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TEMPERATURE EFFECTS ON SHALLOW WATER INFILTRATION RATES IN AN UNDERGROUND ROCK BED BMP

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ABSTRACT Infiltration Best Management Practices (BMPs) are becoming more readily acceptable as a means of reducing post-development runoff volumes and peak flow rates to pre-construction levels, while simultaneously increasing recharge. Sizing BMPs to hold and store a predetermined volume of runoff, typically called the Water Quality Volume, has become a widely accepted practice. This method of sizing BMPs does not account for the infiltration that is occurring in the BMP during the storm event; which could result in significantly oversized BMPs. The objective of this study was to develop a methodology to simulate varying infiltration rates observed from a large scale rock infiltration basin BMP. The system consists of three infiltration beds filled with coarse aggregate, lined with geotextile filter fabric, overlain with pervious concrete and underlain by undisturbed silty sand. Recorded data indicates a wide variation of linear infiltration rates for smaller storm events. A model was developed using the Green-Ampt formula to illustrate the infiltration occurring in the basin for small storm events characterized by an accumulated depth of water of less than 10 cm. The effectiveness and accuracy of the model were determined by comparing the model outputs with observed bed water elevation data recorded from instrumentation on site. Results show that hydraulic conductivity is the most sensitive parameter, and that the storm event measured infiltration rate is substantially less than the measured saturated hydraulic conductivity of the soil. The governing factor affecting hydraulic conductivity and, subsequently, infiltration rate is water temperature.

Keywords: Drainage Modeling, Infiltration, Hydraulic Conductivity, Temperature effects, Best Management Practice, Stormwater Management, Pervious Pavements.

INTRODUCTION Urbanization has a significant effect on the quality and quantity of both the ground water sources and the surface water sources in the nearby environment. With increasing urbanization, there is a quantifiable decrease in area available to stormwater for infiltration. Instead of returning to the soil through infiltration, stormwater bypasses this critical step and alters the hydrologic cycle by flowing over impervious areas such as parking lots, rooftops, and roadways. This results in a drastic increase in direct runoff to nearby surface waters. These elevated volumes of runoff carry sediments, suspended and dissolved solids, metals, and other pollutants to the surface waters. Not only does this adversely affect the ecology and health of the local rivers and streams, but it also has a regional effect, with the potential to cause flooding, erosion, and sedimentation miles downstream from the source.

Best Management Practices (BMPs) are gaining popularity throughout the United States for their beneficial water quantity and quality characteristics. BMPs are designed to reduce volumes and peak flows from stormwater runoff leaving a site, as well as provide a means of "cleaning" the runoff of typical stormwater pollutants such as total suspended solids (TSS), metals, hydrocarbons, and nutrients. Stormwater Best Management Practices (BMPs) include the concept of source control which establishes a passive system that intercepts pollutants at the source and disposes of stormwater close to the point of the rainfall (Barbosa et al. 2001). Infiltrating stormwater locally is increasingly considered as a means of controlling urban stormwater runoff, thereby reducing runoff peaks and volumes, and returning the urban hydrologic cycle to a more natural state (Mikkelsen et al. 1996). These systems are an innovative way to minimize the adverse effects of urbanization by reducing or eliminating runoff from the site.

The design of infiltration BMPs, in particular, is highly dependent on site conditions, specifically site soils, which vary widely from region to region. Unlike detention basins, infiltration basins do not have widely accepted design standards and procedures (Akan 2002). The variables that present the most concern in the design process are the infiltration properties of the soils on site. Many times, designers size infiltration basins with sufficient volume to hold and store a specific amount of runoff volume from over the site's impervious area (typically, this volume is called the Water Quality Volume). This method of sizing BMPs does not account for the infiltration that is occurring in the BMP during the storm event; which could result in significantly oversized BMPs. Not only is the BMP oversized and overdesigned, but the cost of the BMP is heightened due to the increased excavation, soil removal, and aggregate costs associated with infiltration BMPs. Infiltration BMP's are becoming more readily acceptable as a means of reducing post-development runoff volumes and peak flow rates to pre-construction levels, while simultaneously increasing recharge of the groundwater table. However, the design, construction, and operation of infiltration basins to this point have not been standardized due to a lack of understanding of the infiltration processes that occur in these structures.

In order for BMP's to perform effectively they must be designed to maximize the infiltration rate of the stormwater entering the site. This paper describes a method used to analyze the infiltration characteristics of a rock bed infiltration BMP, as well as identify parameters that have the greatest effect on the rate of infiltration through the BMP.

SITE DESCRIPTION The infiltration basin BMP is located on the campus of Villanova University in southeastern Pennsylvania, approximately 32.2 kilometers west of Philadelphia, PA. Geologically, the site is situated on a mix of sand and silty sand, which has a specific yield of approximately 20%. The total drainage area for the BMP is 5,360 square meters, 62% of which (3,330 sq. m.) is impervious due to surrounding rooftops, concrete, and asphalt walkways.

The BMP consists of three large rock infiltration beds arranged in a cascading structure down the center of the site (Figure 1). The research in this report centers on the lower infiltration basin, as it is through this basin that all excess stormwater overflows from the site and is the location of all site instrumentation. As shown in Figure 1, the beds are staggered at different depths due to the natural slope of the site. The beds are separated by earthen berms, which prevent continuous flow from bed to bed and allow the water to remain in each bed for infiltration purposes. Each of the beds is approximately 0.9-1.2 m deep and filled with 7.6-10 cm diameter American Association of State Highway and Transportation Officials (AASHTO) No. 2 clean-washed course stone aggregate. The aggregate produces a void space of approximately 40% within the infiltration beds and allows for quick percolation of stormwater to the soil layer beneath. The void space also provides storage for stormwater during events when the infiltration rate from the beds is slower than the rate of stormwater runoff inflow (Kwiatkowski 2004). At the base of the infiltration beds, directly above the undisturbed native soil and below the stone, is a layer of geotextile filter fabric that extends over the bed bottom and up the side slopes of the BMP. This layer provides separation between the stones and soil to prevent any upward migration of fines into the infiltration bed. The geotextile filter fabric used for the BMP has a flow through capacity several orders of magnitude higher than that of the soil therefore providing uninhibited flow through the fabric. This also ensures the soil to be the limiting factor affecting the BMPs outflow through infiltration. Located above the course aggregate is a 7.6 cm layer of AASHTO No. 57 clean-washed choker course. Above the choker course is a layer of pervious concrete approximately 15 cm thick. The pervious concrete acts as a permeable medium through which stormwater can directly enter the infiltration basin beneath. It should be noted that in addition to the inflow through the pervious concrete, the infiltration beds receive inflow from roof drains tied directly to the beds from adjacent buildings. Figure 2 shows a typical cross section sketch of an infiltration bed. A 10 cm HDPE pipe located in the berm between the beds connects the bottoms of the lower two infiltration beds. This allows water to travel down from the middle bed to the lower bed, maximizing the infiltration area

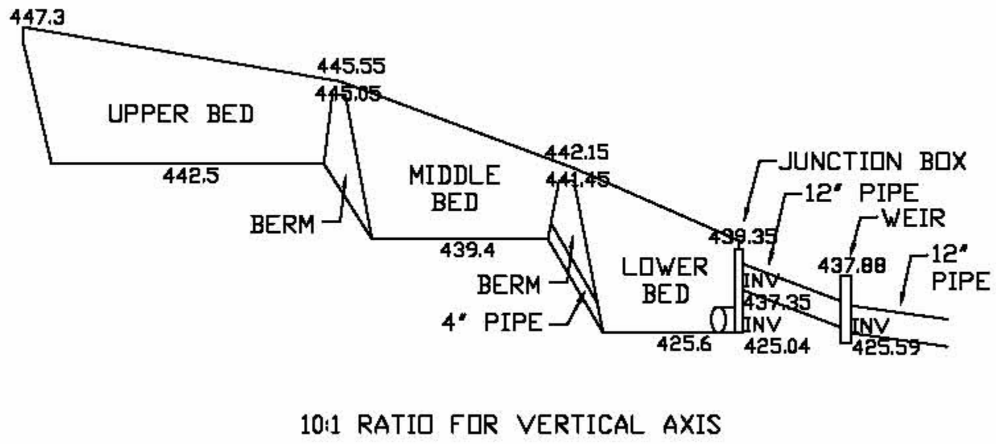

Figure 1. Profile of infiltration beds and overflow pipes

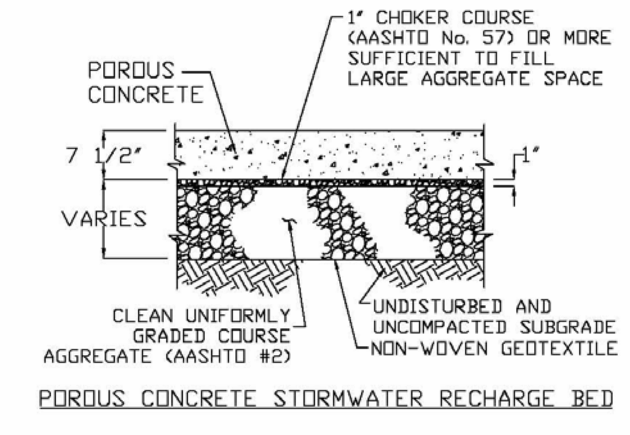

Figure 2. Cross Section of an Infiltration Bed

The soil immediately beneath the lower infiltration bed was classified according to the Unified Soil Classification System (USCS) (ASTM D-2487) by implementing grain-size analysis (ASTM D-422) and Atterberg limits (ASTM D-4318). The Atterberg limits were used to identify the soil’s liquid limit (LL) and plastic limit (PL), which were determined to be 42.9%, and 33.0%, respectively. The resulting plasticity index (PI) was 9.9%. According to the USCS the soil is classified as inorganic silty sand (ML) of low plasticity. With these characteristics and knowing the location of the site, the soil was classified as a Silt Loam under Soil Class - B Type Soil (Rawls et al. 1983). Additionally, a soil sample was taken and a flexible wall hydraulic conductivity test (ASTM D-5084) was performed resulting in a saturated hydraulic conductivity (Ks) equal to 0.61 cm/hr.

The site was instrumented with two Instrumentation Northwest (INW) PS-9805 Pressure/Temperature Transducers manufactured in Kirkland, WA. One was positioned in the lower bed and was used to measure both temperature and infiltration rates. The other was placed in a junction box upstream of a weir and was calibrated to yield flow exiting the system. In-situ monitoring of the infiltration process also was conducted during this study to ensure proper modeling of the site soils. Twelve Campbell Scientific CS616 Water Content Reflectometers manufactured in Logan, UT were installed beneath and immediately outside the lower infiltration bed to monitor the passing moisture fronts as the infiltrating runoff changed the soil moisture content. The reflectometers measure the volumetric water content of the surrounding soil, which changes as stormwater infiltrates through the lower bed and the moisture front passes through the soil profile. The probes were set up to take measurements every 5 minutes and an average of this data was recorded in 15 minute increments (Kwiatkowski 2004). The three probes used in this study were located below the bed bottom and were staggered at 0.3 m (1.0 ft), 0.6 m(2 ft), and 1.2 m (4.0 ft) below the bed bottom, respectively.

MODEL DEVELOPMENT The Green-Ampt formula was used to model the infiltration occurring through the bed bottom of the lower infiltration bed once the water level in the bed had reached its maximum level. Infiltration through the side walls of the BMP was not modeled in this study because it was considered negligible due the fact that the area of the bed bottom highly exceeds the area of the side walls that are submerged during infiltration, especially since the study focuses primarily on events with bed water depths of < 10 cm. Specifically, the model uses the recession limb of the outflow hydrograph, or the infiltration that occurs once the bed has filled to its peak, for each storm in question. Therefore, all rainfall inputs to the system and overflow from the system have stopped and the only outflow is through infiltration.

Between September 2003 and April 2005, the Infiltration Basin BMP had recorded a total of 115 storm events. Of these 115 events, approximately 30 events were shown to produce single peaking hydrographs with a depth of less than 10 cm, and a smooth recession limb. Of these 30, shallow water, single peaking events, 10 were used to create and calibrate the infiltration model (described below) for the site. Five additional events were used for model verification. The success of the calibration was based on how the model reproduced the recession limb of the outflow hydrograph.

A form of the Green-Ampt infiltration equation (Equation 1) was used in the model to reproduce the recession limb of the outflow hydrograph, once the water level in the lower bed had reached its maximum (Viessman and Lewis 2003).

$$f_p = K_s \frac{(S-L)}{L} \tag{1}$$

Where: f_p is the infiltration rate (cm/hr), K_s is the hydraulic conductivity in the wetted zone or the saturated hydraulic conductivity (cm/hr), S is the capillary suction at the wetting front (cm), and L is the distance from the ground surface to the wetting front (cm).

The value for the distance to the wetting front L, an un-measurable parameter, was replaced by three measurable parameters: cumulative infiltrated water, F and the initial moisture deficit *(IMD)* or the difference between the initial and saturated soil moisture content, θ_i and $\theta_{s,}$ due to the relationship, F is equal to the product of L and *IMD*. Making these substitutions and considering that the infiltration rate, f_p, is equal to the change in cumulative infiltrated depth, dF, per time increment, dt, equation (1) was integrated using conditions that F=0 at t=0, resulting in the following equation (Viessman and Lewis 2003).

$$F - S(\theta_s - \theta_i)\ln\left(\frac{F + S(\theta_s - \theta_i)}{S(\theta_s - \theta_i)}\right) = K_s t \tag{2}$$

Where: F is the cumulative infiltrated depth (cm), S is the capillary suction at the wetting front (cm), θ_s is the saturated soil moisture content (% by volume), θ_i is the initial soil moisture content (% by volume), K_s is the saturated hydraulic conductivity (cm/hr) and t is the time (hrs).

This form of the Green-Ampt equation is more suitable for use in watershed modeling processes than equation (1) as it relates the cumulative infiltration, F to the time at which infiltration begins. This equation assumes a ponded surface of negligible depth so that the actual infiltration rate is equal to the infiltration capacity at all times; therefore, the equation does not deal with the potential for rainfall intensity to be less than the infiltration rate (Viessman and Lewis 2003).

In a study completed by Al-Muttair and Al-Turbak (1991) the Green and Ampt model was used to characterize the infiltration process in an artificial recharge basin with a decreasing ponded depth. Using an equation similar to that derived in equation (2) they were able to conduct a continuous system infiltration model and determine the cumulative infiltration at set time intervals using equation (3) in a trial and error method.

$$K_s(t_j - t_{j-1}) = F_j - F_{j-1} - S_{fj} \ln\left(\frac{S_{fj} + F_j}{S_{fj} + F_{j-1}}\right) \tag{3}$$

Where: K is the saturated hydraulic conductivity (cm/hr), t_j is the time at the end of the jth period (hrs), t_{j-1} is the time at the end of the j-1 period (hrs), F_j is the cumulative infiltrated depth at the end of the jth period (cm), F_{j-1} is the cumulative infiltrated depth at the end of the j-1 period (cm), S_{fi} is the variable storage suction factor for the jth period (cm). In this equation, the capillary soil suction, moisture content, and a new parameter, H, to account for a ponded depth, are grouped into one variable, the storage suction factor, S_f, equation (4).

$$S_f = (S + H)(\theta_s - \theta_i) \tag{4}$$

Where: S_f is the storage suction factor (cm), S is the capillary suction at the wetting front (cm), H is the depth of ponded water (cm), θ_s is the saturated soil moisture content (% by volume), and θ_i is the initial soil moisture content (% by volume). All variables in equations (3) and (4) are measurable soil properties, which is why the Green-Ampt formula is characterized as "physically approximate."

The infiltration model developed for this study utilizes the study completed by Al-Muttair and Al-Turbak (1991), using equation (3) as its basis, with appropriate adjustments to account for the geometry of the basin (i.e. – trapezoidal with rock storage bed in lieu of rectangular bed open to the atmosphere). The output from the model is the infiltrated depth over 5-minute intervals beginning from the peak bed water depth to the time at which the bed empties; or the recession limb of the infiltration BMPs outflow hydrograph.

MODEL INPUT PARAMETERS The storage suction factor (S_f) is composed of the soil suction pressure head (S), the hydraulic pressure head (H), and the initial (θ_i) and saturated moisture content (θ_s) (Equation 4). The soil suction pressure head (S) for a Silt Loam under Soil Class B Type Soil is 16.7 cm (Rawls et al. 1983). The hydraulic pressure head (H) is taken from the data collected from the pressure transducer located in the lower infiltration bed. The maximum depth recorded in the bed is used as a starting point for the model. Using this value, the model is run and the next value for hydraulic head is calculated by subtracting the infiltration calculated during that time step (Equation 3) from the initial maximum hydraulic head value.

The initial and saturated moisture contents were determined by analyzing the three water content reflectometers installed beneath the infiltration bed which monitor, in-situ, the passing moisture fronts as the infiltrating runoff changed the soil moisture content of the surrounding soil. The initial moisture content of the soil ranged from 0.21 m^3/m^3 to 0.24 m^3/m^3 depending on the antecedent dry time between storm events, and was used for input to the model based on Table 1. The saturated moisture content is the limiting value for each of the moisture meters after a storm event. This value was shown to consistently approach 0.25 m^3/m^3 regardless of the antecedent dry time between storm events and therefore was used for model calibration.

Table 1. Initial Moisture Content by Antecedent Dry Time

Antecedent Dry Time	Initial Moisture Content
0-2 days	0.24
2-3 days	0.23
3-5 days	0.22
5+ days	0.21

The value for initial infiltrated depth was chosen by evaluating all single peak BMP events in 2004. For each event, the initial infiltrated depth was recorded from the peak bed level to the next recorded value five minutes later. The mean of these values was found to be 0.127 cm.

The hydraulic conductivity of a silt loam at the wetting front, with saturated conditions, under Soil Class - B Type Soil is 0.68 cm/hr (Rawls et al. 1983). However, the hydraulic conductivity resulting from the flexible wall hydraulic conductivity test done on the soil sample on site was 0.61 cm/hr, based on the average of four measurements. Therefore, for the purpose of this study 0.61 cm/hr was used as an initial starting value for hydraulic conductivity since it is the result of actual field data from the site.

MODEL CALIBRATION A preliminary assessment of the model was completed by taking the bed water depth readings from the pressure transducer for each storm, in combination with the input parameters to the model and comparing the model output to the recession limb of the outflow hydrograph. A statistical analysis was performed to determine the Mean Square Error (MSE) between the model results and actual results. A total of 10 storms were analyzed using this procedure and the results show the MSE for each preliminary run to vary between 4.08 and 16.28. It was determined that the resulting MSE could be improved through calibration of the input parameters.

A sensitivity analysis was completed on three input parameters (soil suction pressure head, initial moisture deficit (θ_s-θ_i), and hydraulic conductivity) to determine which parameter had the greatest and most consistent effect on the theoretical infiltration rate according to equation (3). The results of the analysis showed that the soil suction pressure head and initial moisture deficit parameters affected the MSE only slightly and the results varied between events; whereas the hydraulic conductivity had the greatest and most consistent influence on the overall model.

By adjusting the hydraulic conductivity, the MSE for every event dropped to well below 1.0. However, the resulting hydraulic conductivity is different for nearly every event, and considerably lower than the laboratory saturated hydraulic conductivity. To gain a better understanding of how the hydraulic conductivity was changing, the calibrated hydraulic conductivities for each event were plotted as a function of the corresponding mean bed temperature. (Figure 3)

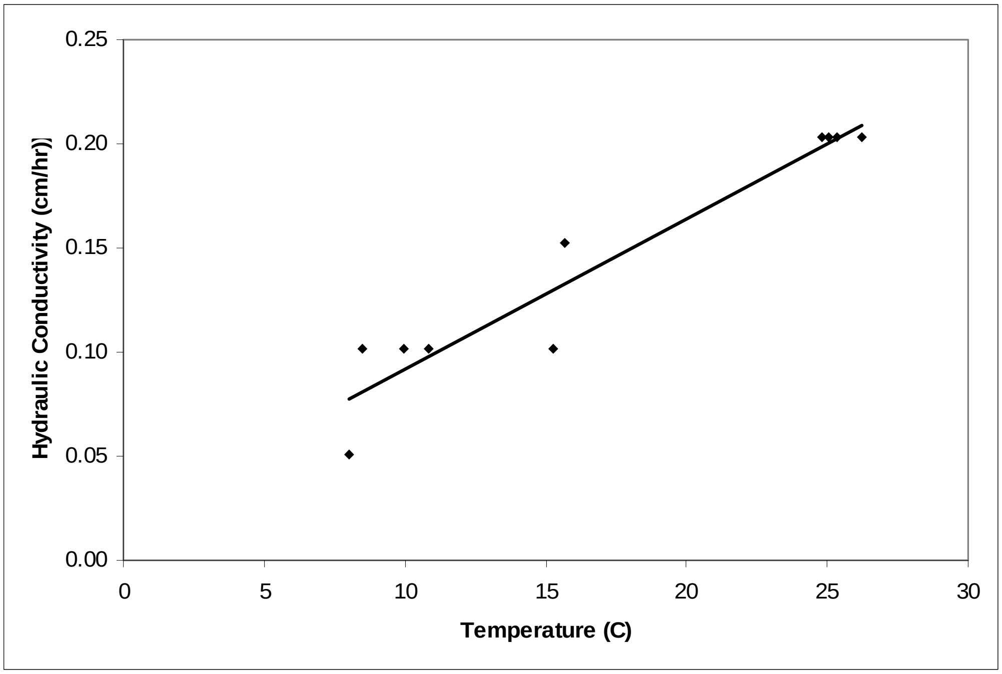

Figure 3. Model Calibration, Hydraulic Conductivity vs. Mean Water Temperature

Figure 3 shows an increasing and relatively strong relationship (R^2=0.92) between the hydraulic conductivity and mean bed temperature. Therefore, to select a hydraulic conductivity to verify the model, a trend line was inserted through the data points and the corresponding best-fit linear equation was determined relating infiltration bed temperature to hydraulic conductivity.

$$K = 0.0072(T) + 0.0196 \tag{5}$$

Where: K is the Hydraulic Conductivity (cm/hr) and T is the Temperature (°C)

MODEL VERIFICATION Five additional storms, not included in the calibration or sensitivity analysis, were used to verify the model in this study. For model verification, a MSE analysis of the resulting recession limb was conducted by comparing the hydraulic conductivity determined from the hydraulic conductivity calibration equation (5) to the event specific hydraulic conductivity, which provided the least MSE. For all verified storm events, the difference between the model and the event specific hydraulic conductivity was less than 20-percent. In every case, the calculated difference between model and actual hydraulic conductivities was between, 0.01 cm/hr and 0.03 cm/hr, proving the reliability of the model for these events. In every event the MSE was well below 1.0.

DISCUSSION The infiltration rate for each event was determined by fitting a linear trend line through the recession limb of the actual and modeled hydrograph. The infiltration rate is the slope of the linear trend line in centimeter per hour. In all cases, modeled and actual, the R^2 values were between 0.996 and 0.999 proving how well the linear trend line matched the data for these smaller depth storm events. The actual infiltration rate varies between 0.06 and 0.09 cm/hr. The model results have a similar range, but underestimate the actual infiltration rate slightly with values between 0.05 and 0.08 cm/hr.

A study completed by Lin et al. (2003) showed a repeating pattern of cyclical changes of infiltration rate as a function temperature. The same trend is observed in this study (Figure 3).

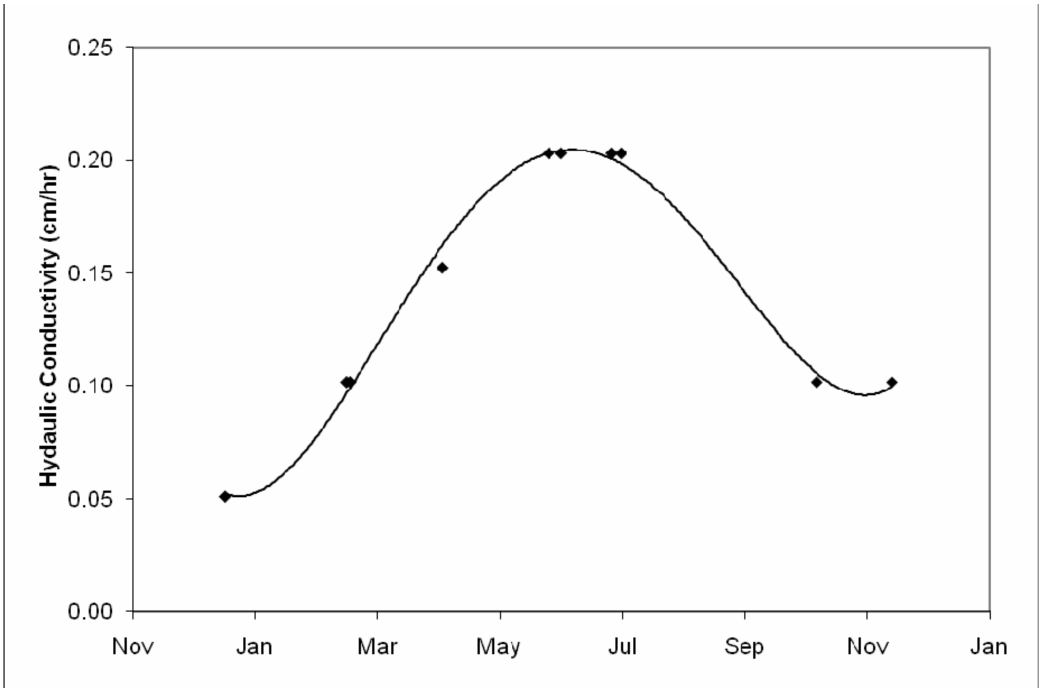

Figure 3. Seasonal Variation of Hydraulic Conductivity

It was discussed in Lin's study that the viscosity of water changes by approximately 2-percent per degree Celsius between the temperature range of 15-35°C, and this change is suggested to lead to an estimated 40% change of infiltration rate between the summer and winter months (Lin et al. 2003). The data in the current study shows a change from 0.127 cm/hr to 0.056 cm/hr over a 7 month period (summer to winter months), a change of 56%. Lin et al. (2003) also found that the temperature effects on infiltration rate tend to be larger by a factor of 1.5-2.5 times than the change expected from effluent viscosity changes alone. Constanz (1982) noted several possible causes for the increase including: (i) the surface tension change caused by temperature; (ii) much greater temperature dependence of viscosity of soil water than of free water (the anomalous surface water approach); (iii) the change of diffuse double-layer thickness with temperature; (iv) temperature-induced structural changes; and (*v*) isothermal vapor flux being more significant than previously thought.

CONCLUSIONS A model was created to characterize the infiltration occurring in an underground infiltration bed with decreasing water depth using a modified form of the traditional Green-Ampt formula. Each of the storms analyzed had a maximum depth of ponded water of less than 10 cm, which then gradually decreased over a given time frame due to infiltration into the bed. Through an evaluation of the soil parameters that affect infiltration including, soil suction pressure head, volumetric soil moisture content and hydraulic conductivity it was determined that hydraulic conductivity plays the most critical role in influencing infiltration rate. Additionally, it was found that the measured hydraulic conductivity of the flow remains constant for each storm event as it moves through the infiltration bed. The results of the model calibration process indicate that there is strong correlation between temperature in the bed and hydraulic conductivity, with a cyclical pattern of higher and lower infiltration rates occurring across the year concurrently with higher and lower temperatures in the infiltration bed.

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REFERENCES

Akan, A. Osman (2002). "Modified Rational Method for Sizing Infiltration Structures." Canadian Journal of Civil Engineering, 29(4), 539-542.

Al-Muttair, Fouad F. and Al-Turbak, Abdulaziz S. (1991). "Modeling of Infiltration from an Artificial Recharge Basin with a Decreasing Ponded Depth." Journal of King Saud University – Engineering Sciences, 3(1), 89-99.

Barbosa, A. E.; Hvitved-Jacobsen, T. (2001). "Infiltration Pond Design for Highway Runoff Treatment in Semiarid Climates." Journal of Environmental Engineering, 127(11), 1014-1022.

Constantz, J. 1982. Temperature dependence of unsaturated hydraulic conductivity of two soils. Soil Sci. Soc. Am. J. 46:466-470.

Kwiatkowski, M. (2004). "A Water Quantity Study of a Porous Concrete Infiltration Best Management Practice." *Masters Thesis*. Villanova University, Villanova, PA

Lin, C.; Greenwald, D.; Banin, A. (2003). "Temperature Dependence of Infiltration Rate During Large Scale Water Recharge into Soil." Soil Science Society American Journal, 67, 487-493.

Mikkelsen, P.S.; Jacobsen, P.; Fujita, S. (1996). "Infiltration Practice for Control of Urban Stormwater." Journal of Hydraulic Research, 34(6), 827-840.

Rawls, W. J.; Brakensiek, D. L.; and Miller N. (1983). "Green-Ampt Infiltration Parameters from Soils Data." J. Hydraulic Div., 109(1), 62-70.

Viessman Jr., Warren and Lewis, Gary L. (2003). "Chapter 7: Infiltration," Introduction to Hydrology, Fifth Edition. Pearson Education, Inc., Upper Saddle River, NJ, 187-190.