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Finite difference method to design sustainable infiltration based stormwater management system

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Infiltration based stormwater best management practices bring considerable economic, social and ecological benefits. Controlling stormwater quantity and quality are primarily important to prevent urban flooding and minimizing loads of pollutants to the receiving waters. However, there have been growing concerns about how the traditional design approach contributes to the failure of infiltration based BMP's that have caused flooding, ponding, prolonged movement of surface water, and frequent clogging, etc. Many of these problems were due to the fact that the current design approaches of stormwater BMP's only focus on surface hydrology and give little or no attention to the underline subsoil permeability rate and other constraints during the design and sizing process. As a result, many newly constructed infiltration based BMP's are failing to function well. This paper presents and demonstrates a new paradigm shift in designing infiltration-based stormwater BMP's by combining subsurface hydrology and undelaying native soil constraints to establish acceptable criteria for sizing infiltration based BMPs.

Key words: Infiltration based BMP's, flood, infiltration, clogging, soil permeability, underdrain, soil saturation rate, drainage basin, urban drainage

INTRODUCTION

Infiltration is the rate at which surface water percolates into the ground. It is often expressed as cm or inches per hour, but the SI unit is m s^{-1}. The infiltration rate depends on a number of factors including soil type, soil moisture, vegetation, and temperature. Typically, the smaller the grains of soil, the more slowly water percolates into the ground. Also, the wetter the ground, the less room there is for water to infiltrate and consequently, the slower the rate (Bauer, 1974; Guo and Gao, 2016). Many methods have been developed to estimate infiltration rates, and better predict runoff from storm events. The following are some of the methods that are commonly used:

1. **Green-Ampt Method:** - The Green-Ampt equation is a physically based model, which can give a good description of the infiltration process. This method for modeling infiltration assumes that a sharp wetting front exists in the soil column, separating soil with some initial moisture content below from saturated soil above. The input parameters required are the initial moisture deficit of the soil, the soil's hydraulic conductivity, and the suction head at the wetting front (Bedient et al., 2008).

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2. **Curve Number (SCS) Method:** The Natural Resources Conservation Service (NRCS, formerly Soil Conservation Service (SCS)) Curve Number method is most commonly used method in the United States to determine the volume of runoff called rainfall excess. The curve number (CN) is used to combine infiltration losses with surface storage, to determine what portion of rainfall will runoff. It assumes that the total infiltration capacity of a soil can be found from the soil's tabulated Curve Number. During a rain event, this capacity is depleted as a function of cumulative rainfall and remaining capacity. The input parameters for this method are the curve number, the soil's hydraulic conductivity (used to estimate a minimum separation time for distinct rain events), and a regeneration constant that describes the restoration of infiltration capacity during dry periods (Ward and Trimble, 2004).

3. **Horton Infiltration Method:** Horton's concept of infiltration capacity is based on empirical observations showing that infiltration decreases exponentially from an initial maximum rate to some minimum rate over the course of a long rainfall event. It measured at the ground surface. Each of the parameters in the Horton Infiltration Equation is a function of surface texture and vegetative cover type. The infiltration rate can also vary with slope (McCuen, 2005).

The methods briefly discussed above are widely accepted methods. Each of these methods have their benefits and limitations. For this study, the Horton infiltration method has been used and discussed subsequently.

HORTON'S THEORY OF INFILTRATION

Horton's theory is based on the fact that infiltration is faster in dry ground, so as rain continues and the ground becomes wetter, the infiltration rate decreases. The reason why infiltration is faster when the ground is dry is that there are more spaces for the water to fit so capillary forces that pull the water down into the ground are stronger (Philip, 1969; Verma, 1982).

$$(f - f_c) = (f_0 - f_c)e^{-kt} \tag{1}$$

Horton's Equation is the governing heuristic equation for infiltration, where: f = infiltration rate; f_0 = (initial) infiltration rate for dry ground; f_c = (asymptotic) infiltration rate for saturated ground, and k = infiltration constant

The infiltration equation is written with (f - f_c) on the left hand side (rather than isolating f) because it is the excess infiltration rate above the value for saturated ground that diminishes exponentially with time (Pitt and Voorhees, 2010).

Integrating Horton's equation over time gives the total depth of water that has infiltrated, F,

$$F(t) = \int f dt = f_c t + \frac{(f_0 - f_c)}{k}(e^{-kt} - 1) \tag{1}$$

Where: $F(t)$ = infiltration depth in inch (or mm) at time t.

LIMITS TO HORTON'S THEORY

Horton's equation and integral assume that the rainfall rate, R is greater than the infiltration rate throughout the rain. If at any time the rainfall rate is slower than the infiltration rate, the ground will lose some water to lower levels, and Horton's theory must be modified (Philip, 1969; Stafford et al., 2015).

MODEL INFILTRATING STORMWATER

Infiltration can be modeled by a layer of ground in which water enters through the top at a rate, $f = f_{in}$ and leaves through the bottom (into the water table) at a rate f_{out}. As soon as any water is stored in the ground, storage S will be greater than 0 and,

$$f_{out} = f_c \tag{3}$$

The depth of water stored in the layer, S, is equal to the total depth of infiltration, F minus the depth of water that has leaked out the bottom of the layer. Except in very permeable soil (such as sand or gravel, water leaks out the bottom so slowly; it is safe to assume that during any rainfall,

$$S = F - f_c t \tag{4}$$

The infiltration rate, f_{in} is limited by the rainfall rate and by the total amount of stored water in the layer,

$$f_{in} = \min \begin{bmatrix} R \\ (f_0 - f_c)\frac{(S_{max} - S)}{S_{max}} + f_c \end{bmatrix} \tag{5}$$

R = Rainfall Rate and S_{max} = maximum depth of water layer can store

Solving Horton's Equation yields the value for S_{max},

$$S_{max} = \frac{f_0 - f_c}{k} \tag{6}$$

The rate at which water is stored in the layer is equal to the infiltration rate minus the outflow rate through the bottom of the layer, or,

$$\frac{dS}{dt} = f_{in} - f_{out} \tag{7}$$

The difficulty with this equation is that Equation (5) for f_{in} is complicated. If rainfall is ever less than the possible infiltration rate, then it is necessary to solve Equuation (7) numerically, using finite difference techniques (Afrin et al., 2016a, b; Lewellyn et al., 2015; Stafford et al., 2015).

FINITE DIFFERENCE TECHNIQUES

The secret of finite difference techniques is to replace derivatives by finite differences. This transforms a differential equation into an arithmetic equation that can be solved easily. Solving a differential equation using finite differences involves several steps (Al-Hamati et al., 2010; Ferguson, 1990).

1. Replace all derivatives with differences.
2. Solve the equation for the unknown (generally the future value).
2. Choose a value for the time step (Δt) or a distance interval.
3. Substitute current values to find the future value of the variable.
4. Iterate, or, update by repeating step 3 as much as needed.

The derivative is defined as,

$$\frac{dS}{dt} = \lim_{\Delta t \to 0} \frac{S(t+\Delta t) - S(t)}{\Delta t} \quad (8)$$

The finite difference technique assumes that the difference equals the derivative. Then we write the infiltration equation, Equation (8) in finite difference form and rearrange to solve for $S(t+\Delta t)$ because it is the only unknown (Krvavica et al., 2018; Kunze and Nielsen, 1982).

FINITE DIFFERENCE INFILTRATION EQUATION

$$S(t+\Delta t) = S(t) + \Delta t(f_{in} - f_c) \quad (9)$$

Finally, overland flow occurs when the rainfall rate is greater than the infiltration rate. In that case,

$$Overland\ flow = R - f_{in} \quad (10)$$

DETERMINATION OF DESIGN STORAGE VOLUME

In designing infiltration based BMPs, the native soil infiltration on the land surface and the design rainfall event dictate the storage volume for the basin. Moreover, the soil water storage capacity beneath the basin sets up the limit for the maximum water depth in the basin including the invert elevation of the underdrain pipe. In most of urban area, infiltration basined BMPs are often placed next to a small, highly paved small urban catchments such as parking lots and business strip. Therefore, the volume-based approach is suitable to predict the peak runoff from such a small urban watershed, and to finding the maximum volume difference between the inflow and outflow volumes under a series of storm events with different durations (Guo, 1999, 2001, 2002, 2003, 2004; Liu et al., 2015). To determine the peak runoff for a small urban watershed, the rational method states:

$$Q_d = \alpha C I_d A \quad (11)$$

Using the Chicago method, the rainfall intensity in Equation (11) can be calculated (Silveira, 2016) as:

$$I_d = \frac{a}{(T_d+b)^n} \quad (12)$$

Where: α= unit conversion factor, equal to 1 for English units, and 1/360 for SI units; C = runoff coefficient, A= watershed area in acres (hectare), I_d = rainfall intensity in inch/hr (mm/hr), T_d = rainfall duration in minutes, Q_d= peak runoff rate in cfs (cms) and a, b, and n= constants on the Intensity- Duration- Frequency (IDF)

Using the above Equations (10, 11 and 12) we can calculate the maximum volume difference between the inflow and outflow volumes under a series of storm events with different duration (Visocky, 1977). The inflow runoff volume is determined by the net rainfall volume as:

$$V_i = \alpha C I_d A T_d \quad (13)$$

The outflow volume can be estimated by the sump inlet capacity as:

$$V_o = QF(T_d) \quad (14)$$

Therefore, the required design storage volume is the difference between Equations 13 and 14. Aided by Equation 1 to 12, the storage volume, V, is obtained as:

$$V_d = (\alpha C I_d A T_d) - QF(T_d) \quad (15)$$

Where: V_d = Design storage volume, A_b = infiltrating area, and α and β = unit conversion factors.

The maximal value of Equation 15 is achieved by setting its first derivative with respect to T_d equal to zero, and it results in:

$$\frac{dV_d}{dT_d} = \left\{CA \propto \left[\frac{-nT_d}{(T_d+b)^{n+1}} + \frac{1}{(T_d+b)^n}\right] - Qf(T_d)\right\} = 0 \quad when\ T_d = T_m \quad (16)$$

In which Tm = the design rainfall duration described by

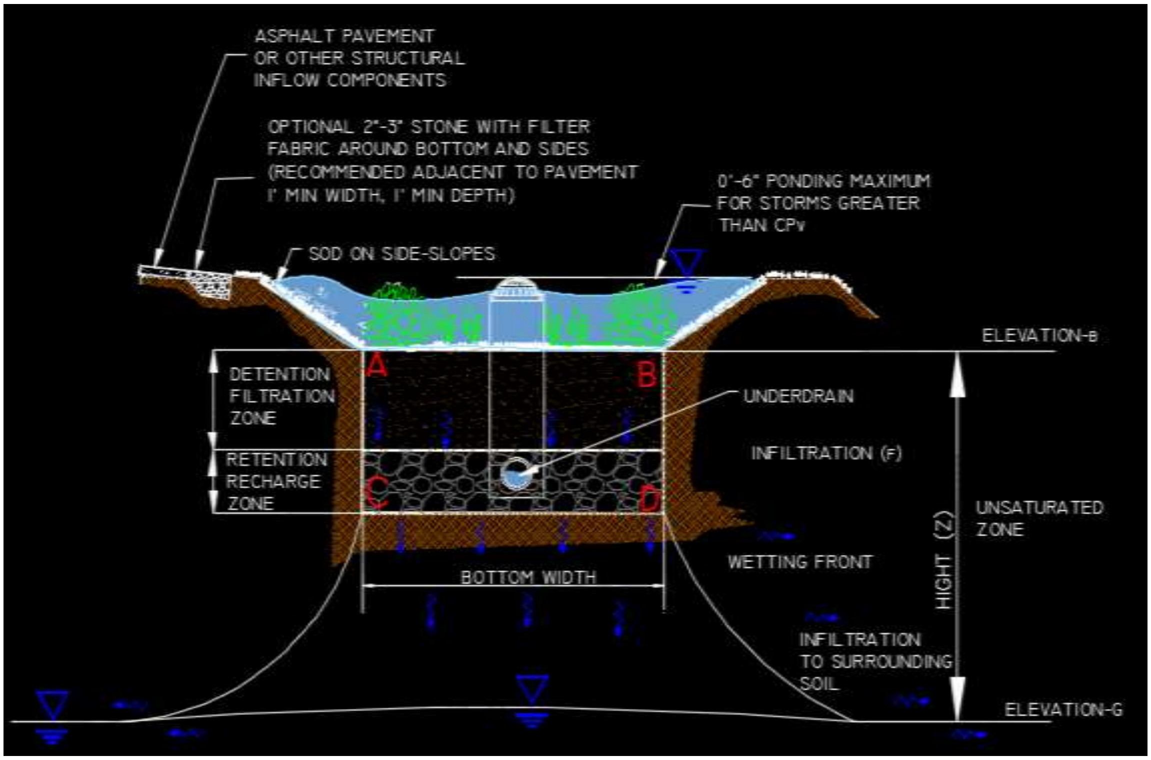

Figure 1. Typical bio-retention infiltration based green infrastructure.

Equation 16. Solution of Equation 16 is:

$$T_m = \frac{1}{n}\left[(T_m + b) - (T_m + b)^{n+1}\frac{Q}{\alpha\alpha CA}\, f(T_m)\right] \quad (17)$$

When the value of b in Equation 16 is numerically negligible, the approximate solution of Equation 16 is:

$$T_m = \left[\frac{2\alpha\alpha CA(1-n)}{Qf(T_m)}\right]^{\frac{1}{n}} \quad (18)$$

Using trial and error of Equation 18 the maximum storage volume, Vm, is

$$V_m = \alpha CI_m AT_m - QF(T_m) \ when \ T_d = T_m \quad (19)$$

The average infiltration rate, f, through the storm duration is:

$$f = \frac{F(T_m)}{T_m} \quad (20)$$

Where $F(T_m)$ = Total Infiltration depth

SIZING INFILTRATION BASED GREEN INFRASTRUCTURE

The above procedure yields a storage volume based on the surface hydrology without taking the subsurface condition into consideration. If the soil infiltration rate at the land surface is higher than the underground seepage rate, the system is backed up and may even cause a failure in the operation. To be conservative, the water storage volume in soil pores can serve as a limit for the water depth in the basin (Guo, 2004; Miles and Band, 2015; Stafford et al., 2015).

The sample plan view of Infiltration based Green Infrastructure in Figure 1, shows the infiltrating water begins with a vertical downward velocity through the unsaturated zone underneath the basin. As the soil water content increases, the diffusive nature of the wetting front results in flow movements in both vertical and lateral directions (Cannavo et al., 2018; Chu et al., 2018). As soon as the seepage flow reaches the local groundwater table, the soil medium beneath the basin becomes saturated and the seepage flow radially disperses into groundwater. Although many studies used the concept of potential function to investigate the vertical seepage flow and the associated water mounding effect (Guira, 2018)., this study applies stream function to describe the movement of the seepage flow through the soil medium. With the consideration of vertical and radial movements, the potential flow model using stream function is developed for the infiltrating flow under a parabolic infiltration basin (Guo, 1999, 2001) as shown in Figure 1.
Infiltration of water into the soil, like many other flow

processes in porous media, is governed by the Richards soil moisture diffusion equation (Celia et al., 1990; Jury et al., 2018; List and Radu 2016). According to the diffusion theory(Green and Ampt, 1911), the seepage flow through the soil medium in Figure 1 can be described as:

$$\frac{\partial \theta}{\partial t} + \frac{\partial f}{\partial z} = 0 \tag{21}$$

in which θ = soil moisture content, t = elapsed time, f = infiltration rate, and z = vertical distance below the basin. Consider the soil medium between the basin bottom and groundwater table as a control volume. The finite difference form of Equation 11 is:

$$\Delta\theta = \frac{\Delta f \Delta t}{\Delta z} \tag{22}$$

As illustrated in Figure 1, the value of Δθ is the difference between the soil initial and saturated moisture contents. The value of Δz is the depth of the soil medium beneath the basin. The value of Δf is equal to the infiltration rate from the basin because there is no recharge to the groundwater table before the wetting front reaches the groundwater table. As a result, Equation 21 becomes:

$$(\theta_S - \theta_0) = \frac{(f-0)(T_d-0)}{(Z_b - Z_g)} = \frac{T_d f}{Z} \tag{23}$$

Where, θs = soil porosity, θo = soil initial water content, Zb = elevation at basin bottom, Zg = elevation of groundwater table, Td = drain time, and Z = distance to groundwater table. Re-arranging Equation 23, the drain time at the basin site is derived as:

$$T_d = \frac{Z(\theta_S - \theta_0)}{f} \tag{24}$$

Equation 24 indicates that the drain time of an infiltration basin is dictated by the storage capacity in the soil pores and the infiltration rate. And the water storage volume in the soil pores is equivalent to:

$$d = Z(\theta_s - \theta_0) \tag{25}$$

Where d= equivalent water depth in soil pores. Equation 25 sets the limit for the water depth in the basin. As a result, the footprint surface area of the basin is:

$$A_b = \frac{V_m}{Z(\theta_S - \theta_0)} \tag{26}$$

Equation 19 defines the required storage volume in the basin; Equation 25 sets the maximum water depth in the basin, Equation 26 defines the minimum basin bottom area, and Equation 24 calculates the drain time to release the stored volume. The above design procedure applies to the soil mediums under an unsaturated condition. During an event, the storm water quality control basin may saturate the soil mediums. It is important to understand that the soil medium beneath a retention basin with a permanent pool or a long-term groundwater recharging pond would have saturated already. Under a saturated condition, the major concern in design is no longer the basin geometry, but the basin sub-surface geometry (Healy, 2010; Tedoldi et al., 2016). In other word, we have to make sure that the infiltrating water rate can be sustained by the underground hydraulic gradient and conductivity.

EVALUATION OF THE LONG-TERM SUSTAINABLE PERFORMANCE EFFICIENCY

To evaluate the long-term sustainable of the infiltration based stormwater management system, the designer should analyse the soil medium saturation effect that could reduce the basin infiltration efficiency. As illustrated in Figure 1, the process of infiltration begins with a vertical downward velocity through the unsaturated zone underneath the basin. As the soil water content increases, the diffusive nature of the wetting front results in flow movements in both vertical and lateral directions (Sharma et al., 2018). If the vertical flow through the soil medium is slower than the infiltration rate of the natural soil underneath the infiltration basin, the excess inflow will cause water mounting effect that may back up the system to cause a failure, prolonged draining operation, and minimizing the life-cycle of the basin. Therefore, an infiltrating basin must be designed under the constraints of the soil pore storage capacity before saturation and the soil conveyance capacity after saturation (Haverkamp et al., 1977; Saraswat et al., 2016; Yang and Chui, 2018).

Most of the time the evaluation of the long-term sustainability of the infiltration based stormwater management system based on; analyzing the drain time (I), hydrologic effectiveness (II), required saturated depth (III) and depth of the trench below the underdrain pipe (IV) is as follows.

Analyzing the drain time

Soils must be sufficiently permeable to ensure that collected runoff can infiltrate quickly enough to reduce the potential for flooding and mosquito breeding (that is, water ponding for no more than four days) (Hazelton and Murphy, 2011). Soils with lower hydraulic conductivities do not necessarily preclude the use of infiltration systems, but the size of the required system may typically become prohibitively large, or a more complex design approach may be required, such as including a slow drainage outlet system. Equation 24 indicates that the drain time of an infiltration basin is dictated by the storage capacity in the soil pores and the infiltration rate (Stafford et al., 2015).

Hydrologic effectiveness

The hydrologic effectiveness of an infiltration system defines the proportion of the mean annual runoff volume that infiltrates. For a given catchment area and meteorological conditions, the hydrologic effectiveness of an infiltration system is determined by the combined effect of the nature/quantity of runoff, the 'detention volume', in-situ soil hydraulic conductivity and 'infiltration area (Bracken and Croke, 2007).

The hydrologic effectiveness of an infiltration system requires long term continuous simulation which can be undertaken using the Model for Urban Stormwater Improvement Conceptualization (MUSIC) (CRCCH, 2005). However, in most situations, where a number of the design considerations can be fixed (that is, frequency of runoff, depth of detention storage, and saturated hydraulic conductivity), hydrologic effectiveness curves can be generated and used as the design tool for establishing the infiltration system size (Davis, 2005; Davis et al., 2009).

Depth of the trench below the underdrain pipe

The depth of the trench below the underdrain pipe is dependent on the native soil infiltration rate, porosity (void space ratio) of the gravel storage layer media (that is, aggregate material used in the stone reservoir) and the targeted time period to achieve complete drainage between storm events. The maximum allowable depth below the pipe can be calculated using the following equation (Irvine and Kim, 2018; Kim et al., 2019).

$$D = \frac{i*T*cf}{\eta*s} \tag{27}$$

Where: D = Maximum stone trench depth below pipe (in); I = Infiltration rate for native soils (in/hr.); c_f = clogging factor (0.5); η= Void space ratio for aggregate used (typically 0.4 clear stone); S= Minimum safety correction factor, and T= Time to drain (design for 48-hour time to drain is recommended)

The designer should keep in mind that the determining factor for recharge systems is the surrounding soil's ability to accept water, not the pipe's ability to deliver water. Although the perforations in the pipe determine the allowable area at which water can be released, it is the soil's ability to accept the water that is the determining factor in designing recharge systems.

DESIGN EXAMPLE -1

A 20-lot subdivision in which on-lot structural BMPs provide volume and infiltration for the net increase in volume for the 10-year storm event. Peak rate calculations are developed using techniques described by Equation 12 (Chicago Method) with a = 96.84, b=15.88 and n = 0.7952. The 20-lot subdivision of 5.0 acre is to be developed with a runoff coefficient of 0.75. The 10-year storm runoff from this watershed will drain into 125-ft. by 20-ft. infiltration based green infrastructure basin. The infiltration rates of the basin are: f_o = 2.50 inch/hr., fc = 0.5 inch/hr., and the time constant k = 0.40 /hr. Based on the given information, the design storm duration (min) calculate, the required detention volume (ac-ft.), the total infiltration depth (inch), and the bottom area of the basin (ac) assume α and β are 70 and 1/12, respectively. The following problem can be solved using Equations 2,15 and 17:

1. Calculating the design storm duration (min), using the given data:

$$T_m = \frac{1}{0.7952}\left[(T_m + 15.88) - (T_m + 15.88)^{0.7952+1}\frac{\frac{1}{12} * A_b}{96.84 * 70 * 0.75 * 5} f(T_m)\right]$$

Where: $f(T_m) = 1.2 + (4.5 - 1.2)e^{-\frac{T_m}{60*6.5}}$; Substituting these variables into Equations will yield $T_m = 250.00$ minute

Calculating the total infiltration depth (inch), and the bottom area of the basin (ac)

$F(t) = \int f dt = f_c t + \frac{(f_0 - f_c)}{k}(1 - e^{-kt})$ and $A_b = \frac{40*100}{43560} \cong 0.092\ ac$

$$F(t) = 0.5(t) + \frac{(2.5 - 0.5)}{0.4}(1 - e^{-0.4(t)}) \Rightarrow 6.14 in$$

Calculating the required detention volume (ac-ft.),

$$V_m = \alpha C I_m A T_m - \beta Q F(T_m) \quad when\ T_d = T_m$$

Substituting these variables into Equations 2, 15, 17 and 19 yields the design storm duration of $T_m = 250.00$ minute. The total infiltration depth, $F(T_m)$= 6.14 in, the calculated bottom area of the basin = 0.092 ac and the required detention volume for this case is 0.737 acre-ft.

DESIGN EXAMPLE -2

At the project site of Example 1, the soil porosity is 0.50 and has initial water content of 0.20. The distance to the local groundwater table is 8 ft. Designing the basin geometry for storage volume of 0.737 acre-ft is calculated in example-1. Calculating the maximum stone trench depth below underdrain pipe (in) assume that the void space ratio for clear stone aggregate used is 0.4.

Under the saturated condition, the water storage volume in the 8-ft. soil medium is:

$$d = 8ft.* (0.50 - 0.20) = 2.40\, feet\ of\ water$$

Assuming that the basin is designed to have the brim-full depth (filled with something to the point of overflowing) of 2.40 feet, the basin area is determined as:

$$A_b = \frac{0.737}{2.40} \cong 0.31\, acre - ft.$$

The final infiltration rate is 0.5 inch/h in Example 1. Therefore, the drain time is:

$$T_d = \frac{2.4 * 12}{0.5} \cong 36hr.$$

Calculating the maximum stone trench depth below underdrain pipe (in):using Equation 27 the Maximum stone trench depth below underdrain pipe (in) is

$$D = \frac{i * T * cf}{\eta * s} = \frac{0.5 * 36 * 0.5}{0.4 * 05} = 45in \cong use\ 3.75\, ft$$

DESIGN EXAMPLE -3

Given a circular infiltration basin has a diameter of 50.0 ft. The groundwater table at the site is 10.0 feet. The basin will have a layer of loamy sand lining that has an infiltration rate of 1.80 inch/hr. The coefficient of permeability for the native soil is found to be 0.75 inch/hr. Evaluate the sustainability of the proposed infiltration based green infrastructure basin operation, the required saturated distance and suggest that weather the proposed basin lining materials infiltration rate shall be maintained or need revision

Given:

$$Radious\ of\ the\ GI\ basin = r_o = \frac{50}{2} = 25ft.\, and\ f = 1.80\frac{in}{hr}$$

$$K_r = Ky = K = 0.75\frac{in}{hr}$$

where

$K_r = Hydraulic\ conductivity\ in\ the\ radial\ direction$;
$Ky = Coefficient\ of\ vertical\ permeability, and$
$K = Coefficient\ of\ permeability$

$Q = f\pi r^2 = \frac{1.80}{12*3600} * 3.1416 * (25)^2$= 0.08 cfs

$$\omega = \frac{1.80}{0.75} = 2.32 \quad where\ \omega = \frac{f}{K_r}$$

$$The\ ratio\ of\ \frac{H}{r_0} = \sqrt{\frac{2.32 * ln(2.32)}{2((2.32)^2 - 1)}} = 0.471 \quad or\ H = 11.78\, ft$$

$$The\ ratio\ of\ \frac{D}{r_0} = 2.32\sqrt{\frac{2.32 * ln(2.32)}{2((2.32)^2 - 1)}} = 1.09 \quad or\ D = 27.25\, ft$$

The required saturated depth calculated as:

$$\frac{Y_0}{r_0} = \frac{D-H}{Y_0} \xrightarrow{yields} Y_0 = 27.25 - 11.78 = 15.33\, ft.$$

The required saturated distance is greater than the available (15.33 >10.00 ft.). Therefore, the design infiltration rate or the design radius of the GI must be reduced.

Conclusion

On this paper, we assessed what contributes to the failure of most recently constructed infiltration based BMP's such as porous pavements, riprap trenches, infiltration beds, retention pools, detention systems, wetlands, and drywells. Examination of the current design approaches further revealed that the serious negligence of site constraints that have caused flooding, ponding, prolonged movement of surface water, and frequent clogging, etc. This paper demonstrates the need in paradigm shift when designing sustainable infiltration based stormwater management system. Using finite difference method to design infiltration based stormwater management approaches integrates all constraints such as underlying soil permeability (k), drain time (Td), hydrologic effectiveness, and the depth of the trench below the underdrain pipe.

Finally, the evaluation of the sustainability of the proposed infiltration based stormwater management operation shall be dependent on the native soil infiltration rate, porosity (void space ratio) of the gravel storage layer media (trhat is, aggregate material used in the stone reservoir) and the targeted time period to achieve complete drainage between storm events. No single method works well for all situations.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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