



## URBAN DRAINAGE AND FLOOD CONTROL DISTRICT

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### TECHNICAL MEMORANDUM

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SUBJECT: Determination of Runoff Reduction Method Equations (UIA to RPA) based on  
Multivariable SWMM Analysis

DATE: March 15, 2018

The purpose of this memorandum is to document model analysis focused on directing runoff from small unconnected impervious areas (UIA) across receiving pervious areas (RPA) for the purpose of infiltrating the Water Quality Capture Volume (WQCV) and to use the model results for the development of regression equations that can be used as a basis for evaluating grass buffer designs. Wright Water Engineers, Inc. (WWE) prepared a memorandum dated October 19, 2017 that evaluated threshold runoff producing events using the EPA Stormwater Management Model (SWMM). The WWE analysis included an exhaustive evaluation of model input parameters to create numerous SWMM model simulations in order to determine the sensitivity of the input parameters on the resulting runoff volume reduction. Based on the model results, WWE provided UDFCD with recommended ranges and/or default values for the various input parameters to use as recommended criteria in the application of the UIA to RPA Runoff Reduction method. These recommendations were then used by Peak Stormwater Engineering (PSE) to run additional SWMM simulations and conduct a multivariate nonlinear regression analysis to develop regression equations for the Runoff Reduction Method.

### Summary of WWE Memorandum

The WWE memorandum summarized the evaluation of several SWMM input parameters (UIA:RPA ratio, overland width, slope, soil type, depression storage, and overland Manning's  $n$ ) to determine the sensitivity of the parameters on the resulting runoff reduction. The various input parameters were combined to create 22,680 different model scenarios and the SWMM results were then evaluated to determine which inputs had the greatest impact and what input range would meet the runoff reduction standard. As stated in the WWE memorandum, one of the primary motivations for this analysis was the *runoff reduction standard* included in the Phase II General Permit for Municipal Separate Storm Sewer Systems (MS4s) which provides an alternative to storing the WQCV, if 60% of the WQCV can be infiltrated. The WQCV within the UDFCD boundaries is defined as a rainfall depth of approximately 0.60 inches as discussed in Chapter 3 of the USDCM Volume 3. For the SWMM analysis, the WQCV rainfall depth was distributed using the UDFCD 2-year, 2-hour rainfall distribution (Note: CUHP requires a 1-hour input of 0.52 inches to generate a 2-hour depth of 0.60 inches).

The WWE analysis used a general catchment area of 10,000 ft<sup>2</sup> (0.23 acres) for the base modeling approach and then subdivided this area into two subarea components (UIA and RPA) based on the selected percent imperviousness. Subarea routing was set to full *pervious* routing in SWMM in order to model all UIA draining onto RPA. Other input parameters were varied as summarized below:

- 3 Soil Types – HSG A, B and C/D (Horton Infiltration set to UDFCD recommendations)
- 7 UIA:RPA Ratios – ranging from 1:1 to no RPA (Subarea imperviousness of 50% to 100%)
- 6 L:W Ratios – ranging from 0.06 (L=25', W=400') to 4.0 (L=200', W=50')
- 10 Slopes – ranging from 0.5% to 40%.
- 2 Impervious Depression Storages – 0.05 and 0.10 inches
- 3 Pervious Depression Storages – 0.10, 0.20, and 0.30 inches
- 1 Impervious Manning's n Value – 0.01
- 3 Pervious Manning's n Values – 0.10, 0.20, and 0.30

The model results from all 22,680 scenarios are presented in 18 separate tables at the end of the WWE memorandum. The model results are dependent on the assumption of a uniform flow distribution across the RPA and that the full RPA is available for infiltration. Based on the model results, WWE provided several conclusions and recommendations, which are summarized below.

- Recommend area <= 1 acre, may be applicable to larger sites with careful grading and flow distribution.
- Recommend UIA:RPA ratios <= 3:1 (75% imperviousness) to meet runoff reduction standard.
- Higher L:W ratios represent an elongated RPA allowing for greater travel times across infiltrating surfaces, decreasing total runoff volumes. Recommend L:W ratio that provides good wetting of full RPA under design conditions.
- Best suited for highly permeable soil types
- Steeper slopes result in higher runoff, recommend slopes < 10% to avoid erosion.
- Recommend an impervious depression storage of 0.05 inches and a pervious depression storage of 0.10 inches (lawns).
- Recommend an impervious overland Manning's n value of 0.01 and a pervious overland Manning's n value of 0.1.

## Additional Sensitivity Analysis

Based on the SWMM results from the WWE memo, additional analysis on the sensitivity of individual input parameters was conducted by PSE to plot the results in various ways to prioritize the variables and identify potential trends. As expected, the soil type (HSG A, B and C/D) and the UIA:RPA ratio have the largest impact on the runoff reduction. For purposes of the SWMM analysis, the UIA:RPA ratio is represented by the subarea imperviousness which equals  $\frac{UIA}{UIA+RPA}$ . The relationship between subarea imperviousness and runoff can be well represented by a 2<sup>nd</sup> order polynomial. Depression storage is also a sensitive parameter, however since the application for the Runoff Reduction Method is intended for runoff from pavement flowing across grass areas, default values for pavement (0.10) and lawns (0.10) will be used in all applications. WWE recommended an impervious depression storage of 0.05 inches to be conservative. However, the long standing

WQCV equation assumes 0.10 inches which is still within the recommended range for pavement and was therefore used in this study to maintain consistency between runoff and WQCV requirements. Manning’s n was determined to have very little impact on runoff and based on the intended application was set to a default value for grass (0.10). Table 1 shows the default input parameters used in the SWMM analysis.

Table 1: Default Hydrologic Parameters used in SWMM Modeling.

Soil Group	Manning’s n for Overland Flow		Depression Storage (inches)		Horton Infiltration		
	Pervious	Impervious	Pervious	Impervious	Initial Rate (in/hr)	Decay Coefficient (hour <sup>-1</sup> )	Final Rate (in/hr)
HSG A	0.10	0.01	0.10	0.10	5.0	2.52	1.0
HSG B	0.10	0.01	0.10	0.10	4.5	6.48	0.6
HSG C/D	0.10	0.01	0.10	0.10	3.0	6.48	0.5

The two remaining input parameters evaluated by WWE were L:W ratio and slope. However, during this follow up analysis it was determined that *total area* is also a sensitive parameter (originally held constant at 10,000 ft<sup>2</sup> in WWE analysis). Therefore, these three parameters were further tested using SWMM to determine their relative sensitivity. All three parameters were determined to have a relatively linear relationship with respect to runoff. Both area and L:W ratio have a negative trend (increasing value results in lower runoff) whereas slope has a positive trend (increasing value results in higher runoff).

When evaluating the impact of area (ranging from 1,000 ft<sup>2</sup> to 80,000 ft<sup>2</sup>) on runoff for different subarea imperviousness levels and different soil types (L:W ratio and slope held constant), the runoff varied by 5% on average (2% to 7%) with impacts being highest for smaller areas. Smaller areas have shorter travel times and less chance for runoff to infiltrate.

However, when evaluating the combined impact of area and L:W ratio on runoff for different soil types (subarea imperviousness and slope held constant), the runoff varied by 7% on average (2% to 15%) with impacts being highest for larger L:W ratios and larger areas. In other words, for small areas the L:W ratio is not a sensitive parameter, but as the total area increases the L:W ratio becomes more relevant. Increasing the area and L:W ratios together compound the runoff reduction effect since both increase the travel time and associated infiltration potential.

Furthermore, when evaluating the combined impact of area and slope on runoff for different soil types (subarea imperviousness and L:W ratio held constant), the runoff varied by 6% on average (2% to 12%) with impacts being highest for larger areas and smaller slopes. In other words, for small areas the slope is not a sensitive parameter, but as the total area increases the slope becomes more relevant. As slope increases the runoff also increases because travel time is decreased. Due to the inverse relationship, increasing slope tends to offset the infiltration benefits of increasing area or increasing L:W ratio.

Understanding the impact of these different input parameters on runoff reduction during a WQCV storm event and the various trends/relationships between parameters helped to guide the development of regression equations as discussed in the next section.

## Multivariate Nonlinear Regression Analysis

The WWE memorandum results and the additional sensitivity analysis conducted to support this memorandum highlighted the trends between the various input parameters and the resulting runoff, set boundaries on parameter ranges, and helped to prioritize the parameter significance. The next step was to take this information and perform a multivariate nonlinear regression analysis to produce equations representative of the data. In order to facilitate this process, a new SWMM model was created to focus on the impact of the five variable input parameters.

In addition to the five watershed parameters, the rainfall depth on the catchment also impacts the runoff volume. Although the standard WQCV rainfall depth is 0.60 inches, the USDCM provides a method to allow other rainfall depths to be used for locations outside of the District. Therefore, additional analysis was conducted to test the results of other rainfall depths and it was determined that a maximum depth of 0.95 inches can be modeled on Type C/D soils before separate pervious areas (SPA) start to produce runoff. In other words, for rainfall depths above 0.95 inches we start to see runoff from pervious areas due to direct rainfall. This complicates the calculation of runoff reduction for UIA runoff flowing across RPA because the runoff from the site is a combination of runoff from the UIA and rainfall onto the RPA. On the other end of the spectrum, rainfall depths below 0.25 inches don't produce runoff for any of the scenarios tested in SWMM. Therefore, rainfall depths between 0.25 and 0.95 inches were evaluated for all of the SWMM scenarios.

Based on the variable input parameters discussed above, the updated SWMM analysis resulted in approximately 34,000 scenarios for each soil type (over 100,000 total scenarios) as shown with the combinations in Table 2. The SWMM model setup was greatly simplified by creating input text files using Excel rather than manually creating the input files.

*Table 2: Variable Hydrologic Parameters used in SWMM Modeling.*

WQ Rainfall Depth (in)	Area ft <sup>2</sup> (ac)	L:W Ratio	Slope (%)	Subarea Imperviousness (%)	Soil Type
0.25	1,000 (0.023)	0.0625	0.5	0	A
0.30	2,000 (0.046)	0.25	1.0	10	B
0.40	5,000 (0.115)	0.50	2.5	20	C/D
0.50	10,000 (0.230)	1.00	5.0	30	
0.60	20,000 (0.459)	2.00	10.0	40	
0.70	40,000 (0.981)	4.00	20.0	50	
0.80	80,000 (1.837)	16.0	33.3	60	
0.90				70	
0.95				80	
				90	
				100	

After running the SWMM scenarios, the runoff results were plotted against various input parameters to confirm the previous findings and determine the best form of equation to use in the regression analysis. Figure 1 shows the relationships between soil type, subarea imperviousness, and runoff for the UDFCD standard WQCV rainfall depth of 0.60 inches. Soil type and the associated infiltration rates have a significant impact on the threshold for runoff producing events (zero runoff intercept as seen in Figure 1) which makes it difficult to fit a single equation to all three sets of results. Therefore, as has been done in previous studies, three separate equations were developed to represent the three soil types. The relationship between subarea imperviousness and runoff is well represented by a 2<sup>nd</sup> order polynomial ( $R^2 = 0.99$ ) as shown in Figure 1. However, the vertical bands of data points at each subarea imperviousness level reflect the variability in runoff due to area, L:W ratio, and slope. To address this variability, the equation needs to be modified beyond the 2<sup>nd</sup> order polynomial to account for the trends of the other three variables.

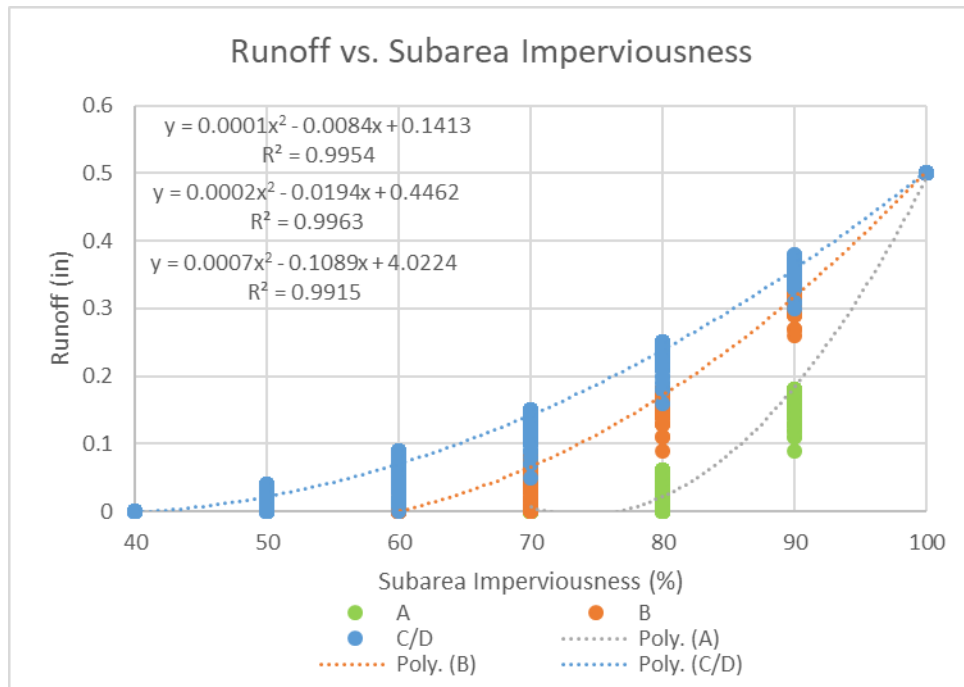


Figure 1: Runoff vs. UIA:RPA Ratio represented by 2<sup>nd</sup> order polynomial (0.6" Rainfall Depth).

In addition to the variability caused by the other three watershed parameters, the impacts of variable rainfall depths were also evaluated. As expected, when rainfall depth increases the resulting runoff increases because infiltration capacity is exceeded. Figure 2 shows the runoff results on Type C/D soils for nine different rainfall depths ranging from 0.25 to 0.95 inches. What is immediately clear from Figure 2 is that the runoff curves are almost identical in shape but are shifted up or down depending on the rainfall depth. In other words, a curve can be fit to one of the rainfall depths and the results from that fitted equation could be scaled up or down by the difference between the two rainfall depths. If the scaled result from the equation is negative then it is just set to zero which represents the condition where the rainfall was fully infiltrated. Similarly to Figure 1, the vertical bands of data points at each subarea imperviousness level reflect the variability in runoff due to area, L:W ratio, and slope.

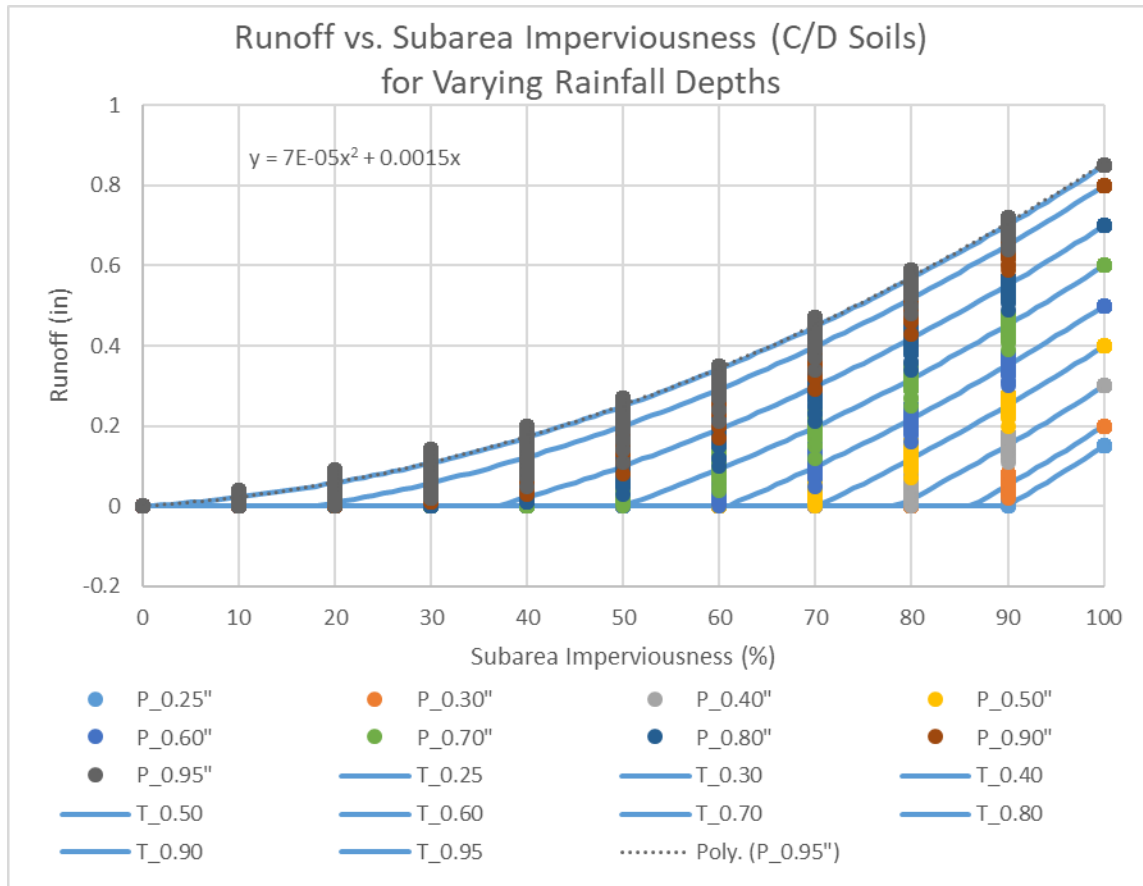


Figure 2: Runoff vs. UIA:RPA Ratio for Variable Rainfall Depths (Type C/D Soils).

To address the variability at each imperviousness level due to rainfall depth, area, L:W ratio, and slope, the 2<sup>nd</sup> order polynomial for imperviousness needs to be expanded. The expanded equation needs to account for the scaling caused by the rainfall depth and the trends of area, L:W ratio and slope. Next, the focus turned back to isolating the impacts of area, L:W ratio, and slope from each other and plotting the variables against the runoff results. Using the different plots of results, several different trendlines were evaluated (linear, logarithmic, power, polynomial, etc.) and it was determined that a linear equation was the best fit for all three variables. Both area and L:W ratio have a negative trend (increasing value results in lower runoff) whereas slope has a positive trend (increasing value results in higher runoff). Therefore, the three linear equations were combined with the rainfall scaling factor and the 2<sup>nd</sup> order polynomial for subarea imperviousness to create a single empirical equation as shown in Equation 1 on the following page.

$$Q = C_0 + C_1(0.95 - P_2) + C_2(\text{Area}) + C_3(L:W) + C_4(\text{Slope}) + C_5(\text{Imp}) + C_6\text{Imp}^2 \quad \text{Equation 1}$$

Where:

Q = Runoff (inches)

P<sub>2</sub> = 2-hour WQCV Rainfall Depth (inches)

Area = total subarea, sum of UIA and RPA (acres)

L:W = Ratio of total flow length to catchment width

Slope = average overland slope (%)

Imp = subarea imperviousness (%) calculated as (UIA / (UIA+RPA)) \* 100

C<sub>x</sub> = coefficients determined through regression analysis

Using the equation above, a 5-variable nonlinear regression analysis was performed on the runoff data to determine the appropriate coefficients (C<sub>0</sub> to C<sub>6</sub>). The regression analysis was performed using Excel's Solver add-in to minimize the sum of squared errors. Figure 3 shows the comparison between the SWMM runoff results and the 5-variable empirical equation runoff results for Soil Type C/D.

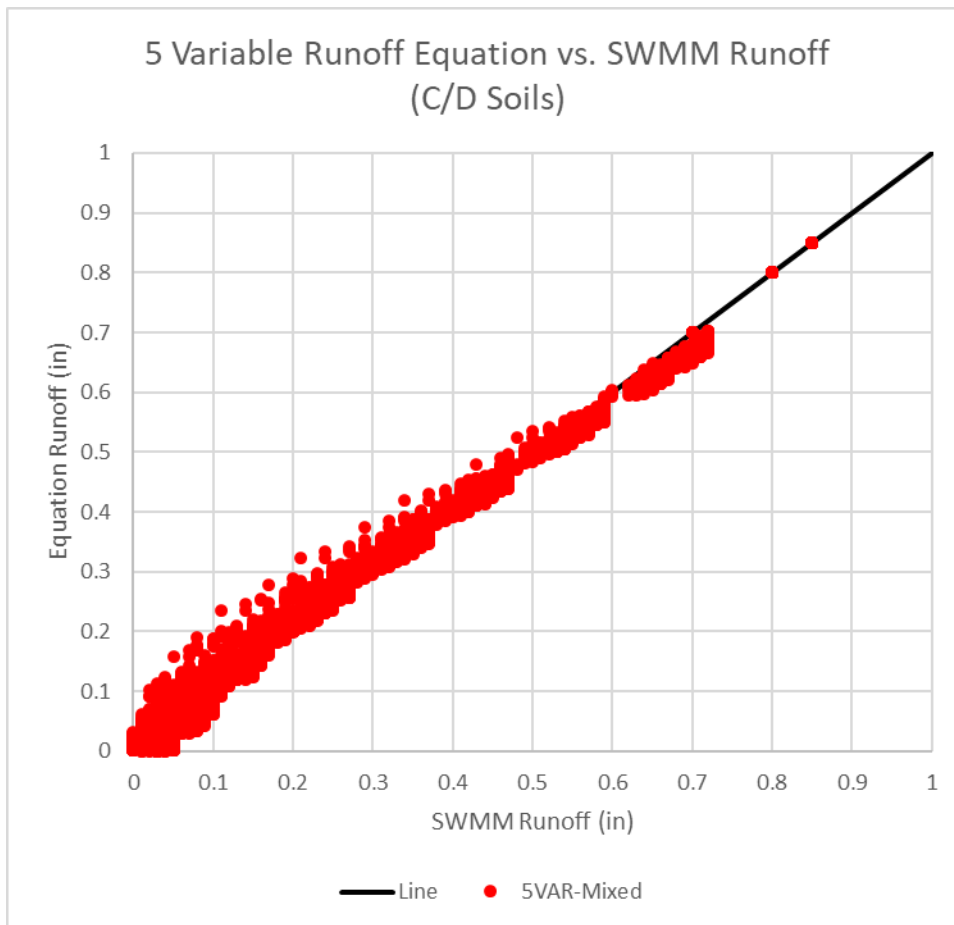


Figure 3: Comparison of 5 Variable Empirical Equation against SWMM Runoff (C/D Soils).

Additional regression analyses were performed using only subarea imperviousness, rainfall depth and 1 or 2 of the other variables (area, L:W ratio, or slope) to quantify the benefits that each additional variable adds. This approach simplified the equation slightly and reduced the number of coefficients required but as seen in Figure 4 (Rainfall, Slope and Subarea Imperviousness, 3 variable regression), the data is not as well represented by the equation. Therefore, it is recommended that all 5 variables be used in the empirical equation, particularly since the equation will typically be applied in an automated spreadsheet.

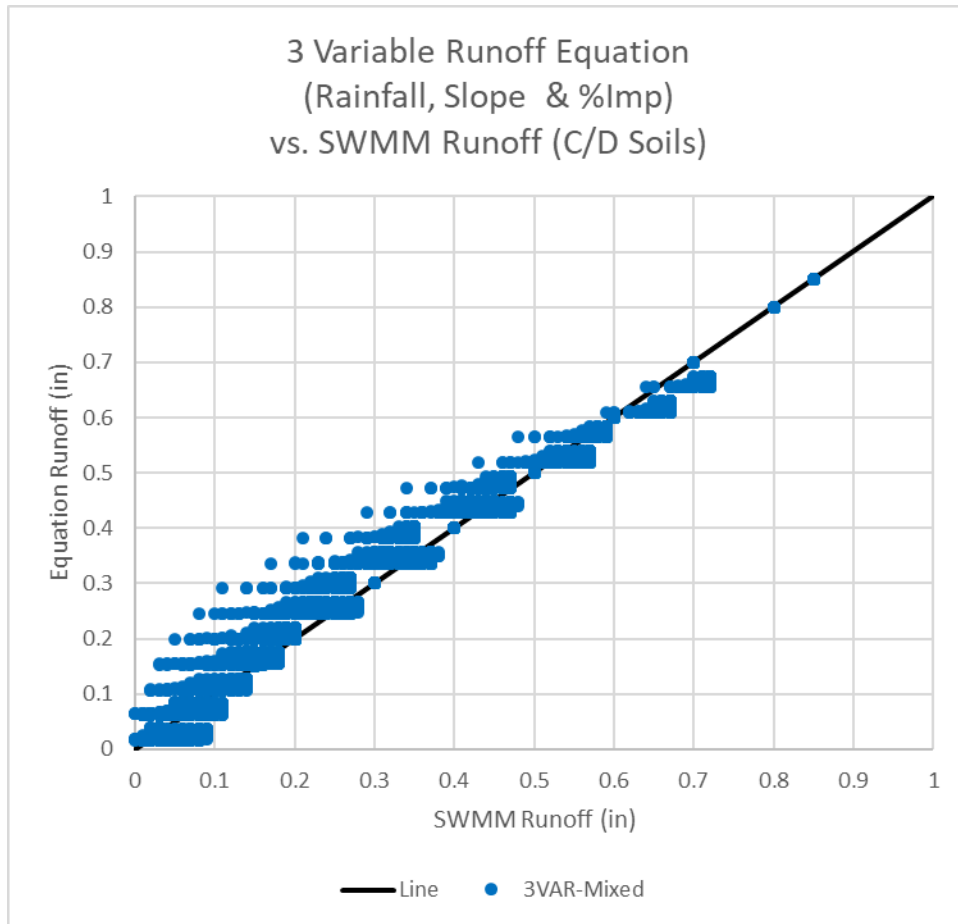


Figure 4: Comparison of 3 Variable Empirical Equation against SWMM Runoff (C/D Soils).



The same methodology was applied to Soil Types A and B with very similar curve fits. The coefficients were all different though due to the shift in the threshold for runoff producing events. Table 3 provides a summary of coefficients determined using Excel Solver that can be plugged into Equation 1 (which is presented again below the table for convenience).

Table 3: Empirical Runoff Equation Coefficients.

Soil Type	Constant C <sub>0</sub>	Rainfall (in) C <sub>1</sub>	Area (ac) C <sub>2</sub>	L:W C <sub>3</sub>	Slope (%) C <sub>4</sub>	%Imp C <sub>5</sub>	%Imp <sup>2</sup> C <sub>6</sub>
A	5.81E-01	-7.79E-01	-1.45E-02	-1.93E-03	7.03E-04	-2.49E-02	2.64E-04
B	-7.77E-02	-9.25E-01	-1.07E-02	-1.45E-03	5.02E-04	-1.36E-04	9.24E-05
C/D	-1.13E-02	-8.99E-01	-1.17E-02	-1.57E-03	5.45E-04	3.55E-03	4.64E-05

$$Q = C_0 + C_1(0.95 - P_2) + C_2(\text{Area}) + C_3(\text{L:W}) + C_4(\text{Slope}) + C_5(\text{Imp}) + C_6\text{Imp}^2 \quad \text{Equation 1}$$

The regression analysis focused on the non-zero runoff results to prevent the curve from trying to fit all the zero values in Type A and B soils for lower subarea imperviousness levels which would have skewed the curve. As a result, the equations are constrained by the subarea imperviousness at which runoff becomes zero (zero intercept as seen in Figure 2 for C/D soils). Below these subarea imperviousness levels, the computed runoff is set to zero.

- 60% ≤ Imp ≤ 100% (Type A Soils)
- 30% ≤ Imp ≤ 100% (Type B Soils)
- 0% ≤ Imp ≤ 100% (Type C/D Soils)

The recommended constraints on the other equation parameters are:

- 0.25 inches < Rainfall, P<sub>2</sub> < 0.95 inches
- 0.025 acres < Area < 2.0 acres
- 0.0625 < L:W ratio < 16.0
- 0.5% < Slope < 33%

As a final test on the equations, a SWMM model with 2,401 scenarios was setup with random combinations of inputs within the recommended constraints. A rainfall depth of 0.60 inches was used for all scenarios. Area was evaluated in 0.01-acre increments from 0.03 to 0.10 acres and then in 0.1-acre increments from 0.1 to 2.0 acres. L:W ratio was evaluated in 11 different increments from 0.0625 to 16.0. Slope was evaluated in 0.5% increments from 0.5% to 33.5%. Subarea imperviousness was evaluated in 1% increments from 50% to 95%. Lastly soil types were evaluated in 7 combinations (all of one soil type, 50/50 mix of two types, and a 33/33/33 mix of all three types). The various input parameters were then randomly mixed to provide 2,401 different scenarios. As shown in Figure 5, the empirical equations provide a relatively tight fit to the 45-degree reference line.

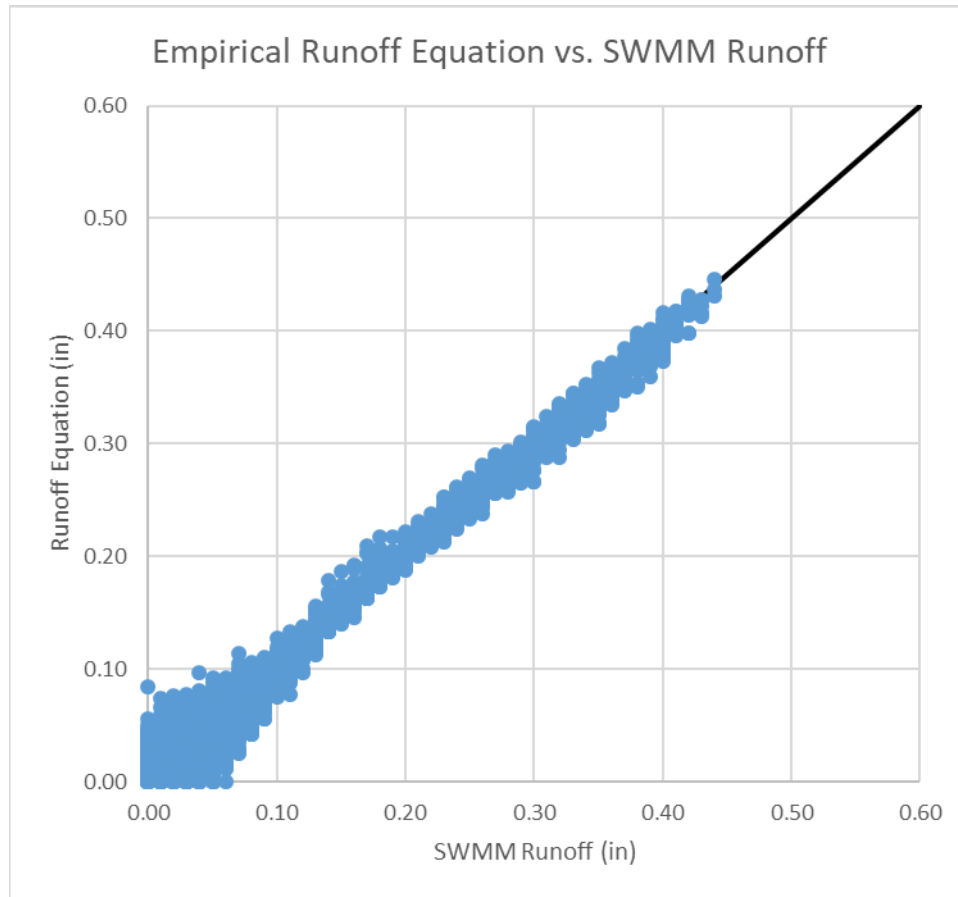


Figure 5: Comparison of Empirical Runoff Equation against SWMM Runoff (All Soil Types).

## Application of Empirical Equations

Application of the empirical equations to estimate runoff from a developed site requires the user to provide appropriate input parameters representative of the site. This may require the user to subdivide the total site area down into several subareas representing DCIA, UIA, RPA, and SPA. Each UIA would have a corresponding RPA and it is very important that the runoff from the UIA is uniformly distributed across the entire RPA. This uniform flow is required to ensure that the entire RPA is being utilized for infiltration consistent with the underlying model assumptions used to develop the equations. If necessary, a level spreader should be used to uniformly distribute flows. Once the site is appropriately subdivided, the equations can then be applied to each UIA:RPA subarea pair.

For purposes of user input simplicity in a spreadsheet application and to avoid potential variable naming confusion, the variables and associated coefficients in Equation 1 (based on SWMM inputs) were modified to be more representative of actual site measurements. The equation input for *area* in acres was changed to square feet and the  $C_2$  coefficient was divided by 43,560. The equation input for *slope* in percent was changed to ft/ft and the  $C_4$  coefficient was multiplied by 100. Lastly, the equation input for subarea imperviousness in percent was changed to the ratio of UIA divided by the sum of UIA and RPA to avoid confusion between the total site imperviousness and the individual UIA:RPA subarea imperviousness. As a result, the  $C_5$  coefficient was multiplied by 100

and the  $C_6$  coefficient was multiplied by  $100^2$ . The updated coefficients and variables are shown in Table 4 and Equation 2 below.

Table 4: Empirical Runoff Equation Coefficients.

Soil Type	Constant $C_0$	Rainfall (in) $C_1$	Area (ft <sup>2</sup> ) $C_2$	L:W $C_3$	Slope (ft/ft) $C_4$	UIA/Area $C_5$	(UIA/Area) <sup>2</sup> $C_6$
A	5.81E-01	-7.79E-01	-3.34E-07	-1.93E-03	7.03E-02	-2.49E+00	2.64E+00
B	-7.77E-02	-9.25E-01	-2.45E-07	-1.45E-03	5.02E-02	-1.36E-02	9.24E-01
C/D	-1.13E-02	-8.99E-01	-2.68E-07	-1.57E-03	5.45E-02	3.55E-01	4.64E-01

### Equation 2

$$Q = C_0 + C_1(0.95 - P_2) + C_2(\text{Area}) + C_3(\text{L:W}) + C_4(\text{Slope}) + C_5(\text{UIA/Area}) + C_6(\text{UIA/Area})^2$$

Where:

Q = Runoff (inches)

$P_2$  = 2-hour WQCV Rainfall Depth (inches)

Area = total subarea, sum of UIA and RPA (ft<sup>2</sup>)

L:W = Ratio of total flow length to catchment width

Slope = average overland slope (ft/ft)

UIA/Area = UIA / (UIA+RPA)

$C_x$  = coefficients determined through regression analysis

The recommended constraints on equation parameters area:

- $0.60 \leq \frac{UIA}{UIA+RPA} \leq 1.0$  (Type A Soils)
- $0.30 \leq \frac{UIA}{UIA+RPA} \leq 1.0$  (Type B Soils)
- $0.00 \leq \frac{UIA}{UIA+RPA} \leq 1.0$  (Type C/D Soils)
- 0.25 inches < Rainfall,  $P_2$  < 0.95 inches
- 1,000 ft<sup>2</sup> < Area < 80,000 ft<sup>2</sup>
- 0.0625 < L:W ratio < 16.0
- 0.005 ft/ft < Slope < 0.333 ft/ft

In order to apply the equation, the user needs to provide the following site measurements for each UIA:RPA subarea pair.

- UIA (ft<sup>2</sup>) for a single UIA:RPA pair
- RPA (ft<sup>2</sup>) for a single UIA:RPA pair
- Slope of RPA (ft/ft), the RPA slope controls the infiltration potential (UIA slope is not needed).
- Interface Width ( $W_{Interface}$ ) between UIA and RPA (ft), represents the width of uniform flow distribution from the UIA onto the RPA (e.g., flow spreader width).

With these input parameters, automated calculations can be performed to determine the required input parameters for the empirical equations and the resulting runoff reduction. These calculations include:

- $Area = UIA + RPA$
- $L:W = (L_{UIA} + L_{RPA})/W_{Interface} = \left( \frac{UIA}{W_{Interface}} + \frac{RPA}{W_{Interface}} \right) / W_{Interface}$
- $Slope = RPA\ Slope$
- $UIA/Area = \frac{UIA}{UIA+RPA}$