Introduction to the Tennessee Runoff Reduction Assessment Tool
UT SMART Center and TDEC
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1. Purpose

The purpose of this document is to provide a description of the proposed Tennessee Runoff Reduction Assessment Tool (RRAT), which is designed to give practitioners a logical, easily-understood, and easily-used tool for designing stormwater management systems. The document itself is written for designers and engineers with a sufficient understanding of hydrology and stormwater practices to understand the fundamental hydrologic approach. It is not meant as a User Guide for actual use of the tool.

2. Background

2.1. Broad goals based on federal regulations implemented with respect to the TN Water Quality Control Act

In linking stormwater management to the goals of the Clean Water Act, EPA's ultimate stormwater management strategy (EPA, 2005; EPA, 2009; EPA, 2010a) is to minimize three common negative impacts of development on site hydrology: 1) reduced infiltration, which results in less groundwater recharge and baseflow; 2) higher peak runoff rates, causing flooding and increased stream channel erosion; and 3) a first flush of contaminants—usually from impervious surfaces—resulting in poor water quality. EPA's preferred solution to this is a combination of infiltration, detention, and treatment practices that will restore the site hydrology as much as possible to what would occur in the "natural" pre-development condition, defined as the established forest, grassland, or rangeland that would have been on the site before human intervention. Failing that, EPA provides for an alternative approach based on the understanding that in most locations the vast majority of rainfall occurs in relatively small storms, so being able to infiltrate and treat those will go a long ways towards minimizing the runoff and first flush negative impacts. The flooding problem is already largely managed in many jurisdictions through large-storm detention requirements, which leaves a primary need for enhancing onsite stormwater reduction and first-flush treatment.

EPA's interpretation of the Clean Water Act is implemented in Tennessee by the Division of Water Resources of the Tennessee Department of Environment and Conservation (TDEC) under the Tennessee Water Quality Control Act. A substantial element of this implementation is the Tennessee Stormwater General Permit, which encourages application of the stormwater management strategy through a permitting process for all Phase 2 Municipal Separate Storm Sewer Systems (MS4s) in Tennessee.

2.2. Tennessee Stormwater Permit requirements

The Tennessee Stormwater General Permit designed to help meet stormwater management objectives has the following goal(TDEC, 2010 [section 4.2.5.2.1]):

- implementation of measures to allow no runoff from the first inch of every rainfall event;
- if that is not possible, removal of at least 80% of the Total Suspended Solids (TSS) from any of the first inch that cannot be infiltrated.

Inability of a design to meet these standards—except in special cases of naturally-limited infiltration or special landuse areas (such as redevelopment)—may allow the alternative of off-site mitigation or payments into a stormwater fund, if so desired by the local stormwater program.

As the Permit language makes clear, the ultimate goal of stormwater management is the removal not only of TSS, but of all the contaminants normally found in the urban setting. Given the difficulty in even listing all such contaminants, that one of the primary contaminants of interest is always sediment, and that many contaminants are in fact bound to sediment, TSS is used as a surrogate for all contaminants.

In more closely parsing the Permit language described above, the goal is to adequately deal with what we will call the "action volume", which is the runoff associated from the first inch of rainfall onto contaminated (impervious) surfaces. This is assumed to contain the great majority of contaminants, so is the volume of primary interest. The Permit also clearly gives priority to capture of the action volume, where "capture" is defined as management in such a way that the contaminant is not only removed, but that the volume itself is not allowed to run off. This can only be done by practices that either infiltrate or harvest and reuse the action volume. Capturing 100% of the action volume thus not only meets the Permit's contaminant removal goals, but also its runoff reduction targets. The Permit also requires that in any case all of the action volume should be treated to at least 80% contaminant removal before being allowed to go offsite.

In order to provide for greater flexibility, it is possible to break apart the dual goals of contaminant removal and runoff reduction. In doing so, a design will be defined as meeting the Permit's primary goal if for the defined representative rainfall event the design captures 80% of the Action Volume, and provides for at least 1" of runoff reduction sometime during the entire event. If this is not possible, the Permit allows for the local stormwater program to permit meeting the secondary fallback goal if the design does the following:

- makes clear why the primary goal cannot be met;
- uses some combination of capture (as much as possible) along with filtration, settling, or other means of contaminant removal to reduce the action volume contaminant release by at least 80%;
- reduces the runoff volume from the entire rainfall event by at least 1".

If the design can meet all of these requirements onsite except the third (runoff reduction), the Permit allows the local stormwater program to provide offsite runoff reduction alternatives such as mitigation or fee-in-lieu. Even in such a case the 80% contaminant removal requirement must be met.

The Permit also states that "pre-development infiltrative capacity of soils at the site must be taken into account". In other words, if under "natural conditions" the area's natural hydrology would reduce the possible runoff from the relatively severe event by less than 1", no more than that reduction will be required from the design. For the purpose of this Permit, "natural conditions" are defined as those which would occur if the current area was allowed to go through the vegetative succession process to the climax vegetation. Practically, this means that infiltration under natural conditions would be modeled for the current soils and the expected climax vegetation for an area, probably either long-term grassland or woodland for almost all of Tennessee. If under this scenario the "natural conditions" due to near-surface bedrock or other limitations result in less than 1" of runoff reduction, then a system design will only be expected to reduce runoff by that same amount rather than by the 1" defined above. The expectation of an 80% TSS reduction for the entire action volume remains in place.

2.3. Stormwater control measures: Runoff reduction vs. flood detention

As described above, the overarching goal of stormwater management includes both flood control and runoff reduction, but the differences in design goals for flood detention and runoff reduction systems are dramatic and very important. Flood detention is the temporary storage and slow release of runoff from large design storms, usually defined as occurring once in anywhere from two to 100 years. As an example, Knoxville experiences about 80 rainfall events a year, so a two-year storm would occur about once every 160 events, or only 1/160 = 0.6% of rainfall events. In other words, this is the 99.4 percentile event. A 100-year storm is rare indeed, occurring only about 1/(100 * 80) = 0.01% of rainfall events, or a 99.99 percentile event. For flood detention we deal with such large events because those can cause downstream flooding with an extremely high cost, resulting in destruction of property and possible loss of life. In addition, as we move through the flood detention design process we almost always err on the conservative side, again because of the high cost of failure of flood detention systems.

In contrast, for the runoff reduction goal addressed by the Stormwater Permit and the RRAT, the goal is the shifting of water from surface runoff back towards the more "natural" infiltration, deep percolation, and baseflow. This is not very dependent on any specific storm or site, but is rather a longer-term and broad-area phenomenon, trying to get water to infiltrate throughout the watershed. For example, the natural baseflow to a creek may have infiltrated somewhere in the watershed weeks, months, years, or possibly decades earlier. While a specific infiltration measure failing to operate as designed at a given point or time is unfortunate, the cost of that failure is likely small compared to failure of a flood detention measure. Other similar runoff reduction measures scattered through the watershed may provide more infiltration than expected, yielding the same overall watershed-scale benefit. In the same way, if the measures operate correctly for most events, failure to do so for a single event is not catastrophic, as over the long term the benefit will continue to accrue.

Runoff reduction measures may slightly affect flood routing and detention design because more water will be retained, but a flood routing design must still be generated after the runoff reduction design is completed. The impact of the runoff reduction system will generally be minor for large detention design storms, with at most perhaps retention of 1" from a 6" storm. In addition, once the rainfall at the beginning of a large event overcomes the diminishing infiltration rate and fills runoff reduction storage, the runoff reduction system will have very little impact on the remainder of the storm, including doing very little to reduce the peak runoff rate. Finally, runoff reduction designs will need to take into account the very large volumes and especially the large flow rates associated with those design storms so that the runoff reduction measures themselves are not damaged. This commonly requires building bypass systems for the runoff reduction measures under large flow rates, but may also require designing those measures to handle very high flows.

In order to follow normal usage and to emphasize this differentiation between the large flood detention events and smaller runoff reduction events of interest, we will reserve the term "design storm" for the former, and will speak in terms of "retention rainfall event" for the latter.

2.4. Why a runoff reduction assessment tool?

As described above, the TN Permit interpretation provides clearly defined performance criteria that a runoff reduction design must meet in order to be considered in compliance, so there are two other parts of a complete package for implementing that permit. The first is a manual of acceptable measures and their design specifications modeled on measures that have been successfully used elsewhere, or new measures that can—through clear empirical evidence—be shown to provide satisfactory performance. Such a Manual has been developed by TDEC and the SMART Center, and this document serves as a companion to that manual.

The other necessary element for successful Permit implementation is a tool to determine the extent to which a proposed design meets the permit performance requirements. The rest of this document provides a detailed description of such a tool developed by the SMART Center and TDEC.

3. Runoff reduction design assessment tool requirements

In designing a runoff reduction system to meet Tennessee Permit requirements as described above, we must estimate how much runoff reduction occurs across a wide variety of stormwater control measures (SCMs). In order to have general applicability, a tool used to determine the success of a design in meeting the requirements must contain the following elements:

1) a well-defined retention rainfall event, providing important rainfall characteristics specific to the geographic area. This should provide a relatively severe standard in order to comply with the Tennessee Permit (TDEC,

2010). In addition, the event should address the specific performance criteria of the Tennessee Permit, which requires (barring special circumstances) retention of 1" of rainfall and removal of 80% of TSS from the first 1" of rainfall.

2) for SCMs using infiltration into the underlying soil, the tool must reflect the primary factors controlling infiltration, including soil and management differences and water storage within the SCM. Because of the sensitivity of infiltration to these factors, it is best if the tool can provide a relatively fine gradation between varying conditions. For example, differentiating between the four hydrologic soil groups is probably the minimum required resolution, though having more soil gradations is preferred, especially within the fine textured soils, which have high silt and especially clay contents. Similarly, the tool should allow designs with relatively fine gradation of management conditions (e.g., good condition lawn versus poor-quality grass) rather than just a few management conditions. Ideally, the tool will also reflect the hydrologic impact of SCM details such as the various layers of media (e.g., fine over coarse vs. coarse over fine), the presence or absence of an underdrain, etc.

3) an ability to "route" flows between design elements, at a minimum allowing the designer to direct runoff from impervious areas to specific SCMs. Ideally, the tool would allow for unlimited "SCM trains", where any runoff from one measure could be directed to a second measure, and so on. Further, the tool must be able to track the runoff from the first 1" of rainfall, since this portion of the rainfall event must be treated for TSS removal.

Beyond those specific minimum requirements, it must be remembered that the purpose of a design tool is not to serve as a scientific modeling engine, but rather to allow designers to efficiently compare alternatives and choose the best design. Variables without *a priori* well-known values should not be included even if they may seem conceptually important, as including poorly known variables only adds error and confusion to the resulting predictions and designs. As such, it is essential that the tool be easily understood, be robust, and provide the flexibility required to model all likely SCMs and SCM trains.

3.1. Comparison of available design tool approaches

There are at least two very different approaches commonly used in existing runoff reduction design tools. The first approach might be termed the "*coefficient*" method, based on lumped empirical values describing by what portion a measure reduces runoff (e.g., a rain garden in a type C soil will infiltrate 70% of the incoming water), then adjusting that coefficient up or down depending on the specific situation. In analogy to a more familiar flood detention design tool, this is like selecting a runoff coefficient C value in using the Rational Method, then adjusting that for soil type and rainfall intensity (Schwab et al., 1992).

The second approach directly calculates intermediate values such as infiltration based on more physically-based site descriptions instead of relying on coefficient values. For example, to calculate infiltration in a rain garden at a minimum the following are needed: the volume of water available within the rain garden, an infiltration rate at that point in time for the soil texture/vegetation combination, the depth of soil, and the area of the rain garden. Though such an approach is still likely to be based largely on empirical data describing infiltration and the impact of vegetation, it takes into account not only the controlling factors but also their interactions throughout the time of a rainfall event, combining the factors at each time step to determine the runoff. We will call this the "*time step-mass balance*" approach, as it strictly enforces a mass balance at each time step. What follows is a comparison of these approaches.

3.1.1. Coefficient approach

As described above, the coefficient approach begins with a single value for a measure's runoff reduction, then adjusts that for soil and climate characteristics. The most common source of these single values is the substantial infiltration data collected and summarized in the International Stormwater BMP Database (ISBD, 2011), where the data represent a wide range of situations with various soils, land uses, and rainfall events. This broad range of data has been combined to give average or median runoff reduction values used as the starting points for this approach. These values may then be adjusted to represent the rainfall characteristics, land use, and sometimes soil types for the specific design situation. The greatest strength of this approach is that it is based on the central value of all collected data, which means that it is not likely to give a completely unreasonable answer. One of the biggest weaknesses of the approach is that new designs will have unpredictable performance if they are developed using values beyond the range of collected values used to develop the coefficients.

An unstated assumption in this approach is that the range of values seen by each location using the approach will be similar to the range of values where the ISBD data were collected so that using the mean or median really makes sense, but this assumption may not always hold true. For example, a measure in a specific part of the country experiencing long-term light rainfall may infiltrate 80% of the applied water, but the same measure in another part of the country experiencing primarily high-intensity short-duration rainfall may only infiltrate 50% of the applied water. The average value of 65% runoff reduction is probably adequate for either location, but adjusting upward from this based on soil or management wouldn't make sense for the high-intensity location, and adjusting downward wouldn't make sense for the low-intensity location. In other words, combining all these data and taking the average can hide important interactions between factors. On the other hand, use of the average value without adjustment for soil type or land use violates one of the requirements stated above, so just using the 65% in both cases really isn't adequate either.

Another difficulty in using the *coefficient* approach lies in determining just how much to "spread things back out" based on factors such as soil type. For example, if the average runoff reduction for a practice is 65% and this is assumed to apply to some mid-range soil, by how much should this be raised or lowered for a high-clay soil? This can to some degree be determined by querying the database for this information, but that ignores interactions with other factors such as climate. Given the large number of factors that contribute to an estimate of infiltration for a given measure, once the database is fully limited to those factors describing a particular setting of interest there may not be a suitable number of data point to provide much statistical power.

Additionally, using a single centralized value masks that the data represent everything from very small events—for which all of the water infiltrates—to very intense events where probably very little of the water infiltrates. In other words, even for a specific site the runoff reduction for a specific measure is likely to vary significantly for different rain events, so the central value should be adjusted for rainfall characteristics. The key problem here is that the *coefficient* approach does not account for how the essential factors interact over time, though it is generally accepted in infiltration science that not just the rainfall depth but also the time distribution of rainfall intensity within the event will significantly control how much infiltration occurs.

Finally, the *coefficient* approach may lead to difficulties with the routing of runoff from one area to the next, as the runoff reduction for a specific measure will clearly depend on the total incoming volume, which in turn depends on the contributing area. The problem, of course, is that the ratio of contributing area to measure area is one of the things that varies greatly between data sources. This difficulty was addressed to some degree in an additional data analysis (ISBD, 2012) that attempts to make an adjustment on the basis of contributing and measure areas, but this does not address the other issues described above.

3.1.2. Time-mass approach

The alternative to the *coefficient* approach can be termed the *time-mass* approach. Rather than beginning with the broad range of measured values, this approach begins by describing the primary controlling process, which is water infiltrating into the soil. It recognizes the time-sensitive relationship between precipitation intensity and the resulting infiltration and runoff rates, applies a mass balance at each time step defining the mass of water introduced to the area by rainfall or run-on, and subsequently calculates the resulting infiltration or runoff during that time step. The key to this approach is the ability to adequately model the infiltration process over time, reflecting the impacts of soil and management practices. This is generally the approach used in the EPA SWMM (Storm Water Management Model [EPA, 2010b]) which is a broad stormwater model that not only estimates the impact of stormwater control measures on runoff reduction, but also allows for detention calculations. Though our tool uses a similar time step mass balance, it uses a different specific approach for estimating time-varying infiltration than does the SWMM model, as described below.

The advantages of the *time-mass* approach for runoff reduction estimation are the following: 1) it adjusts for the time relationships between rainfall intensity and infiltration rate; 2) it meets the requirement of adjusting infiltration for the controlling factors of rainfall characteristics, soil, management; and 3) because the mass balance is done at each time step, it becomes relatively easy to route the water between areas, as the mass leaving one area simply becomes part of the supply to the next area. In other words, it offers the stormwater engineer greater flexibility of design, such that she can take credit for having a larger or smaller rain garden than those generally populating the ISBD. Also, if the rain garden is too small to accommodate all the run-on into it, subsequent downstream measures can be added as needed.

The greatest weakness of this approach is that it does not specifically take into account the database of measured runoff reduction values such as the ISBD. On the other hand, with the database runoff reduction data for many of the measures often displaying a tremendous range of values (ISBD, 2011 [p.20ff]), it is likely that the calculated values will fall within that range anyway.

4. Development of the RRAT time-mass approach

The approach for the Runoff Reduction Assessment Tool (RRAT) very closely follows the infiltration approach in the EPA SWMM model (EPA, 2010b), but has its sole focus on runoff reduction while incorporating better means to account for differing land management practices. Further, since the tool is meant to be used in a design driven fashion rather than as a scientific tool, we purposefully elected not to include variables and measured values that cannot be reasonably well predicted, and have attempted to place limits on parameters that might be unreasonably manipulated; e.g., the user cannot simply enter a soil's permeability.

4.1. The RRAT approach: Basic time-mass infiltration modeling

As with the infiltration component of SWMM, because many of the SCMs are based on infiltration, the core of RRAT is in the modeling of time-varying infiltration. Infiltration is extremely variable in both time and space and is affected by a host of inputs, but the dominant factors are the soil texture, land use, and the time-sequenced availability of water to infiltrate, which includes both rainfall and run-on. The potential infiltration rate per elapsed time assuming runoff conditions are maintained (i.e., that there is a constant water supply rate equal to or greater than the soil can take it in) is generally described by what are called infiltration capacity (or sometimes infiltrability) curves (Hillel, 1998; Ward and Trimble, 2003). Figure 1 shows examples of infiltration capacity curves, with typical high maximum infiltration rates at the beginning of the event when the soil is dry and acts like a sponge, pulling water into the soil through matrix suction (Hillel, 1998). As the wetting front deepens, the relative effect of soil suction diminishes, and the infiltration capacity approaches a rate equal to a soil's hydraulic conductivity, which is the y-value of the curve as the slope approaches zero.

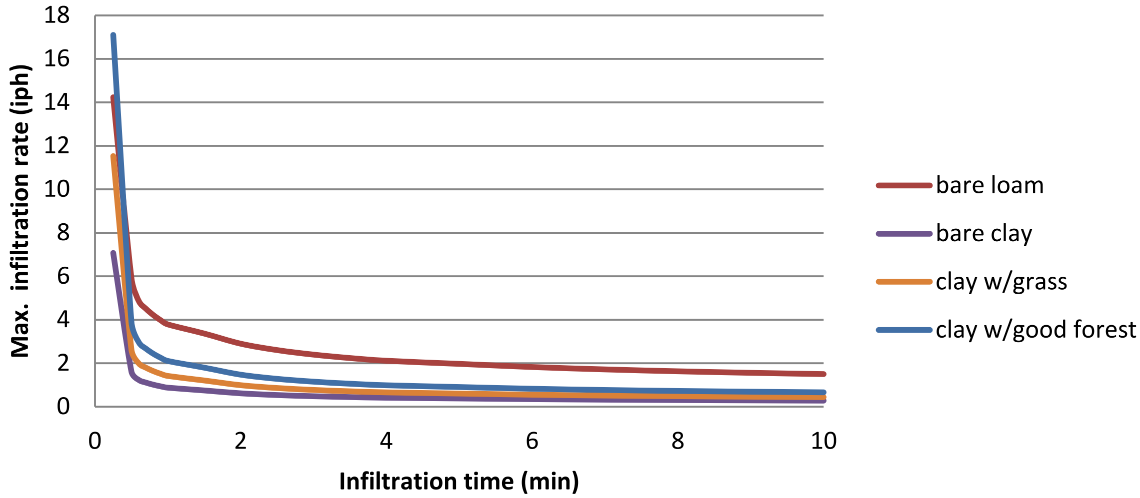

Figure 4.1. Infiltration capacity curves for several soils and land uses, using the approach of USDA-NRCS (2012) and the RRAT approach for modeling the impact of management, both described below.

How this potential infiltration rate changes over time is especially important because of how its timing coincides with the timing of water application, including both rainfall and/or run-on. If at the beginning of water application the water is applied at a high rate during the period of high infiltration capacity, the soil can infiltrate more of it than later when the infiltration capacity is reduced. If the water is applied at a rate higher than the infiltration capacity, the actual infiltration rate will equal the infiltration capacity and any excess applied water will run off. If water is applied at a rate lower than the infiltration capacity, all of the available water will infiltrate, and the infiltration capacity will essentially be stretched out over a longer duration, since the wetting front is at a shallower depth that it would otherwise have obtained had the assumed upper boundary condition (saturated/runoff condition) been maintained. However, since many rainfall events begin and end with a low intensity and have a higher intensity in the middle, it is quite common that water delivery is initially less than the infiltration capacity, exceeds it during the middle of the event, then falls back below the infiltration capacity towards the end of the event.

This same information can be presented in perhaps a more intuitive way by summing the infiltration over time to get the total infiltration depth, then dividing by the soil porosity to yield the depth to the wetting front, assuming full saturation behind the wetting front. This is shown in Figure 4.2 for the same bare loam soil shown in Figure 4.1. This shows the expected behavior, with the infiltration rate decreasing quickly as the infiltrated depth increases. In other words, as the depth of water trying to move through the soil increases the relative impact of soil suction decreases, so the flux (and therefore infiltration rate) approaches the saturated hydraulic conductivity. This is somewhat more intuitive because it is clearer that the infiltration rate doesn't really depend on time, but really on the depth of infiltrated water. Time as shown in Figure 4.1 is really just a surrogate for infiltrated depth under specific conditions.

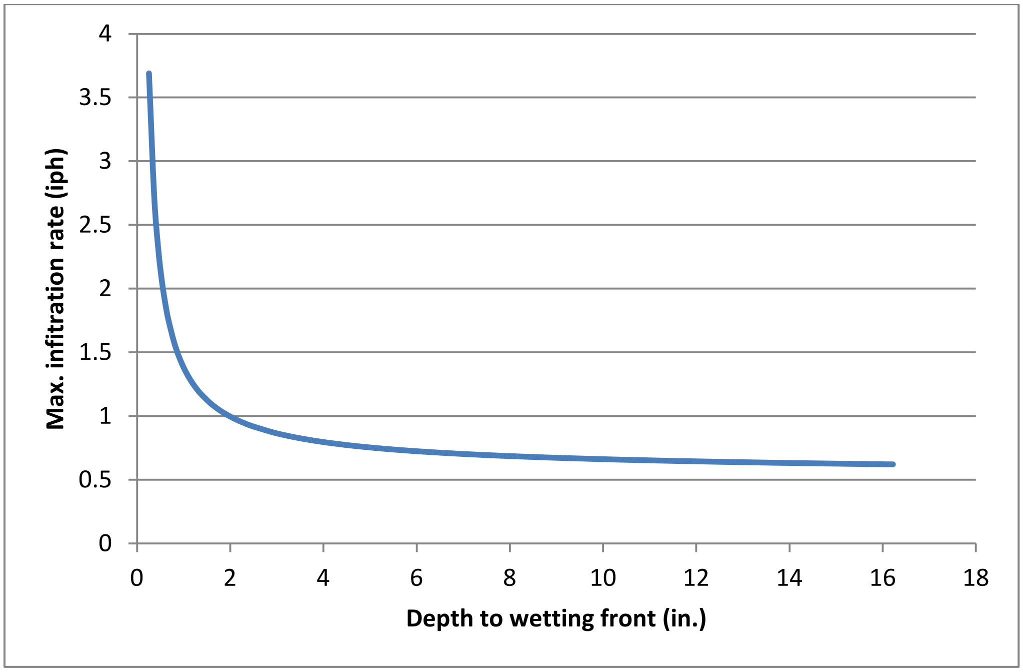

Figure 4.2. Plot of infiltration capacity vs. depth to wetting front for the bare loam soil shown plotted vs. time in Figure 4.1.

It is also instructive to contemplate Figures 4.1 and 4.2 to shed further light on the Section 2.3 discussion regarding the different approaches for flood detention design storms and retention rainfall events. For the very large events associated with flood detention design storms, we are far out to the right on the tails of infiltration capacity curves, so the additional infiltration depth represented by the high initial rates becomes relatively insignificant. In that case the rainfall timing also becomes much less important, because how the rainfall intensity coincides with the infiltration rates doesn't matter. On the other hand, for the smaller events of interest for runoff reduction the total infiltration time and depth are relatively small so the initial high infiltration rates are critical, as are how the rainfall intensity lines up with those.

The SWMM model provides three alternatives for estimating infiltration. The first option is to use the SCS Curve Number (CN) method, which was developed to estimate large-event runoff from rural watersheds, but has also been applied to urban watersheds for decades (USDA-NRCS, 2004). The big advantage of this approach is that well-established curve numbers (*CN*) are available describing a wide range of managements and their relative impact on runoff. The biggest problem is that this approach does not include any measure of rainfall intensity nor how it interacts with the infiltration process. This may be a reasonable simplifying assumption for the very large storms usually of concern for flood detention design, but not for estimating the complex interaction between rainfall and runoff rates for smaller events, and certainly not for attempting to estimate which portion of the rainfall is infiltrated. This concern becomes even more acute due to the size of storms (~1") that need to be modeled for runoff reduction. In many cases, the 1" rainfall depth will be near to value of the CN initial abstraction, where the veracity of runoff prediction from the method is at its worst. Because of this and difficulties in setting the values associated with the initial abstraction, it is usually recommended that the SCS CN method not be used to estimate infiltration from smaller storms (Haan et al., 1994 [p.63]; Garen and Moore, 2005 [p.381], Van Mullem et al., 2002).

Besides the SCS CN method, the other two infiltration methods available in SWMM (the Green-Ampt and Horton methods) are just two of the many available empirical ways of developing the infiltration capacity curves shown above (Ward and Trimble, 2003). All of these other methods can produce curves with shapes similar to those in Figures 4.1 and 4.2, representing how infiltration capacity changes with time or infiltrated depth. These curves all show the classical infiltration capacity shape, with high rates early when the soil is drier, then dropping quickly to a long-term asymptotic value when the wetting front is deep enough that soil suction plays little role and infiltration is controlled by the soil hydraulic conductivity. In addition, if data are available, the curves can be calibrated to show the impact of land use / management that will shift the curves somewhat. Management generally controls infiltration through several impacts, including whether or not surface sealing occurs, the formation of macropores and other preferential flow paths that ease the flow of water through the soil, and increasing evapotranspiration. Unfortunately, it appears that few data are available to describe the management impact on infiltration as represented by Green-Ampt, Horton, or most similar approaches, so these SWMM methods generally suggest the use of commonly available hydraulic parameters based on soil texture without management adjustment, violating one of the principles defined above.

The Green-Ampt approach for developing the infiltration capacity curves is the most commonly used in modeling small-scale infiltration, partly because it attempts to estimate infiltration using soil parameters that are relatively easy to measure. Green-Ampt and similar methods can generate infiltration capacity curves based on soil hydraulic parameters such as wetting front soil suction and saturated hydraulic conductivity, fitting especially well with the conceptual model shown in Figure 4.2. Unfortunately, these are not good at representing the large portion of infiltration through fractures and macropores generally occurring in areas with well-established vegetation and that so strongly affect flow at larger scales, and especially so in soils with higher clay content. In addition, the primary Green-Ampt parameters most commonly referenced for modeling infiltration are taken from Rawls et al. (1983), but an examination of that report shows that its purpose was to predict Green-Ampt parameters based on yet other soil properties, and that the all-important saturated hydraulic conductivity values for almost all soil textures are about ½ of the measured values in the underlying paper (Rawls et al., 1982).

The other similar approaches (Horton, Holtan, and others) are generally purely empirical approaches, using measured infiltration data to set coefficients that provide the best fit to the data, usually through use of an exponential or power function. A search for the best data set to define the infiltration capacity curves led to flood irrigation literature, where infiltration estimates are critical to designing large-scale water application systems. The literature in this field generally deals with infiltration on a large scale, reflecting the impact of preferential flow far better do than the small-scale tests usually associated with Green-Ampt. Based on the availability of a range of large-scale supporting data, we chose the Kostiakov-Lewis (KL) method (Walker and Skogerboe, 1987), as used by USDA-NRCS to estimate infiltration in flood irrigation systems (USDA-NRCS, 2012 [p.4-24ff.), and based on numerous large-scale measurements of areas being flood irrigated. As described in Walker et al. (2006), these values were originally based on a series of large field studies using double-ring infiltrometers, then were expanded to include a wide range of infiltration data from large flooded areas representing seven studies across a wide range of soils and locations. Such studies generally included adding a known flow rate to the large area, then measuring the water exiting the opposite side of the plot.

The equation for this approach is

$$I = k * t^{a} + f_0 * t \tag{1}$$

where I = cumulative infiltration capacity depth (ft), k, a, and f_0 are the empirical fit coefficients for the desired soils as listed in Table 4.1, and t is the elapsed time (min). The equation assumes saturated conditions at the surface, so that the water supply is not limiting. The infiltration capacity rate i (ft/min) at any time is thus the rate of change in I *(i.e., dI/dt)*, or

$$i = k * a * t^{(a-1)} + f_0 \tag{2}$$

Table 4.1. Kostiakov-Lewis soil coefficients for a range of soils (USDA-NRCS, 2012).

Soil Texture	Normal Hyd. Group	a	k	f_0
Sand	A	0.601	0.017310	0.0012078
Loamy sand	B	0.533	0.012556	0.0009970
Sandy loam	B	0.510	0.011070	0.0008805
Loam	B	0.478	0.009236	0.0007084
Silt	C	0.468	0.008784	0.0006642
Silt loam	C	0.458	0.008302	0.0006161
Sandy clay loam with 20% < clay < 27.5%	C	0.445	0.007781	0.0005635
Sandy clay loam with clay > 27.5%	C	0.430	0.007220	0.0005060
Clay loam with 27.5% < clay < 34%	C	0.411	0.00659	0.0004433
Clay loam with clay > 34%	C	0.399	0.006241	0.0004097
Silty clay loam with 27.5% < clay < 34%	C	0.386	0.005883	0.0003750
Silty clay loam with clay > 34%	C	0.371	0.005496	0.0003386
Sandy clay with 35% < clay < 45%	D	0.354	0.005060	0.0003010
Sandy clay with clay > 45%	D	0.333	0.004617	0.0002621
Silty clay	D	0.278	0.003540	0.0001809
Clay with 40% < clay < 50%	D	0.242	0.002893	0.0001392
Clay with 50% < clay < 60%	D	0.197	0.002076	0.0000963
Heavy clay with clay > 60%	D	0.153	0.001170	0.0000616

This method can easily be transformed to the form shown in Figure 4.2 above. This means that at the beginning of any time step j we know the depth to the wetting front, and with that can calculate the infiltration capacity rate i_j. Multiplying that by the time increment yields the incremental infiltration capacity depth I_j. If during a time step the applied water (rainfall plus run-on) exceeds I_i, the total infiltrated depth is increased by I_j and any excess applied water becomes runoff. If instead during a time step the applied water is less than I_j, then all the precipitation infiltrates. In either case, the depth of water infiltrated is added to adjust the depth to the wetting front for the next time step.

Note that though the KL method was chosen due to its foundation on large-scale data (field, plot, and large infiltrometer), any of the similar methods (Horton, Green-Ampt, etc.) that are based on infiltration capacity curves could be used if large-scale supporting data were available. All the relationships provide similar infiltration capacity curves, so the specific relationship used is not a critical factor in estimating infiltration.

Because the data for the KL approach were collected under field conditions, the results represent a range of initial soil water contents, generally unmeasured but representing relatively dry conditions at the surface and wetter conditions underneath. For the purpose of the RRAT, we assume that at the beginning of the modeled event the bare-soil water content is close to field capacity, while for vegetated soil conditions the initial water content is one third of the way from wilting point to field capacity.

4.2. The RRAT approach: Adjusting infiltration for management

Using the infiltration approach above adjusts the infiltration rate for soil texture, but not for the various vegetations and other cover managements associated with stormwater design. In fact, since the infiltration parameter values listed above are for irrigated fields, they are for a recently-tilled soil, generally bare of much vegetation or surface cover. Unfortunately—as mentioned above—there do not appear to be substantial data sets relating infiltration parameters to management for the infiltration capacity models, though it is clear that management greatly affects infiltration (Ward and Trimble, 2003). To recap, management affects infiltration in at least the following three important ways: 1) it protects the surface from soil sealing by minimizing erosion and by breaking soil surface seals through physical and biological activity; 2) substantial vegetation results in root channels, worm holes, and other macropores providing large subsurface flow paths; and 3) vegetation also increases evapotranspiration, resulting in drier soils that yield higher initial infiltration rates.

The best information source we found relating infiltration and runoff to a broad range of land uses is still the SCS CN literature. As described previously the SCS CN approach has significant weaknesses when used to calculate infiltration directly, so we instead used the valuable information contained within the *CN* values themselves for various land uses. The RRAT does **not** use the SCS CN method to define infiltration, but rather employs the relative *CN* values to scale the KL curves for the various management scenarios. This approach uses the fact that in the SCS CN approach the value of $S = (1000 / CN) - 10$ represents the total storage available in the system, or the amount of rainfall that will be retained and not seen as runoff.

The RRAT approach begins with defining the bare condition represented by the KL infiltration parameter numbers above as the *Bare soil (poor row crop)* values found in most *CN* tables. We then define the management infiltration ratio (*MIR*) as

$$MIR = \frac{S_{current}}{S_{bare}} \tag{3}$$

where $S_{current}$ is storage depth (in.) for the current management condition, and S_{bare} (in.) is that for the bare soil condition most representative of the KL data conditions, using the *CN* values for the various land uses defined in most *CN* tables and shown in Table 4.2.

Table 4.2. Land use values associated with infiltration calculation of the Management Infiltration Ratio (*MIR*). Values are from Haan et al. (1994).

Land use	*CN* values for respective soil hydrologic group			
	A	B	C	D
Impervious surface	98	98	98	98
Bare soil (poor row crop)	72	81	88	91
Poor range	68	79	86	89
Good range	39	61	74	80
Fair Lawn	49	69	79	84
Good lawn	39	61	74	80
Dense natural grass (meadow)	30	58	71	78
Poor forest	45	66	77	83
Good forest	25	55	70	77

In recalling the earlier discussion of infiltration curves in Figures 4.1 and 4.2, it seems likely that management will have less impact near time zero (on the left end of the curves)—where soil suction forces are significant—than on the right ends of the curves, where the pore size distribution controls the saturated hydraulic conductivity. In order to provide realistic infiltration rates through time, rather than simply multiply the time-varying infiltration capacity values by the *MIR* we use the *MIR* to move to another infiltration curve in the set. In other words, the management shifts the infiltration behavior to be more similar to that of a different soil, with the degree of that shift defined by the *MIR*.

The approach of adjusting infiltration for management / vegetation begins by calculating the total bare-soil infiltration capacity for an 8-hour period (see below) for the current soil type using the KL approach. This is multiplied by the *MIR* calculated as defined above for the particular management / land use for this practice, as:

$$I_{8\,hr\,current} = I_{8\,hr\,bare} * MIR \tag{4}$$

This new management-adjusted depth is then used to interpolate new adjusted a, k, and f_0 values for an equivalent soil that under bare conditions in 8 hours would have infiltrated $I_{8\,hr\ current}$. Those adjusted infiltration curve parameters (the adjusted a, k, and f_0 values) are then used for the model infiltration calculations. The 8-hour duration was selected for this process because preliminary examination of rainfall data (see below) indicated that most representative rainfall events would have durations of at least 8 hours. In addition, we examined the use of durations as short as 2 hours and as long as 24 hours, and those caused very little difference (< 7%) in the expected shift in infiltration depths for those representative rainfall events.

As an example of the approach, we take the following:
- soil = *Clay loam with 27.5% < clay < 34%* in Table 4.1
    - mid-range hydrologic class C soil
    - KL parameter values a = 0.411, k = 0.00659, and f_0 = 0.0004433
- $I_{8,bare}$ = 3.88" using Eqn. 1
- current management = *good lawn:* CN = 74, so $S_{current}$ = 3.51
- for *Bare soil (poor row crop):* CN = 88, so , S_{bare} = 1.36
- *MIR* = $S_{current}$ / S_{bare} = 3.51 / 1.36 = 2.58, so we estimate that the *good lawn* will allow 2.58 times as much infiltration as would be expected for the base condition *Bare soil (poor row crop)*
- $I_{8,cover}$ = 2.58 * $I_{8,bare}$ = 2.58 * 3.88 = 9.99
- new adjusted KL parameters by interpolation are: a_{cover} = 0.5141, k_{cover} = 0.01137, and $f_{0,cover}$ = *0.0005612.*

The differences between the infiltration capacity curves for the two cases can be seen in Figure 4.3. In looking at Table 4.1 above, this indicates that with the *good lawn* management the soil / management combination is expected to behave more like a *Sandy loam* than like the original *Clay loam with 27.5% < clay < 34%* for a bare soil.

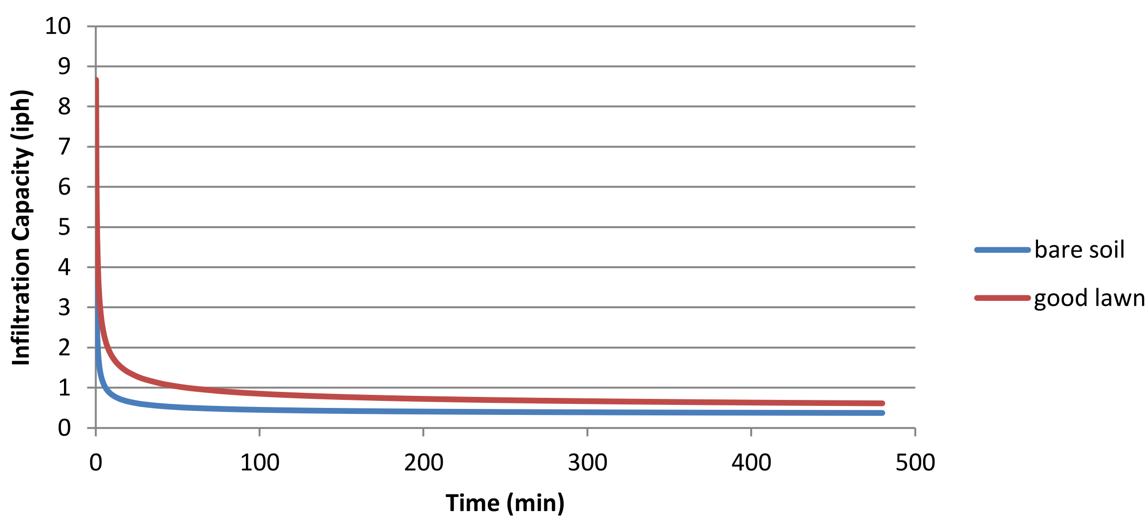

Figure 4.3. Infiltration capacity curves for a clay loam soil with bare soil and good lawn conditions in the example described above.

4.3. The RRAT approach: Defining the retention rainfall event

With the infiltration capacity method described above accounting for both soil and management characteristics, the next step is to define a retention rainfall event for testing the design. This description begins with hourly precipitation data for the most recent 30 years of record for a series of locations in Tennessee. It then defines rainfall events as being separated by at least 6 hours with no rainfall. This is different from approaches that use daily rainfall, which arbitrarily divides rainfall into 24 hour periods at midnight. In addition, this approach allows storms lasting more than 24 hours, which cannot occur with the daily rainfall definition. Overall, this more realistic 6-hour no rain definition leads to fewer but larger events. We also did not truncate events less than 0.1" as proposed by the EPA manual (EPA, 2009).To date, we have conducted the required event analyses for Bristol, Knoxville, Chattanooga, Monterey / Crossville, Nashville, Jackson, and Memphis, but the hourly rainfall data needed to calculate representative events for other locations in the state may be available.

Following the lead of the EPA Manual (EPA, 2009), we chose to use the 95th percentile storm depth. In order to use the time-step mass balance approach, we need not only the event depth but also the duration, as this impacts rainfall intensity. Looking at all the storms in the percentile range from 92.5 to 97.5, we took the median duration as our event duration. Finally, the event was then defined as having rainfall intensity over time matching an SCS Type II distribution. Any time intensity distribution could be used, but the Type II is considered representative of most of the US (and all of Tennessee), and is the typical distribution used for design storm modeling for this part of the country (Haan et al., 1994).

4.4. The RRAT approach: Modeling runoff reduction

The time-varying precipitation and infiltration estimates described above are combined in a modeling approach very similar to that in SWMM, running through a series of small time steps. For each user-defined element within the design, for each time step the logic is as follows:

1. If the element has surface area (SCMs such as cisterns and subterranean infiltration vaults do not), calculate the rainfall depth during this time step based on the rainfall intensity at that time (defined by the event depth and the Type II distribution) and the time step length;
2. add in the run-on water coming from any upstream element in this time step and any water currently already stored in this element to get the total available water for this time step;
3. if this element causes infiltration into the underlying soil, use the infiltration capacity for this time step (based on this element's soil type, management, and current infiltration depth) to calculate the potential infiltration (infiltration capacity) during the time step;
4. if the element causes infiltration, calculate the actual infiltration in this time step by adjusting the potential to account for available supply, and calculate the new total infiltration depth at the end of the time step;
5. if the element has a reuse component, remove the reused volume from the available storage;
6. if the element has an underdrain, calculate the flow out of that underdrain during this time step;
7. calculate the amount of water remaining in this subarea at the end of the time step as initial storage plus inflow (rainfall plus flow from upstream) minus infiltration and use;
8. compare this remaining volume to the available element storage. If the remaining water is greater than the storage, the difference runs off into the next downstream element, or offsite if there is no downstream element. If the remaining water is less than or equal to the storage, the water is stored in this element until the next time step.

Within each element, the mass balance is also carried out downward through a series of layers, if there are any. Each element is topped by a "surface" layer representing what happens above the surface. Below this, the program adds the number of layers required by the selected measure, ranging from zero layers for a cistern to many layers for a complicated bioretention design. If the SCM uses infiltration and the total depth of the combined layers is still above what the user defines as the depth to a restrictive subsurface layer, the program then adds a layer of underlying native soil to that depth. This will be the specified by the designer based on either a soil survey or on a textural analysis for disturbed soils. Finally, a restrictive layer is added to the bottom, modeled as heavy clay. If the depth of the combined SCM layers puts the bottom below the boundary between the underlying soil and restrictive layer, only the restrictive layer is added below the measure.

For each time step, the mass balance process begins with the surface layer and works its way down. Storage within the surface layer consists only of interception and surface depression storage for elements with surface area, or of the specified storage volume for a device without specified surface area. For each time step, we add to the current storage the amount of rainfall entering this element (zero for any SCM without defined surface area) and any run-on from any upstream element/s. We subtract the amount reused or that infiltrates into the next layer down, as described below. If the remaining volume exceeds the surface layer storage capacity, the excess runs off onto the downstream element, or offsite if there is no downstream element. The mass balance in lower layers is somewhat simpler, as for most of them the only input is infiltration from the layer above and the only outflow is infiltration into the next lower layer. Maximum storage in these layers is the void space within the layer, defined by the material that makes up the layer.

Infiltration into an underlying layer depends first on the water supply available in the current layer, which is limited to the amount of stored water above the layer's field capacity. Next, infiltration is controlled by what happens in the underlying layer, because many runoff reduction SCMs create a situation where a lower saturated layer (e.g., a coarse gravel layer that stores water above the underlying soil) is part of the design, clearly affecting how much water can infiltrate into that layer. As a lower layer fills up, this reduces the possible infiltration from the layer above in the next time step. As demonstrated by modeling with the Hydrus subsurface flow model (USDA-ARS, 2005), the infiltration rate into a layer is essentially unaffected by the lower impervious boundary until the nearly-saturated wetting front hits that lower boundary, at which point the infiltration rate into this layer goes to almost zero. This effect is implemented in the RRAT by adjusting the value of the KL parameter f_0 , which is the primary control on long-term infiltration, already modified for management as described above. This value is set to 0.0 any time the receiving layer's void space is full of water, reducing the infiltration rate into that layer to almost zero. If the water cannot infiltrate into the next lower layer, it will build up in this layer and so on all the way back up to the surface, at which point there may be runoff.

The final complexity of layer modeling is the impact of an underdrain at the bottom edge of a layer. If the drain invert is defined as being at or below the layer bottom, then any layer storage above field capacity will be drained out. If the invert is defined as being at some higher point, then only water above field capacity in the layer above the elevation of the invert will drain. The user can define whether this underdrain flow goes to the receiving subarea or goes directly offsite.

4.5. The RRAT approach: Modeling Total Suspended Solids (TSS) removal

The removal of TSS from runoff can be very complex, depending on many hydrodynamic processes including settling, physical filtering, adhesion, and chemical precipitation. Because of this, the RRAT does not currently attempt to model those processes. Instead, it assumes 100% TSS removal for all water infiltrating into the underlying soil or restrictive layer, 100% TSS removal for any water that is harvested and reused, and for all other measures uses pre-defined TSS removal effectiveness. These removal values should to the greatest extent possible be based on published values or collected data.

Because the performance criteria require that the TSS be removed from the runoff associated with the first 1" of rainfall, the RRAT tracks this water separately. Most manmade surfaces are defined as yielding "dirty" runoff from the first 1" of rainfall, with all other subareas (natural and/or good cover) yielding "clean" water. All runoff from rainfall after the first 1" on all surfaces is also considered clean. The RRAT separately tracks the "dirty" water through the system, assuming immediate full mixing with any stored water. Any outflow from a subarea layer is assumed to contain a portion of dirty water equivalent to the percentage of this water contained in the mixed storage.

4.6. The RRAT approach: Modeling total infiltration time

In addition to meeting the runoff reduction and TSS removal requirements as described above, one additional demand is made of the design. The Permit language states that the design must account for an event following 72 hours of no rainfall. In other words, the program design should be completed with the assumption that an event occurred 72 hours earlier. This is done in the RRAT by an initialization run to determine how much of the SCM storage is still occupied by water from the previous event. It the element drains completely between events, this is zero. If not, the program will loop until it converges on a single initial storage value. If this value is greater than 0, the storage still filled at the beginning of the second event will not be available for that new event, so infiltration into that element will be slowed. In addition, if water is stored on the surface for more than 24 hours in elements indicated as having "normal" (not facultative or hydrophilic) vegetation, the RRAT will indicate that the timing requirements are being violated. The thought here is that normal vegetation (such as turf) will be damaged by extended submergence, resulting in reduced positive impact of the vegetation for subsequent events.

4.7. The RRAT approach: Model inputs

In order to make the calculations described above, the RRAT requires from the designer the following information:

- selection of the location from the pre-defined list of Tennessee cities, choosing the location most similar to the design location. This defines the representative rainfall event depth and duration;
- the number of elements included in the design, each representing a unique combination of soil, SCM / management, contributing element/s, and downstream element;
- for each of these elements, the method requires the following additional information:
  - the area of the element (if any);
  - the element to which this one discharges, which may be offsite;
  - the element SCM or management selected from a predefined list;
  - a soil type from a predefined list (for any infiltration SCM);
  - if there is a soil, the depth to a restrictive layer within this element, which could be due to a severely impeding layer, a saturated zone, a man-made barrier, etc.

The SCM and management descriptions are pre-defined, and new ones may only be developed and saved by high-level users. Each description contains a list of inputs, including the following:

- the type of SCM, which indicates whether it collects rainfall, has infiltration, or is simply a volume-based device;
- if the SCM is exposed to the surface, whether it includes vegetation, and whether that is normal, facultative, or hydrophilic vegetation. If the vegetation is defined as "normal" (e.g., most grass), the program will reject a design if the vegetation is calculated to be submerged for more than 24 hours, as this is presumed to damage the vegetation for subsequent events;
- for infiltration SCMs, best estimates of Curve Number (*CN*) values for the land use or vegetation impact at the soil/water contact surface, based on the four soil hydrologic groups. These values may be available from tables, or may need to be assumed based on existing values for similar managements. These values should not take into account any impact of measure storage on *CN*, but rather just the impact of the soil / management combination as if it were at the surface. These values are used for the *MIR* calculations described above;
- definition of rainfall interception and depression storage resulting from the SCM / management. This should account for surface wetting and for small surface depression storage that must be filled before runoff can begin;
- special characteristics of the SCM, including the following: whether the practice is considered to contribute pollutants to the flow (generally just the more impermeable surfaces or bare soils); the portion of TSS removed by the SCM, and—if the SCM is a volume-based unit—the water removal (reuse) rate;
- if the SCM has layers, the characteristics of each layer. If the SCM is simply a vegetated soil or a thin impervious surface it has a single layer, defined as having zero depth above the soil. For other practices, the following characteristics must be defined for each layer:
  - the material filling the layer, which may be "None" for open storage space;
  - whether that material is mandated for this type of SCM, or another material may be selected by the user;

- the normal layer thickness design value, and the corresponding minimum and maximum allowable thicknesses;
- whether the layer has an underdrain, and if so, the elevation of its invert;
- whether the layer has an impervious bottom, not allowing flow to lower layers or to the underlying soil;
- at what rate water is pumped out of the layer for reuse.

Designers making use of these pre-defined SCMs / managements in their plans may be able to override such values as material type or layer depth to the extent allowed by the underlying description and the user's degree of control.

The SCM / management descriptions also make use of pre-defined descriptions of materials used in the measure. For example, a rain garden description may require a layer of a "soil based media", under which may be found a layer of "medium gravel". For each of these materials, the following characteristics must be defined:

- water content at saturation, at field capacity, and at wilting point;
- the analogous material that could be said to control infiltration of water into this material.

With all of this information in place, the RRAT calculates movement of water into an element and potentially down through the layers, with outflow through either a subdrain or over the surface and onto a downstream element. Based on these results, the RRAT will calculate the runoff reduction for each element and route any remaining runoff through the downstream elements, ultimately tracking how much runoff (and which runoff) leaves the site.

This hierarchical structure of defining the design system (system description uses SCM descriptions, SCM description uses material descriptions) allows for the definition, saving, and reuse of descriptions of each of the "objects", allowing novice users to use previously-defined descriptions rather than requiring them to define their own.

5. Summary

This document proposes an approach and tool for assessing whether stormwater control measure system designs meet the requirements specified in the Tennessee General MS4 permit. The approach is similar to the EPA SWMM model, but it includes more flexibility in specific areas needed such as better flexibility towards management factors. We believe that this tool will provide a robust and flexible method of enabling designers and regulators to assess stormwater runoff reduction plans throughout Tennessee, and that the approach could be more broadly applicable.

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