Effective Saturated Hydraulic Conductivity of an Infiltration-Based Stormwater Control Measure

Peter T. Weiss, M.ASCE[1]; and John S. Gulliver, F.ASCE[2]

Abstract: Infiltration rates into field soils have a large variability, and a statistical value that represents the overall infiltration in a site is needed. The Green-Ampt equation was used to develop a one-dimensional, multisoil model to predict the water surface drawdown in an infiltration-based stormwater control measure (SCM) as a function of time. Results were used to compare the accuracy of assuming the SCM was comprised of a single soil with an overall effective saturated hydraulic conductivity set equal to (1) the geometric mean of the spatially distributed hydraulic conductivity values of the multisoil SCM, (2) the arithmetic mean of the hydraulic conductivity values, and (3) a best-fit hydraulic conductivity value. Results indicated that the use of the geometric mean consistently underestimated infiltration and use of the arithmetic mean consistently overestimated infiltration. A relationship to more consistently and accurately predict the best-fit value of saturated hydraulic conductivity used a weighted sum of 0.32 times the arithmetic mean and 0.68 times the geometric mean. **DOI: 10.1061/JSWBAY.0000801.** © *2015 American Society of Civil Engineers.*

Author keywords: Infiltration; Stormwater control measure; Green-Ampt; Saturated hydraulic conductivity.

Introduction

Federal stormwater regulations (U.S. EPA 2000) have spurred widespread efforts to have hydrologic conditions of developed watersheds mimic predevelopment conditions. To achieve this objective, stormwater management now often includes low-impact development (LID) and corresponding practices that encourage the infiltration of stormwater runoff into the existing soil (Prince George's County 2000a, b). Such infiltration can reduce stormwater runoff peak flows and total runoff volumes and is often assumed to reduce pollutant mass loads based on the assumption that infiltrated water is removed from the conveyance system. Thus, knowing or being able to estimate the depth of stormwater runoff that will infiltrate over a specified time period is important in both the design and maintenance of stormwater control measures (SCMs) that infiltrate runoff.

Stormwater runoff that infiltrates into a SCM is flowing through porous media. Modeling infiltration into a porous media often utilizes the Green-Ampt assumptions with Darcy's law (Dingman 2002), the fundamental equation for flow through porous media

$$f = \frac{Q}{A} = K_{\mathrm{sat}}\left(\frac{h_0 + \psi + L}{L}\right) \tag{1}$$

where f = infiltration rate; Q = total flow rate into the soil; A = area over which flow occurs; K_{sat} = saturated hydraulic conductivity of the soil; h_0 = piezometric head of water above the soil; ψ = soil suction head at the wetting front (a positive value); and L = assumed thickness of saturated soil.

If the SCM was designed to have two or more horizontal layers of media with different K_{sat} values (e.g., sand, gravel, existing soil, etc.), the single value of K_{sat} to use in Eq. (1) when modeling vertical infiltration is given by Freeze and Cherry (1979) as

$$K_{\mathrm{sat}} = \frac{d}{\sum_{i=1}^{n}\frac{d_i}{K_{\mathrm{sat}i}}} \tag{2}$$

where d = total vertical thickness of all horizontal layers; d_i = thickness of individual layer, i; $K_{\mathrm{sat}\,i}$ = saturated hydraulic conductivity of the media in the individual layer; and n = total number of layers.

To apply Eq. (1), the K_{sat} value of the soil must be known. Several methods, such as the Guelph infiltrometer, double-ring infiltrometer, and the modified Philip-Dunne infiltrometer (Ahmed et al. 2014a), are available to determine K_{sat} values of a soil at a specific point or location (Erickson et al. 2013). Soil K_{sat} values have been shown to vary by several orders of magnitude, however, even in close proximity to each other. This has been documented within a single SCM with engineered media (Asleson et al. 2009), in the undisturbed native soil of a park (Olson et al. 2013), and in agricultural fields (Logsdon and Jaynes 1996), and believed to be primarily due to local compaction differences (Pitt et al. 2008). Due to the spatial variability of K_{sat} values, Ahmed et al. (2015) recommended measurements of K_{sat} be obtained at approximately 20 locations within a SCM in order to obtain a representative estimate of the geometric mean. The geometric mean was used because Ahmed et al. (2015) found K_{sat} values to be lognormally distributed and the mean of a lognormal distribution is the geometric mean of the sample. For measurements at 20 locations, the uncertainty to the 95% confidence interval was approximately twice the geometric mean, whereas for 10 measurements it was 2.8 times the mean and for 40 measurements it was 1.7 times the mean. Thus, 20 measurement locations were recommended as a balance between accuracy and effort.

Given the variability of K_{sat}, to accurately model the infiltration of stormwater into a SCM, a multidimensional fluid transport analysis would be required. A relatively small grid could be used to model highly variable K_{sat} values that may vary by orders of

[1]Professor, Dept. of Civil Engineering, Valparaiso Univ., Valparaiso, IN 46383 (corresponding author). E-mail: Peter.Weiss@Valpo.edu

[2]Professor, Dept. of Civil Engineering, Univ. of Minnesota, Minneapolis, MN 55414. E-mail: gulli003@umn.edu

Note. This manuscript was submitted on February 27, 2015; approved on June 8, 2015; published online on July 14, 2015. Discussion period open until December 14, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Sustainable Water in the Built Environment***, © ASCE, 04015005(5)/$25.00.

magnitude over short distances. This process, however, would be time consuming, if not tedious and cumbersome. A simpler approach would be to use an effective overall average value of K_{sat} for the entire SCM and model infiltration with this single value of K_{sat}. The single effective overall average value of K_{sat} that would most accurately model a SCM (i.e., $K_{best\text{-}fit}$) with highly spatially variable K_{sat} values would be a function of the spatially distributed K_{sat} values within the SCM. Point measurements to determine K_{sat} at specific locations within the SCM could be made to characterize the SCM with respect to saturated hydraulic conductivity (and other relevant properties), but the function relating these point measurement values to $K_{best\text{-}fit}$ is not known. This paper seeks to address this issue by finding a relationship between multiple spatially distributed K_{sat} values within a SCM and the single overall average value of K_{sat} that will most accurately model infiltration into the SCM (i.e., $K_{best\text{-}fit}$).

Possible $K_{best\text{-}fit}$ values that could be used include the arithmetic mean and the geometric mean of the spatially distributed K_{sat} values within the SCM. For vertical flow only (as was assumed in this study), use of the arithmetic mean would weight all K_{sat} values equally and include the inherent assumption that all SCM areas, despite their highly varying K_{sat} values, participate equally throughout the infiltration process, independently of time and independently of each other. Use of the geometric mean would reduce the contribution of areas with high K_{sat} values. This may be appropriate due to the fact that areas with high K_{sat} values will initially infiltrate at a greater rate, but the infiltration capacity of high K_{sat} areas will be more rapidly reduced because the thickness of the saturated zone, L, will increase more quickly than that of regions with lower K_{sat} values, and their contribution to the overall infiltration process will decrease (relative to their initial contribution) with time. Another option would be to calculate $K_{best\text{-}fit}$ as a weighted average of the arithmetic and geometric means. The harmonic mean was not considered because, in addition to Ahmed et al. (2015) finding the distribution of K_{sat} to be lognormally distributed, the harmonic mean, like the geometric mean, would reduce the contribution of areas with high K_{sat} values and the effect would be redundant.

Modeling Method

In order to determine the optimum value of $K_{best\text{-}fit}$, a one-dimensional vertical infiltration model was developed to model a flat-bottom, infiltration-based SCM that initially contained standing water. This model approximated vertical infiltration into the bottom of a SCM with variable soil properties, including K_{sat}. The model was based on the Green-Ampt assumptions for infiltration, which, with a significant depth of standing water (or head) on the soil, results in the equation

$$f = K_{sat}\left[\frac{(\theta_i - \theta_f)(\psi + h_0)}{F} + 1\right] \qquad (3)$$

where f = infiltration rate into the soil; θ_i = initial volumetric moisture content of the soil; θ_f = final volumetric moisture content of the soil (after infiltration); and F = cumulative depth of surface water infiltrated. The difference between the initial and final moisture content is often called the moisture deficit, $\Delta\theta$.

The model was developed to include a variable number of adjacent, equal surface area cells, each potentially having different Green-Ampt soil parameters (e.g., K_{sat}, $\Delta\theta$, and ψ). Such a scenario is represented in Fig. 1 with known soil properties at 10 spatially distributed areas represented by the hexagonal cells.

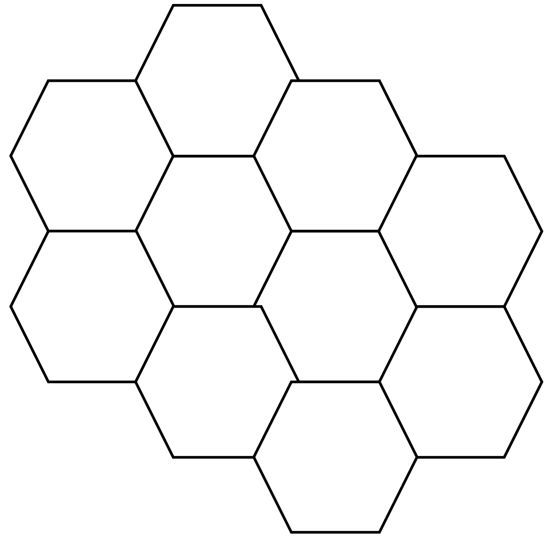

Fig. 1. Plan view of modeled stormwater control measure with 10 cells (18 to 37 cells were used in the modeling effort)

The model considered one-dimensional infiltration vertically downward into the soil through the surface of each cell. Infiltration into the sides of the SCM was not considered and lateral (i.e., horizontal) movement of infiltrated water was not considered. With these assumptions, the model allowed the user to input a starting value of water depth in the SCM (i.e., an initial value of h_0) as well as K_{sat}, $\Delta\theta$, and ψ values for each of the cells. Typical maximum design water depths in an infiltration basin are 0.61 m (2 ft) or more. For example, Wisconsin and New Jersey design guidelines specify a maximum depth of 0.61 m (2 ft), whereas Minnesota specifies 1.22 m (4 ft) (WI DNR 2004; NJ DEP 2009; Minnesota Stormwater Steering Committee 2005). Thus, the initial value of h_0 was set to 0.5 m, as it is slightly below a typical maximum water depth. The initial value of F for each cell could also be varied but was set to 5 cm to avoid division by zero and discretization errors in Eq. (3).

With soil properties and starting conditions known, a value of infiltration rate, f, was calculated for each cell using Eq. (3). With potentially different soil properties entered for each cell, each cell could have a distinctly different infiltration rate as compared to other cells. The infiltration rate for each cell was computed using explicit differences, and the total depth of infiltrated water below each cell was modeled by adding the total infiltrated depth of water over the time step to the value of F at the beginning of the time step. Due to differing infiltration rates into each cell, the model, in theory, would then have different depths of water over each cell at the end of the time step. At this point, the total volume of water remaining in the SCM that had not infiltrated was determined and this value was divided by the total SCM surface area to calculate a corresponding average depth of water, h_0. To account for the fact that the water depth over every cell will, in reality, always be equal, the head, h_0, on every cell within the SCM was set to h_0. Due to the fact that water would never be at different depths over different cells, care was taken to minimize this effect by keeping the time step relatively small and ensuring that each cell had equal values of h_0 at the start of every time step. The value of F for each cell, however, could vary because this value (after time equal to zero) was dependent on the soil properties of each cell. With every cell having equal values of h_0, the process was repeated for a total of 200 time steps with the duration of the time step adjusted so that no water remained in the SCM at the end of the last time step.

A sensitivity analysis into the effect of the size of the time step on the model results revealed that cutting the time step in half impacted the results (i.e., water surface elevations) by less than 2%, which was deemed an acceptable error. The model was applied to 12 sites for which sufficient Green-Ampt soil property data had been obtained. These sites will be discussed in detail in the following section.

In addition to the model that accounted for individual cells, the 1D Green-Ampt equation [Eq. (3)] was used to model each of the 12 SCMs as a single soil SCM using three different values of an overall effective saturated hydraulic conductivity in Eq. (3). This was done to investigate what single value of overall effective saturated hydraulic conductivity would yield results most similar to the multicell model. The single values investigated were (1) the arithmetic mean of the individual K_{sat} values; (2) the geometric mean (Anderson et al. 2014) of the individual K_{sat} values; and (3) a best-fit value of saturated hydraulic conductivity, $K_{best\text{-}fit}$, as found by minimizing the sum of the error squared between the model water elevations and the water elevations as found by Eq. (3) for each time step. The concept of the third item was to determine the relationship, if any, between $K_{best\text{-}fit}$ and individual spatially distributed K_{sat} values of the SCM that were assigned to the individual model cells. For each of these scenarios, the values of $\Delta\theta$ and ψ used in Eq. (2) were set equal to the arithmetic averages of the individual cells.

Sites Modeled and Data Collection

The 12 sites selected for these computations are listed in Table 1. They were chosen because they had a sufficient number of measurements, n, to justify an estimate of infiltration through the bottom of an SCM. Sites were selected if they had at least 18 measurement locations of Green-Ampt soil parameters at spatially distributed locations within the SCM.

All measurements of K_{sat} and ψ were made with MPD infiltrometers (Ahmed et al. 2014a), which utilize a falling head concept to allow multiple simultaneous measurements. Of the Green-Ampt equation soil parameters (i.e., K_{sat}, $\Delta\theta$, and ψ), values of K_{sat} have the largest potential variability. As noted previously, values of K_{sat}, even in close proximity to each other, have been found to vary by several orders of magnitude. Values of moisture deficit, $\Delta\theta$, can be no larger than the soil porosity, which has been shown to range from 0.4 to 0.5 (Rawls et al. 1983). If the soil is initially wet, $\Delta\theta$ could be reduced to any value less than the porosity, approaching zero. Values of soil suction at the wetting front, ψ, have been shown to range from ~5 cm (for sand) to ~32 cm (for clay) (Rawls et al. 1983). Ranges for values of $\Delta\theta$ and ψ are typically less than one order of magnitude. With values of K_{sat} ranging over several orders of magnitude, this variable has the largest potential to significantly affect modeled infiltration rates into the soils of SCMs. Thus, this investigation focuses on the variability of K_{sat} and the optimum value of $K_{best\text{-}fit}$. Sensitivity analysis of the model with varying values of $\Delta\theta$ and ψ over typical ranges were investigated, but, for reasons just described, this variation did not affect results to the same extent as varying K_{sat}. Thus, average values of $\Delta\theta$ and ψ were used when modeling the SCM with one overall effective value of K_{sat}.

Also listed in Table 1 for each site is the number of measurement locations, average ψ, average $\Delta\theta$, and the arithmetic mean and standard deviation of the spatially distributed K_{sat} values.

Results and Discussion

As previously discussed, the water surface elevations of each of the 12 sites were modeled with the multicell model. In the model, the Green-Ampt soil properties of each cell were set to correspond to the Green-Ampt parameters measured at different locations within the SCM. In addition to the multicell model, the water surface elevation of each site was modeled using a single overall effective value of K_{sat} in Eq. (3). Values used for the overall effective value of K_{sat} included (1) the arithmetic mean, (2) the geometric mean, and (3) $K_{best\text{-}fit}$ (found as previously described). Thus, the water surface elevation of each site was modeled four different ways, with the multicell model being the most accurate.

A typical set of the results for the four methods is shown in Fig. 2. The best-fit curve, which models the water surface over time with $K_{best\text{-}fit}$ and closely approximates the multicell model results, indicates that it is possible to accurately model infiltration into a SCM that has many highly spatially variable values of K_{sat} with a single overall effective value of saturated hydraulic conductivity, $K_{best\text{-}fit}$. In general, the geometric mean underestimates infiltration over time. The use of the geometric mean reduces the impact of the high K_{sat} cells but reduces the impact much more than indicated by the model. The use of the arithmetic mean overestimates infiltration

Table 1. Sites Selected for Computation of Water Surface Elevation from Measurements of Green-Ampt Parameters

Site	Type of SCM	n	Average ϕ (cm)	Average $\Delta\psi$	Arithmetic mean K_{sat} (cm/h)	Geometric mean K_{sat} (cm/h)	Best effective $K_{best\text{-}fit}$ (cm/h)
Cottage grove[a]	Bioinfiltration	20	19.5	0.20	18.5	16.0	16.9
Burnsville[a]	Bioinfiltration	20	26.0	0.20[b]	13.2	9.6	11.4
UM-St. Paul[a]	Bioinfiltration	37	97.1	0.21	2.9	0.9	1.5
UM-Duluth[a]	Bioinfiltration	18	36.7	0.17	9.2	1.7	4.3
Infiltration basin[c]	Infiltration Basin	33	29.0	0.11	14.1	6.8	8.3
HWY 51 north[d]	Swale	18	2.0	0.29	14.5	6.5	10.6
HWY 51 center[d]	Swale	18	11.4	0.25	6.57	2.97	4.07
HWY 51 south[d]	Swale	21	40.9	0.23	6.38	1.99	2.27
HWY 47[d]	Swale	21	20.7	0.21	20.6	11.5	14.2
HWY 212 east[d]	Swale	21	26.7	0.20	4.65	1.18	1.73
HWY 212 center[d]	Swale	21	32.8	0.20	2.50	0.44	0.78
HWY 212 west[d]	Swale	20	1.71	0.18	25.8	8.32	15.5

Note: n = number of spatially distributed K_{sat}, $\Delta\theta$, and ψ measurement locations at each site.
[a]Data from Asleson et al. (2007, 2009).
[b]Value is assumed (actual measurement unavailable).
[c]Data from Ahmed et al. (2014b, 2015).
[d]Data from Ahmed et al. (2011).

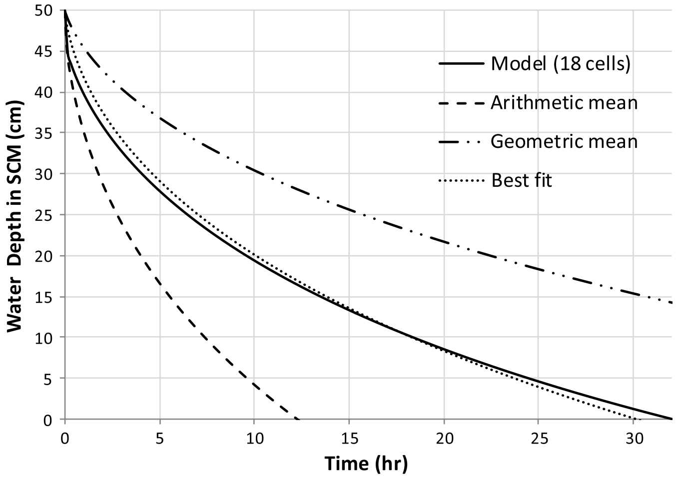

Fig. 2. Water surface elevations in the University of Minnesota-Duluth bioinfiltration practice as modeled by various methods

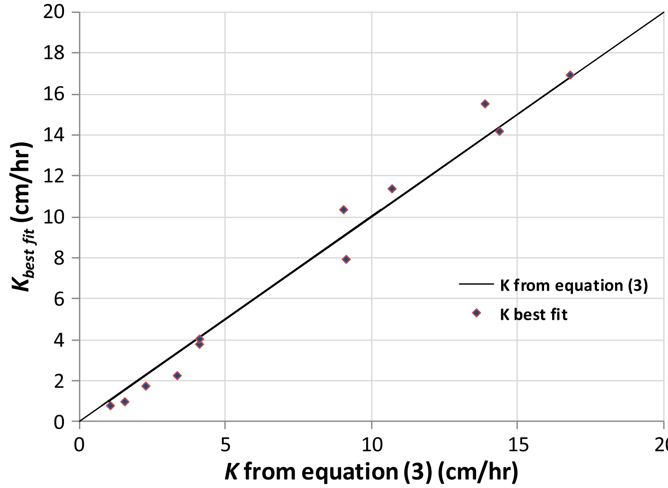

Fig. 3. Eq. (4) predictions versus individual $K_{\text{best-fit}}$ values for 12 modeled sites

into the SCM over time. As shown, the arithmetic mean results in a drain time of about 12 h, whereas the multicell model estimates the drain time to be approximately 32 h. In this case, the impact of high K_{sat} cells has not been reduced enough to accurately match the results of the multicell model. These trends were observed for all 12 sites.

The arithmetic mean, geometric mean, $K_{\text{best-fit}}$, the duration of the time step, and total modeling (or drain) time for each site are shown in Table 2. To determine if the mass (or volume) of water in the model was conserved, the average of the cells' cumulative infiltration depth, F, at the drain time was calculated. With all cells in the model having the same surface area, the average final infiltrated depth, if mass is conserved, is expected to be the total depth of water in the SCM at time zero (50 cm) plus the assumed depth of water already infiltrated at time zero (5 cm). In all scenarios, the average total depth infiltrated was found to be 55.0 cm, which confirms that water mass was conserved.

The results of modeling the water surface elevation over time using the arithmetic and geometric mean values of K_{sat} as an overall effective value suggests that some proportion of each mean may be used to estimate the optimum value of $K_{\text{best-fit}}$. This proportion may be estimated by using the 12 $K_{\text{best-fit}}$ values and performing a regression on the equation

$$K_{\text{best-fit}} = \beta K_{\text{Arit}} + (1 - \beta) K_{\text{Geo}} \quad (4)$$

Table 2. Time Step and Total Drain Time for Each Site

Site	Arithmetic mean K_{sat} (cm/h)	Geometric mean K_{sat} (cm/h)	$K_{\text{best-fit}}$ (cm/h)	Time step (h)	Drain time (h)
Cottage Grove	18.5	16.0	16.9	0.040	8.0
Burnsville	13.2	9.6	11.4	0.053	10.7
UM-St. Paul	2.9	0.9	1.5	0.300	59.4
UM-Duluth	9.2	1.7	4.3	0.160	32.1
Infiltration basin	14.1	6.8	8.3	0.100	20.2
HWY 51 north	14.5	6.5	10.6	0.092	18.4
HWY 51 center	6.57	2.97	4.07	0.185	37.0
HWY 51 south	6.38	1.99	2.27	0.212	42.4
HWY 47	20.6	11.5	14.2	0.048	9.6
HWY 212 east	4.65	1.18	1.73	0.380	76.8
HWY 212 center	2.50	0.44	0.78	0.773	154.6
HWY 212 west	25.8	8.32	15.5	0.068	13.6

where K_{Arit} = arithmetic mean; and K_{Geo} = geometric mean of the individual K_{sat} values, respectively. A regression on Eq. (4) was run with the resulting value of β equal to 0.32. The predicted versus the actual $K_{\text{best-fit}}$ values are shown in Fig. 3 ($R^2 = 0.984$, standard error = 0.723). For example, the $K_{\text{best-fit}}$ value for HWY 51 North was found to be 10.6 cm/h (Table 2) and Eq. (4) estimates the value of $K_{\text{best-fit}}$ to be 9.1 cm/h. This data point is found at a horizontal axis value of 9.1 cm/h and a vertical axis value of 10.6 cm/h. If Eq. (4) estimated all $K_{\text{best-fit}}$ values without any error, all data points would fall on the solid diagonal line.

The comparisons made herein provide insight into what is the most accurate overall effective saturated hydraulic conductivity value if an infiltration practice is to be modeled with a single overall effective value of saturated hydraulic conductivity, which is found by taking 0.32 times the arithmetic mean plus 0.68 times the geometric mean values of K_{sat}.

Summary and Conclusions

A model based on the Green-Ampt equation was developed to model one-dimensional vertical infiltration into a flat bottom SCM. The model accounted for different Green-Ampt soil parameters (i.e., K_{sat}, ψ, and $\Delta\theta$) at spatially distributed locations within the SCM. Twelve SCMs for which Green-Ampt parameters were measured at spatially distributed locations were modeled. The soil properties at each measurement location were represented by a different cell in the model.

Results were used to determine the accuracy of assuming the SCM was a single cell (i.e., single soil) infiltration device with one overall effective value of saturated hydraulic conductivity. Results showed that use of the geometric mean consistently underestimated infiltration, use of the arithmetic mean consistently overestimated infiltration, and the most accurate approximation of the best single overall effective saturated hydraulic conductivity, $K_{\text{best-fit}}$, is given by the weighted sum of 32% of the arithmetic mean and 68% of the geometric mean of the spatially distributed K_{sat} values measured within the SCM.

Thus, it can be concluded that when modeling an infiltration-based SCM, multiple soil measurements should be made to accurately represent the soil properties throughout the SCM. The SCM can be modeled as a single-cell, one-dimensional infiltration device using a value of $K_{\text{best-fit}}$ as estimated by Eq. (4). This approach will incorporate the spatial variability of K_{sat} throughout the SCM while providing a simple and quick estimate of drain time.

Notation

The following symbols are used in this paper:

A = area over which flow occurs;
d = total vertical thickness of layers through which vertical infiltration is to be modeled;
d_i = vertical thickness of one horizontal layer (of multiple layers) through which vertical infiltration is to be modeled;
F = cumulative depth of surface water infiltrated;
f = infiltration rate;
h_0 = piezometric head of water above soil;
$\bar{h}_0$ = average piezometric head of water above soil;
K_{Arit} = arithmetic mean of spatially distributed saturated hydraulic conductivity values;
$K_{best\text{-}fit}$ = best-fit overall effective soil saturated hydraulic conductivity;
K_{Geo} = geometric mean of spatially distributed saturated hydraulic conductivity values;
K_i = saturated hydraulic conductivity of one horizontal layer (of multiple layers) through which vertical infiltration is to be modeled;
K_{sat} = soil saturated hydraulic conductivity;
L = assumed thickness of saturated soil;
n = total number of layers through which vertical infiltration is to be modeled;
Q = total flow rate;
z_w = head of water on the soil;
θ_f = final volumetric moisture content;
θ_i = initial volumetric moisture content;
$\Delta\theta$ = moisture deficit; and
ψ = soil capillary suction at the wetting front (a positive value).

References

Ahmed, F., Gulliver, J. S., and Nieber, J. L. (2011). "Performance of low impact development practices on stormwater pollutant load abatement." *SAFL Project Rep. No. 560*, Univ. of Minnesota, Minneapolis.

Ahmed, F., Gulliver, J. S., and Nieber, J. L. (2015). "Field infiltration measurements in grassed swales." *J. Hydrol.*, in press.

Ahmed, F., Nestingen, R., Nieber, J. L., Gulliver, J. S., and Hozalski, R. M. (2014a). "A modified Philip-Dunne infiltrometer for measuring the field-saturated hydraulic conductivity of surface soil." *Vadose Zone J.*, 13(10), in press.

Ahmed, F., Natarajan, P., Gulliver, J. S., Weiss, P. T., and Nieber, J. L. (2014b). "Assessing and Improving Pollution Prevention by Swales." *Final Rep. 2014-30*, Research Services and Library, Office of Transportation System Management, Minnesota Dept. of Transportation, St. Paul, MN.

Anderson, D. R., Sweeney, D. J., Williams, T. A., Camm, J. D., and Cochran, J. J. (2014). *Statistics for business & economics*, 12th Ed., South-Western Cengage Learning, Independence, KY.

Asleson, B. C., Nestingen, R. S., Gulliver, J. S., Hozalski, R. M., and Nieber, J. L. (2007). "Development and application of a four-level rain garden assessment." *St. Anthony Falls Laboratory Project Rep. 494*, Univ. of Minnesota, Minneapolis.

Asleson, B. C., Nestingen, R. S., Gulliver, J. S., Hozalski, R. M., and Nieber, J. L. (2009). "Performance assessment of rain gardens." *J. Am. Water Resour. Assoc.*, 45(4), 1019–1031.

Dingman, S. L. (2002). *Physical hydrology*, 2nd Ed., Waveland Press, Long Grove, IL.

Erickson, A. J., Weiss, P. T., and Gulliver, J. S. (2013). *Optimizing stormwater treatment practices: A handbook of assessment and maintenance*, Springer, New York.

Freeze, R. A., and Cherry, J. A. (1979). *Groundwater*, Prentice-Hall, Englewood Cliffs, NJ.

Logsdon, S. D., and Jaynes, D. B. (1996). "Spatial variability of hydraulic conductivity in a cultivated field at different times." *Soil Sci. Soc. Am. J.*, 60(3), 703–709.

Minnesota Stormwater Steering Committee. (2005). "The Minnesota stormwater manual." Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN.

NJ DEP (New Jersey Department of Environmental Protection). (2009). "New Jersey stormwater best management practices manual." Trenton, NJ.

Olson, N. C., Gulliver, J. S., Nieber, J. L., and Kayhanian, M. (2013). "Remediation to improve infiltration into compact soils." *J. Environ. Manage.*, 117, 85–95.

Pitt, R., Chen, S., Clark, S. E., Swenson, J., and Ong, C. K. (2008). "Compaction's impact on urban storm-water infiltration." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)0733-9437(2008)134:5(652), 652–658.

Prince George's County. (2000a). "Low-impact development analysis." Dept. of Environmental Resources, Programs and Planning Division, Largo, MD.

Prince George's County. (2000b). "Low-impact development design strategies." Dept. of Environmental Resources, Programs and Planning Division, MD.

Rawls, W. J., Brakensiek, D. L., and Miller, N. (1983). "Green-Ampt infiltration parameters from soil data." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1983)109:1(62), 62–70.

U.S. EPA (United States Environmental Protection Agency). (2000). "Stormwater phase II final rule, small MS4 stormwater program overview." *EPA 833-F-00-002*, Washington, DC.

WI DNR (Wisconsin Department of Natural Resources). (2004). "Storm water post-construction technical standards." Madison, WI.