A HYDROLOGY MODEL FOR MIMICKING PRE AND POST DEVELOPMENT RUNOFF VOLUMES

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Abstract. The Energy Independence and Security Act, passed by Congress in 2007, included a section commonly referred to as EISA 438. This section of the Act requires any new development or redevelopment of federal facilities, involving more than 5,000 square feet, to retain on-site a sufficient volume of rainfall to mimic the pre-development hydrology. The retained rainfall must be dissipated by means of infiltration into the ground, ***evapo-transpiration***, or reuse. It cannot be directly discharged into a storm drain or surface water. Therefore, ***detention*** basins are not an appropriated best management practice (BMP) for complying with this regulation, since they have direct discharges.

The Federal Environmental Protection Agency (EPA) published a guidance document for complying with the regulation entitled, "Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act". This guidance document presents two options for estimating the ***retention*** capacity for designing best management practices to comply with this regulation. Option one is based on a statistical analysis that requires 95% of the average annual rainfall be retained and dissipated. The problem with this option is that it fails to consider soil infiltration or changes in ground cover, which are the primary factor influencing the runoff volume. This option is appropriate for site planning estimates, but not BMP design.

Option two puts forward the concept of modeling the pre-development and post-development hydrology to estimate the appropriate storage capacity. Although Option two suggests a continuous simulation model, the method presented in Appendix A of this guidance document is an analysis for a single 24-hour rainfall event. The single event analysis has the problem that it fails to consider the dissipation rate, and subsequently it fails to consider the actual storage volume available for the next rainfall. Described in the following paragraphs is the "Retention Volume Simulation Model" (RVSM). The RVSM is a continuous simulation, volume based hydrology RVSM, appropriate for estimating the retention capacity for BMPs to comply with new EISA 438 regulation.

INTRODUCTION

Most hydrology models available today were created to estimate runoff and flow rates from a single 24-hour rainfall event. These models do not directly estimate volume, nor do the models account for the dissipation of capture rain water between rainfall events. Usually it takes a couple of days for the water held on the ground to evaporate or infiltrate. Yet often there can be rainfall events that occur within a day or two. Therefore, it is essential that the model be a continuous simulation volume-based[1] hydrology model over a sufficient period of time to predict pre-development and post-development performance.

The curve number hydrology model, known as "Technical Report 55"[2] (TR-55) from the National Resources Conservation Services provides volume estimates for a single 24-hour event. Since water remaining on the surface or saturating the soil from a previous rainfall has the effect as if it were part of the subsequent rainfall, the TR-55 model can be transformed into a continuous simulation by: adding the retained water from the previous day (minus any dissipated water) to the rainfall for the next day.

PRE-DEVELOPMENT RVSM SETUP

The RVSM is setup on an Excel spreadsheet using about fifty years of continuous local rainfall data to minimize variability in the simulation results. The estimate retained moisture volume (Rn) from the previous day is added to the rainfall data to calculate the adjusted precipitation (Pa). The adjusted precipitation and the "S" value associated with the pre-development CN number are used in TR-55's runoff equation to calculate the runoff volume, on a continuous base. The ground moisture volume is the difference between the adjusted precipitation volume and the calculated runoff volume, minus the volume of water dissipated by infiltration and evapo-transpiration (Q_d). The RVSM assumes that the daily dissipated water volume equals the maximum precipitation volume before runoff would begin, which corresponds to TR-55's "initial abstraction" (Ia).

$$P_a = P + R_n$$
$$R_n = Pa - Qn - Q_d$$
$$Q_d \approx I_a \text{ .... (Model Assumption)}$$
$$I_a = 0.2S \text{ .... (eq. 2-2, TR-55)}$$
$$S = (1000/CN) - 10 \text{ .... (eq. 2-4, TR-55)}$$
$$Q_n = (P_a - 0.2S)^2 / (P_a + 0.8S) \text{ .... (eq. 2-3, TR-55)}$$

P = *24-Hour Precipitation*
P_a = *Precipitation adjusted for retained moisture*
R_n = *Retained moisture*
Q_d = *Dissipation volume from infiltration and evapo-transpiration*
I_a = *Initial abstraction*
S = *Potential maximum retention after runoff begins*
Qn = *Pre-Development Runoff*

NOTE: All volumes are unit volumes of inches over the catchment area.)

POST-DEVELOPMENT RVSM SET UP

The post-development RVSM is set up to simulate the performance of a “best management practice” (BMP) intended to retain a given volume of runoff and dissipate that water through infiltration into the ground, evaporation and plant transpiration into the air, or the reuse of the water for such things as irrigation or ***gray-water*** for flushing toilets. The RVSM follows the conservation of mass principle, where the retained volume equals the sum of the water coming into the BMP minus the sum of the water leaving (illustrated below in FIGURE 1). The water coming into the BMP (Q_1) is calculated using the TR-55 runoff equation for the post construction surface conditions. The water contained in the BMP ($V_{(n)}$) is either dissipated by whatever means intended for the BMP; evapo-transpiration (Q_{ET}), infiltration (Q_{INF}), or reuse (Q_R) or any combination, and if the retention capacity is exceeded there is an overflow discharge (Q_2).

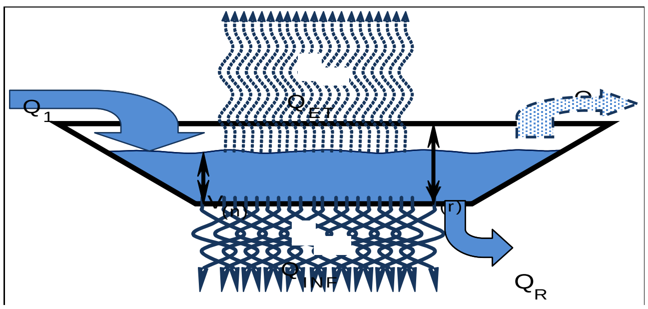

FIGURE 1. Continuity Diagram for Volume Control BMPs

$$Q_1 = (P - 0.2S)^2 / (P + 0.8S) \text{ .... (eq. 2-3, TR-55)}$$
$$Q_D = Q_{ET} + Q_{INF} + Q_R$$
$$Q_1 = Q_D + Q_2$$
$$V_{(n)} = Q_1 + V_{(n-1)} - Q_D$$
$$\text{if } V_{(n)} > V_R \text{ then } Q_2 = V_{(n)} - V_{(r)}$$
$$\text{else } Q_2 = 0$$

Q_1 = *Post-Development Runoff Volume into the BMP*
Q_D = *Daily Dissipation Volume which is the sum of the daily evapo-transpiration, infiltration, and reuse volumes*
P = *24-Hour Precipitation*
S = *Potential maximum retention after runoff begins*
$V_{(n)}$ = *Volume of water retained by the BMP*
$V_{(n-1)}$ = *Volume of water retained by the BMP the previous day*
$V_{(r)}$ = *Maximum Retention Capacity of the BMP*
Q_2 = *Overflow discharge from the BMP into a drain pipe or surface water*

(NOTE: All volumes are unit volumes of inches over the catchment area.)

COMPARING PRE AND POST VOLUMES

The RVSM consists of four variables; the pre-development and post-development curve numbers (CN_n and CN_d respectively), the BMP’s maximum retention volume (Vr), and the daily dissipation volume (QD). The curve numbers are determined by using standard tables found in TR-55 which are based on the hydrologic soil type and ground cover for the ***catchment area***. The values for both the maximum retention volume and daily dissipation volume are initially assumed in the set up of the RVSM. A comparison is made between the pre-development runoff (Qn) and the post-development BMP discharges (Q_2). The maximum retention volume or the daily dissipation volume is varied in an iterative process until the pattern of post-development discharges comes closest to mimicking the pre-development runoff.

The standard Rainfall-Runoff Chart used in TR-55 can be used to compare the patterns of post-development discharges with the pre-development runoff generated by the RVSM (FIGURE 2). The resulting chart shows that the runoff and discharge patterns are not identical, nor will any changes to the four variables bring those patterns to precisely coincide. This difference in the two patterns can be explained by the fact that the post-development BMP has a single point discharge, whereas the discharge from a pre-development condition normally as multiple discharges from numerous small depressions.

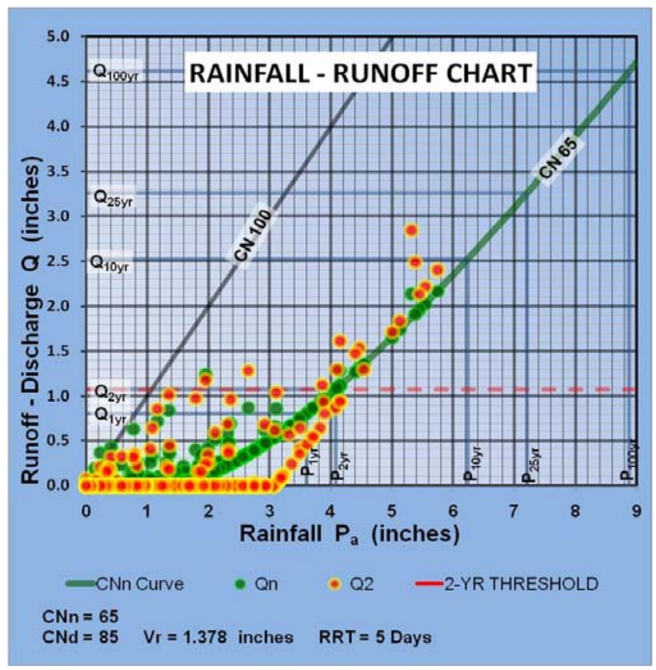

FIGURE 2. Typical Pre & Post Runoff Volume Comparison

If the patterns don’t coincide, “What constitutes a mimicking of the pre-development runoff volume?” A comparison of volumes or of frequencies can be used as a basis for answering that question. Since the goal of the regulation is to mimic the pre-development volume, it would intuitively seem appropriate to compare a summation of the post-development discharge volumes with the pre-development runoff volumes. However, since the rainfall data and resulting volumes include the more extreme, infrequent rainfalls, the resulting BMP retention volume or daily dissipation volume will be skewed higher than necessary to meet the stream bank protection objective of the regulation. It is generally accepted that stream bank erosion occurs whenever rainfalls exceed approximately the two-year return frequency. Therefore, matching the frequency of discharges that exceed the two-year runoff volume is a better indicator for assessing whether a BMP “mimics” the pre-development hydrology. The RVSM makes this comparison by doing a conditional count of the runoff volumes and discharge volumes that exceed the pre-development runoff volume for a two-year rainfall. Once the RVSM is set up, the BMP’s retention volume or dissipation rate is then adjusted through an iterative process until the frequencies equal. The modeler will discover that there is actually a range of retention volumes or daily dissipation volumes that satisfy this equality of frequencies. This situation is caused by the fact that the volumes are real numbers whereas the frequencies are integer numbers. Therefore, it is recommended that the average between the lowest and highest values satisfying the equality of frequencies be the solution value used.

RELATING DISSIPATION TO RETENTION

The daily dissipation volume can be related to a BMP’s retention volume in terms of how many days it would take to empty the BMP after it was filled, which is referred to as the “Retention Recovery Time” (RRT). The RRT is calculated by dividing the BMP’s retention volume by the daily dissipation rate. The RRT affects the size of a BMP’s design retention volume, and the serviceability of “reuse” type BMPs. A shorter RRT will result in a smaller required retention volume. While a longer RRT means that the captured runoff will more likely meet the reuse demand and be less likely to require a supplemental source of water.

CREATING A TABLE OF RETENTION VOLUMES

The RVSM consists for four primary variables; pre and post CN numbers, BMP retention volume, and RRT. Although, the setup for the RVSM is not complicated, the results could vary between different modelers. These variations may be caused by using different sets of local rainfall data, or deviations in the spreadsheet setup. A local reviewing agency can avoid this problem by using the RVSM to pre-determine the BMP retention volumes required for various combinations of pre-development and post-development CN numbers, and RRTs. The results from modeling each combination of variables can be placed in a table and published as the design standard. The process previously described can be automated using a ***macro*** to evaluate all the combinations of pre and post CN numbers and RRTs. The macro places these results in a table of pre-development CN numbers verses post-development CN numbers for a given RRT. Tables for RRTs of 1, 2, 3, 4, 5, 6, 7, 10, 14, 21, and 28 days are recommended. Once the tables are created they can be used to provide a consistent design and evaluation of any proposed volume control BMP within the local area.

DEVELOPING A BMP RETENTION EQUATION

A best fit equation for computing a BMP’s required retention volume can be developed using the data from the table associated with the highest retention recovery time (28 Days). The resulting equation will calculate the required retention volume as a function of the pre and post development CN numbers, and the retention recovery time.

The process of creating this equation begins by plotting a three-dimensional chart (FIGURE 3) of retention volumes verses CN numbers from the modeling data table with the shortest retention recovery time (3 days). This chart will be used to compare the calculated retention values with the RVSM results to confirm that the equation results are a close fit with the modeling results.

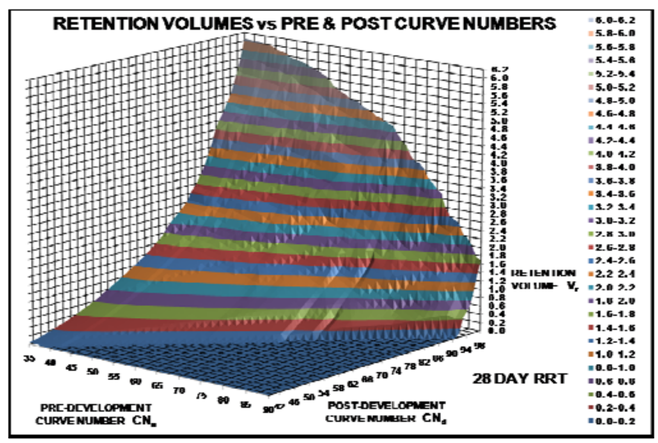

FIGURE 3. Retention Volume Chart for 28-Day RRT

Next, two two-dimensional charts (FIGURE 3) are plotted. One chart is of the retention volumes for the highest post-development CN (CN_d=98). The other is of the retention volumes for the lowest pre-development CN (CN_n=33). A “best-fit” equation is derived from the charted data.

EQUATION 1: $V_1 = f(CN_d)$

EQUATION 2: $V_2 = f((CN_n)$

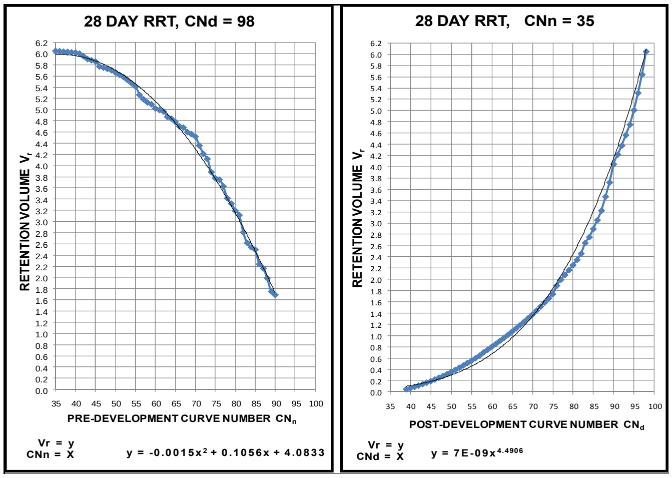

FIGURE 4. Best Fit Equations Charts

A best fit equation approximating the three-dimensional surface created by the chart (FIGURE 3) of the retention volumes for the 28-Day RRT is derived by adding Equations 1 and 2 and subtracting value for the retention volume with a pre and post development curve number of 35 and 98 respectively ($Vr_{(35,98)}$). The general form of the combined equations is:

EQUATION 3:

$$V_r = f(CN_d, CN_n, RRT_{28}) = f(CN_d) + f(CN_n) - Vr_{(35,98,28)}$$

Equation 3 is used in creating a table of calculated retention volumes, given an RRT of 28 days. A statistical evaluation, similar to standard deviation, called the "Standard Error of Estimate"[3] (StdEE), provides an indication or measure of how close the equation matches the retention volumes derived by the RVSM. A visual comparison can also be made by creating a three-dimensional chart of the RCSM retention volumes and placing it next to an identical 3-D chart of calculated values derived from Equation 3 (FIGURE 5).

ADDING RETENTION RECOVERY TIME TO THE EQUATION

Equation 3 is derived from the RVSM results for a given Retention Recovery Time of 28 days. Separate equations for the different retention recovery times could be developed by repeating the previous steps for each table created with different assumed retention recovery times. However, a more useful alternative is to expand Equation 3 previously developed for the 28-Day RRT to include the retention recovery time as a function variable. The result is a single equation to calculate the retention volume as function of the other three primary variables CN_n, CN_d, and RRT (Equation 5).

An observation of the three-dimensional charts for each table having different RRTs will note that the volumes are zero when the pre-development CN is greater than or equal to the post-development CN, regardless of the retention

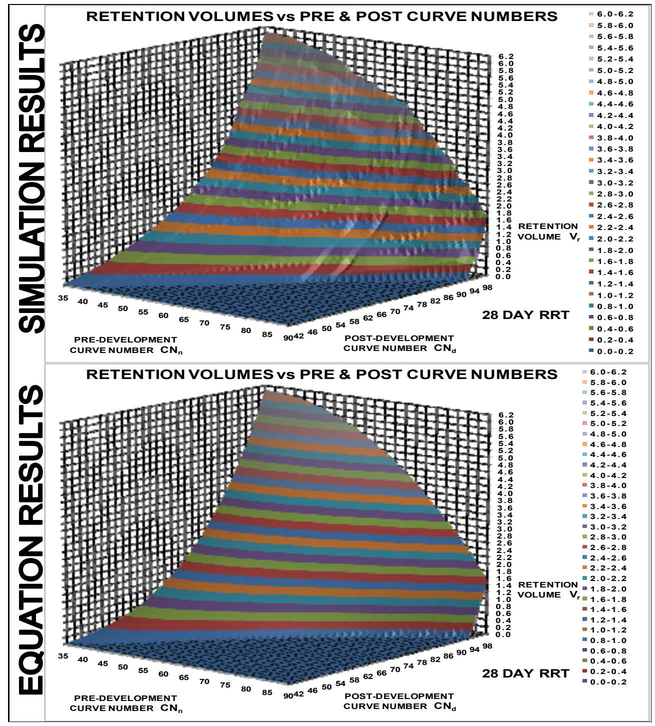

FIGURE 5. 3D Surface Charts comparing Simulation Results with Equation Results for the 28-Day RRT (StdEE = 0.20)

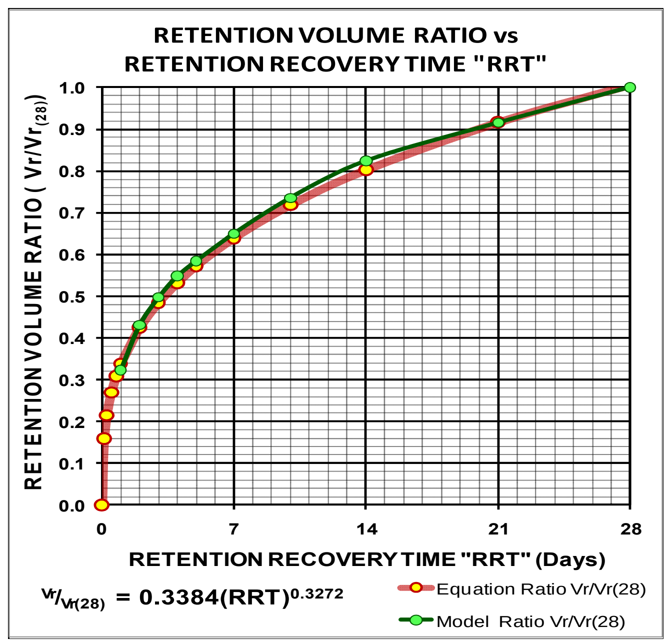

FIGURE 6. Best Fit Equation Chart for various RRTs

recovery time. Also, the primary difference between the various chart surfaces is the slope, which decreases as the retention recovery times become shorter. Therefore, in general terms, the retention recovery time variable can be incorporated into the function by multiplying the function just developed for the 28-Day RRT by a function for RRT (Equation 4).

EQUATION 4:

$$f((RRT) = f(Vr_{(35,\,98,\,RRT)} \,/\, Vr_{(35,\,98,\,28)})$$

EQUATION 5:

$$f(CN_d, CN_n, RRT) = f(CN_d, CN_n, Vr_{(35,\,98,\,28)}) \times f((RRT)$$

The function for the retention recovery time $f((RRT)$ is a ratio derived by taking the value of the retention volume from each of the tables for the various RRTs where CN_n equals 33 and CN_d equals 98, and dividing them by the retention volume from the table having a 28-Day RRT, which is placed in a chart of the retention volume ratio verse retention recovery time (FIGURE 6). A regression equation is derived from these plotted points, which forms the function, $f((RRT)$. A statistical evaluation is performed to compare the values derived from the equation with the value generated by the RVSM to determine the ***standard error of estimate***. The value determined by standard error of estimate is a measure of the range of deviation for 70% of the calculated values relative to the RVSM values. Figure 7 shows the development of the equations and the associated standard error of estimate that was created using rainfall data from the airport in Columbus, Georgia. A visual comparison can also be made by creating 3-D charts of the retention volumes generated from by RCSM for each given RRT and placing it alongside 3-D charts of the values derived using Equation 4 (FIGURES 8a, 8b, 9a & 9b).

RETENTION VOLUME EQUATION
DEVELOPED FOR THE COLUMBUS, GA AREA

EQUATION 1

$$f(CN_d, RRT_{28}) = Vr = 7E\text{-}09CNd^{4.4906}$$

EQUATION 2

$$f(CN_n, RRT_{28}) = Vr = -\,0.0015(CNn)^2 + 0.1056(CNn) + 4.0833$$

$$Vr_{(35,98,28)} = 6.051$$

COMBINING THE ABOVE EQUATIONS

EQUATION 3

$$f(CN_d, CN_n, RRT_{28}) = 7E\text{-}09CN_d^{4.4906} - 0.0015(CN_n)^2 + 0.1056(CN_n) - 1.9677$$

EQUATION FOR THE RETENTION RECOVERY TIME RATIO

EQUATION 4

$$f((RRT) = Vr_{(35,98,RRT)} / Vr_{(35,98,28)} = 0.3384(RRT)^{0.3272}$$

FINAL EQUATION

EQUATION 5

Design Retention Volume Vr =

$$f(CN_d, CN_n, RRT) = f(CN_d, CN_n, RRT_{28}) \times f((RRT) =$$

$$\left[7E\text{-}09(CN_d)^{4.4906} - 0.0015(CN_n)^2 + 0.1056(CN_n) - 1.9677\right] \times 0.3384(RRT)^{0.3272}$$

STATISTICAL EVALUATION

StdEE = ±0.20 inches

FIGURE 7. The Retention Volume Equation for the Columbus, Georgia area

CONCLUSION

The result is a single equation for estimating the required retention volume as a function of the pre and post development curve numbers and an estimated daily dissipation volume (i.e. the retention recovery time, RRT). This equation can be used for designing or evaluating any BMP intended to reduce the post-development discharge volume to match the pre-development runoff volume that will be located with the region where the rainfall data was collected. This can be applied to any BMP that has a retention and dissipation function such as bio-swales, rain gardens, terraces, porous pavements, and vegetative roofs. The RVSM and the equation developed from the modeling results are a more precise estimate of a BMP's performance then the "one size fits all" statistical design parameter presented in Option 1 of the EPA's guidance manual.

CONTINUING DISCUSSION OF BMP VOLUME CONTROL DESIGN

The dissipation of the retained runoff is a key element in the design of BMPs intended to reduce the discharge volume sufficiently to mimic pre-development runoff volumes. The primary means for dissipating this water is through infiltration and evaporation. The dissipation rate for both is a function of area. The larger the area that can be used for infiltration, or the larger the surface area for plants and exposure to the atmosphere, the faster the water will be dissipated and subsequently reduce the required storage volume. Therefore, BMPs intended for runoff volume control require that the captured runoff be spread over as large an area as possible, which requires a paradigm shift in our perspectives about the function and design of our drainage systems.

The current "flow control" paradigm is to collect, transport, detain, and then discharge the rainwater. The new "volume control" paradigm will be to collect, distribute, retain and dissipate the rainwater. Rather than collecting the rainwater into small, remote areas such as detention or retention ponds, the drainage systems should be designed to distribute the runoff as close to the collection area as possible and spread it over the largest possible surface or subsurface area.

The new paradigm can present a problem with conflicts with land use, because it may require an increased use of land resources. Mitigating this conflict will require creative drainage system designs that blend with the surrounding landscape and possibly become an enhancement that adds value to the property and the community. Porous pavements become attractive because they serve dual purposes; plus they can enhance safety and reduce the nuisance caused by flowing water or puddles of water on the paved surface. Vegetated roofs not only reduce the runoff volume but reduce a building's HVAC energy costs and can increase the longevity of the roof. Also, it makes sense to find ways to reuse the rainwater. Since the expenditure of financial resources is already required for the capture and clean-up of the runoff, we must begin to see this as a valuable resource rather than a filthy nuisance. This new paradigm, along with better design tools such as the one presented here, can guide us in creating better, more sustainable communities in closer harmony with the natural environment.

LITERATURE CITED

[1] Andrew J. Reese, Stormwater Journal, "Volume-Based Hydrology, (September 2009), 10-6, pp 54-67

[2] U.S. Department of Agriculture, Natural Resources Conservation Service, "Urban Hydrology for Small Watersheds", Technical Release 55, (June 1986), pp 2-1

[3] David M. Levine, Ph.D. and David F. Stephan, "Even You Can Learn Statistics", Pearson Prentice Hall, (2005), pp 194

GLOSSARY OF TERMS

catchment area is the upstream area that collects the rainfall and gathers the runoff into a place of interest such as a discharge point or BMP.

detention is the temporary storage of runoff to limit the discharge flow rate.

evapo-transpiration is the combined processes of changing water into vapor through evaporation and plant transpiration.

gray-water is water that has not been treated to meet drinking water standards.

macro is a subroutine program written within a computer application such as Microsoft Excel for performing repetitious operations or calculation solutions to complex functions.

retention although commonly confused with retention, it is the storage of water, but without any discharge

standard error of estimate is a statistical indicator of the deviation between a given data set and a set of calculated values, and is a measure of the range within which 67% of the given data is from the calculated values.

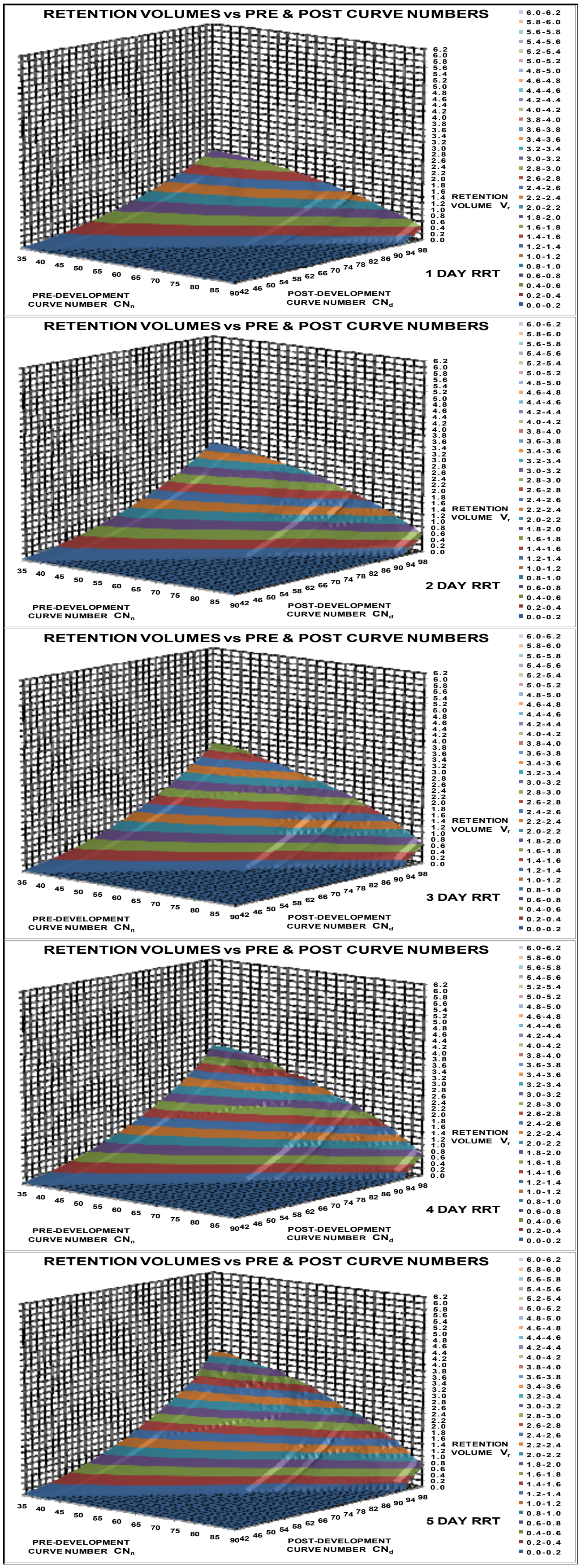

FIGURE 8a. Charts of RVSM Results 1 – 5 Day RRTs

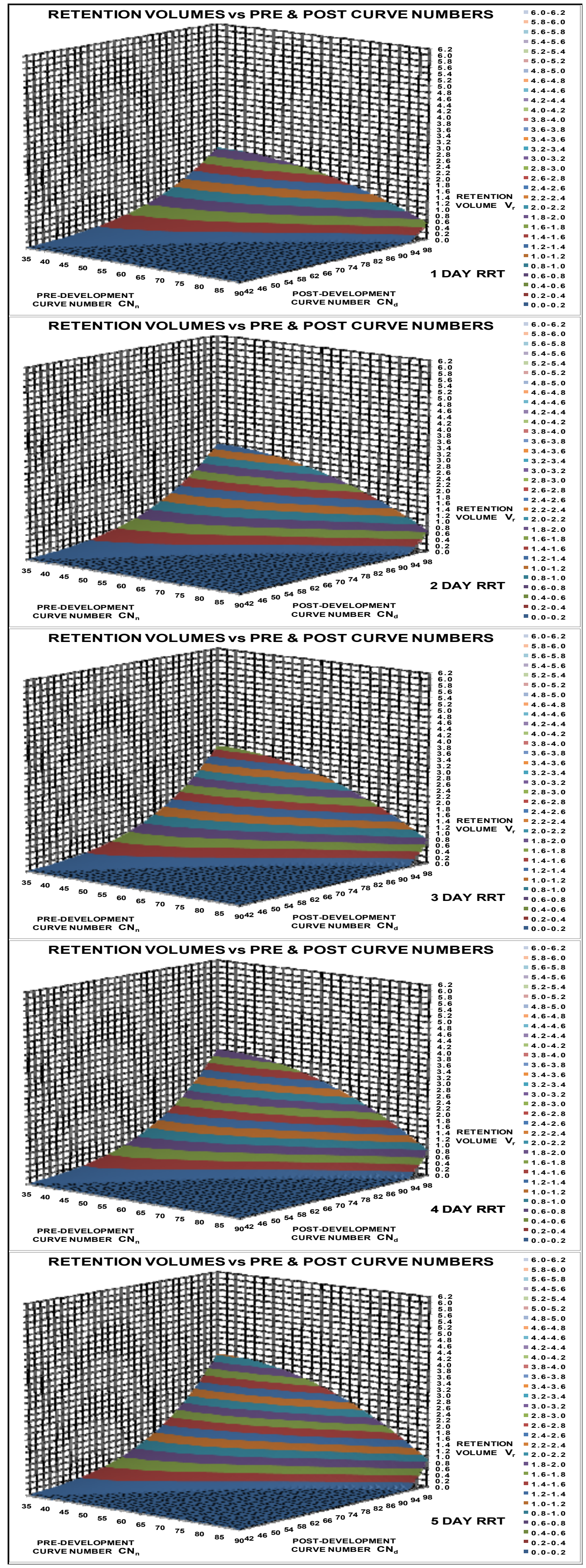

FIGURE 8a. Charts of Equation Results 1 – 5 Day RRTs

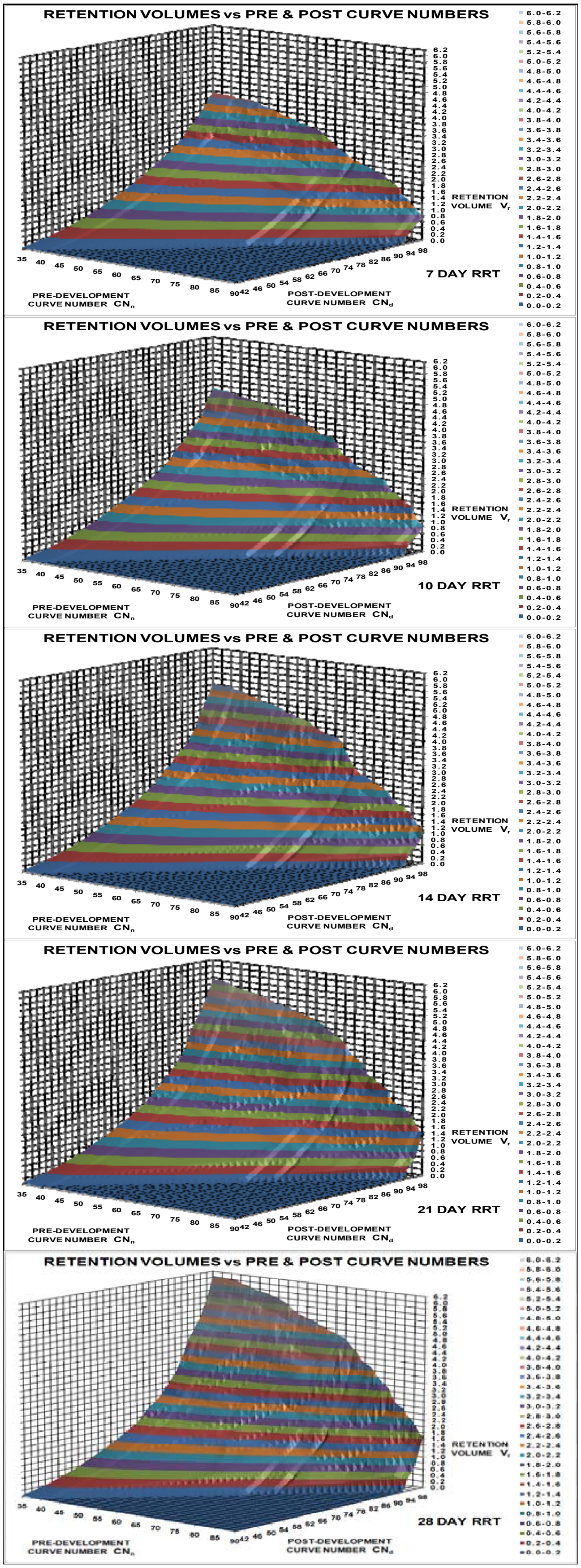

FIGURE 9a. Charts of RVSM Results 7 – 29 Day RRTs

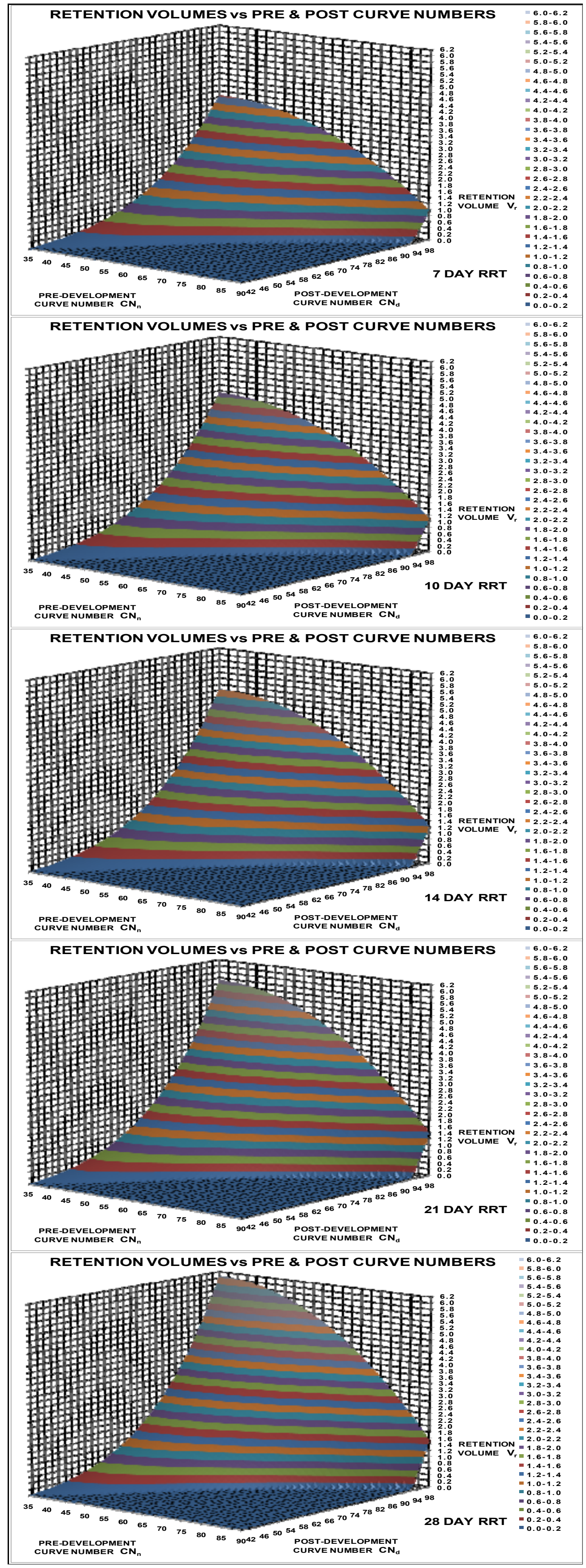

FIGURE 9b. Charts of Equation Results 7 – 28 Day RRts