# MODELING INFILTRATION IN A STORMWATER CONTROL MEASURE USING MODIFIED GREEN AND AMPT

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ABSTRACT

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Accurate predictive models of infiltration in stormwater control measures (SCMs) are not readily available. While it is common to model infiltration at the watershed level using stochastic models such as the SCS Curve Number Method, stochastic models require a lot of data to develop, and unfortunately that data is not available or has not been processed for SCMs. Physics-based models (solutions to the Richards equation) are desirable, however they are too complex to parameterize and can tend to increase computational times. The Green and Ampt solution of the Richards equation is a physics-based solution that is appropriate for infiltration where standing water is not present, and it is easy to parameterize and simple to solve because of the approximations made to develop the solution. This has been recognized and Green and Ampt has been made available for use in EPA's Stormwater Management Model (SWMM) for storage basin nodes, which can be used to model SCMs.

However, the Green and Ampt model used for watersheds has two major shortcomings when used to model an SCM: the SCM has a 2- or 3-dimensional shape that affects the infiltration rate, and engineered soil layers add an important dimension to the performance. In SCM models, the

importance of infiltration variability is increased because inflow rates can be an order of magnitude higher than rainfall alone, and pond emptying time is an important variable. To rectify these shortcomings, additions were made to the Green and Ampt model to account for the shape of the basin and the depth of water therein, soil layering, and the variability of infiltration due to temperature (other variabilities from storm size and soil wetness are inherent in the Green and Ampt solution).

This modified Green and Ampt model was correlated against data from two distinct bioinfiltration rain gardens on Villanova University's campus, showing that the model is able to predict the infiltration proces over a wide range of conditions. Data from the sites were analyzed to show that about half of the natural variability of infiltration rates comes from a combination of storm size and temperature variation, and the rest of the variability is from soil moisture conditions. The correlations also produced a lower-bound distribution of soil moisture conditions, showing that typical values for Green and Ampt infiltration parameters are conservative engineering estimates ($95^{th}$ percentile conservative) for the sites analyzed. Therefore, this study concludes that the Green and Ampt method, once modified to account for temperature dependence, soil layers, and water depth and shape dependence, is complete and accurate for use in predicting infiltration rates in SCMs, especially for conservative soil moisture conditions. It is recommended that these modifications be incorporated into the USEPA SWMM program for widespread use.

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# 1. INTRODUCTION

With large areas of impervious surfaces generating unnaturally high stormwater runoff, it is common to see stormwater control measures (SCMs) constructed to mitigate the effects of the increased runoff. Past practices were primarily designed to control the peak flows into sewer systems and the adjacent natural watershed. Awareness of non-point source pollution, stream channel erosion, and groundwater depletion are among the reasons that advanced understanding and increased functionality of SCMs is now desirable. One such area of research is increasing our understanding of the infiltration process in SCMs. A better understanding of this process would have several beneficial effects: cost reductions due to better design (choosing an optimal soil and configuration, requiring an appropriate capacity due to infiltrated volumes); policy changes to allow for "dynamic" routing of stormwater, evapotranspiration, and groundwater recharge; and increased understanding of SCM longevity. The present movement toward low impact development (LID) and green infrastructure (GI) – with its focus on volume control and infiltration – makes a physics-based modeling approach essential.

Villanova University is among the leaders in stormwater control measure research. The Villanova Urban Stormwater Partnership (VUSP) has received funding and support for several research-oriented SCMs on campus: three bioinfiltration rain gardens (Heasom et al, 2006), a bioretention rain garden, a green roof (Feller et al, 2010), an infiltration trench (Emerson et al, 2010), a stormwater wetlands (Burke and Wadzuk, 2009), several porous asphalt/concrete sites (Kwiatkowski et al, 2007), and more. Research on these sites provides several years of continuous data that can be used to study the infiltration process (e.g. Braga et al, 2007). The focus of this thesis will be on the bioinfiltration rain gardens, although the same principles should apply to any stormwater infiltration basin that is not permanently ponded. A rain garden is a storage depression created to catch, hold, and then infiltrate stormwater runoff, usually with an overflow bypass.

Until recently, there were very few options available to model infiltration within an SCM. Within popular hydrologic models such as SWMM and HEC-HMS, it has been feasible only to supply the model with a constant-rate infiltration, and even this might need to be done by adding in an "outflow device," rather than an option to supply the infiltration rate. As recently as April of 2009, USEPA SWMM (Rossman, 2010) was altered to adopt the Green and Ampt infiltration model for storage basins. However, this poses several questions: is Green and Ampt appropriate to model an infiltration basin? Will it give good results? Under what conditions does it produce good results? Is there a better model to use? There is a dearth of research available showing infiltration in SCMs; both the actual performance over time and the correlation of models. Some of the potential problems with Green and Ampt are that it does not capture any of the natural variability that occurs in a physical system, it is a one-dimensional model and many infiltration basins are not one-dimensional, and many infiltration basins do not have a single homogenous soil layer. After exploring the state of the science in Section 3, Literature Review, this thesis will present the Green and Ampt infiltration model with some modifications to try and make it more suitable for modeling an infiltration basin. Then, the sensitivities of the model will be explored, and the model will be correlated to data from two of Villanova University's bioinfiltration rain gardens. These two rain gardens are sufficiently different in soil type and configuration so that the model will be correlated to a range of conditions. This study will help determine the suitability of Green and Ampt for infiltration basins, provide guidelines for its use, and highlight the variability that soil moisture plays in the infiltration process.

# 2. PROBLEM STATEMENT

There is not a well-documented and practical model for infiltration in a stormwater control measure (SCM). The Green and Ampt model is a practical, physics-based solution that has been made available for storage basins within the USEPA SWMM model, however there is little or no research available to determine if and how Green and Ampt should be used in that regard. Additionally, the Green and Ampt method does not model all of the important physical processes in an SCM – namely temperature variation, depth of water and its spatial variability, and soil layering. It would benefit the field of stormwater modeling to modify the Green and Ampt method to encompass these processes, and to show that the model works for real SCMs.

## 3. LITERATURE REVIEW

In 1983, the US Environmental Protection Agency (EPA) released the results of the Nationwide Urban Runoff Program. This study suggested that "infiltration can be very effective in controlling both urban runoff quality and quantity problems. This strategy encourages infiltration of urban runoff to replace the natural infiltration capacity lost through urbanization and to use the natural filtering and sorption capacity of soils to remove pollutants" (Pitt, et al. 1999). Since then, stormwater control measures have become more common and modeling of stormwater for research and design is commonplace. The modeling design tools are, however, rapidly evolving and span a wide range of complexities and model types. The most simple are single parameter models, but because of rapidly advancing computer resources, "it is tempting to model at ever-increasing resolution and comprehensiveness" (NRC, 2009, p251). However, increasing resolution and comprehensiveness generally results in models that cannot be used effectively by design engineers. The NRC review committee notes this tradeoff and the debate that "exists within the literature as to the relative advantages of detailed process-based models that may not have adequate information for parameterization, and the more empirical, data-based approaches" (NRC, 2009, p270). What can be said for certain about stormwater design was concisely summarized by Burian et al (1999): "user-friendly design methods and tools are required."

The need for user-friendly design methods is where necessity meets reality. The research community is so far unable to develop usable, accurate, process-based infiltration models to fit into an integrated urban stormwater analysis. Graham (2004) confirms that "two inter-related challenges need to be overcome to enable more widespread application of low impact development (LID) approaches. The first is the lack of models that are developed specifically to address LID hydrology. The second challenge is the need to shift the earlier emphasis on peak flow control to volume control." The NRC committee recognizes this need to "extend, develop, and support current modeling capabilities, emphasizing… more mechanistic representation of stormwater control measures. … Emerging distributed modeling paradigms that simulate interactions of surface and subsurface flow paths provide promising tools that should be further developed and tested for applications in stormwater analysis" (NRC, 2009, p277). Infiltration SCMs are difficult to model not only because of the increased complexity over watershed areas (if not increased heterogeneity), but also because the use of an infiltration SCM model must fit within the framework of continuous simulation, which "was determined to be the most satisfactory method for urban drainage design" (Burian et al, 1999). This sentiment is echoed by the NRC council, who say that "event-based modeling is inappropriate for water quality purposes because it will not reproduce the full distribution of receiving water problems" (NRC, 2009, p255). Infiltration is unquestionably easier to model for a single-event design storm, since infiltration is highly dependent on antecedent soil moisture and atmospheric conditions, which are difficult to represent over a continuous simulation model. Once again, the need for the continuous simulation infiltration model is countered by the usability factor; the NRC council suggests that for such models "data and information requirements are typically high, and a level of process specificity may outstrip the available information necessary to parameterize the integrated models" (NRC, 2009, p264). In other words, even if an accurate continuous flow model exists for infiltration SCMs, it is necessary that they be sufficiently simple to be usable.

At the 2005 World Water Congress, Lucas (2005) summarized the state of available software for evaluating runoff in SCMs and in "low-impact design runoff management practices" (or LID SCMs). Lucas (2005) notes that heavily used continuous simulation models such as SWMM are not capable of accounting for volume reduction caused by infiltration SCMs, which he cites as being "increasingly recognized as being perhaps the most important element of [SCM] design," even more so than event-mean concentration reduction. According to Dietz (2007), "engineers are using models like RECARGA, WinSLAMM, and P8 to design LID practices, although they may use another model such as SWMM for hydraulic routing on the site." Elliott and Trowsdale (2007) presented a review of the 10 most commonly used models for LID stormwater control design. They confirmed that the models either include infiltration through an outflow device (difficult to parameterize), or the timestep is too coarse for accurate flow predictions. Lucas (2005) goes on to show the "disconcerting gulf between what is needed, and what has actually been achieved in the LID modeling field in [the regard of volume reduction]." One major problem is computing the infiltration in SCMs. Lucas (2005) describes the most advanced LID SCM model – the Delaware Urban Runoff Management Model (DURMM) – which has been used in Delaware. Unfortunately, the infiltration capability for infiltration basins in this model has not advanced beyond a constant-rate infiltration. Lucas (2005) finishes by recommending to the World Water Congress that these models such as DURMM be upgraded to include a physically based infiltration algorithm to better predict volume losses in LID SCMs. In response to this void in modeling tools, SWMM recently (2009) included Green and Ampt as an infiltration option within a storage basin. To be precise, the original Green and Ampt solution neglects ponding head as a term in the solution and assumes constant rainfall. Philip (1954, 1993) solved the variable head ponding and variable rainfall problems, which is actually what is programmed into SWMM. However, following convention, the Philip's solution is referred to as Green and Ampt.

There are two classes of infiltration models: stochastic and physics-based models. For stormwater control measures, the stochastic models are limited to constant-rate infiltration; other stochastic models like the SCS Curve Number method for watersheds have not yet been derived for SCMs. Many recent studies have used constant rate infiltration: Lee et al (2006) for highway BMPs, Heasom et al (2006) for a bioinfiltration rain garden, and on the planning scale Williams and Wise (2006) who tried to modify the soil moisture accounting (SMA) method in HEC-HMS to represent the capacity of the soil to infiltrate and store water. Constant rate infiltration is simple to implement and understand, however without having a physics-based infiltration theory, knowing the infiltration rate would be impossible without field data of the site under study or a similar SCM. The problem is, as noted by Roy et al (2008), "many planners and engineers remain skeptical of results from different regions with similar climate and soil conditions." That is, there is resistance by planners to incorporate design strategies based solely on similarity assumptions. Stating a constant infiltration rate falls into such a category, and so is not an effective design strategy. Engineers and planners need physics-based solutions to their design problems.

Physics-based infiltration models rely on a solution to the Richards equation. The Richards equation is a partial differential equation to solve for the water content throughout a volume of soil. The one-dimensional form of the Richards equation is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial \psi(\theta)}{\partial z} + 1\right)\right]$$

Where conductivity (K) and matric suction ($\psi$) are functions of soil moisture ($\theta$) depending on the soil type. To solve the equation, detailed soil properties must be known that are generally not available to an engineer, and the computational power required to solve the equation would dominate runtimes in larger watershed models. As such, despite the fact that there are programs available to model infiltration using the Richards Equation such as “RECHARGE” (Dussaillant et al, 2004), it is doubtful that these models will ever be practical for widespread use even if computers speed up greatly due to the difficulty in correctly parameterizing the models. Because a physics-based model must solve the Richards equation, the only other option available is the Green and Ampt method, which is an analytic solution to the Richards equation that makes the approximation that the wetting front of the infiltrating water column is sharp. Thus, the Green and Ampt method is inherently limited to areas where the water table is sufficiently below the soil surface to allow for vertical infiltration. Here is the Green and Ampt equation in a common form:

$$f(t) = K\left[\frac{\psi\Delta\theta}{F(t)} + 1\right]$$

K and ψ are now constants, Δθ is a constant for initial soil moisture deficit, f(t) is the infiltration rate, and F(t) is the infiltrated volume of water. Because this is not a spatially varying equation, it can be solved easily.

Dussaillant et al (2005) later introduced “RECARGA,” a simpler form of their infiltration basin model that uses Green and Ampt instead of the full Richards equation solution. By comparing RECHARGE to RECARGA, they showed that in general, Green and Ampt is sufficient for modeling an infiltration in a stormwater control measure. Unlike SWMM, RECARGA has an option to model several soil zones, however RECARGA is limited by only using Curve Number watershed hydrology, and by modeling the infiltration basin as a constant-area structure (the basins have no shape). The Green and Ampt solution has also been used recently to study ponding in irrigation basins and wetlands (Loáiciga and Huang, 2007), although very few if any other studies have been done for stormwater infiltration.

One problem with Dussaillant's analysis of the Green and Ampt method is that they did not study the effect of pond shape, and Green and Ampt is a one-dimensional model. This may be a good approximation for many infiltration devices, however, the solution form needs to be able to accommodate the shape of the infiltration basin if that is an important factor. Because the infiltration rate is dependent on the ponded depth, the depth needs to be accurately represented; a real basin seldom has a flat bottom, so the depth varies considerably across the basin. Warrick et al (2005) did some analysis to study the effect of using an average depth vs. the variable depth in an irrigation basin. They found that in terms of total infiltrated volume, the difference was not considerable; however, those results were only for sandy soil, and they did not consider the effect on peak depth, which might be important in stormwater management. Further study is necessary to determine the importance of basin shape in infiltration.

If Green and Ampt is to be used for modeling infiltration, the natural variability of infiltration must also be considered. Two of the main drivers of variability are temperature and antecedent moisture conditions. The importance of temperature has recently come into view as infiltration rates in an infiltration basin have been observed to vary by over a factor of two with temperature (Braga, et al, 2007). It is also known that infiltration rates are highly dependent on antecedent soil moisture conditions (SMC) (Castillo et al, 2003). Although the soil moisture is an input variable in the Green and Ampt method, there is no widely used method for determining the antecedent moisture conditions via physically derived water budget methods. For watershed runoff, there exist some stochastic methods for determining antecedent conditions, many contained within the Curve Number methodology (Lamont et al, 2008; Mishra and Singh, 2004; Kannan et al 2008). But as mentioned earlier, stochastic methods for watershed runoff cannot be assumed to work for infiltration basins. Physics-based water budget methods for determining antecedent conditions are difficult because they must necessarily track both evapotranspiration and deep percolation. To add these components to the Green and Ampt infiltration model would greatly increase the amount of information necessary to parameterize the model and thus may never be feasible.

Calder et al (1983) reviewed some of the early soil moisture deficit models with comparisons to daily data using neutron probes from several field plots in the United Kingdom. As this information was primary used for agriculture instead of for infiltration modeling, these early models consist only of the rainfall and actual evapotranspiration (ET). The actual ET is predicted based on a potential ET model and a "root constant" function. The conclusions of this study are a precaution that more data is not always better: the mean climatological potential ET function performed better in all years than local, daily, climatological models. This is good news, because a mean climatological model would be easy to implement into a design model, and the user would not have to worry about parameterizing ET. Later, more complete water balance equation (WBE) models were introduced to track the SMC. These models track rainfall, runoff, ET, soil storage, and deep percolation (DP). Karnielli and Ben-Asher (1993) present a WBE based model that is more stochastic than physical, making it a good starting point but not quite usable for an engineer. Liu et al (2006) more recently reviewed and tested some parametric (that is, stochastic) deep percolation models. Brocca et al (2008) present a complete WBE based SMC model that uses the Green and Ampt infiltration equation, although the matric suction was considered an independent variable and not calculated from the SWCC. This model showed very good agreement to SMC over simulation periods of one year. Brocca used a simple, quasi-physics-based estimate of deep percolation: using the unsaturated hydraulic conductivity as defined by Brooks and Corey (1964). Compared to one of the simple stochastic DP models

(Georgakakos and Baumer 1996), the authors did conclude that a physics-based DP equation was a necessity to capture the quick percolation immediately after a storm, and the significant tailing off of the percolation rate afterward. A limitation of this model for practical use is that the soil was represented as one layer, and this method is dependent on the soil zone thickness. This dependence on the soil zone thickness leaves a stormwater engineer with the need to parameterize a variable that is not based on a physical property; this defeats the purpose of the proposed model.

The "simple" options for deep percolation are limited in the literature to either a stochastic equation (Karnielly and Ben-Asher, 1993; Liu et al 2006) or estimating the flux as the unsaturated hydraulic conductivity (Dussaillant et al, 2003; Brocca et al, 2008). The more accurate option is to solve the Richards equation for the soil profile between the surface and the groundwater table. This is inherently taken care of with a full Richards equation infiltration model, such as RECHARGE (Dussaillant, 2004). There are three main reasons why using the Richards equation in a practical model is not effective: one is computational cost; two is ability to parameterize (both SWCCs and evapotranspiration); and three is over-parameterization (the soil properties are not known to that level of detail anyway). However, the deep percolation estimates based on unsaturated conductivity already make use of the SWCC, so that requires the same level of parameterization – although, depending on the use of the curve, different tolerances can be allowed for its accuracy (Fredlund, 2006). In other words, the SWCC needs to be known to greater precision to solve the Richard's equation than to use a Green and Ampt model. A potential solution to the other problems might be adapted from the work of Ross (2003). Ross presented a computationally fast solution to the Richards equation; rather than solving the Richards partial differential equation for the soil water profile, the fast solution solves a mass balance between only a few (order 10) soil zones. This idea has the potential to help solve the computational time problem: the Richards equation is based on Darcy's law combined with mass balance; Ross' solution is the same principle, but on a much "coarser" scale, and one that does not require heavy discretization. The downside is accuracy, but Ross showed that results comparable to the full Richards solution could be achieved with a solution time increase of about 25-50 times: quite a significant increase. Potentially, with such a fast solution method, this could be used for the ponded infiltration solution. However, in that case, the necessary level of confidence in the SWCCs will increase (Fredlund, 2006), and the solution will end up being somewhat slower than the solution to Philip's equation. Still, by selecting this type of soil-moisture accounting modeling approach, the solution becomes dependent on soil atmospheric boundary conditions and discretization, which significantly decrease user-friendliness.

Finally it should be noted that accurate, process-based soil moisture accounting on the scale of a stormwater control measure is extremely difficult due to the nature of the dominant physical processes: primarily evapotranspiration and unsaturated water flow. In fact, in the original release of the National Engineering Handbook, NEH-4, (NRCS 1993), the curve number hydrology method accounted for antecedent moisture conditions I, II, and III (dry, normal, and wet conditions as determined by 5-day antecedent rainfall). However, in the most recent release (NRCS 2004), this notion has been abandoned because this classification over-simplifies the situation, and in fact the infiltration is not a strong function of antecedent 5-day rainfall. The present recommendation by the NRCS is to note the variability in infiltration rates, and consider the variability random. This might be in fact the best possible solution, but even random variables must be parameterized based on physical principles in order to be correct. Therefore, it is not likely that soil moisture accounting will be a viable option for a practical model. Since stochastic models need more data than is available to develop, and the best physics-based models are too difficult to parameterize, this leaves Green and Ampt (without soil moisture accounting) as the best available solution framework to the infiltration basin model. Because soil moisture accounting is not very practical, this leaves the question of how to use the model in continuous flow.

# 4. METHODS

## 4.1. Infiltration Model

Commonly referred to as the Green and Ampt method, Philip (1993) developed a solution to the variable head ponded infiltration problem for a one-dimensional area with variable rainfall using the assumption of delta function potential (sharp wetting front), and conservation of mass:

$$\frac{dF}{dt} = K\left(1 - \Delta\theta + \Delta\theta \frac{\psi + R(t)}{F}\right) \tag{1}$$

Where F is the infiltrated water volume (length), K is the mean hydraulic conductivity (length/time), Δθ is the soil moisture deficit $\theta_{saturated}$-$\theta_{initial}$, $\psi(\theta)$ is the matric suction (length), and $R(t)$ is the amount of rainfall prior to time $t$ (length). To adapt this equation to an infiltration basin, the rainfall term must be replaced with the net volume ($V_{net}$) from all sources. From a simple water balance, $V_{net}$ = R + I – E – Q, where R is the cumulative rainfall directly on the pond area, I is the cumulative inflow volume (length) from runoff, E is the cumulative evaporated depth, and Q is the cumulative outflow volume (length). The total water balance for the pond is R + I = F + E + Q + D, where D is the depth of water in the pond (inflows R and I = outflows F, E, and Q + storage D). The water balance equation can be substituted into (1) to make D the primary variable of interest, rather than F (this substitution becomes necessary for accurate numerical solution because several variables – I, Q, Area, and F – are functions of D). Time derivatives of water volumes are denoted with lower case letters.

$$r + i - e - q - \frac{dD}{dt} = K\left(1 - \Delta\theta + \Delta\theta \frac{\psi + R + I - E - Q}{R + I - E - Q - D}\right) \tag{2}$$

If the soil parameters, rainfall, inflow, outflow, and evaporation are known, (2) can be solved for D(t) numerically. However, the assumption is that the pond has uniform depth over the entire surface, whereby it is trivial to convert inflow and outflow volumes (length$^3$) into depths (length). Additionally, the equation is not equipped to handle infiltration over a 2 or 3 dimensional area (it assumes an infinitely large, 1-D area). Because many infiltration devices are bowl-shaped – and not infinitely large – it is desirable to modify (2) to be used to solve for the total depth in the pond, assuming that the inflow *volume* hydrograph (length$^3$) is known.

## 4.2. Basin Shape Dependence

The shape of the basin affects the mean infiltration rate in three distinct ways: through infiltrating area, through variable depth head, and through variable infiltrated water length (F). The latter means that F will be largest at the lowest area of the pond and smaller out at the edges. In the Green and Ampt model, the assumption must be made that F is the same at all ponded areas, or an analytic solution would not be possible. The only way to include this effect in the model would be to discretize the equation into 2 dimensions, which would increase the computational time and complexity of the model. Therefore, this effect is ignored. The second effect, that of basin area, refers to the nature of the total infiltrated volume being infiltration rate*area (length/time*length$^2$ = volume/time). This consideration does not appear in watersheds where the area is a constant, however in infiltration basins the infiltrating area generally increases with depth. All that is needed to add this effect is a function or table for depth versus area. The current implementation of Green and Ampt in SWMM has this feature. Finally the third way that shape affects infiltration is in depth. SWMM currently uses the peak depth as the head term in equation (1) (head is added to the matric suction term), however, it would be more accurate to account for the variable head throughout the pond area.

To develop the modification to equation (2) for the shape of the bowl, the bowl can be discretized into a series of "rings" of constant elevation (Figure 4.1). An approximation that must be made is that infiltration occurs in one dimension (vertically downward) over the entire area. The $i^{th}$ ring has an area $A_i$, a depth $D_i$, an infiltrated volume $F_i$, and an elevation above the bottom surface of the device, denoted $y_i$. Because the water surface in the pond will always equalize to a flat surface, $D_i + y_i$ is a constant for each ring, so $D_i + y_i = D$. Water budget parameters without a subscript refer to their values at the deepest point.

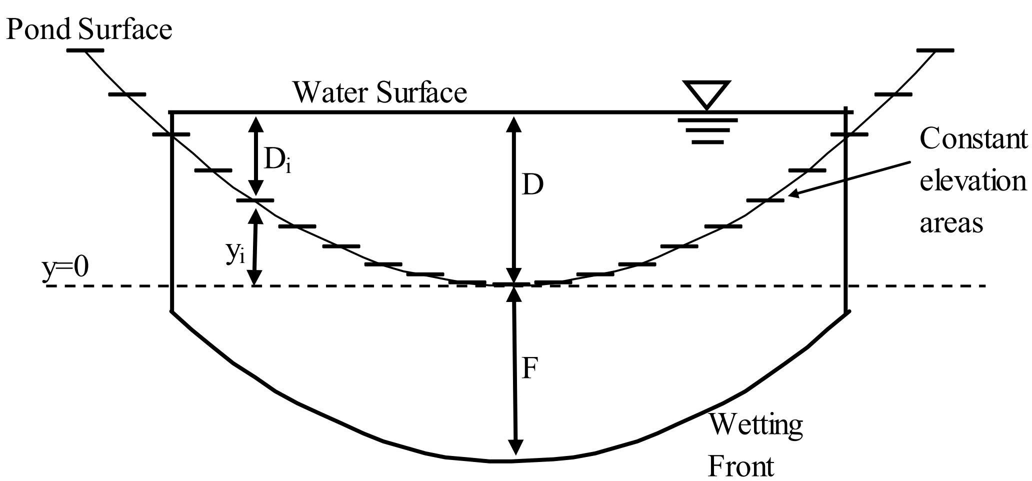


Figure 4.1 Discretization of infiltration bowl geometry.

By making the approximation that the water surface instantaneously redistributes to form a level surface, the pond mean infiltration rate is equal to the area-average infiltration rate:

$$\frac{dF_{pond}}{dt} = r + i - e - q - \frac{dD}{dt} = \frac{\sum_i A_i \frac{dF_i}{dt}}{A} \quad (3)$$

And so, combining equations (2) and (3) gives:

$$\frac{dD}{dt} = r + i - e - q - \frac{1}{A}\sum_i A_i K\left(1 - \Delta\theta + \Delta\theta\frac{\psi + (R + I - E - Q)_i}{(R + I - E - Q - D)_i}\right) \tag{4}$$

The summation in equation (4) can be simplified to an analytic expression if one important assumption is made: that at all times, the infiltrated depth $F_i$ is the same at all differential areas that are ponded. In other words, the wetting front below the ponded area has the same shape as the bowl. Because $F_i = F_j$, the water balance shows that $(R + I – E – Q)_i – D_i = (R + I – E – Q)_j – D_j$ for all areas i, j. Because depth and elevation are related, this can be rewritten as $(R + I – E – Q)_i + y_i = (R + I – E – Q)_j + y_j$. These relationships among the infiltration rings also apply to the area at the deepest point in the pond – whose values are denoted without a subscript – so $I_i$, $E_i$, $Q_i$, and $D_i$ can all be related to I, E, Q, and D at the deepest point. This will allow for the total (peak) depth of the pond, D, to be the primary unknown variable in equation (4):

$$\frac{dD}{dt} = r + i - e - q - \frac{1}{A}\sum_i A_i K\left(1 - \Delta\theta + \Delta\theta\frac{\psi + (R + I - E - Q) - y_i}{(R + I - E - Q - D)}\right) \tag{5}$$

Variables without a subscript i are not functions of the area i, so these can come out of the sum:

$$\frac{dD}{dt} = r + i - e - q - K\left(1 - \Delta\theta + \Delta\theta\frac{\psi + (R + I - E - Q) - \frac{1}{A}\sum_i A_i y_i}{(R + I - E - Q - D)}\right) \tag{6}$$

The last term in the numerator of equation (6) is the area-averaged bowl surface elevation (denoted $\bar{y}$), and is a function of depth that can be computed easily if the area versus depth is known for the pond (note that D minus $\bar{y}$ is equal to the average depth $\overline{D}$). So, the summation in equation (6) can be eliminated:

$$\frac{dD}{dt} = r + i - e - q - K(1 - \Delta\theta) - K\Delta\theta\frac{\psi + (R + I - E - Q) - \bar{y}(D)}{(R + I - E - Q) - D} \tag{7}$$

The form in equation (7) has yet to address the problem of how inflows, evaporations, and outflows should be expressed as a length (measured from the deepest point), given the variable pond geometry. The evaporation rate $e = e(t)$ is not a function of depth or surface area, so the expression for E over the deepest point is:

$$E(t) = \int_0^t e(t)dt \tag{8}$$

If the total evaporated volume (in length$^3$) is a desired quantity, tracking the integral of $e \cdot A$ over time would be necessary. In general, evaporation rates during a storm event will be small compared to infiltration rates, so they can often be ignored.

Generally, the inflow volume will be known from the inflow hydrograph in terms of volumetric flow rate $v_{\mathrm{in}}$ (length$^3$/time), plus the rainfall rate $r$ in length/time. The outflow rate $q$ is typically also known as a volumetric flow rate $v_{\mathrm{out}}$, and for most storage/outflow devices, $v_{\mathrm{out}}$ is a function of the depth D (e.g. the outflow might pass over a weir). Therefore, $q$ and $i$ are:

$$i = \frac{v_{in}(t)}{A(D)} \quad \text{and} \quad q = \frac{v_{out}(D)}{A(D)} \tag{9), (10}$$

I and Q are the time integrals of $i$ and $q$. However, since D = D(t), these integrals become:

$$I(t) = \int_0^t \frac{v_{in}(t)}{A(D(t))}dt \quad \text{and} \quad Q(t) = \int_0^t \frac{v_{out}(D(t))}{A(D(t))}dt \tag{11), (12}$$

Now, I, E, and Q and their time derivatives are either known functions of time, or functions of time and depth, so equation (7) can be solved for D(t). This solution will in general not be analytic, so equation (7) must be solved numerically. Preliminary studies with data from Villanova's bioinfiltration rain garden showed that a 5 minute timestep is too long for a 2$^{\mathrm{nd}}$ order implicit integration scheme, for high intensity storms. A 4$^{\mathrm{th}}$ order Runge-Kutta integration with variable timestep appears to be the most computationally-efficient solution method. When programming the equation, great care must be taken to account for several of the variables which are functions of depth, not time. The explicit Runge-Kutta solution form is seen in equation (13), which is a function of four other functions $F_1$ through $F_4$ that evaluate the differential equation at different time increments:

$$D(t+\Delta t) = D(t) + \tfrac{1}{6}\left(F_1 + 2F_2 + 2F_3 + F_4\right) \tag{13}$$

$$F_1 = \Delta t \cdot f\left(D(t), t\right) \tag{14}$$

$$F_2 = \Delta t \cdot f\left(D(t) + \tfrac{F_1}{2}, t + \tfrac{\Delta t}{2}\right) \tag{15}$$

$$F_3 = \Delta t \cdot f\left(D(t) + \tfrac{F_2}{2}, t + \tfrac{\Delta t}{2}\right) \tag{16}$$

$$F_4 = \Delta t \cdot f\left(D(t) + F_3, t + \Delta t\right)$$

$$f(D,t) = r(t) + i(D,t) - e(t) - q(D) - K\left(1 - \Delta\theta\right) - K\Delta\theta \frac{\psi + (R(t) + I(D,t) - E(t) - Q(D,t)) - \bar{y}(D)}{(R(t) + I(D,t) - E(t) - Q(D,t)) - D} \tag{17}$$

$i$(D,t) and $q$(D) are given by (9) and (10), and I and Q must be integrated numerically:

$$I(D, t+\Delta t) = I(D,t) + \frac{v_{in}(t)}{A(D)}\Delta t \tag{18}$$

$$Q(D, t+\Delta t) = Q(D,t) + \frac{v_{out}(D)}{A(D)}\Delta t \tag{19}$$

Extra care must be exercised when using the model during pre-ponding. Unlike the case of rainfall, where the intensity is assumed to be evenly distributed over the area, inflow volume to an infiltration SCM is not evenly distributed across the basin, so the question of when ponding begins is more difficult to answer. The area function – A(D) – is an important part of this question. The assumption contained within equation (7) is that the inflow water is deposited directly into the deepest point of the basin. In some cases, this might be true, but in many cases, the water may flow over some soil before it gets to the bottom of the pond. If the latter case is true, then the former case – the assumption in the model – will be a conservative estimate, because water flowing over soil to get into the pond will infiltrate more than water directly deposited at the bottom. When the depth is zero, equation (7) requires evaluation of the term $v_{in}$/A(D): the inflow volume expressed as a depth over the pond bottom. Therefore, the area function at depth equal to zero must not be zero, but must be some finite area over which the inflow water is deposited prior to ponding. In general, this may be difficult to determine precisely, but will not be very important for low conductivity soils or high inflow rates where ponding is likely to occur quickly. In other words, the user must assume that the pond area has a small "flat bottom" area.

Finally, equation (7) is derived so that during pre-ponding, the depth at time $t+\Delta t$ will be a negative solution, indicating that the infiltration capacity is higher than the water available for infiltration. Therefore, an "if" statement must be included in the model to reset the depth at time $t+\Delta t$ to zero if the solution is negative, before moving on to the next time step. As long as the area function at negative depth equals the area function at depth equal to zero, this step will not violate the conservation of mass.

## 4.3. Temperature Dependence

The temperature dependence of infiltration comes from the properties of water: viscosity and density are temperature dependent properties. The definition of the hydraulic conductivity is:

$$K = \kappa \frac{\rho g}{\mu} \tag{20}$$

Where κ is the intrinsic permeability of the soil (temperature independent), ρ is the mass density of water (varies with temperature, though negligibly for atmospheric temperatures), g is the acceleration due to gravity, and μ is the viscosity of water, from which the temperature dependence of K arises. A functional form for expansion of this temperature dependence around $20^{o}$ C is given by Fogel'son and Likhachev (2001):

$$\mu(T) \approx \left(3.5\times10^{-9}\,\frac{lb\cdot s}{in^2}\right)\times10^{\frac{247.8}{T-140}} \tag{21}$$

With T in Kelvin. The published values for hydraulic conductivity will generally be given at $20^{o}$ C. Using that information, the user can solve for the intrinsic permeability, and then use the temperature dependent form of the equation.

## 4.4. Layered Soils

Often, infiltration basins are constructed with an engineered soil mixture near the surface to allow for faster infiltration of water or to allow better growth of plants, or both. There are two possibilities when dealing with layered soil that must be treated differently: the first will generally be the most common, when the upper soil zone is higher hydraulic conductivity than the lower, native soil; and the second is when the upper soil zone is lower conductivity than the lower soil.

When the hydraulic conductivity decreases with increasing depth, the treatment of the soil zones in the model is trivial. The assumption that must be made is that initially, the matric suction is the same for each soil zone. This is a fair assumption (as fair as for one soil zone, anyway), as a gradient in matric suction would result in flow of water until the gradient is gone. In this case, there is no modification needed to the model other than to keep track of the infiltrated water depth ($F/\Delta\theta$), and when that depth exceeds the soil layer depth, then K and $\Delta\theta$ must be switched to the values of the new soil. This works because the lower conductivity soil will drive the infiltration rate; once the water column reaches the low conductivity soil, the infiltration rate will be the same as if the entire soil thickness were the low conductivity soil. In fact, it is trivial to add as many soil zones as needed, as long as the conductivity decreases with each zone going down.

The second possibility is that the upper soil zone has a lower conductivity than the soil beneath it. This is more difficult to model and in fact, the model assumption of having a sharp wetting front will break down at this point. When the infiltrating water column reaches the higher conductivity soil, the entire water column cannot speed up because the top part of the column is limited by the low conductivity soil above. Thus, only the amount of water that leaves the first soil zone will enter the higher conductivity zone and so that amount of water will begin to infiltrate away faster than the rest of the column, breaking up the sharp wetting front. Within the framework of this model, the result of entering the second soil zone would be that the infiltrated water depth F would become constant ($F/\Delta\theta$ = depth of first soil zone), and as water enters the soil below, it would become wetter (but not saturated), so the matric suction would begin to decrease at an unknown rate. The only way of treating this scenario accurately would be to use the Richards Equation, which is not easily solved in this scenario, would necessitate knowledge of the second soil/water characteristic curve ($K(\theta)$), and would also make a detailed picture of the first curve ($\psi(\theta)$) more critical. In other words, the full solution of this problem is outside the scope of this model, because it would increase the computational power needed, and decrease user-friendliness.

However, within the framework of the model, it is possible to bound the solution with an upper and lower infiltration rate. At the upper end, assume that the conductivity of the lower soil zone approaches infinity. In this case, the lower soil zone will act as an infinite reservoir for the infiltrating water, and any water that enters it will be immediately "whisked away." Thus, the infiltrated water depth becomes constant ($F/\Delta\theta$ = depth of first soil zone), but the matric suction would also remain constant because the water content would not increase. This is treated easily within the model framework. At the lower end of infiltration rate, one could assume that there is no change in soil type. In other words, adding the higher conductivity soil underneath cannot slow the infiltration rate down from the case that all the soil had a lower conductivity. In many cases, it is likely that the actual performance will be close to one or the other case; if the conductivity of the two zones are similar, it will behave like the "lower end" case, and if the second soil has an order of magnitude higher conductivity, then it will behave much like the "upper end" case.

## 4.5. Green and Ampt Soil Parameters

The ponded infiltration model presented relies on the Green and Ampt infiltration parameters $K$, $\psi$, and $\Delta\theta$. Many tables are available for "typical" Green and Ampt values for the

USDA classification of soil types. However, these values may not necessarily be the most appropriate values to use. In general, to solve the Richards equation, two soil/water characteristic curves (SWCCs) are needed: $K(\theta)$ and $\psi$ $(\theta)$ or $K(\psi)$ and $\theta(\psi)$. One of the benefits of using the Green and Ampt solution is that all of the infiltrating water is assumed to completely saturate the soil, up to the sharp wetting front. For this reason, the conductivity SWCC ($K(\theta)$) is not needed, only the saturated hydraulic conductivity is needed. However, typical Green and Ampt conductivities are about half the saturated hydraulic conductivity, owing to the unsaturated soil beneath the wetting front having a small conductivity and from cyclical wetting conditions creating air pockets in the soil. The practical implication is that Green and Ampt conductivities are needed – not saturated hydraulic conductivities.

The remaining two parameters – $\psi$ and $\Delta\theta$ – are often taken independently from tables as well. Although the SWCC relating these two parameters is not needed to solve the equation, it is often overlooked that these two parameters are related. For example, to study the effect of changing $\psi$, it would not be appropriate to keep $\Delta\theta$ as a constant; doing so would create a set of solutions that are not physically possible. Increasing $\psi$ for a given soil will always correspond to increased $\Delta\theta$ (the soil is drier), and vice-versa. Thus it is better to have either $\psi$ or $\Delta\theta$ be the one independent variable, and use the SWCC curve to determine the other. Fredlund (2006) describes how using the SWCC in this way does not require great accuracy in the curve, as it would in solving the Richards equation. This statement is confirmed later in the model sensitivity studies. What this implies is that using one of the table SWCCs (e.g. Maulem - van Genuchten values can be found in tables) will be sufficient for the model, but will be a large improvement over having $\psi$ and $\Delta\theta$ be separate independent variables. For this thesis, $\psi$ will be considered the independent variable rather than $\Delta\theta$ because its interpretation does not depend on the soil type.

Ideally, for a model correlation, all three of the soil properties would be known for each storm event. However, that is "easier said than done." One reason is that the values for the Green and Ampt model are averages over the entire basin, both area and depth. So, even if several soil moisture probes were taking readings in the basin, it is unlikely that the data would directly correspond to $\Delta\theta$ used in the equation. Similarly, taking a core sample of the soil and doing a hydraulic conductivity test does not guarantee finding K for the Green and Ampt equation. However, using available data at the site can yield information about the value for K: it can be shown that the recession rate – dD/dt – decreases over time during any event, but its magnitude will always be greater than or equal to K, under any circumstances (taking the limit of equation (7) shows this). Therefore, a study of ponded recession limbs should provide an estimate of K(T). As the initial moisture content approaches saturation, the infiltration rate more closely approaches K. Therefore, it can be assumed that given enough data, some recession rates will be quite close to K.

The typical recession limb of a depth versus time plot will be roughly linear. As such, the average recession rate can be measured by performing a linear regression of the recession limb. When the recession rates are plotted against temperature, there is a large variation at each temperature, but the minimum recession rate increases with T with the same functional dependence as K. Figure 4.2 demonstrates this principle with data from the Villanova traffic island (VTI). The variation at each temperature is due to changes in storm size (more water infiltrated will reduce the recession rate) and antecedent moisture conditions (initially wet soils will have a lower recession rate). An assumption that must be made is that given enough events, the minimum recession rates will approach K. If this is true, then the relationship K(T) can be drawn such that it creates a lower bound of the recession rate data. If the assumption is not true, then K(T) drawn in this manner will be slightly high. The line showing the upper-limit of K in Figure 4.2 was found by using equations (20) and (21) for the functional form of conductivity versus temperature, and iterating on κ, the intrinsic permeability, until the line creates a lower bound of all data. From this lower-bound, K at 20 $^{o}$C reads 0.13 in/hr, whereas the class average K value for Sandy Clay Loam is generally between 0.1 and 0.2 in/hr, depending on your source. In other words, this line is probably close to the actual value of K, rather than being very high.

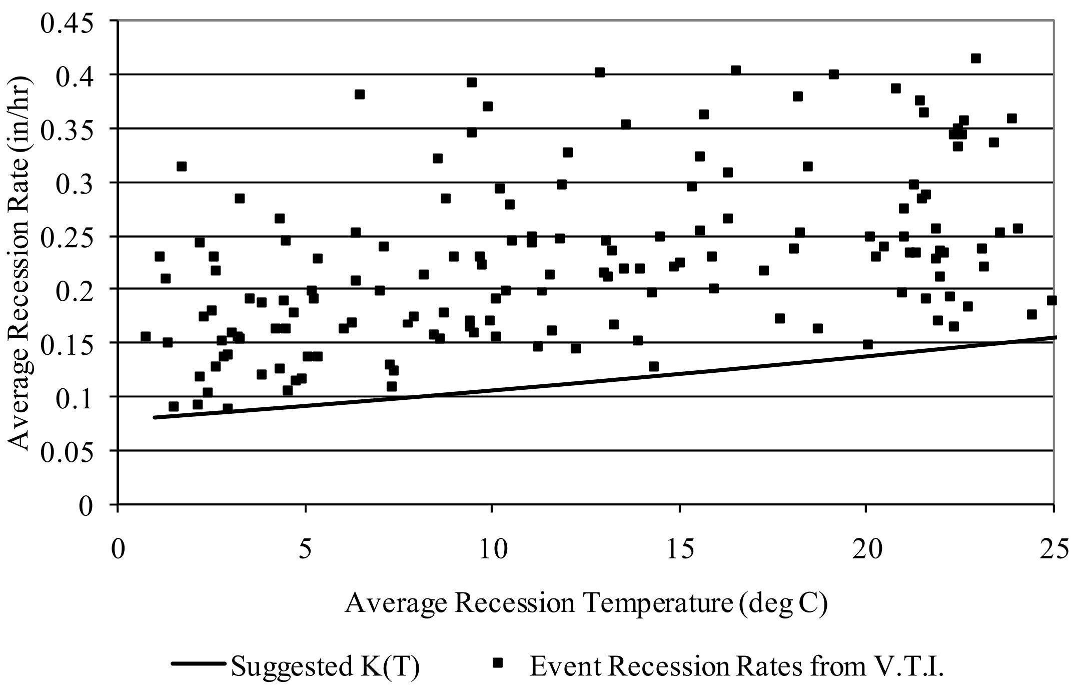


Figure 4.2 Plot of average event recession rates from the Villanova Traffic Island from 2003-2007.

By using the value of K derived in this manner, the model can be used to iteratively solve for the best value of ψ for each storm event. Because there is no way to know whether this value of K(T) is accurate, it can only be assumed as an upper limit. With an upper limit of K, all values of ψ determined this way will be a lower limit. Thus, by knowing an upper bound of K, the model can be used to determine a lower bound on ψ. This should yield some useful information about the actual conditions in an infiltration basin, and thankfully, one of the sites at Villanova University (VTI) has enough data to accomplish this. The other site, the Fedigan Rain Garden (FRG), does not have enough data to do this, both because of time of operation and because it has such a higher infiltration rate that it is rarely ponded.

## 4.6. Computational Methods

MATLAB was the software used to run these analyses. The model equations were programmed with a 4th order Runge-Kutta explicit integration. The explicit integration uses adaptive stepsize control (Press et al, 1988, Section 15.2): at each data timestep (5 minutes at Villanova Traffic Island, 1 minute at Fedigan Rain Garden), the solution is performed at the data timestep and half the data timestep. If the two solution pond depths differ by more than 10e-6, then the new timestep is determined by equation (22):

$$dt_{new} = 0.90 * dt_{smallest} * \left({10^{-6}}/{\Delta D}\right)^{0.25} \tag{22}$$

For the model correlation studies, instead of depth being the primary unknown variable, the initial matric suction is the primary unknown variable, and the depth is known (as a function of time). However, the only way to solve the equation for ψ is iteratively. MATLAB comes with an optimization routine that will find a least-squares solution for the error between model depth and actual depth. The routine is "lsqnonlin" for least-squares nonlinear. This routine finds the best-fit solution with as few iterations as possible.

## 4.7. Summary of Model Assumptions/Approximations

Several important assumptions and approximations are included in this model. Most fundamentally, this is a one-dimensional infiltration model, and it assumes that the groundwater table is at great depth. It is likely that the 1-D approximation is not valid if the saturated zone is immediately beneath the soil surface. A shallow groundwater table also violates the assumptions of the development of the hydraulic gradient in the Green and Ampt and Philip's infiltration models. Some other assumptions and approximations are:

- Soil hydraulic properties are homogenous over area and depth.
- The wetting front takes the shape of the wetted bowl surface. During recession, this will cause the wetting front to become more curved than the bowl geometry over time.
- The wetting front is sharp, as in the Green and Ampt method.
- The initial matric suction is the same for all soil zones.

# 5. MODEL SENSITIVITIES

All of the working components of a model must be checked for sensitivity. If a part of the model is very sensitive, then it requires an accurate knowledge of that parameter. If, on the other hand, a parameter is very insensitive, then it can sometimes be eliminated entirely from the model. The sensitivity must be evaluated in terms of uncertainty of model inputs, and how that uncertainty affects the model outputs: in this case the primary model output is average infiltration rate. The model inputs are the soil properties: the saturated hydraulic conductivity (K), the initial matric suction ($\psi$), and the initial soil moisture content ($\theta$) – as determined through the soil water characteristic curve (SWCC); and the bowl shape.

The soil property sensitivity studies will be conducted with a hypothetical rain garden that has the shape of a rectangular trough, where the bottom and top area are specified, and the area in between is linear with respect to depth. This shape is such that the length to width ratio does not affect any terms in the model. The rainfall and inflow hydrograph will be from a 0.99" storm randomly selected from the Villanova traffic island data because of the round number. The inflow volume from this event is 2275 $ft^3$, and the bowl shape was picked to have a volume of 2000 $ft^3$ such that the bottom flat area is 500 $ft^2$, the top area is 1500 $ft^2$, and the height is 2 ft. The soil conductivities are taken from Rawls et al (1992), and the SWCC is a van Genuchten model parameterized with values taken from the USDA's *Rosetta* model (Schaap 1999).

## 5.1. Hydraulic Conductivity Sensitivity

The saturated hydraulic conductivity (K) is expectedly an important/sensitive factor in determining the infiltration rate. For this study, the baseline soil properties were that of a Sandy Clay Loam (K = 0.118 in/hr), but a check was run with Loamy Sand (K = 2.406 in/hr) to ensure that the results hold for all soil types. Sand would have even higher infiltration rates, but those rates are so high that ponding is difficult to achieve with typical inflow rates. In each case, the matric suction is about 80" – a value that is slightly lower (i.e. higher-moisture) than field capacity (132"). Figure 5.1 shows the plot of several model runs where K is varied by a factor between 0.5 and 2.0. The change in average recession rate is shown on the vertical axis. The data plots a nearly straight line with a coefficient of 0.83, meaning that if K increases by 100%, the average recession rate will increase by 83%. Thus, K is the most important model input. This also shows the importance of including the temperature variability of K: a 10 degree Celsius change in temperature will result in about a 25-30% change in K, which in turn will produce a 20-25% change in recession rate per 10 degrees.

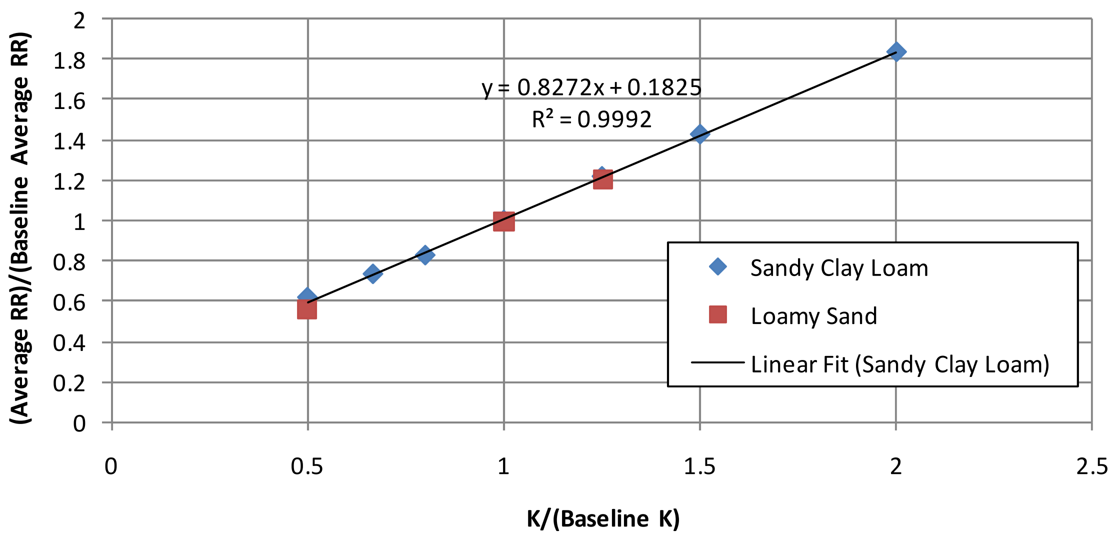


Figure 5.1 Plot of change in conductivity (K) vs. change in average recession rate (RR).

## 5.2. Matric Suction Sensitivity

The matric suction is the only variable input parameter in the model. The conductivity may vary with temperature, but the matric suction can vary based on the user's discretion, as it is dependent on many factors, including antecedent weather and dry time, although a clear relationship has not been discovered. Perhaps, a soil moisture accounting model would be able to get close to predicting the matric suction. Note that as the matric suction changes, the initial soil moisture content also changes, but the relationship is fixed (via the soil water characteristic curve). The sensitivity of that relationship will be considered in Section 5.3. As with the hydraulic conductivity, the sensitivity of the matric suction will be evaluated primarily with sandy clay loam, and then verified with loamy sand. Figure 5.2 shows the plot of several model runs where $\psi$ is varied from the "baseline" run of 82 inches – a number that is simply used as a reference point. The change in average recession rate (relative to the baseline) is shown on the vertical axis. The data plots a strong correlation with a linear coefficient of 0.47, meaning that if $\psi$ increases by 100%, the average recession rate will increase by 47%. This makes $\psi$ an important parameter in determining the infiltration rate, but is also not so dominant that some uncertainty will completely undermine the results of the model run. Figure 5.3 is the same plot, though re-centered around a lower suction value, 20 inches. This plot shows that for lower values of suction (higher moisture content), the sensitivity is lower, with a coefficient of 0.18 rather than 0.47. This is good for a design engineer, who might wish to use the model conservatively (i.e. with wet initial conditions). Thus, a conservative solution can be reached without much sensitivity to suction, so one might decide to use a value from a Green and Ampt parameter table, which tend to be low suction values.

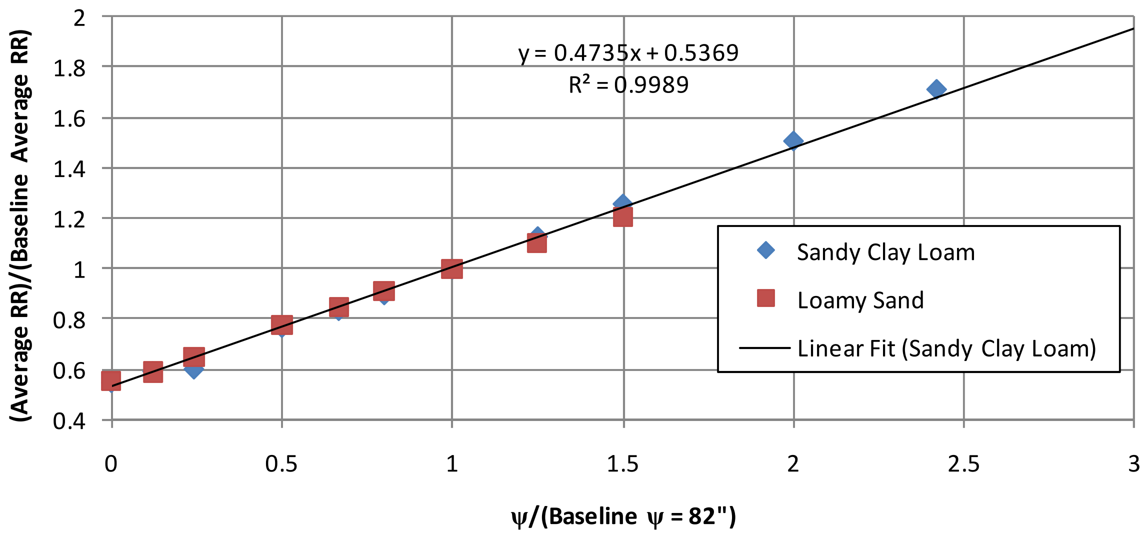


Figure 5.2 Plot of changes in matric suction (ψ) vs. change in average recession rate (RR), centered at values of ψ near field capacity (82 inches is center).

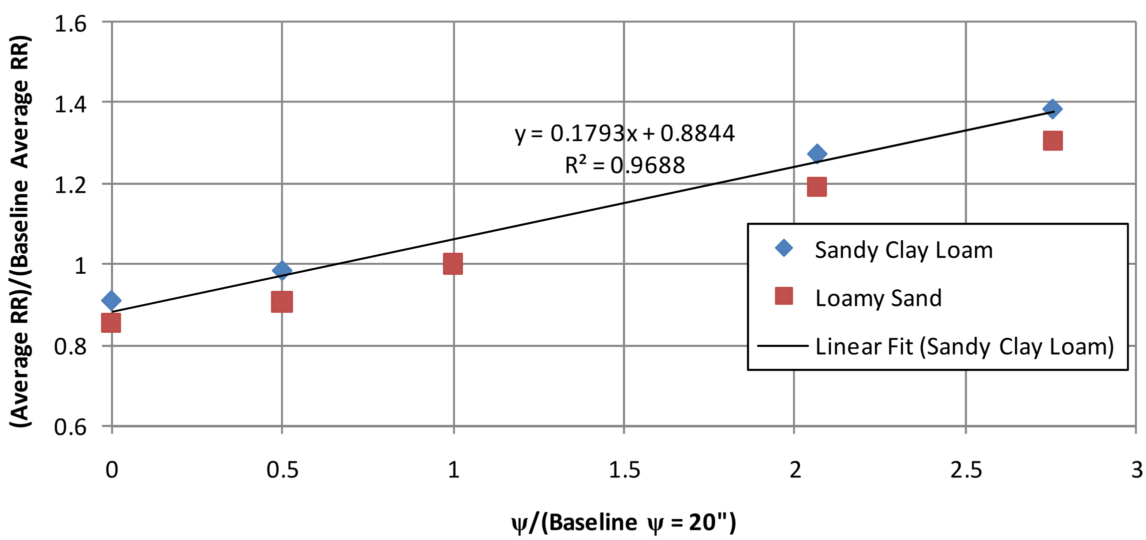


Figure 5.3 Plot of changes in matric suction (ψ) vs. change in average recession rate (RR), centered at low values of ψ near saturation (20 inches is center).

## 5.3. Soil/Water Characteristic Curve Sensitivity

There are a wide range of soil water characteristic curves (SWCC), and every soil will be different. The curve enables one to determine the value of soil moisture content ($\theta$) given the matric suction ($\psi$), or vice-versa. Because the curve is not linear, the effect of changes in the curve must be evaluated at different values. For this study, the SWCC is modeled with the van Genuchten (1980) form of the equation:

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha\psi)^n\right]^{1-1/n}} \tag{23}$$

There are four model parameters: $\theta_r$, $\theta_s$, $\alpha$, and n, which are the residual soil moisture, the saturated soil moisture, and two curve-fitting parameters, respectively. Tables are available to parameterize this equation with soil class average values. Generally, a standard deviation is provided with the value, which can result in a very wide range for each parameter. In order to get an understanding of the sensitivity, the model will be run with the equation from “adjacent” soil types (adjacent in this case means the soil class with the closest value of hydraulic conductivity, not the soil class with the closest grain-size distribution), rather than trying to apply a Monte Carlo approach using the given standard deviations. In the latter case, there is no guarantee that the values follow a normal distribution, and additionally it is almost certain that the model parameters do not vary independently. Therefore, a Monte Carlo approach would probably not be an accurate representation of SWCCs from that soil type.

Figures 5.4 and 5.5 are plots of average recession rate vs. matric suction for Loamy Sand (LS) and Sandy Clay Loam (SCL), respectively. For the LS analysis, the hydraulic conductivity is held constant while the SWCC is changed to the mean values for Sand (S) and Sandy Loam (Sa. L), which are the two closest soil classes in terms of hydraulic conductivity. For the similar SCL analysis, the SWCC is changed to Silt Loam (Si. L) and Clay Loam (CL), again the closest classes for conductivity. It can be seen that there are no major deviations from changing the SWCC. The biggest change in RR was 13% at the highest values of ψ (300 inches) for the SCL, but the rest of the curves for SCL and LS were within 10% of the baseline. This implies that the SWCC is not particularly sensitive for this kind of analysis, which is a good thing for a design engineer who will likely not have a SWCC tested for their soil, but who may use a grain-size distribution based Pedo-transfer function to compute the SWCC (e.g. Fredlund et al, 2002). If one were to do a complete Richard's equation solution rather than the Philip's solution, it is highly likely that the SWCCs (there would be two curves – one for ψ and one for K) would be more sensitive (Fredlund 2006); for practical purposes it is well that the SWCC has a low sensitivity. Changes in the SWCC will also affect infiltration in multiple soil zones – changes in θ affect the available pore space, thus affecting the timing of the infiltrating water hitting a second soil zone.

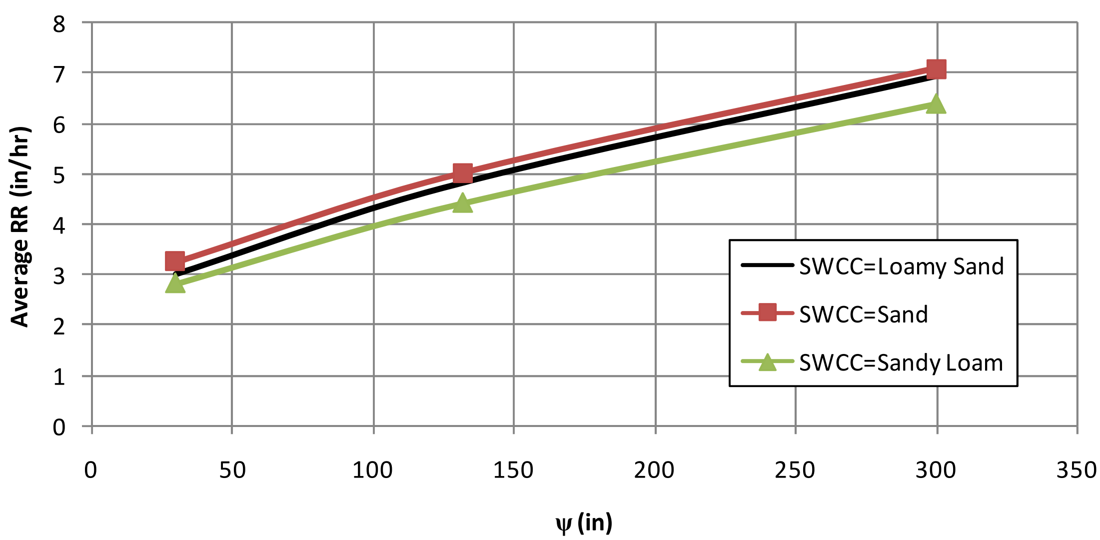


Figure 5.4 Average recession rate (RR) vs. matric suction (ψ) for Loamy Sane with SWCC varied.

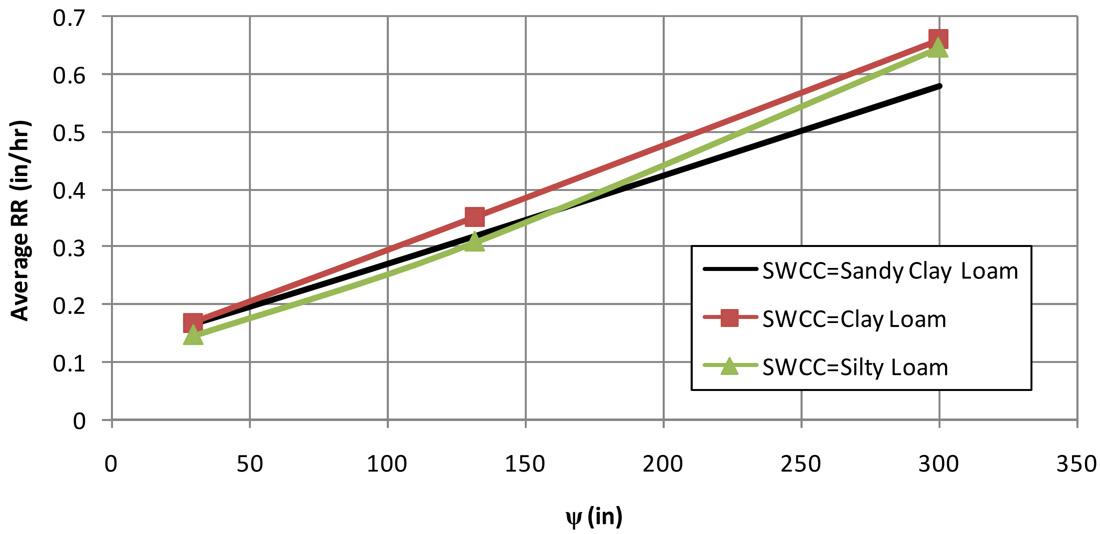


Figure 5.5 Average recession rate (RR) vs. matric suction (ψ) for Sandy Clay Loam with SWCC varied.

## 5.4. Basin Shape Sensitivity

Two types of shape dependence are considered: that of the infiltrating area and that of variable head. Several analyses were performed to show the effect of the infiltrating area. The runs are done with a Sandy Clay Loam soil, with bowls that are all 2000 $ft^3$ in volume, and the amount of inflow from the 0.99 inch storm is 2275 $ft^3$. Table 5.1 shows the results of the analysis. The first three entries are 2 ft depth basins with varying bottom areas and side slopes. This does not have a major effect on the average recession rate (RR) which varies from 0.22 to 0.23 in/hr, or on the peak filled volume which varies from 1179 to 1200 $ft^3$. However, the next three entries are basins with flat bottoms and 90 degree side slopes – a shape that might be used as an average bowl area. This results in a fairly drastic range in infiltration rate, between 0.217 and 0.292 in/hr. Because the correct average bowl area would change based on the size and shape of the storm event hyetograph, it becomes important to get a close representation of the bowl shape rather than an "equivalent" basin with 90 degree side slopes. For this 0.99 inch storm event, if using a constant-area basin, the basin area has a sensitivity coefficient of 0.24, meaning there is a 2.4% change in recession rate for every 10% change in area. For the typical basin that does not have constant area, the wetted area changes significantly for every storm event. Thus, modeling side slopes is important, although getting the exact curvature is not important. Thus, the engineer should beware of models that use vertical side-slopes for an infiltration basin (SWMM uses the basin area for infiltration).

Table 5.1 Results of bowl shape sensitivity analysis.

| **Basin Dimensions** | | | **Event Results** | |
|---|---|---|---|---|
| Top Area | Bottom Area | Depth | RR | Peak filled volume |
| *ft^2* | *ft^2* | *ft* | *in/hr* | *ft^3* |
| 1500 | 500 | 2 | 0.224 | 1193 |
| 1750 | 250 | 2 | 0.22 | 1200 |
| 1250 | 750 | 2 | 0.23 | 1179 |
| 1000 | 1000 | 2 | 0.236 | 1157 |
| 2000 | 2000 | 1 | 0.292 | 950 |
| 667 | 667 | 3 | 0.217 | 1227 |

The other effect of basin shape comes in through the depth head term. In the model development, the variable depth head term was accounted for by including the term $\bar{y}$ in equation (7). Thus, the effect of using average depth vs. peak depth can be determined by running the analysis with and without the $\bar{y}$ term (excluding this term is equivalent to using peak depth as the depth head, and is the current implementation in SWMM). To simplify these analyses, a dimensionless watershed and basin is used; the $\bar{y}$ term is given as a fraction of the depth, and inflows are described in terms of basin depth. In this way, the area of the watershed and basin do not matter. The shape factor does not have to be a linear function of depth, however, for these analyses $\bar{y}$ equal to 0.5*D is used. This would be the shape factor for a triangular trough. The actual factor will vary between a small fraction of D (around 0.1) for a flat bottom with nearly vertical sides, to even greater than 0.5 if there is a depression of small area on the bottom. Several runs are performed, with 3 different soil types (Loamy Sand, Sandy Loam, and Sandy Clay Loam), different values of matric suction (12 and 132 inches – 132 inches being a typical value for field capacity), and different pond depths (12, 24, and 48 inches). The mean infiltration rate is compared between runs with $\bar{y}$ equal to 0.5*D and $\bar{y}$ equal to 0. These results are presented in Table 5.2.

Table 5.2 Results of model runs comparing with and without shape factor.

| Soil Type *USDA* | K *in/hr* | ψ *in* | Max. Depth *in* | Mean f, ybar=0 *in/hr* | Mean f, ybar=0.5*D *in/hr* | Error *%* |
|---|---|---|---|---|---|---|
| LS | 1.73 | 12 | 12 | 2.425 | 2.343 | 3.5% |
| LS | 1.73 | 12 | 24 | 2.240 | 2.140 | 4.7% |
| LS | 1.73 | 12 | 48 | 2.145 | 2.032 | 5.6% |
| LS | 1.73 | 132 | 12 | 19.800 | 19.560 | 1.2% |
| LS | 1.73 | 132 | 24 | 11.890 | 11.650 | 2.1% |
| LS | 1.73 | 132 | 48 | 7.300 | 7.040 | 3.7% |
| SL | 0.63 | 12 | 12 | 1.234 | 1.165 | 5.9% |
| SL | 0.63 | 12 | 24 | 1.041 | 0.966 | 7.8% |
| SL | 0.63 | 12 | 48 | 0.938 | 0.859 | 9.3% |
| SL | 0.63 | 132 | 12 | 10.350 | 10.240 | 1.1% |
| SL | 0.63 | 132 | 24 | 5.500 | 5.380 | 2.2% |
| SL | 0.63 | 132 | 48 | 3.040 | 2.918 | 4.2% |
| SCL | 0.12 | 12 | 12 | 0.143 | 0.140 | 2.4% |
| SCL | 0.12 | 12 | 24 | 0.137 | 0.134 | 2.9% |
| SCL | 0.12 | 12 | 48 | 0.134 | 0.130 | 3.2% |
| SCL | 0.12 | 132 | 12 | 1.205 | 1.190 | 1.3% |
| SCL | 0.12 | 132 | 24 | 0.606 | 0.592 | 2.2% |
| SCL | 0.12 | 132 | 48 | 0.354 | 0.342 | 3.5% |

Looking at the results of Table 5.2, a couple trends can be identified. First, the importance of the shape factor is heavily dependent on pond depth. This makes sense because $\bar{y}$ will generally be an increasing function of depth, so more depth increases the importance of the term. Also, the shape factor is sensitive to initial matric suction. It is most important when matric suction is small (initially wet conditions) because $\bar{y}$ is directly compared to $\psi$ in the model equation, so when $\psi$ is smaller, $\bar{y}$ is more important relatively. Finally, the results depend on the soil type, but not in an obvious way. Sandy Loam was the most sensitive soil type, but its conductivity is between Loamy Sand and Sandy Clay Loam. For many stormwater control basins, ignoring the shape factor term may be acceptable, as error will be around 5% or less. However, it might become important for large infiltration basins (>3 ft depth). Unfortunately, leaving out this term (as in SWMM) is always un-conservative, since the mean depth is always less than the peak depth. Although ignoring the variable depth is un-conservative, the error associated is generally less than the uncertainty of other parameters such as conductivity and matric suction.

# 6. MODEL APPLICATIONS

## 6.1. Villanova Traffic Island

### 6.1.1. Site Overview

The primary data set used for model calibration and verification will be from the Villanova Traffic Island (VTI), seen in Figure 6.1. The VTI has been in operation since the end of 2002, with a nearly continuous data record of rainfall and pond depth at 5 minute intervals. The pond depth is measured using an ultrasonic distance sensor. A survey of the pond has been performed to determine the geometry, which is necessary as a model input. Additionally, a soil particle-size distribution test has been done (Isaac-Ricketts, 2008, and Gilbert Jenkins et al, 2010), which allows for a reliable estimation of the soil type. The primary limitations of this data set are that soil moisture is not measured, and the inflow volumes are not measured. Therefore, the inflow volumes must be estimated using the NRCS Curve Number method (NRCS, 1993; Neitsch et al, 2005).

The traffic island has a total watershed area of 1.21 acres (0.5 acres of impervious surface). The curve numbers used for this watershed are 98 for the impervious surface and 80 for the pervious surface. The infiltration basin itself has an area of 1550 $ft^2$ (0.036 acres) and a volume of 1270 $ft^3$ when the depth is 1.72 ft at start of overflow. The traffic island was constructed with 4 ft of engineered soil – native soil mixed with sand in a one-to-one ratio. In this area of campus, there is a significant clay component (30%) near the soil surface, which results in a Sandy Clay Loam type soil after mixing. However, at depth greater than 3 feet, the clay component is reduced significantly to below 20% (Soil Survey Staff, 2011), meaning that the soil underneath the constructed soil has a higher conductivity even than the mixed soil. As discussed in Section 4.5, an upper bound can be placed on the Green and Ampt conductivity for this site at 0.13 in/hr. So, analyses run with this conductivity will yield a lower bound on matric suction values.

Figure 6.1 Villanova traffic island while ponded.

### 6.1.2. Model Correlation

There is no official "validation" of the model because the initial matric suction, $\psi$, is an unknown variable. So here, the model is run iteratively on $\psi$ until a least-squares fit is achieved with the depth vs. time data. One major problem with this correlation is that the inflow hydrograph is not known, but predicted using the curve number method (98 for impervious surface, 80 for pervious surface). Due to obvious discrepancies in the inflow volume, and also because of missing data and freezing temperatures, several ponding events were excluded from this correlation. There are a total of 66 events for the model correlation, between January 2003 and March 2008. These events are defined by ponding duration, so some of the events include multiple distinct storm events. Qualitatively, the model is able to produce a good fit to the data in all cases. Quantifying this is difficult because of uncertainties in the inflow volume and error in the data (the depth sensors tend to fluctuate with temperature).

Figures 6.2 and 6.3 are two of the storm events (more are in Appendix A) that highlight some important points of the model: Figure 6.2 shows a large storm event (actually three successive storms, but close enough together that the pond does not empty) of 4.54 inches of rain, and Figure 6.3 is a small event of only 0.35 inches of rain. The large event shows clearly that the infiltration rate is constant; the infiltrating water has passed the constructed soil and entered the higher-conductivity soil beneath. As discussed in the Methods section, this results in a constant infiltration rate. The smaller event is one where the infiltration rate can be seen to be decreasing over the recession limb. This is consistent with the infiltrating water column being all within the same soil layer. At this site, the decreasing infiltration rate is only visible on a few number of events; most events larger than 0.5 inches or so infiltrate through the engineered soil before the inflow and rainfall cease.

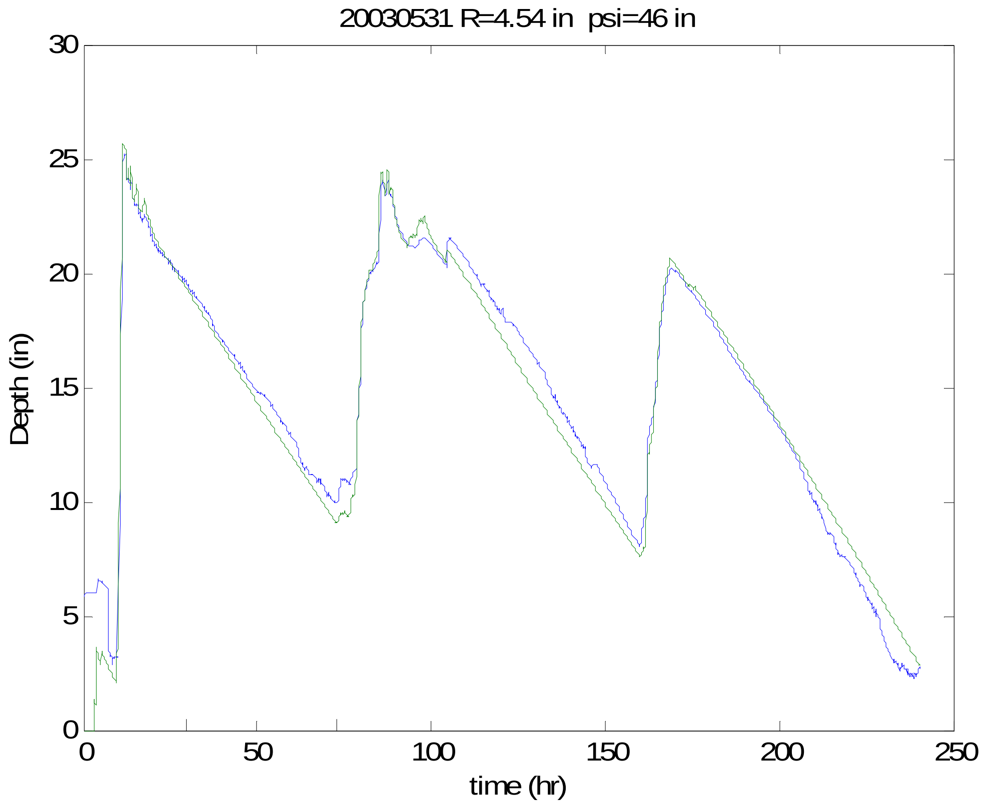


Figure 6.2 Model and actual depth vs. time for a 4.54 inch rain event. Constant infiltration rate is visible.

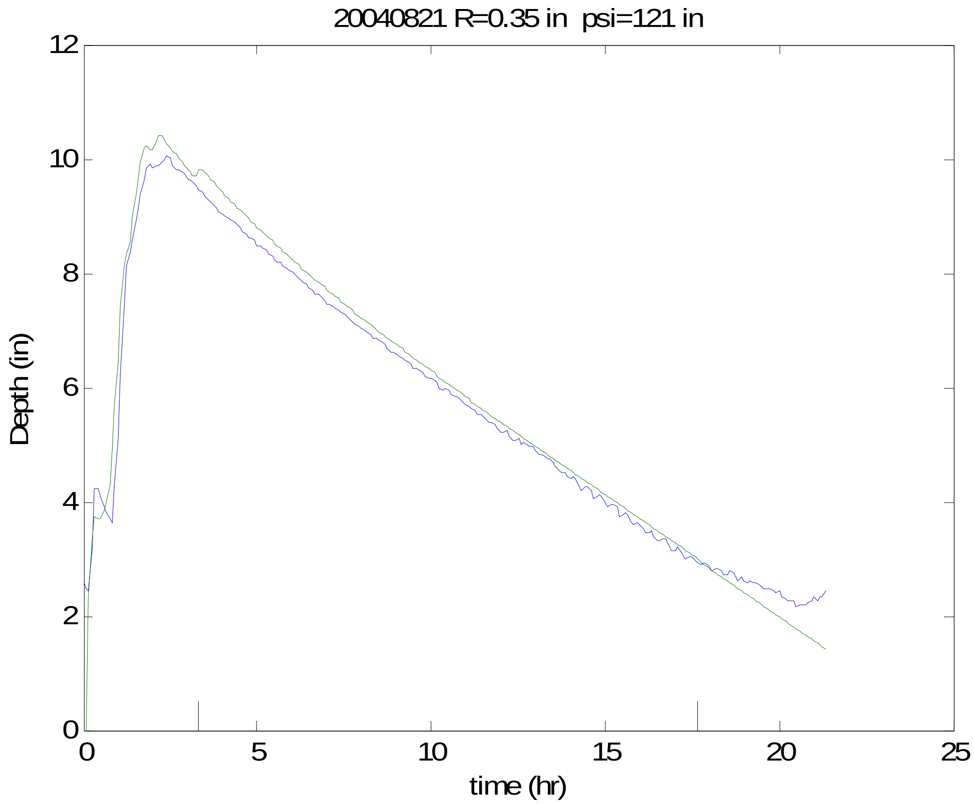


Figure 6.3 Model and Actual depth vs. time for a 0.35 inch rain event. Decreasing infiltration rate is visible.

As a quantitative analysis of the model performance, event recession rates are compared to the data. Recession rates are determined by doing a linear regression of a part of the pond recession limb after inflow and rainfall has stopped. Figure 6.4 shows the comparison of actual and model recession rates. Although close, the model rates are not exactly equal to the data, because the objective of the correlation was an overall least-squares fit rather than an exact recession rate fit. Because of the error range in the depth sensors, recession rates cannot be measured exactly in most cases. Figure 6.5 shows the distribution of matric suction values from these correlations. The values lie between 7 and 147 inches, with a mean of 62 and a standard deviation of 34 inches. The table value for Sandy Clay Loam soil in the SWMM manual is 8.6

inches, which is about a 99th percentile low suction event based on the 66 events analyzed at this site. Finally, from data only the recession rate can be measured once inflow has stopped. But by analyzing the model data, the event mean infiltration rate can be computed (i.e. the time averaged infiltration rate during ponding). This distribution is plotted in Figure 6.6. Note that the value for hydraulic conductivity is variable depending on temperature, and ranges between 0.06 and 0.15 in/hr. However, even the lowest event mean infiltration rate is greater than 0.15 in/hr.

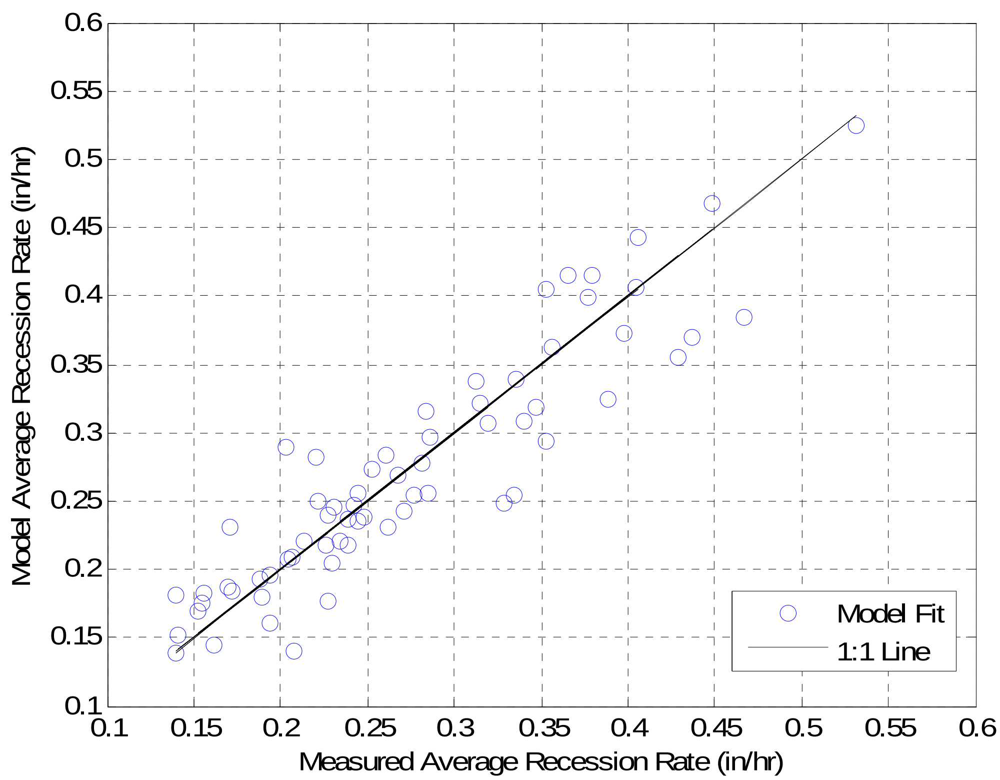


Figure 6.4 Comparison of average recession rates between best-fit model and data.

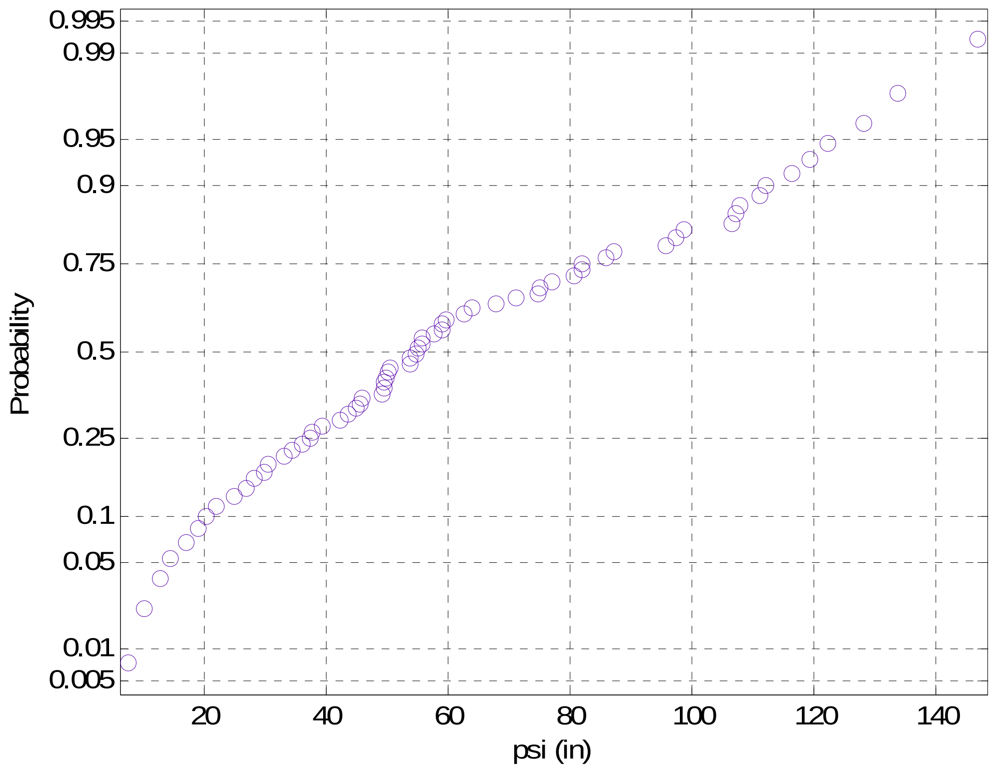


Figure 6.5 Distribution of matric suction values from model correlations.

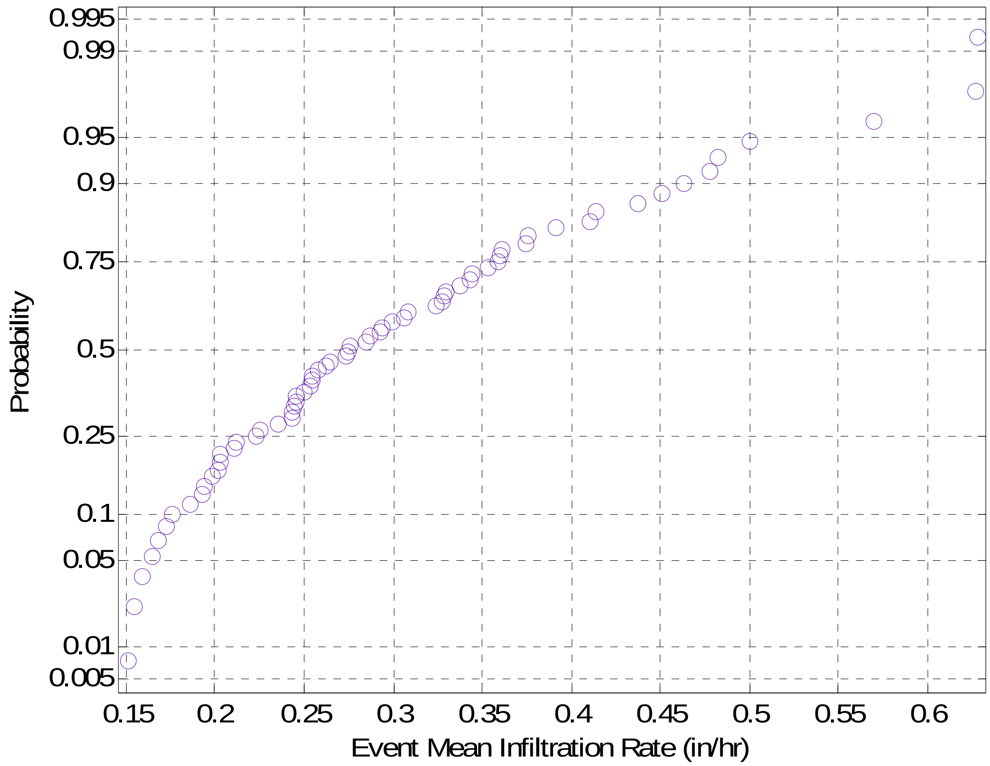


Figure 6.6 Distribution of event mean infiltration rates from model correlations.

Clearly, there is a wide variation seen on infiltration rate. To better understand this variation and what parameters drive it, a multiple linear regression is performed on the infiltration rate data. Although not a simple function, the model is nonetheless a function of only three parameters: K(T), ψ, and hydrologic variables (rainfall, inflow, outflow, and evapotranspiration). Other parameters that show up in the model – D, F, and Δθ – are functions of the listed inputs. In order to simplify the hydrology, only the total rainfall amount (R) is considered as an independent variable (mean rainfall intensity was also considered, but is not a very significant variable). So the linear regression for mean infiltration rate ($\bar{f}$) takes this form:

$$\bar{f}(K,\psi,R) = C_1 + C_2K + C_3\psi + C_4R$$

The best fit coefficients are -0.2011,-0.0067,2.8516, and 0.0030, respectively, resulting in a fit with $R^2$ = 0.945. These coefficients by themselves are difficult to interpret, but the regression can be used to show the effect that a range in each variable has on the range of $\bar{f}$, by taking the coefficient times the difference between the maximum and minimum observed variable. Comparing the relative weights of the range each variable has on $\bar{f}$, it can be shown that the variables K, ψ, and R account for 58%, 35%, and 7% of the variability, respectively. To better visualize this regression, it can be performed as a function of K and ψ only, neglecting R. This results in a correlation with $R^2$ = 0.935, and can be plotted as in Figure 6.7. This figure shows the data point for each event, and the orientation of the 3-D plot is such that the plane of the linear regression best-fit appears as a line, so that the goodness of fit can be viewed.

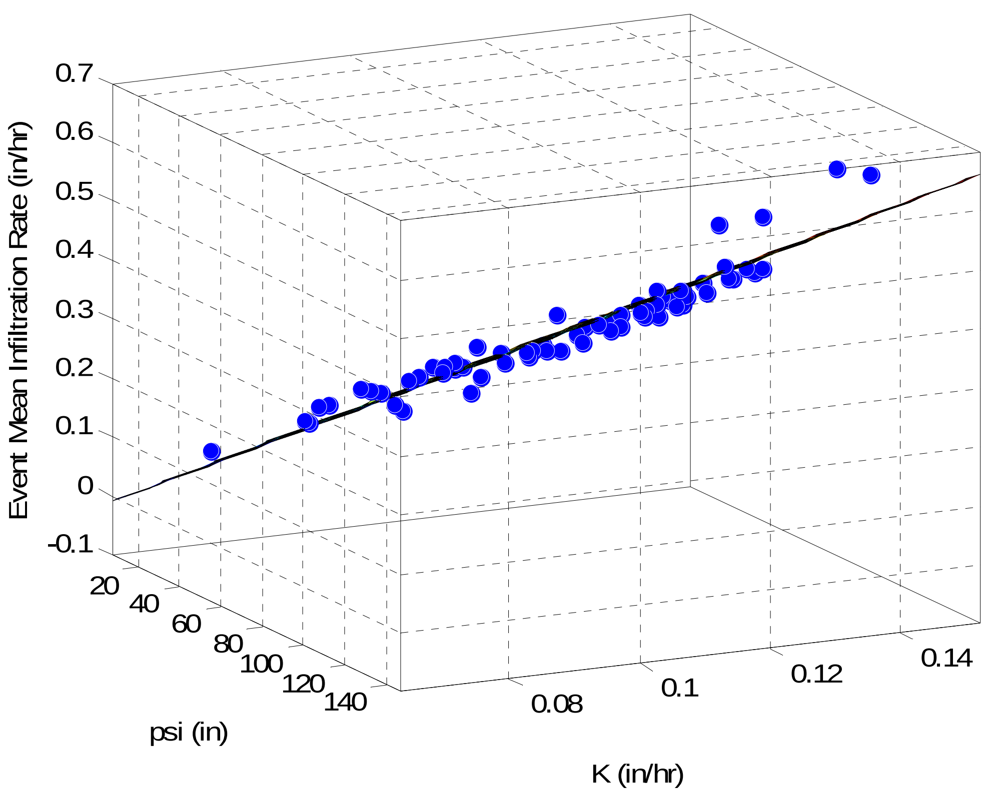


Figure 6.7 Plot of linear regression of mean infiltration rate as a function of K and ψ only. The black line is the cross-section of the plane of best-fit.

Finally, to gauge the appropriateness of the assumption that K at 20° C equals 0.13 in/hr (see Section 4.5, selection of K is based on observed recession rates and is an upper bound on K), the model correlations are run with K reduced by 20% and by 40%. As K is reduced, the values of ψ increase to match the data. The distribution of ψ is shown in Figure 6.8 for each case (upper bound – K100%, reduced by 20% is K80%, and reduced by 40% is K60%). The minimum value of ψ increases from 7 to 21 to 42 inches as K decreases. This is evidence that the actual K for the site is near the upper limit; it would be expected that of the 66 events, some would be initially wet (Pennsylvania is in a climate where it can rain frequently).

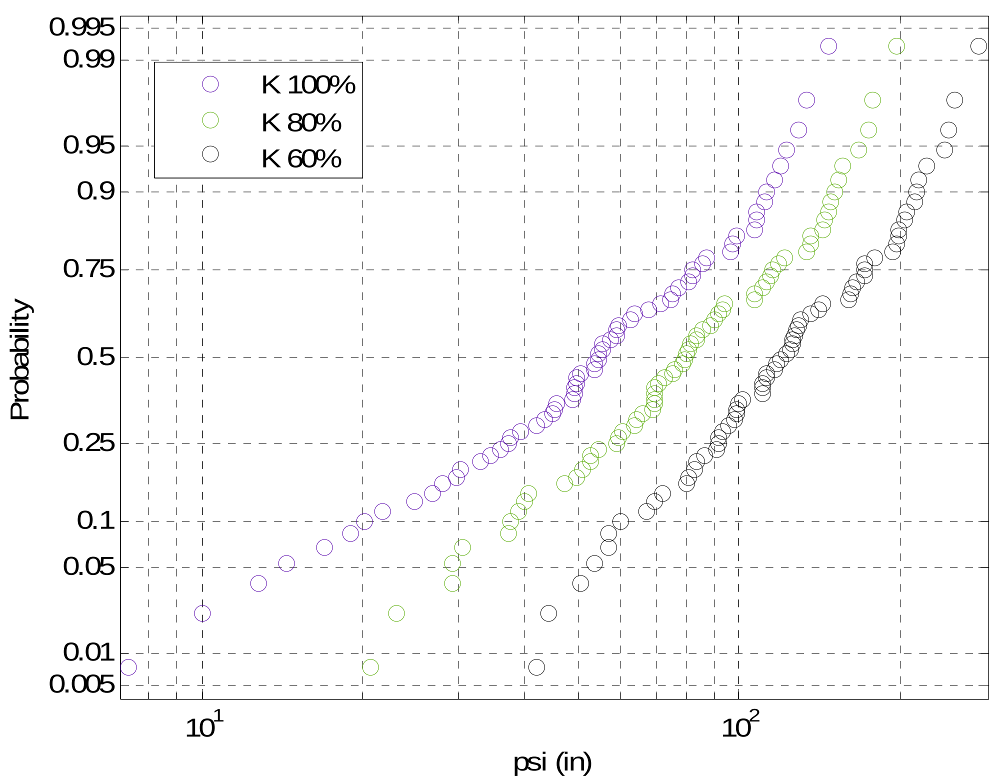


Figure 6.8 Distribution of matric suction values after reducing the conductivity by 20% and 40%.

## 6.2. Fedigan Rain Garden

### 6.2.1. Site Overview

The Fedigan Rain Garden (FRG), as seen in Figure 6.9, was recently built to capture the runoff from the roof of the Fedigan building, a dormitory on Villanova University's campus. The area of roof captured is about 1700 $ft^2$, and the area of the rain garden at start of overflow (1 ft depth) is about 750 $ft^2$ with a storage volume of about 550 $ft^3$. Unlike at the traffic island, no site survey was performed, so only construction plans were used for dimensioning and soil classification. The engineered soil is 1.5 feet deep, and is classified as USDA type Loamy Sand. The native soil is Sandy Loam. At this site, inflow, pond depth, and outflow are measured using pressure transducers. The inflow comes in through a 60 degree V-notch weir, and the overflow goes through an 8 inch Thel-mar weir. Depths at the inflow weir, outflow weir, and in the pond are measured using pressure transducers.

The FRG is considered a "verification" of the model rather than a "validation" because there are so few storm events available for comparison, as the site is still under development. During the data collection from August 2010 through November 2010, there were three events with ponding recorded in the pond pressure transducer. Of these, only one had a significant amount of ponding. For ponding less than an inch or so, the site data collection and setup is not very accurate or reliable. The exact relationship between the pond bottom and the bottom of the pressure transducer is not known, and the model assumption that there is a wide, perfectly flat area will never be the case in reality. Those small variations in the actual pond bottom make correlating to small pond depths difficult. This would be a measurement limitation at any site with shallow ponding and a "natural" bottom.

Figure 6.9 Fedigan bioinfiltration rain garden. Inflow V-notch weir shown.

### 6.2.2. Model Correlation

Only three events were available for correlation. Two of them have such brief and shallow ponding that the results must be taken lightly because the bottom surface of the pond is not known that accurately. Table 6.1 summarizes the correlation results. Although these are not the same events that were correlated to at the first bioinfiltration rain garden, the values of matric suction are higher. However, the matric suction values at VTI were lower bound values, and no such restriction is placed here, as the value of K used at FRG is simply a table value. In other words, since K is unknown a comparison of $\psi$ between the two sites is not possible. Figures 6.10, 6.11, and 6.12 show the depth correlations for each event. Figure 6.10 shows a spike of ponding that is difficult to see; this is intentional to highlight how brief the ponding is over the course of a 12+ hour storm event, and notice also how shallow the spike is (< 0.25 in). Figure

6.11 is also a shallow and brief ponding event, though not so much as in Figure 6.10. In Figure Y, the noisy signal between 13-15 hours and after 16 hours are "empty" readings, but show the variability of the pressure transducer used.

Table 6.1 Correlation results for three events at FRG.

| Rainfall (in) | Matric Suction (in) | Measured Recession Rate (in/hr) | Modeled Recession Rate (in/hr) |
|---|---|---|---|
| 0.95 | 89 | 3.7 | 4.1 |
| 1.95 | 168 | 2.9 | 2.7 |
| 7.42 | 139 | 1.4 | 1.5 |

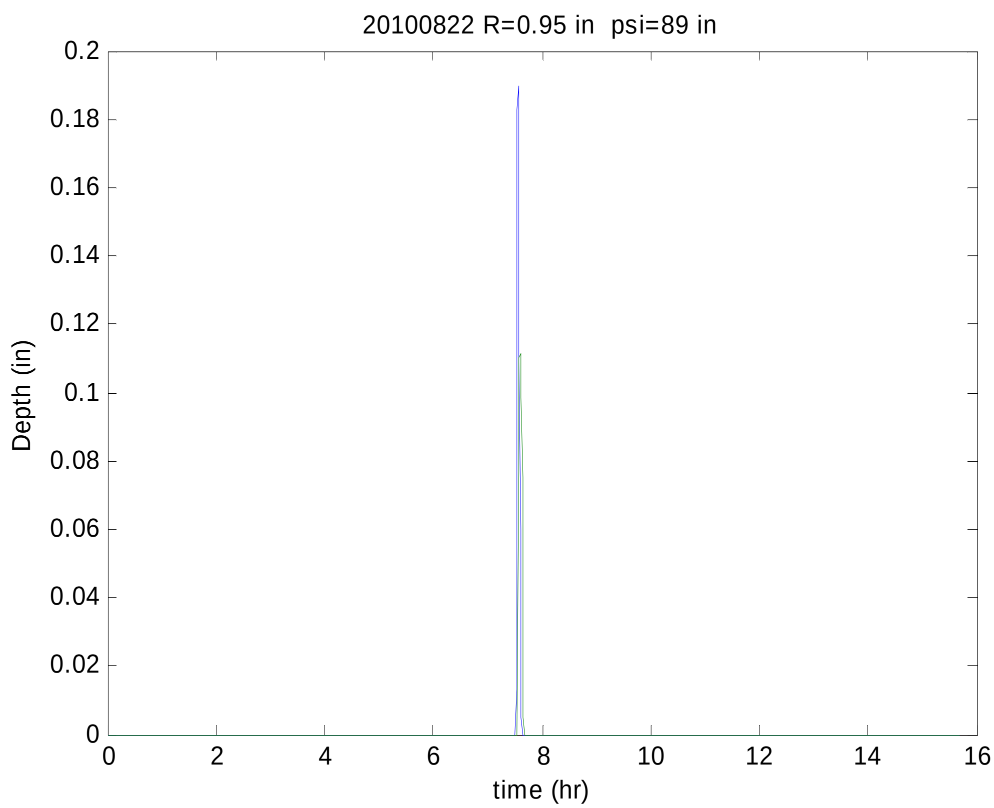


Figure 6.10 Depth vs. time plot from a 0.95 inch rainfall event. Only a brief surge in ponding.

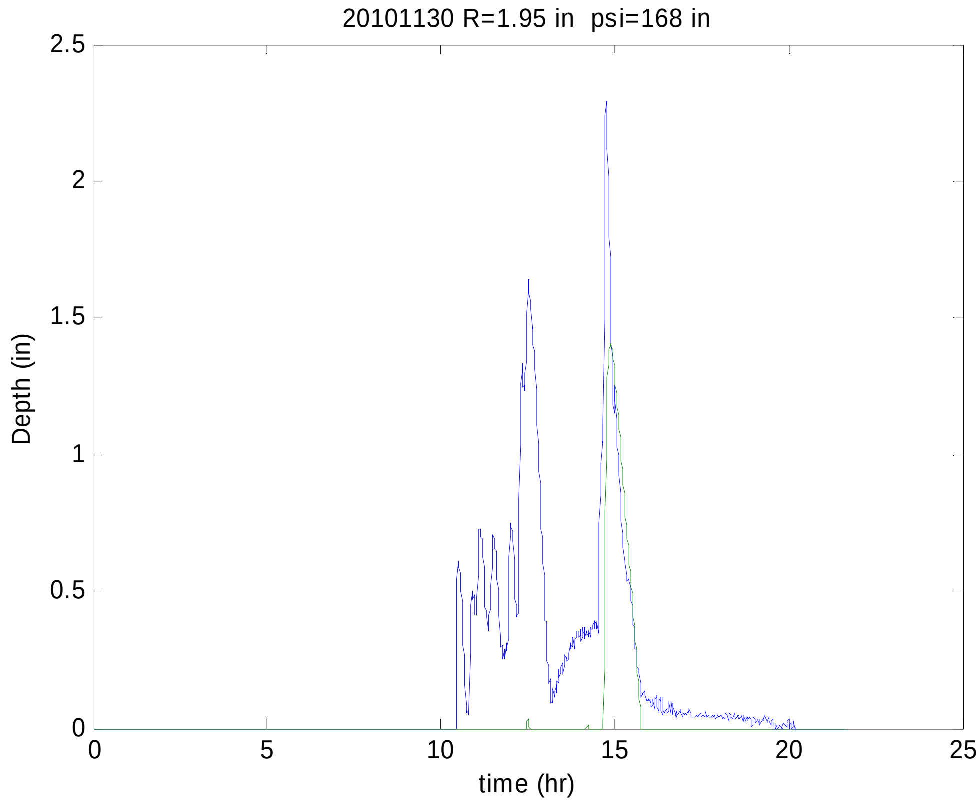


Figure 6.11 Depth vs. time plot from a 1.95 inch rainfall event.

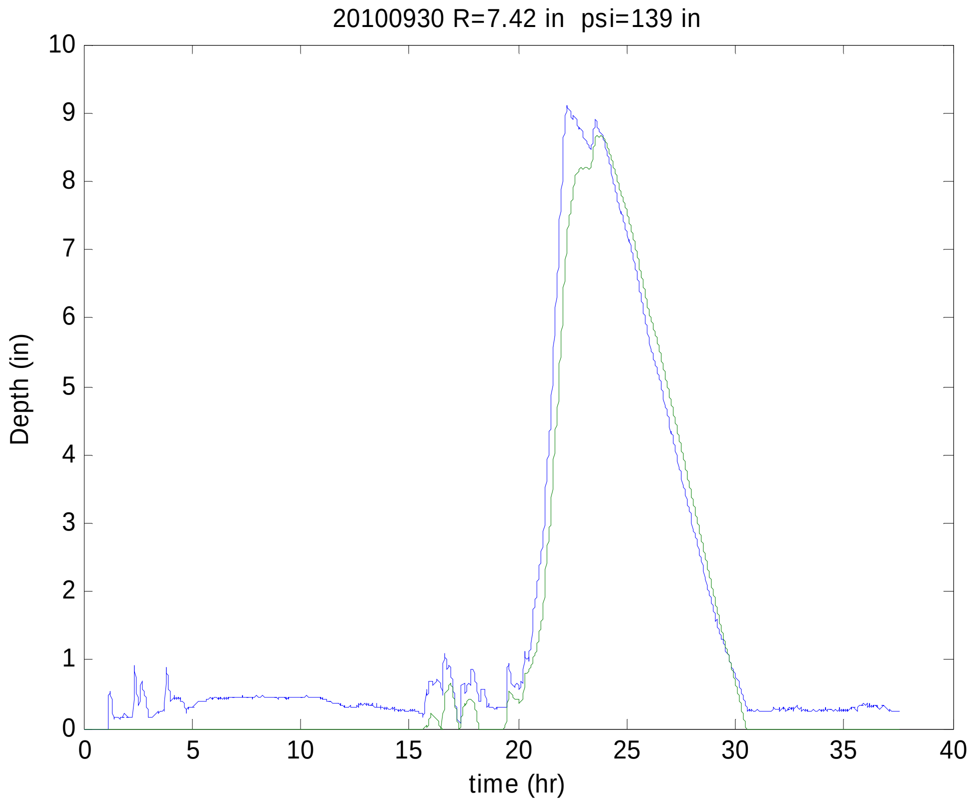


Figure 6.12 Depth vs. time plot from a 7.42 inch rainfall event.

Although the brief, shallow ponding bursts were not matched exactly, these events highlight the model's ability to work in the pre-ponding regime. For example, the timing of the ponding in Figure 6.10 is matched perfectly even though it is 7 hours into the event, near the end of the rainfall. That was the time of the highest intensity, in which the inflow happened to finally exceed the infiltration capacity. Figure 6.13 below shows for the large event the inflow and infiltration rates, converted into in/hr. For the first 15 hours of the event, the infiltration rate equals the inflow rate, because the inflow rate is below the infiltration capacity. Eventually the infiltration capacity decreases below the inflow rate causing ponding. In all three events, this ponding timing is matched well by the model, showing that the model is good for high conductivity soils where ponding is not a given.

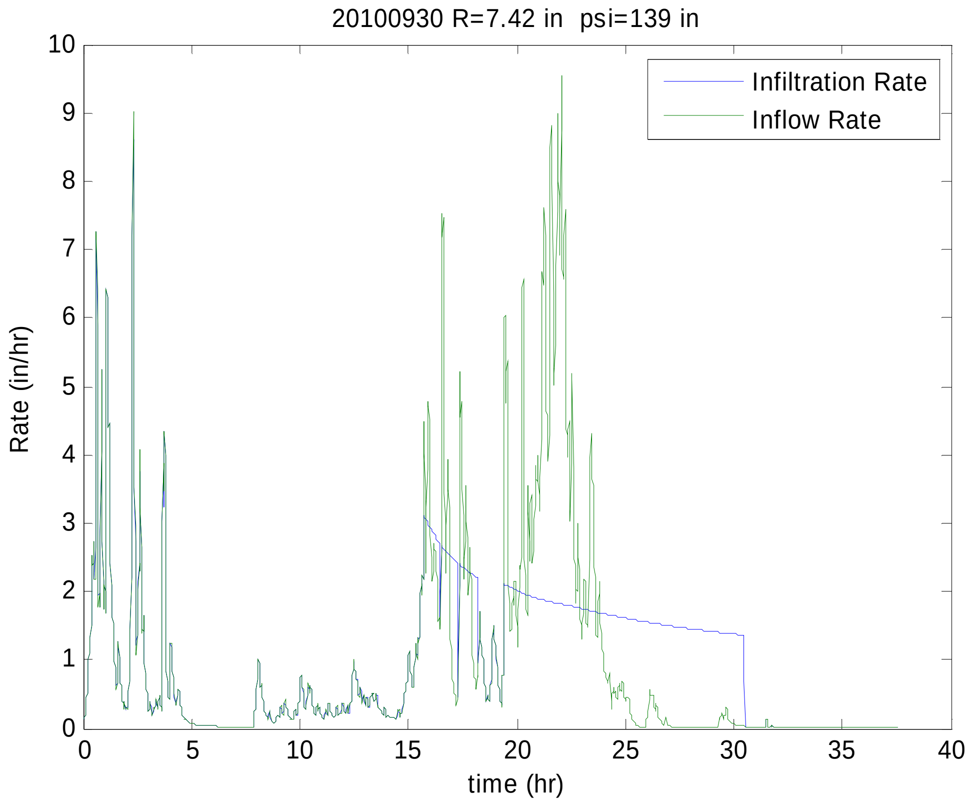


Figure 6.13 Inflow and infiltration rates during the 7.42 inch rainfall event. The rates are equal while the inflow rate is below the infiltration capacity, and so there is no ponding. When the infiltration capacity decreases enough, ponding begins.

## 6.3. Discussion

Because a lumped model necessarily averages together properties of the system, and also because it makes some approximations to simplify the solution, there is no real way to actually measure all the model inputs even at these heavily monitored research sites. Therefore, a true model correlation is not possible. However, much was learned from the storm event correlation to these two bioinfiltration sites: it was shown that the model can mathematically represent a full range of actual operating conditions; it was shown that actual matric suction conditions vary greatly and are generally higher than those used for Green and Ampt watershed modeling; and it was shown that temperature and soil zones are important additions to the Green and Ampt model for infiltration basins.

The two sites evaluated represent a wide range of conditions: VTI has slow infiltration rates (0.15-0.5 in/hr) resulting in long ponding times, and it has engineered soil flowing into a native soil that has a higher conductivity; FRG has high infiltration rates (up to 4 in/hr observed during ponding, much higher during preponding) and a lower conductivity native soil. The data represents a full range of storm sizes, temperatures, and antecedent conditions. Perhaps the largest void in the set of observed conditions is that it does not represent very dry, desert conditions. Of the 69 total events (66 at VTI and 3 at FRG), there were none in which the model was unable to closely recreate the depth versus time plot (qualitatively). The deficiency of this statement is that the correlations were done with matric suction as a free term, and it was observed that uncertainties in K and $\psi$ can correct each other, resulting in a good fit for a set of input parameters rather than one unique solution. However, as with VTI, the set of values that produce a good fit generally lie within a reasonable range surrounding the expected values. VTI has a Sandy Clay Loam soil, which in the SWMM manual has a Green and Ampt conductivity of 0.12 in/hr. From the available data, an upper limit was placed at 0.13 in/hr, and reducing that number by 40% (0.08 in/hr) began to produce unreasonable results (very dry soils with too high initial infiltration rates). This provides evidence that although $\psi$ was a free parameter in the correlations, unreasonable values of it were not permissible to come up with a good correlation.

Despite the uncertainty in the precise values of $\psi$ due to uncertainty in K, because of the ability to place an upper bound on K, a lower bound was placed on the actual values of $\psi$ at VTI over several years of data. Philadelphia is a fairly wet climate, and there were many events of the 66 analyzed in which the pond was empty beforehand for less than a day, so it would be expected that some events would have moist soil. Still, a 95$^{th}$ percentile lower bound was placed on matric suction at a little over 12 inches for this site. Looking at the suggested Green and Ampt values in the SWMM manual (Rossman, 2010), 12 inches is as high as any soil class gets. This analysis then provides strong confidence that using Green and Ampt suction values will provide a conservative design estimate for any soil type or climate.

To get an actual expected suction distribution would require further knowledge of the site environment and the actual field capacity of the soil. A predictive model for suction would necessarily require detailed soil properties and a good model for evapotranspiration. However, analysis of the results of these correlations showed that much of the variation in infiltration rate is a result of both storm size and temperature (through conductivity). At VTI, suction was 58% of the variation, however the unusual site design that has a lower conductivity engineered soil naturally reduces the importance of storm size (this is because the infiltration rate stops decreasing once the engineered soil is saturated; this generally happens after less than 0.5" of rainfall). Although there is not enough data at FRG to make any statistically significant statements, those three events were strongly correlated to rainfall amount, more than to suction or temperature. Therefore, it might be deduced that for a typical site with either one soil or an engineered soil with higher K than the native soil, storm size would have a higher impact on infiltration rate variation, so the combination of temperature and storm size would account for greater than the 42% observed at VTI. These two parameters are the ones that are easily (or inherently) implemented into the framework of SWMM.

# 7. CONCLUSION

Accurate predictive models for infiltration in stormwater control measures are not widely found in the literature. As such, there is not enough data available for stochastic modeling of infiltration rates, and there may never be. Physics-based modeling is generally too difficult to parameterize unless the Green and Ampt solution to the Richards equation is used to simplify the solution. This thesis studied the use of the Green and Ampt infiltration model for stormwater control measures, and found it to be a satisfactory model over a wide range of conditions. Green and Ampt is presently available as an infiltration model in SWMM, however it is lacking some important model components: most importantly temperature dependence and soil layering; and, of less importance, water-depth averaging. Analysis of two bioinfiltration rain gardens showed that the addition of temperature dependence (coupled with the storm size effect – a natural consequence of the model) would account for on the order of 50% of the natural variation in infiltration rate. The rest of the variation comes from changes in soil moisture at each storm event. However, because soil moisture accounting models are under-developed and difficult to parameterize, an engineer designing the site would likely have to use a conservative value for soil moisture, even if variable soil moisture models were an option. This means that with the recommended additions to the SWMM model (soil zones, temperature dependence, and depth-averaging), Green and Ampt can be a usable, accurate, physics-based solution for infiltration in stormwater control measures.

# 8. RECOMMENDATIONS

Using the available Green and Ampt model for storage basins within USEPA SWMM would yield misleading results in many cases. It is recommended that at the minimum, an engineered soil zone be added to the SWMM model. The engineered soil is an important component of most SCMs, and will affect the infiltration in potentially unpredictable ways depending on the precipitation patterns. Another recommendation is to replace the maximum pond depth with the area-averaged pond depth within the Green and Ampt calculation. This will correct an error of up to 10%, which is always an un-conservative error (yields artificially high infiltration rates). Finally, it would be optional for SWMM to include the temperature dependence of conductivity. This is optional because the engineer can make a judgment of what temperature to assume when computing the conductivity, depending on the season being studied for flow control.

The next step in studying Green and Ampt for SCMs might be to correlate the model to additional sites, especially in different climate areas, to show its universality. Additionally, to make the model more practical, it would be beneficial to have more information about the behavior of the initial soil moisture. It would be enough to develop an understanding of what are acceptable engineering values to use, but even more interesting would be to develop a physics-based soil moisture accounting method that is viable for practical use. However, as has been discussed in this paper, it may not ever be practical to accurately predict initial soil moisture in such a model.

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