model. The work of Munoz-Carpena et al. (1999) focused primarily on the transport of solids and the effects that a buildup of suspended solids (or wedge) would have on the solids' transport. The work relies on Manning's kinematic wave equation and Einstein's total transport function to model the settlement of solids. Winston et al. (2017) modeled suspended solids removal in various vegetative slopes using the rationale method, Manning's equation, and particle settling equations developed by Deletic (2005)

In addition to understanding spatial pollutant deposition, it is critical to be able to interpret time-dependent pollutant loading. This is what has been referred to as the first flush phenomenon (Deletic, 1998; Kang et al., 2008; Maniquiz-Redillas et al., 2022). The first flush phenomenon is described as the runoff's washing effect on impervious surfaces, which causes the initial discharges to have a greater concentration of pollutants than discharges occurring later throughout the storm (Kang et al., 2008). Although there has been disagreement in the actual interpretation of the first flush, pollutant load discharging directly from an impervious surface will certainly be washed by runoff. This is shown in Kang's research which describes that in watersheds smaller than 250 acres with 80% impervious cover pollutant peaks would occur before peak flow. In the GA Blue Book (2016) the first flush is represented by the water quality treatment volume which is considered the first 3 cm of precipitation.

The research done for this paper includes experimentation results interpreting pollutant size and infiltration characteristics of a roadside vegetative slope, as well as modeling to determine where and when pollutants will be deposited in the slope. In addition, this study observes the collective interactions that lead to pollutant deposition and their correlation with each other to provide efficiency estimations of G-I systems.

3 EXPERIMENTATION METHODS

The focus of this study was to observe and model pollutant deposition in vegetative slopes used for stormwater management green infrastructure. To understand the size of incoming suspended solids, small samples of soil were collected from a roadside vegetative slope in Georgia, United States, using a 21-inch soil sampler probe. Soil samples were collected at every 2.5 cm of depth up to 10 cm and every meter along the slope, the samples are shown in Figure 1. In addition, Shelby tube samples with a diameter and height of 7 cm and 15 cm respectively were collected.

Figure 1. *Soil Samples were collected from the slope at varying length and depth intervals.*

Organic (plant) matter was removed from the samples collected at varying depths throughout the slope through oxidation using 30% hydrogen peroxide and by methods used by (Schumacher, 2002). The soil was subjected to mixing with hydrogen peroxide and periodically dried at 105° C to expedite the oxidation. Measurement of total organics was not performed for the scope of this study.

Once organics were removed to the point where they were no longer visible, grain size analysis was performed for each 2.5 cm of soil collected, and a total of 32 samples were analyzed. The procedure described in ASTM D6913 (2017) was followed for sieve analysis of the coarse grain material. To accommodate the modest sample sizes (average mass of 22.6 g), 7.5 cm diameter sieves were used with a miniature vibratory table frame. The fine-grain portion of the samples passing the No. 200 (75 µm) sieve was analyzed using a Mastersizer 3000 Particle Size Analyzer (PSA).

The samples collected via Shelby tube were used to determine the specific gravity of sediment that is deposited in the roadside vegetated slope. Specific gravity was determined via a water pycnometer and vacuum system following the procedure described in ASTM D854 (2014). Fall cone tests were also performed on the Shelby tube samples to determine soil indices properties to characterize the soil type.

In addition to looking at suspended solids, dissolved solids were also considered. Dissolved solids settle in vegetative slopes through flocculation (via attachment to suspended materials that settle) or dispersion (via infiltrating runoff). Therefore, the infiltration into vegetative slopes was considered to better understand dissolved solids removal. Infiltration characteristics were determined using a modified Philip Dunne Infiltrometer (MPD-I). To use the MPD-I, initial in-situ moisture content was collected before running the test using a Field Scout TDR 150 Soil Moisture Meter. The MPD-I device, shown in Figure 2. MPD-I device: (A) SOLIDWORKS design drawing; (B) final construction of device from Georgia Institute of Technology's Civil Engineering Machine Shop; (C) device in use., was then driven two inches into the soil and filled with approximately four liters of water. Falling head measurements were taken at varying time intervals until all the water had drained into the soil, this took an hour and 15 minutes. The test concluded with a final in-situ moisture content to obtain the soil's effective moisture content, which is the difference in moisture content before and after wetting is completed.

Site characteristics were also considered for the vegetated slope that was observed. Total surveying stations were used to determine topographic and watershed data of the area. The grade and length of the slope were measured. The watershed components were determined by the width, grade, and length of the road that the slope lies adjacent to.

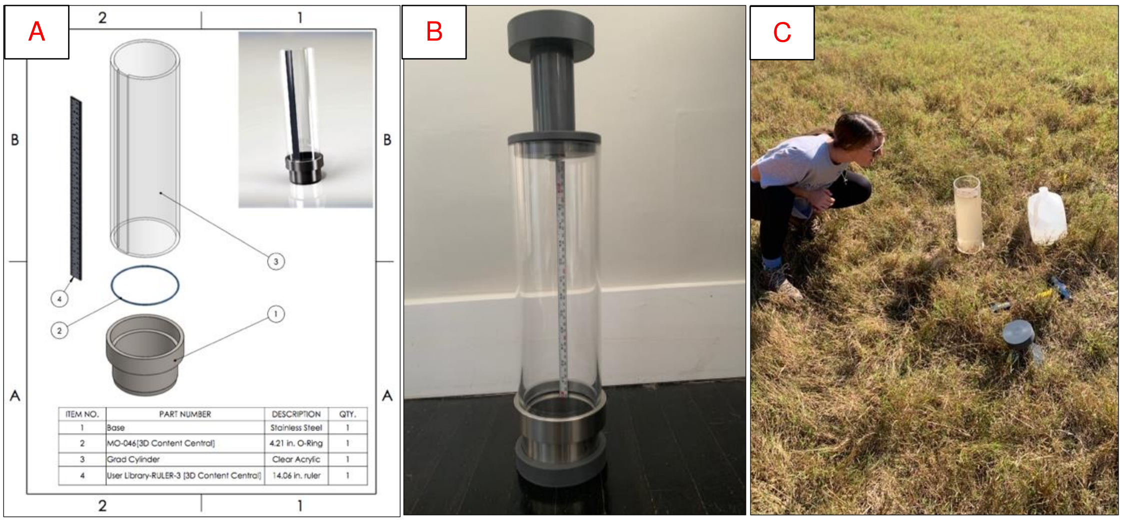

Figure 2. *MPD-I device: (A) SOLIDWORKS design drawing; (B) final construction of device from Georgia Institute of Technology's Civil Engineering Machine Shop; (C) device in use.*

4 MODELING

To estimate suspended and dissolved solids deposition in G-I systems, calculations need to consider two-dimensional movement, laterally over the slope and vertically toward and into the ground. Both movements must take flow depth (y_p) into consideration which can be evaluated using equation (1) and is dependent on the travel time it takes for the runoff to flow through the G-I system (T_c), the flow rate entering the G-I system (Q_i), the area of the G-I system (A_{GI}), and the rainfall intensity (i).

$$y_p = 3600 * T_c * \frac{Q_i}{A_{GI}} + T_c * i \quad (1)$$

The travel time is estimated using a kinematic wave equation (2) that is dependent on precipitation (P), friction from the vegetation or surface cover (n), G-I system slope (S), and G-I system length (L). The equation provides the travel time (T_c), in hours, that it takes for the runoff to flow through the G-I system. A unit converter is included to switch between S.I. ($k = 1\, {m^{1/3}}/{s}$) or U.S. units ($k = 1.49\, {ft^{1/3}}/{s}$).

$$T_c = L \Big/ \left(3600 * \left(\frac{k}{n} * P^{\frac{2}{3}} * \sqrt{S}\right)\right) \quad (2)$$

The inflow rate (Q_i) can be evaluated using the Rational Method, equation (3). This method is dependent on the rainfall intensity (i), the inflow surface (C), and the area of the watershed entering the G-I system (A_w). This method is most suitable for highly impervious surfaces and small drainage areas; roadside vegetated slopes fall into this category (GA Blue Book, 2016).

$$Q_i = CiA_w \quad (3)$$

Vertical movement of runoff and its constituents can be predicted by evaluating the infiltration rate into the ground and by evaluating the settling velocity of varying particle types and sizes. The infiltration rate was determined using a loss of precipitation-infiltration method known as the Green-Ampts Theory (Green & Ampt, 1911). The Green-Ampts theory provides an equation (4) that is derived from Darcy's equation and is dependent on hydraulic conductivity (K), effective moisture content ($\Delta\theta$), matric suction at the wetted front (ψ), and the cumulative infiltration (F).

$$f(t) = K * \left(1 + \frac{\Delta\theta\psi}{F(t)}\right) \quad (4)$$

Integrating the infiltration rate with the accumulated time provides an estimation of the loss of precipitation, and therefore an estimation of pollutants deposited through dispersion. If the pollutant load is known or predicted, then this value would decrease by the amount of runoff that has infiltrated. In addition, a new flow depth, and therefore a new flow rate, can be calculated by subtracting the amount infiltrated by the original flow depth.

Suspended solids and any attached dissolved solids will also deposit due to gravitational forces. Gravitational forces will cause suspended solids to settle at a velocity that is dependent on the pollutant size (D) and density (ρ_p), runoff fluid characteristics viscosity (μ) and density (ρ_f), and the acceleration of gravity (g). Stoke's Law can be rewritten to provide equation (5) and used to determine the smallest particle radius (D_{min}) that would be removed given the evaluated flow depth and travel time through the considered vegetated slope. The flow depth divided by the travel time is considered the velocity to which a particle would need to settle.

$$D_{min} = 2 * \left[\frac{y_p}{T_c} * \frac{9}{2*g} * \frac{\mu}{(\rho_p - \rho_f)}\right]^{1/2} \quad (5)$$

5 RESULTS AND DISCUSSION

Particle size distributions were created for all 32 samples; however, it was hard to depict a pattern from the abundant number of samples. Instead, the samples were grouped by their location along the slope to detect differences in the grain sizes. Figure 3 shows how the slope was sectioned off, the inflow section included the first three meters of the slope closest to the road, the midflow section consisted of the next three meters, and the final three meters were considered for the outflow.

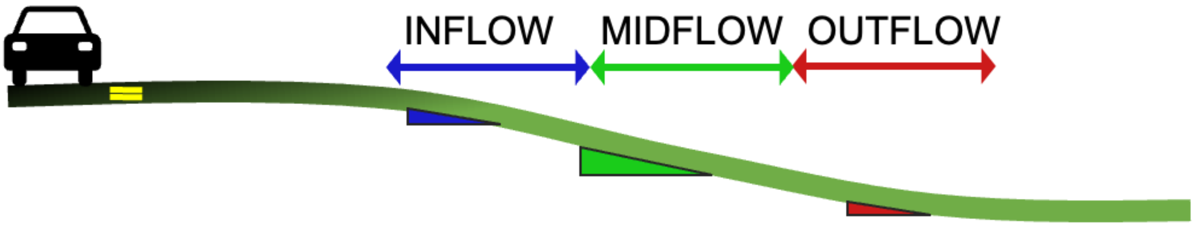

Figure 3. *Side view of slope and how the field samples were combined for average grain size distributions.*

The grain size distributions were averaged for each section and are shown in Figure 4. The range of grain sizes in each section is highlighted in the top figure and then individualized in the bottom figures. From this, the grain size is smallest at the midflow section, followed by the outflow, and then largest at the inflow; this is proven further by observing the average 80% finer grain diameter (D_{80}), 50% finer grain diameter (D_{50}), and the 10% finer grain diameter (D_{10}) values specified in Figure 4. The grain sizes range the most in the midflow section with minimum values similar to the inflow section, especially for coarser materials. The outflow had the smallest range of particle sizes.

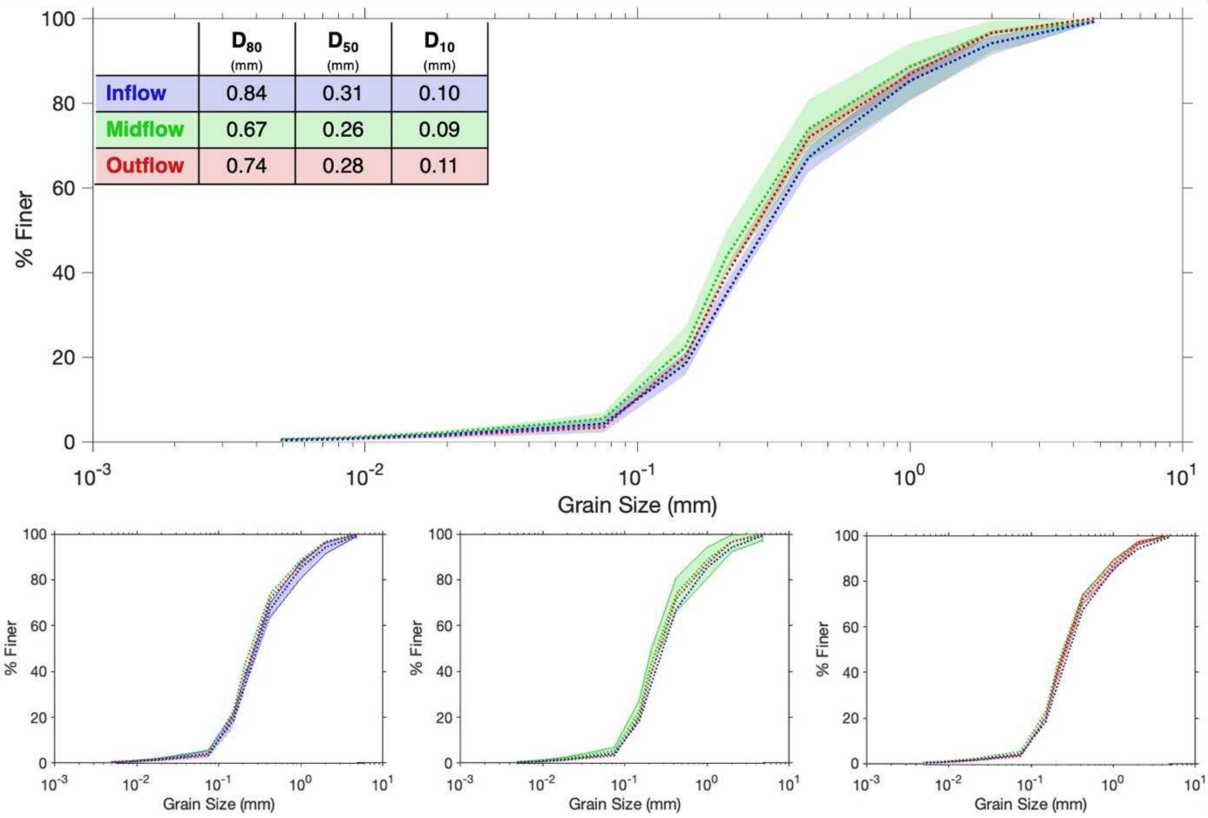

Figure 4. *The range of grain sizes and their distributions for the top inch of soil is displayed for the inflow (blue), midflow (green), and outflow (red).*

The results of all soil characterization experiments are presented in Table 1. The MPD-I test was used to estimate the hydraulic conductivity (k) and the matric suction at the wetted front (ψ). Results from sieve analysis, PSA, and Fall Cone tests were used to characterize the soil using the Unified Soil Classification System (USCS). The Fall Cone test provided estimations of liquid limit (LL), plastic limit (PL), and plasticity index (PI).

Table 1. *Measured soil and site characteristics*

Test	Symbol	Results	Units
Soil Characteristics			
Effective Moisture Content	$\Delta\theta$	31	%
MPD-I	K ψ	3.4E-04 144.0	cm/s cm
Sieve Analysis **Particle Size Analyzer**	Soil Type	SM (silty sand)	--
Fall Cone Test	LL PL PI	37.3 26.7 10.6	% % %
Site Characteristics			
Specific Gravity	G_s	2.607	--
Slope Grade (V/H)	S	18	%
Slope Length	L	5.6	m
Slope Area	A_{GIS}	117	m^2
Watershed	A_w	230	m^2

The most effective parameter in the removal of pollutants was found to be the runoff flow rate. Sensitivity analyses were done on the experimental and modeling results to show how flow rate affects pollutant transport, and therefore G-I system efficiency. The design variables that dominate flow rate include slope and vegetation density (i.e., friction caused by vegetation). Figure 5 shows how both slope and vegetation affect the flow rate for a storm that led to a flow depth of 3 cm. The figure provides varying slopes and roughness coefficients (n), it also provides the estimated peak flow rate of the observed G-I system to be 0.17 m/s, based on the site properties. This analysis provides an understanding of how slope and vegetation type and coverage work together to slow the flow of runoff. With information about the land and climate, the G-I system flow rate can be predicted and used to estimate pollutant removal efficiencies.

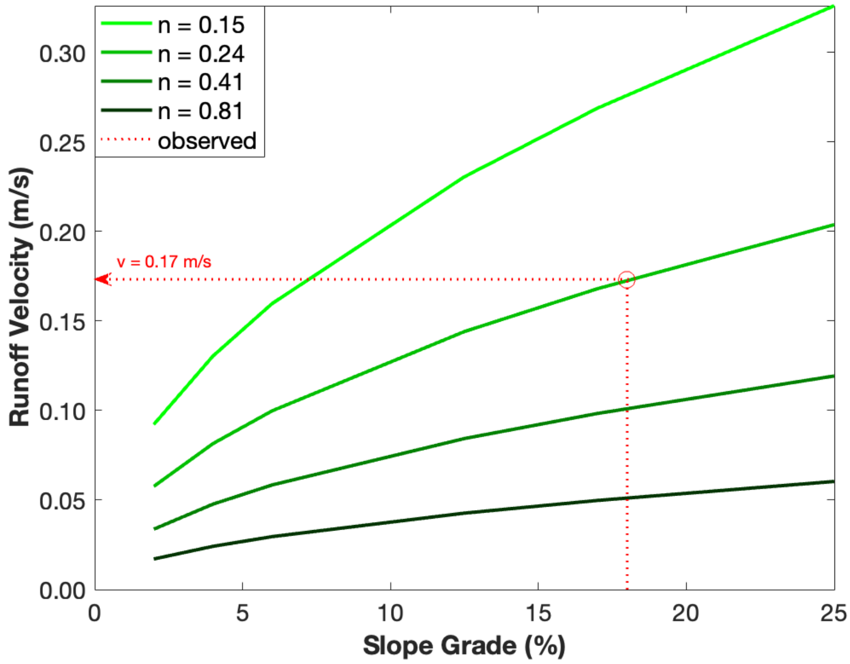

Figure 5. *Runoff velocity provided for varying slope percentages (vertical/horizontal) and vegetation densities (n).*

The peak flow rate affects soil deposition because the slower the flow rate the more time pollutants have for deposition and for stormwater to infiltrate into the pervious surface of a G-I system. Figure 6 provides an analysis of infiltration in varying soil types for the initial portion of a storm known as the first flush. The first flush is considered the most polluted runoff due to the washing effect of stormwater and according to an analysis of over 403 stormwater studies the first flush ranges from the first five minutes of runoff formation to the first hour (Kang et al., 2008). The soil types are differentiated by hydraulic conductivity, matric suction, and porosity. The amount of runoff infiltrated in the observed G-I system was estimated to be 32.4% and 5.6% for the first five minutes and one hour respectively and is depicted in Figure 6. The proportion infiltrated is much higher at the beginning of the storm because the soil is the most unsaturated and the accumulated runoff will be lower than after an hour. Rainfall depth, duration, and intensity are the most dependent values in the occurrence of first flush washing and infiltration; however, studies have been contradictory as to which factor abrades the most pollutants (Perera et al., 2019; Wong & Kerkez, 2016).

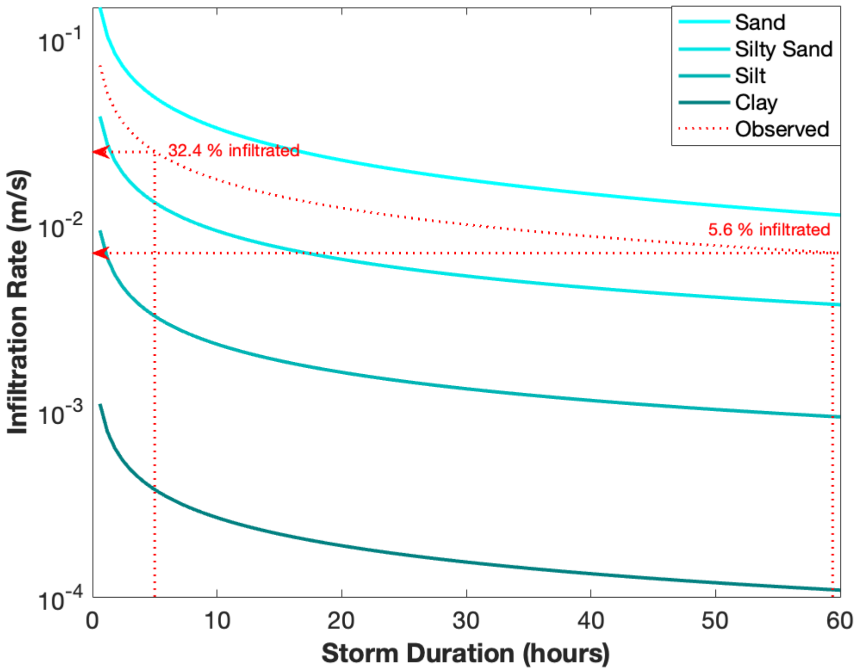

Figure 6. *The infiltration rate in varying soils provided for the first hour of a storm to consider first flush filtration.*

Suspended solids deposition was analyzed based on the overland flow rate and settling velocity of pollutants. The pollutants will settle at different rates depending on their size and density, as well as the availability of time to settle. Larger particles of the same density will settle out sooner due to their larger mass, therefore the particle with the smallest diameter that settles out was observed with the assumption that all larger particles would settle sooner. Suspended solids settlement was analyzed in two ways, by varying common pollutant densities, given a constant length of the flow path (5.6 m based on the observed G-I system), and then by varying flow paths and just one pollutant density (2.607 g/cm^3 based on the sediment from the observed G-I system), shown in Figure 7, left and right respectively. Based on the observed location and the flow rate determined from Figure 5, the observed minimum diameter was found to be 0.032 mm. In reference to Figure 4, this equates to nearly 97% of sediments and any attached pollutants being removed. Although the G-I system is efficiently removing the proportion of sediment sizes entering the system, it is especially important to target smaller particles because they are more likely to have other polluting particles sorbed to them due to their high surface area (Baum et al., 2021). This phenomenon has also raised concern about how efficiency is measured and therefore proportional efficiency is not always preferred (Kang et al., 2008).

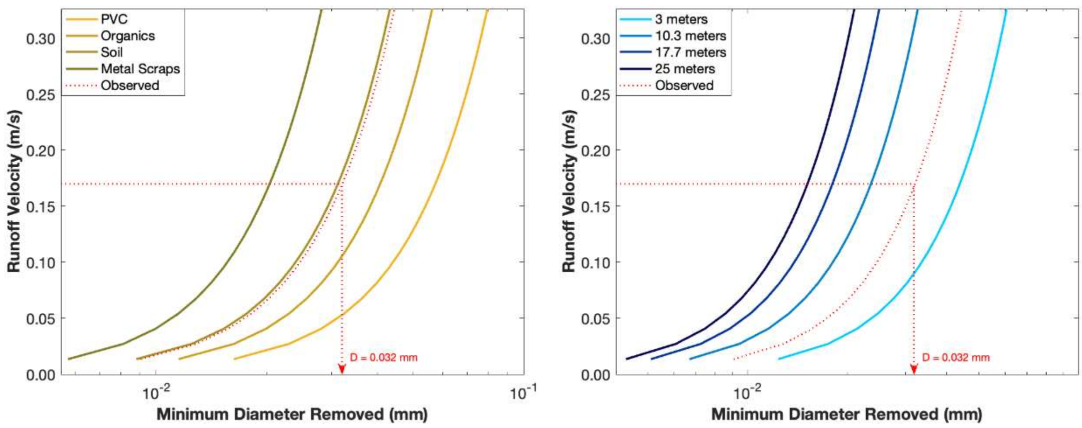

Figure 7. *The minimum diameter of pollutants removed due to particle deposition provided for varying particle densities given a constant 5.6 m slope (left) and for varying slope lengths given a constant 2.607 g/cm^3 particle density (right).*

6 CONCLUSION & FUTURE RESEARCH

The sensitivity analyses done for this study helped determine the interaction of flow rate, infiltration, and suspended solids deposition in a roadside G-I system consisting of a vegetated slope in Georgia, U.S. Flow rate, mostly controlled by the slope and vegetation friction has the most influence on suspended solid deposition because a slower flow rate will provide more time for deposition to occur; however, if the flow rate becomes too slow, the flow depth will increase requiring the pollutants to travel further to deposit. Infiltration aids in slowing the flow rate and decreasing the flow depth, therefore promoting infiltration is an important factor in the design and efficiency of G-I systems. In addition, infiltration benefits pollutant removal through dispersion and filtration effects.

Infiltration will be higher at the beginning of the storm due to the moisture state of the porous media it is flowing over, in this case for the observed G-I system, silty sand. It can be assumed that the infiltrated runoff is distributing dissolved and suspended solids on the ground surface through dispersion, therefore depositing an equal proportion of pollutants. In addition to infiltration being higher at the beginning of the storm, so will the pollutant load due to the first flush, or abrading, of pollutants that have been collected on the road. As the soil becomes more saturated infiltration will slow and pollutant load in the runoff will most likely decrease as well. For the observed G-I systems, the removal of suspended sediments was high and after comparing the grain size distributions with the minimum diameter removed, it was found that nearly 97% of sediments were removed.

To further analyze the interaction of runoff and its constituents in G-I systems it is important to look further into other pollutants such as heavy metals, nutrients, and micro- and nano-plastics. In the future analyzing the sorption of dissolved solids to the suspended solids in the runoff as well as to the vegetation and soil media installed in the G-I system should be looked at. In addition, it would be beneficial to observe the filtration capabilities of the G-I system's vegetation and potentially measure optimal plant species for filtration as well as flow rate reduction. Lastly, the adaptation of such models and analyses to other G-I systems that are more complicated in design and function than a roadside vegetated slope would assist in the design and implementation in urban areas.

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