Date: February 12, 2018 (updated)
To: John Mathews, Ohio EPA
From: Jay Dorsey and Ryan Winston, Ohio State University Stormwater Management Program
Re: WQv Analysis

Summary

The primary goal of this analysis was to identify the water quality capture volume (WQv) that would ensure Ohio post-construction stormwater management practices remove 80 percent of the average annual total suspended solids (TSS) load from stormwater runoff. The WQv is calculated, on a unit area basis, as the product of a rainfall event depth and a volumetric runoff coefficient (Rv) that converts the rainfall depth to runoff. An evaluation of both the WQv event precipitation depth and volumetric runoff coefficient was necessary to determine the combination of those two inputs that result in 80% TSS reduction for climatic conditions in Ohio. Based on our evaluation, we recommend that Ohio EPA:

- utilize the linear relationship between Rv and impervious area; and
- increase the WQv precipitation event depth to 0.90 inches.

Introduction

The State of Ohio acknowledged the importance of managing runoff from small, frequent storm events when it established prescriptive post-construction runoff management criteria in the 2003 NPDES Construction Stormwater General Permit (CGP; Ohio EPA, 2003). According to Ohio EPA the intent of post-construction best management practices (BMPs) was “to assure that storm water runoff from developed land does not negatively impact receiving streams, either through hydrologic impacts or pollutant discharges” (Ohio EPA, 2007).

Ohio EPA outlined in the *Post-Construction Q & A Document* (Ohio EPA, 2007) the process used to identify a “maximized capture volume” for Ohio that resulted in selection of a 0.75-inch rainfall depth for the water quality volume (or WQv) storm event in the 2003 CGP. The WQv is “the amount of stormwater runoff from a given storm that should be captured and treated in order to remove a majority of stormwater pollutants on an average annual basis” which is defined as removal of at least 80% of the average annual total suspended solids (TSS) load (Ohio EPA, 2007).

In preparation for the 2018 renewal of the NPDES Construction Stormwater General Permit (CGP), Ohio EPA revisited the current post-construction stormwater management criteria (Ohio EPA, 2013) to verify whether meeting those criteria resulted in attainment of established stormwater management goals.

The analysis consisted of the following activities:
(1) An evaluation of volumetric runoff coefficient;
(2) An analysis of historic precipitation data to develop depth-frequency relationships for weather stations representing different climatic regions of Ohio;

(3) For the same weather stations, quantification of (unrouted) percent volume captured based on WQv event depth;

(4) Development of Storm Water Management Model (SWMM) version 5.1.012 (US EPA https://www.epa.gov/water-research/storm-water-management-model-swmm) models and continuous simulation using representative historic precipitation data to predict percent routed stormwater runoff volume captured for a representative BMP under current (P = 0.75 inches, Rv = $0.0858i^3 - 0.78i^2 + 0.774i + 0.04$) post-construction WQv criteria.

(5) Development of SWMM models and continuous simulation using representative historic precipitation data to quantify routed stormwater runoff percent volume captured for four stormwater BMPs (dry extended detention basin, wet extended detention basin, permeable pavement, and bioretention) sized for WQv precipitation depths of 0.75, 0.85, 0.90 and 1.00 inches.

(6) Results from activities (4) and (5) above were combined to compare percent routed stormwater runoff volume captured for a representative BMP under current (P = 0.75 inches, Rv = $0.0858i^3 - 0.78i^2 + 0.774i + 0.04$) and proposed (P = 0.90 inches, Rv = 0.05 + 0.009*I) criteria.

VOLUMETRIC RUNOFF COEFFICIENT EVALUATION

Purpose

A volumetric runoff coefficient (Rv) that converts rainfall depth to a stormwater runoff treatment volume is needed to size post-construction stormwater management practices. The purpose of this technical analysis is to evaluate the current method for calculating the volumetric runoff coefficient in the Ohio NPDES Construction Stormwater General Permit (CGP; Ohio EPA, 2013) against other methods for determining Rv.

Background

Research in environmental hydrology has highlighted the importance of managing small, frequent storms (the approximately 98% of events less than 2" rainfall depth) for both water quality and receiving channel stability (WEF, 1998; Pitt, 1999; NRC, 2009). Small storm hydrology is a widely used method for the estimation of stormwater runoff volume from rainfall events with depths (i.e., 0.25 – 1.5 inches) typical of groundwater recharge, volume reduction or water quality treatment requirements (CALTRANS, 2015). A primary reason for the use of small storm hydrology is that the curve number method commonly used for estimating runoff from small urban watersheds (NRCS, 1986) is not intended to be used for small rainfall events (Hawkins et al., 1985; Claytor and Schueler, 1996). Small storm hydrology can be expressed (CALTRANS, 2015):

$V_{runoff} = Rv*P*A$ Equation 1

Where:
V_{runoff} = volume of runoff
Rv = volumetric runoff coefficient

P = rainfall depth
A = drainage area

The volumetric runoff coefficient (Rv) is an empirically derived value that indicates the fraction of rainfall converted into runoff for that land use (Pitt, 1987; Schueler, 1987). The two most common ways Rv is determined are (Claytor and Schueler, 1996; CALTRANS, 2015): (1) from an equation in which Rv is a function of the impervious area within the contributing drainage area; or (2) from look-up tables in which Rv is a function of both land use/cover and rainfall depth.

Rv as Function of Impervious Area

The most common small storm hydrology method for predicting runoff volume establishes a linear relationship between Rv and site imperviousness (Schueler, 1987; Claytor and Schueler, 1996; CALTRANS, 2015) in the form:

$$Rv = 0.05 + 0.009*I \qquad \text{Equation 2}$$

Where:
I = site imperviousness (%)

This relationship was the best fit linear regression of volumetric runoff coefficient versus watershed imperviousness ($r^2 = 0.71$) from two years of data collected at 44 monitored development sites with varied percentages of impervious area (Figure 1; Schueler, 1987). This relationship plots mean runoff coefficient values against imperviousness, and thus reflects the average rate of rainfall conversion to runoff over a full range of rainfall depths. The data came primarily from the *Nationwide Urban Runoff Program* (NURP), the first nationally-coordinated effort to understand urban runoff quantity and quality (USEPA, 1983).

Equation 2 is used by a number of states and municipalities to estimate runoff volume for smaller storms (CALTRANS, 2015), and has been used in the Simple Method water quality model for estimating pollutants load since that model's introduction by Schueler (1987). Other linear relationships between Rv and site imperviousness have been proposed but are used less widely (CALTRANS, 2015).

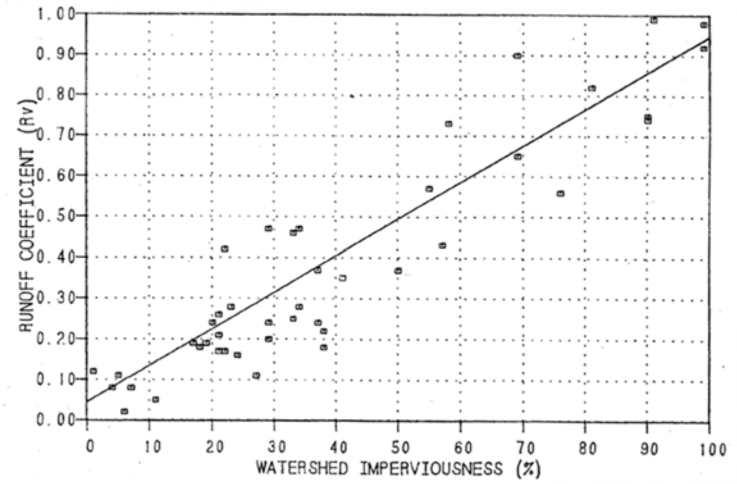


Figure 1. Relationship between volumetric runoff coefficient (Rv) and watershed imperviousness (I). (Schueler, 1987)

Urbonas et al. (1989, 1990), also using the NURP data, found a best-fit relationship between volumetric runoff coefficient and watershed imperviousness ($r^2 = 0.72$) using a third-order polynomial equation (Figure 2):

$$Rv = 0.0858i^3 - 0.78i^2 + 0.774i + 0.04$$ Equation 3

Where:
i = impervious fraction of the development site

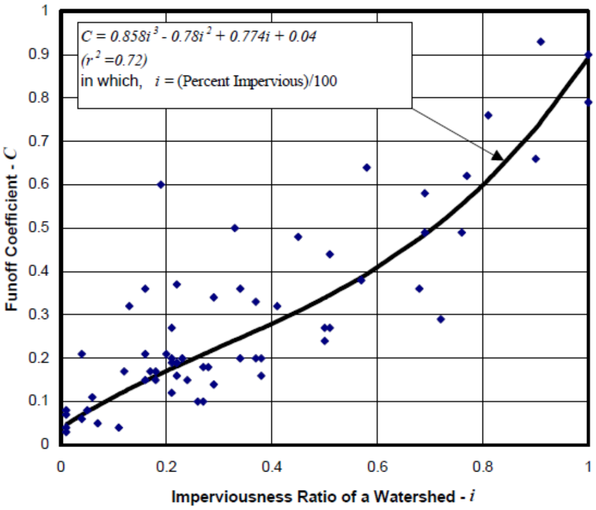


Figure 2. Volumetric runoff coefficient as a function of imperviousness (Urbonas, et al., 1989).

Equation 3 was included in the WEF manual of practice *Urban Runoff Quality Management* (WEF/ASCE, 1998) but has found limited use among regulatory authorities (CALTRANS, 2015).

Current Ohio NPDES Post-construction Approach

The volumetric runoff coefficient Rv (denoted as C in the current CGP; Ohio EPA, 2013) can be determined one of two ways: (1) by calculating Rv using Equation 3; or (2) by looking up the value for a particular land use in CGP Table 1 (Figure 3). A comparison of Rv values derived from Table 1, Equation 2 and Equation 3 is shown in Figure 4. Though we are unsure how they were derived, Table 1 values closely track Equation 2.

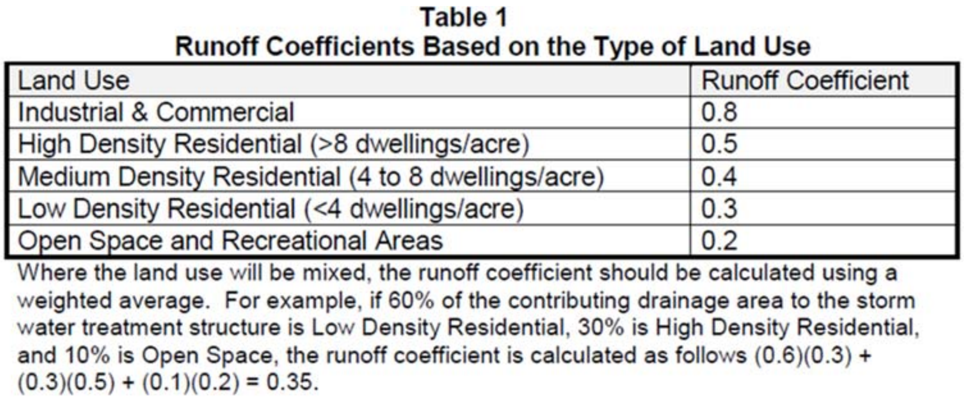


Table 1
Runoff Coefficients Based on the Type of Land Use

Land Use	Runoff Coefficient
Industrial & Commercial	0.8
High Density Residential (>8 dwellings/acre)	0.5
Medium Density Residential (4 to 8 dwellings/acre)	0.4
Low Density Residential (<4 dwellings/acre)	0.3
Open Space and Recreational Areas	0.2

Where the land use will be mixed, the runoff coefficient should be calculated using a weighted average. For example, if 60% of the contributing drainage area to the storm water treatment structure is Low Density Residential, 30% is High Density Residential, and 10% is Open Space, the runoff coefficient is calculated as follows (0.6)(0.3) + (0.3)(0.5) + (0.1)(0.2) = 0.35.

Figure 3. Volumetric runoff coefficient by land use (Ohio EPA, 2013)

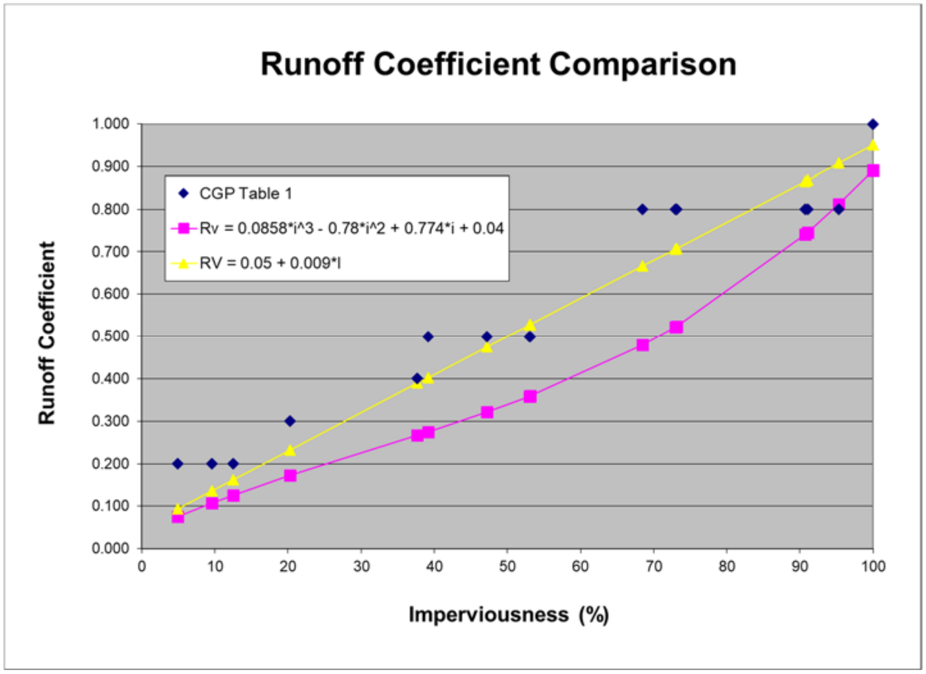


Figure 4. Rv as determined by Equation 2, Equation 3 and CGP Table 1.

Small Storm Hydrology – Rv as Function of Both Land Cover and Rainfall Depth

A more explicit approach to small storm hydrology utilizes Rvs that both: (1) are specific to the individual land uses or land covers present in the contributing drainage area (i.e., not just the degree of imperviousness); and (2) change with the depth of the rainfall event (Figure 5) (Pitt, 1987; 1999; PV & Associates, 2015). This approach allows for differences in runoff generation among impervious land surfaces (e.g., pitched roofs vs flat roofs vs smooth pavement vs rough pavement) as well as among pervious land surfaces (e.g., sandy vs silty vs clayey soils). This approach adjusts the (land cover specific) runoff coefficients with rainfall depth, resulting in event-specific runoff coefficients for rainfall events from 0.01” to 5” or more. The runoff volume for a single rainfall event is calculated from an area-weighted Rv:

$$Rv_{watershed} = \frac{Rv_1*A_1 + Rv_2*A_2 + Rv_3*A_3 + \ldots \ \ldots Rv_n*A_n}{A_{watershed}} \qquad \text{Equation 4}$$

A common way to implement this is through the use of a look-up table that lists Rvs based on land cover and rainfall depth. The look-up table provided for illustration (Figure 6) is used to calculate single event runoff depths in the WinSLAMM model (PV & Associates, 2015). For rainfall depths that fall between values in the table, the Rv is determined by interpolation.

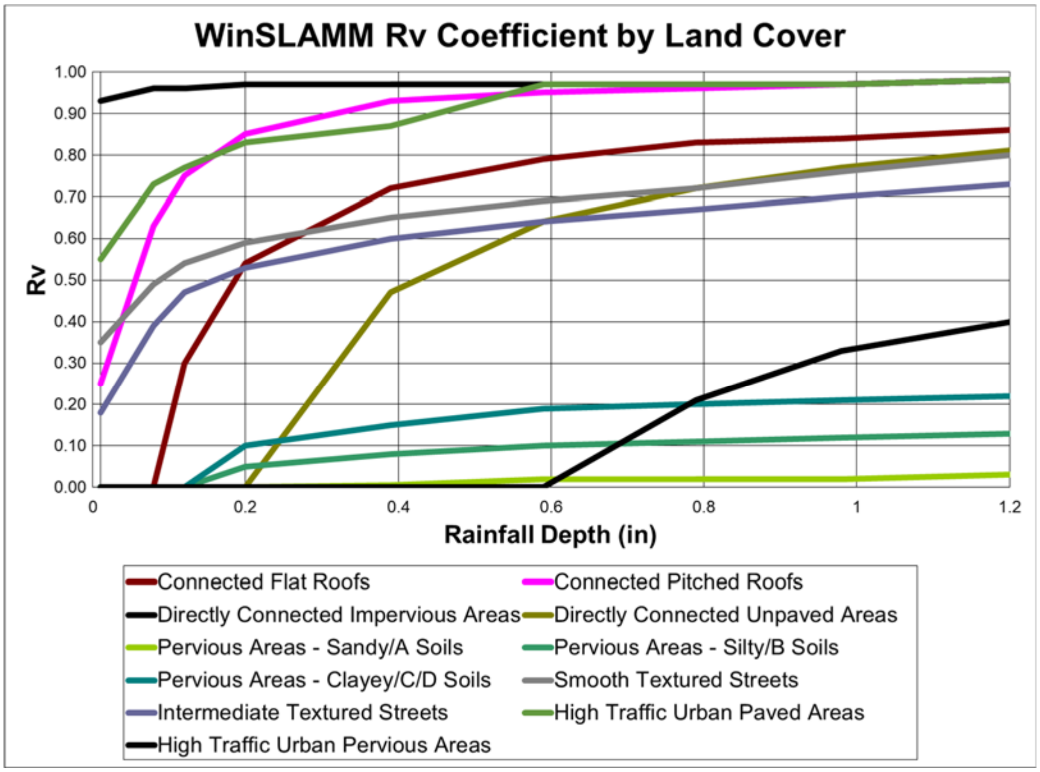
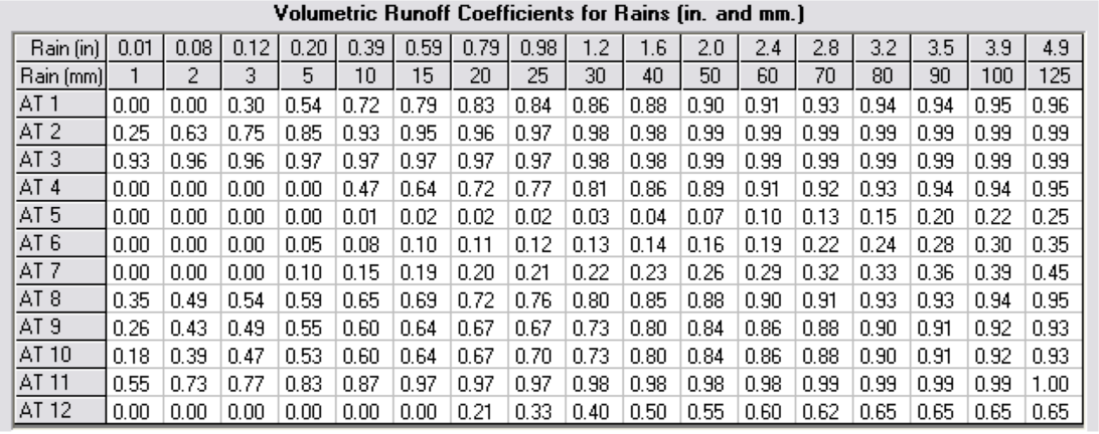


Figure 5. Rv as a function of land cover and rainfall depth (following PV & Associates, 2015).



Volumetric Runoff Coefficients for Rains (in. and mm.)

Rain (in)	0.01	0.08	0.12	0.20	0.39	0.59	0.79	0.98	1.2	1.6	2.0	2.4	2.8	3.2	3.5	3.9	4.9
Rain (mm)	1	2	3	5	10	15	20	25	30	40	50	60	70	80	90	100	125
AT 1	0.00	0.00	0.30	0.54	0.72	0.79	0.83	0.84	0.86	0.88	0.90	0.91	0.93	0.94	0.94	0.95	0.96
AT 2	0.25	0.63	0.75	0.85	0.93	0.95	0.96	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99
AT 3	0.93	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99
AT 4	0.00	0.00	0.00	0.00	0.47	0.64	0.72	0.77	0.81	0.86	0.89	0.91	0.92	0.93	0.94	0.94	0.95
AT 5	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.02	0.03	0.04	0.07	0.10	0.13	0.15	0.20	0.22	0.25
AT 6	0.00	0.00	0.00	0.05	0.08	0.10	0.11	0.12	0.13	0.14	0.16	0.19	0.22	0.24	0.28	0.30	0.35
AT 7	0.00	0.00	0.00	0.10	0.15	0.19	0.20	0.21	0.22	0.23	0.26	0.29	0.32	0.33	0.36	0.39	0.45
AT 8	0.35	0.49	0.54	0.59	0.65	0.69	0.72	0.76	0.80	0.85	0.88	0.90	0.91	0.93	0.93	0.94	0.95
AT 9	0.26	0.43	0.49	0.55	0.60	0.64	0.67	0.67	0.73	0.80	0.84	0.86	0.88	0.90	0.91	0.92	0.93
AT 10	0.18	0.39	0.47	0.53	0.60	0.64	0.67	0.70	0.73	0.80	0.84	0.86	0.88	0.90	0.91	0.92	0.93
AT 11	0.55	0.73	0.77	0.83	0.87	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.99	1.00
AT 12	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.33	0.40	0.50	0.55	0.60	0.62	0.65	0.65	0.65	0.65

Figure 6. Lookup table for Rv based on land use and rainfall depth (PV & Associates, 2015).

Mixed Approach

Several states and municipalities have expanded on the simple linear relationship to provide some level of specificity or flexibility where it supports program goals, for example in the implementation of a runoff volume reduction program (Hirschman et al., 2008; Battiata, 2010; CWP, 2012; VDEQ, 2016). In such cases, all impervious areas are typically assigned a single Rv value (e.g., Rv = 0.95) for the target rainfall event depth, whereas pervious areas may have varied Rv values that reflect soil type and/or soil management (Figure 7).

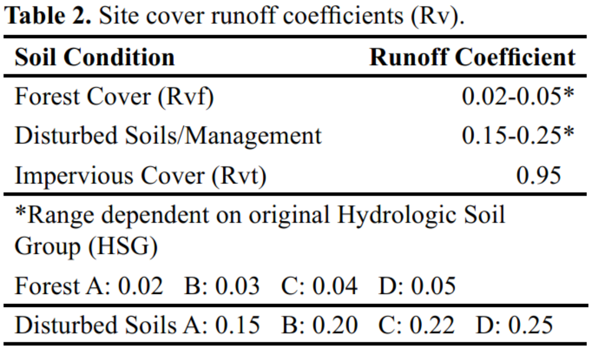


Table 2. Site cover runoff coefficients (Rv).

Soil Condition	Runoff Coefficient
Forest Cover (Rvf)	0.02-0.05*
Disturbed Soils/Management	0.15-0.25*
Impervious Cover (Rvt)	0.95

*Range dependent on original Hydrologic Soil Group (HSG)

Forest A: 0.02 B: 0.03 C: 0.04 D: 0.05

Disturbed Soils A: 0.15 B: 0.20 C: 0.22 D: 0.25

Figure 7. Soil specific runoff coefficients (Battiata et al., 2010).

Discussion

Both the third-order regression Rv equation currently used by Ohio (Equation 3 above; Ohio EPA, 2013) and the linear relationship Rv = 0.05 + 0.009*I (Equation 2 above) are based on the relationship between runoff volume and impervious area developed from the NURP data (USEPA, 1983). The coefficient of determination (r^2) for the more complicated third-order regression equation was 0.72 compared to an r^2 of 0.71 for the linear (first-order regression) equation. In its review, CALTRANS (2015) theorized Rv may not be a linear function of imperviousness, and that the greater slope in the third-order equation at higher percent imperviousness (>75%) may reflect that excess runoff at high imperviousness "overwhelms" the infiltration capacity of pervious areas. However, the similarity of the coefficients of determination suggests neither regression model is superior to the other.

The direct, linear relationship between Rv and imperviousness has several practical benefits including simplicity in communication and calculation. This may explain why most states that have a water quality treatment volume requirement (similar to Ohio's WQv) base their calculation of treatment volume either on the linear equation for Rv (Equation 2; e.g., AK, CT, DC, IA, MD, MN, NC, NH, NY, VA, VT, WV) or simply by assigning an Rv of 1.0 to impervious areas (e.g., MA, RI) (CALTRANS, 2015; USEPA, 2016). CALTRANS (2015) noted most municipal design manuals they reviewed also used Equation 2. Ohio and California (CASQA, 2003) appear to be the only states that use Equation 3. Denver's Urban Drainage and Flood Control District (UDFCD, 2010) uses a third order regression equation based on Equation 3, as does Texas Commission on Environmental Quality for protection of the Edwards Aquifer (TCEQ, 2005).

The most compelling reasons for considering the use of Equation 2 instead of Equation 3 are: (1) simplicity in applying to redevelopment (i.e., previously developed) sites; and (2) compatibility with Runoff Reduction Method implementation (Battiata, 2010). Equation 2 equates to an assignment of Rv = 0.95 to all impervious surfaces and Rv = 0.05 for all pervious areas. This facilitates the use of a simple WQv relationship for redevelopment sites using Rv as a function of pre-project (existing) and post-project impervious area. Also from this basis, it is simple to keep Rv = 0.95 for impervious areas but expand the menu of pervious area Rvs to better reflect both soil type (HSG) and/or soil management (e.g., preserved vs disturbed vs compost amended; forested area vs managed turf) (Figure 7).

The approach used by Washington D.C. assigns a Rv value of zero (0.0) to "natural cover", a Rv value of 0.25 to "compacted cover" and Rv = 0.95 for impervious area. A similar approach adopted by Ohio would appropriately credit the relatively high hydrologic function maintained by preserved soils or recovered by amending soils, and acknowledge the reduced hydrologic function of typical development site soil degradation.

$$Rv = [A_{nat\text{-}am*}(Rv_{nat\text{-}am}) + A_{graded*}(Rv_{graded}) + A_{imp}*(Rv_{imp})] / A_{total} \qquad \text{Equation 5}$$

Arguments against switching:

- People are used to the current "C" equation. Switching will only confuse things.
- Switching will increase the WQv treatment volume requirement by an average of 34% (minimum 6%, maximum 47%) (Figure 4, Table 1).

Arguments for switching:

- The linear Rv equation correlates the data as well as the more complicated equation but is simpler to understand and use. Widespread adoption of the simpler formula and lack of adoption of the third-order regression show the more complicated equation holds little appeal beyond those who developed it.

Table 1. Comparison in WQv when Rv calculated by Equation 2 and Equation 3 (P_{WQv} = 0.75 in).

SLU - Standard Land Use	Imp%	Rv = fn (i^3) (Eq3)	WQv ft^3/Ac	Rv = 0.05 + 0.009*I (Eq2)	WQv ft^3/Ac	Increase WQv %
Urban Open Space	**5**	**0.08**	**209**	**0.09**	**259**	**24**
Urban Parks	**10**	**0.11**	**301**	**0.14**	**381**	**27**
Low Density Residential	**20**	**0.17**	**464**	**0.23**	**626**	**35**
Med Density Residential	**35**	**0.25**	**686**	**0.36**	**994**	**45**
High Density Residential	**50**	**0.34**	**924**	**0.50**	**1361**	**47**
Multi-Family Residential	**60**	**0.41**	**1113**	**0.59**	**1606**	**44**
Office Park	**75**	**0.54**	**1480**	**0.72**	**1973**	**33**
Commercial Strip Mall	**90**	**0.73**	**1988**	**0.86**	**2341**	**18**

- The linear correlation between imperviousness and runoff volume lends itself to a simple accounting method based on site (or drainage area) imperviousness. This will prove useful for both redevelopment site WQv accounting and Runoff Reduction Method accounting.
- One potential benefit would be more straightforward, logical assignment of volumetric runoff coefficients to land covers other than impervious area, including different hydrologic soil groups and/or preserved soil, amended soil or compacted soil.
- The median 34% increase (range 7% to 48%) in WQv treatment volume is part of the total adjustment to the WQv necessary - either through modification of the volumetric runoff coefficient or an adjustment to the WQv rainfall event depth - to achieve 80% TSS removal.

Conclusions/Recommendations

We see no advantage to using Equation 3, whereas Equation 2 is compatible with the assignment of Rvs for planned Runoff Reduction Method implementation. The negligible improvement in correlation from Equation 2 to Equation 3 seems to reflect an academic exercise rather than any verifiable improvement in predicting runoff based on imperviousness. In addition, the direct, linear relationship between Rv and imperviousness has several practical benefits including simplicity in communication and calculation.

We recommend, at minimum, Ohio EPA switch to volumetric runoff coefficients (Rv) based on the linear relationship between runoff volume and impervious area. We further recommend Ohio EPA consider the establishment of differentiated Rv values for better quality (preserved or compost-amended) soils and graded (compacted) soils to appropriately credit and incentivize protection or restoration of soil function.

WATER QUALITY VOLUME PRECIPITATION DEPTH EVALUATION

Background

Removal of 80% of total suspended solids (TSS) from average annual runoff is a non-point source water quality standard established by US EPA (US EPA, 1993, 2005) and adopted by Ohio EPA as a primary metric of post-construction stormwater BMP performance (Ohio EPA, 2007). The 90th percentile event depth has been suggested as a method to determine the runoff volume that should be managed to meet the water quality treatment performance standard (Claytor and Schueler, 1996; Schueler et al., 2007; MDEQ, 2014), whereas US EPA (2009) recommended capture of the 95th percentile event for construction of new federal facilities. Both approaches exclude from the analysis rainfall events with depth of 0.10 inches or less as "non-runoff producing events."

During discussions with Ohio EPA Stormwater staff, we concluded that percent runoff volume captured by the WQv BMP was a more accurate metric of runoff treated than the 90th percentile rain event depth. We made an assumption that thoughtful designs of the better-performing BMPs (wet extended detention basin, wetland extended detention basin, permeable pavement and bioretention) were capable of 90% TSS removal for runoff that does not bypass the BMP's treatment mechanism (extended detention, filtration, infiltration, etc.) resulting in 80% TSS removal if we could capture 90% of the annual runoff volume. Therefore, in addition to identifying the 90th percentile rain event depth, we evaluated the precipitation data to identify the rainfall depth that resulted in capture of 90% of the annual runoff volume without routing through the stormwater management practice. We then employed the US EPA's Storm Water Management Model (SWMM) as described below to estimate the routed capture volume.

Approach – Precipitation Analysis

We based our precipitation analysis on historic data from a geographically distributed set of Ohio, Kentucky, and West Virginia-based weather stations. Our initial target was to analyze between 15 and 20 historic precipitation data sets that represented both the geographic and climatic diversity in Ohio. An approach to assuring geographic diversity was to attempt to have one or more data sets from each of the ten (10) isohyetal regions (Figure 8) identified by Huff and Angel (1992) in the *Rainfall Frequency Atlas of the Midwest*.

Our initial criteria for acceptance of a precipitation data set were (1) a minimum 30-year period of record, preferably the most current 30 years; (2) a reasonable temporal scale (<=1-hour rainfall data), (3) 0.01-inch rain gage recording precision and (4) clean, quality data (few questionable or missing periods of record). All data sets utilized in the analysis were downloaded from NOAA's National Climatic Data Center (NCDC).

We began by evaluating precipitation data sets for the weather stations managed by the National Weather Service (NWS) at seven (7) Ohio airports (Akron-Canton, Cleveland, Columbus, Dayton, Mansfield, Toledo, Youngstown), plus two (2) stations located just across the state border at Huntington, WV and the Cincinnati-Northern Kentucky (NKI) airport (Figure 9). All these weather stations met our criteria.

Figure 8. Isohyetal regions for Ohio (Huff and Angel, 1992)

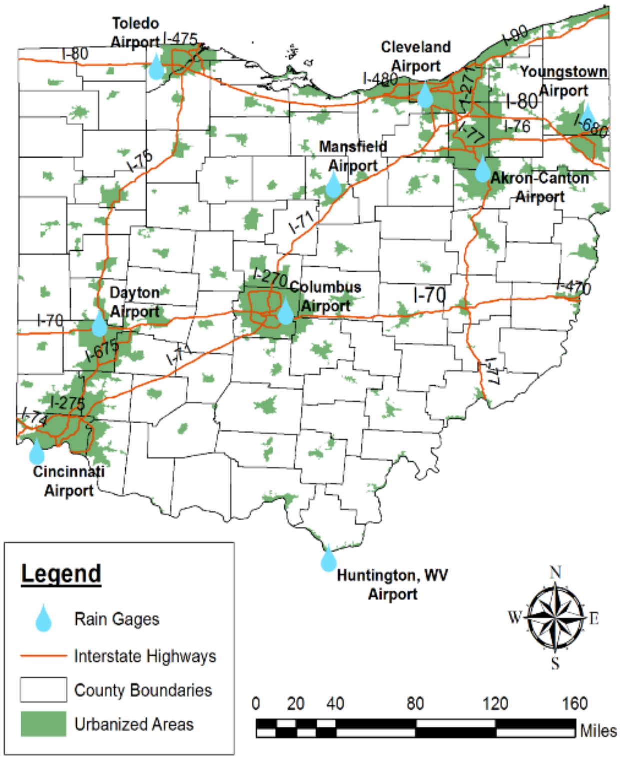


Figure 9. Location of rainfall gages used in analysis.

We also downloaded, reviewed and evaluated the historic precipitation data from over 40 cooperator weather stations concentrated in geographic areas (primarily south, east and southeast Ohio; NW Ohio between Dayton, Columbus, and Toledo; and north central between Cleveland and Toledo) in-between the airports. No cooperator station data sets met our criteria because of: (1) substantial periods of bad or missing data; and (2) a switch in recording hourly precipitation depth from hundredths (i.e., to the nearest 0.01 inch) to tenths (i.e., to the nearest 0.10 inch) during the period of record (mostly around 1985-1986) which eliminated the recording of individual events less than 0.1 inch. The lowering of recording precision likely combined, in many cases, multiple small (<0.1-inch) events into a single 0.1-inch reading. Based on analysis of the data from such sites and comparison against the NWS data at the airports, this change in depth reporting has substantial impacts on the precipitation depth-frequency relationship, rendering these data unrepresentative of long-term precipitation patterns. For these reasons, we have not included precipitation data from any cooperator stations in our analyses.

For the nine airport weather stations, we identified the 50th, 60th, 70th, 75th, 80th, 85th, 90th, 95th, and 100th percentile rainfall depth (i.e., cumulative event depth frequency); and quantified cumulative runoff volume captured across a range of specified WQv depths. These statistics were developed for the historic precipitation data sets for all events and with events less than 0.10 inches removed; subsequent discussion focuses only on the results from analysis with events less than 0.10 inches removed as these events do not generate measurable runoff (Claytor and Schueler, 1996; US EPA, 2005). Summary descriptive statistics (lat-long, period of record, start date, end date, average annual precipitation depth, average annual number of events >= 0.1 inch, etc.) for each station were collated (Table 2).

Gage Location	**Latitude**	**Longitude**	**Start Date**	**End Date**	**Years of Record**	**Average Annual Precip (in)**	**Average Annual Number of Events ≥ 0.1 in**
Akron-Canton Airport	**40.917**	**-81.433**	**8/1/1948**	**12/31/2013**	**65.5**	**36.8**	**73.1**
Cincinnati Airport	**39.067**	**-84.672**	**12/3/1950**	**12/31/2013**	**63.1**	**41.6**	**71.6**
Cleveland Airport	**41.406**	**-81.852**	**8/1/1948**	**12/31/2013**	**65.5**	**37.3**	**75.7**
Columbus Airport	**39.983**	**-82.867**	**8/5/1948**	**12/31/2013**	**65.4**	**38.3**	**72.3**
Dayton Airport	**39.906**	**-84.219**	**8/4/1948**	**12/31/2013**	**65.5**	**37.7**	**69.2**
Huntington WV Airport	**38.365**	**-82.555**	**1/1/1962**	**12/31/2013**	**52.0**	**41.9**	**75.3**
Mansfield Airport	**40.817**	**-82.517**	**12/1/1959**	**12/31/2013**	**54.1**	**39.7**	**73.6**
Toledo Airport	**41.587**	**-83.806**	**8/11/1948**	**12/31/2013**	**65.4**	**32.9**	**64.8**
Youngstown Airport	**41.255**	**-80.674**	**8/8/1948**	**12/31/2013**	**65.4**	**37.5**	**76.7**
Mean					**62.4**	**38.2**	**72.5**

Table 2. Summary descriptive statistics for rain gages used in analysis.

Results and Discussion – Precipitation Analysis

The precipitation data record for the nine NWS-managed airport weather stations revealed excellent quality data that met our criteria. Airport weather stations are located in 6 of the 10 Ohio isohyetal regions identified by Huff and Angel (1992; Figure 8) – Regions 1, 3, 5, 6, 7, and 8 – with Region 10 (southeast Ohio) the biggest geographic area not represented in the airport data (a map of the weather stations used in this analysis is included as Figure 9). The Cincinnati NKI airport weather station is across the Ohio River from Region 8, and the Huntington WV airport weather station is located across the Ohio River from Region 9. The airport data, in our opinion, nicely bracket the ranges of rainfall distributions likely to be found in Ohio with the Cincinnati data representing one extreme (higher frequency occurrence of larger events) and the Huntington data leaning that way, and Youngstown, Akron-Canton, and Cleveland representing the other extreme (lower occurrence of larger depth events). Columbus data tracks very closely to the mean of the 9 airports, with Toledo, Mansfield, and Dayton closer to the mean than to the extremes.

Table 3 and Figure 10 summarize the cumulative event depth-frequency distribution (from 50th to 95th percentile) for Ohio precipitation data. This summary data let us discuss geographic variability, ranges of depths/volumes for the 50th to 95th percentile events, and where the 0.75-inch WQv event (the current Ohio EPA standard) fit within those ranges. The 0.75-inch WQv depth represents, on average, the 81st percentile event with a range from the 77th percentile event at the Cincinnati airport to the 83rd percentile event at Youngstown, well below the 90th percentile storm recommended as the water quality event by Schueler et al. (2007). The 90th percentile storm event depth for Ohio ranges from 0.98 inches for Youngstown to 1.18 inches for the Cincinnati airport, with a mean of 1.07 inches.

Gage Location	**50th Percentile (in)**	**75th Percentile (in)**	**80th Percentile (in)**	**85th Percentile (in)**	**90th Percentile (in)**	**95th Percentile (in)**
Akron-Canton Airport	0.32	0.58	0.67	0.81	**0.99**	1.36
Cincinnati Airport	0.37	0.71	0.82	0.98	**1.18**	1.64
Cleveland Airport	0.31	0.57	0.67	0.80	**1.00**	1.33
Columbus Airport	0.34	0.63	0.73	0.87	**1.07**	1.48
Dayton Airport	0.35	0.65	0.75	0.90	**1.12**	1.54
Huntington WV Airport	0.35	0.66	0.77	0.93	**1.17**	1.56
Mansfield Airport	0.33	0.64	0.76	0.90	**1.11**	1.51
Toledo Airport	0.32	0.61	0.71	0.84	**1.02**	1.39
Youngstown Airport	0.31	0.58	0.66	0.79	**0.98**	1.29
Mean	0.33	0.63	0.73	0.87	**1.07**	1.45

Table 3. Rainfall depth-frequency distribution (events $\leq$ 0.1-in removed).

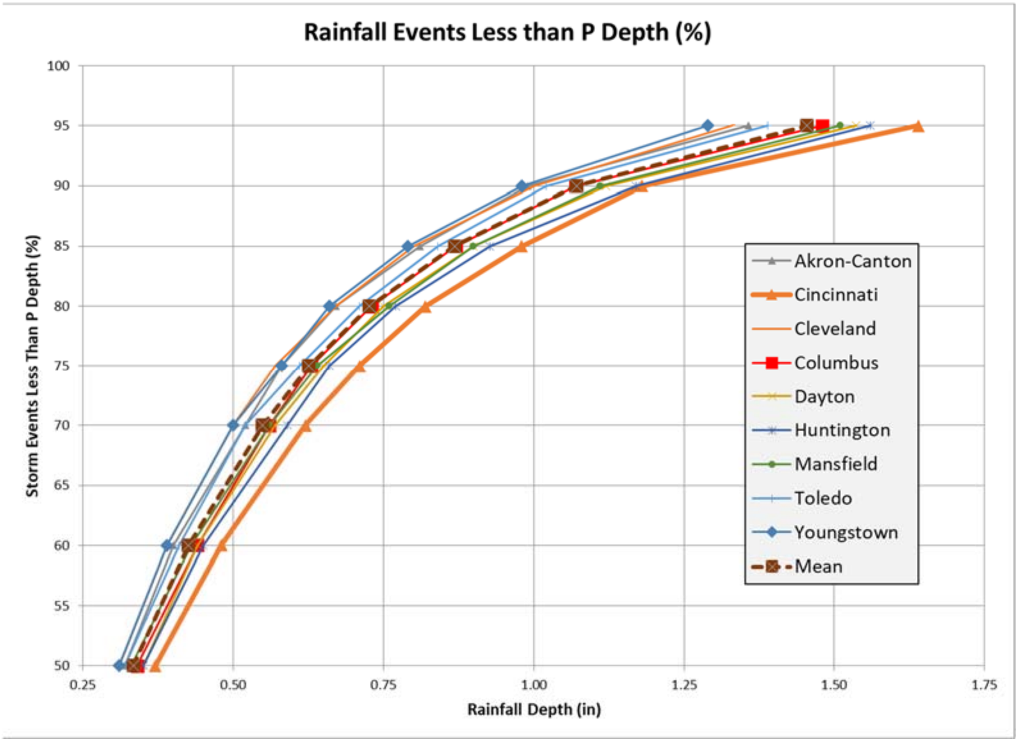


Figure 10. Cumulative precipitation event depth-frequency distribution.

A better predictor of water quality treatment is the percent annual runoff volume captured by the water quality BMP at a given WQv depth. In our analysis, we quantified the runoff volume captured in two ways:

1. Unrouted or "instantaneous" capture volume – This "capture volume" was calculated by simply removing the WQv event depth from each individual storm event in the historic precipitation record. As an example, all storm events with depths less than or equal to the WQv precipitation depth would be fully captured, whereas for larger storm events the WQv precipitation depth would be captured with the remainder considered to have bypassed the treatment mechanism of a properly designed BMP and therefore not be captured. This analysis likely would result in very conservative estimates of WQv precipitation depth necessary to capture the 90th percentile event.
2. Routed capture volume – This "capture volume" was estimated by performing a continuous simulation for the full period of the 65-year historic precipitation record for Columbus, Ohio using SWMM models in which a BMP was sized according to Rainwater and Land Development manual guidance adjusted for the WQv precipitation depth. That SWMM modeling exercise and analysis is detailed in the next section of this report.

The results of the unrouted capture volume analysis are summarized in Table 4. These data show that the 0.75-inch WQv event depth results in an annual mean unrouted capture volume of 79.5% with a range from 75.7% (Cincinnati) to 82.8% (Youngstown).

Gauge Location	0.50-in (%)	0.75-in (%)	0.90-in (%)	1.00-in (%)	1.10-in (%)	1.25-in (%)	1.50-in (%)
Akron-Canton Airport	69.0	81.2	85.9	88.2	90.1	92.3	94.9
Cincinnati Airport	62.2	75.7	81.1	83.9	86.3	89.0	92.2
Cleveland Airport	69.4	81.6	86.3	88.7	90.6	92.8	95.3
Columbus Airport	66.6	79.5	84.4	86.9	89.0	91.4	94.4
Dayton Airport	64.9	77.9	82.9	85.5	87.8	90.4	93.6
Huntington WV Airport	64.0	77.1	82.2	84.9	87.2	90.0	93.3
Mansfield Airport	65.4	78.3	83.4	86.1	88.3	91.0	94.1
Toledo Airport	68.5	81.2	86.1	88.6	90.6	93.0	95.6
Youngstown Airport	70.5	82.8	87.3	89.7	91.6	93.7	96.0
Mean	66.7	79.5	84.4	86.9	89.1	91.5	94.4

Table 4. Percent runoff volume captured by WQv depth (unrouted).

The difference in precipitation characteristics between far southern Ohio (as represented by the Huntington, WV and Cincinnati airport data) and northern Ohio (as represented by the Youngstown, Akron-Canton, Cleveland and Toledo data) suggest use of regional WQv depths should be considered. Some states have designated different regional WQv depths based on substantial differences in regional rainfall characteristics (e.g., MD, NC). In Ohio, there is a 20% difference between the minimum 90th percentile event depth (0.98 inches at Youngstown) and the maximum (1.18 inches at the Cincinnati airport). The mean of 1.07 inches falls roughly midway between these values. If considering a 0.9-inch WQv capture depth, the difference in unrouted annual volume capture between the minimum (81.1% at Cincinnati) to the maximum (87.3% at Youngstown) is about 8 percent. These differences are not as extreme as some other states (NC) but are similar in magnitude to rainfall regions treated separately in MD. These differences, and the logistics of managing a post-construction program with multiple WQv values, should be weighed against benefits gained by region-specific requirements.

Approach - SWMM Runoff Modeling Analysis

The US EPA Storm Water Management Model (SWMM) version 5.1.012 (US EPA, 2017; hereafter referred to as SWMM) was used to quantify the average annual runoff volume captured by water quality BMPs sized for various WQvs. The goal was to identify which combination of volumetric runoff coefficient and WQv precipitation depth resulted in capture and treatment of 90% of the average annual runoff volume through the BMP's primary treatment mechanism (i.e., flow treated through the extended detention outlet for water quality basins, through the filter media for bioretention, or through infiltration for permeable pavement systems). It was assumed that runoff discharging through a BMP's overflow structure bypasses its primary treatment mechanism (i.e., extended detention/settling, filtering or infiltration) and would have significantly lower water quality than treated runoff.

Model inputs for all SWMM models included:

- Hourly precipitation data record for Port Columbus Airport (August 1948 – December 2013) [Note: Port Columbus Airport statistics closely tracked statewide mean and median values within the statewide analysis (see Table 3, Table 4, Figure 10), suggesting Port Columbus data were representative.]
- Monthly evaporation was developed from data reported for the OSU University Farm in Columbus, Ohio (Farnsworth and Thompson, 1982 as reported in Harstine, 1991).
- Stormwater BMP inputs were developed following guidance in the Rainwater and Land Development manual (ODNR, 2006) adjusted for WQv.
- Subcatchment, drainage network, storage unit and LID inputs followed standard SWMM modeling guidance as detailed in Rossman and Huber (2016a, 2016b) and James et al. (2010). [Note: A sensitivity analysis was conducted to test effect on the BMP capture volume by changing - within the range of potential values - SWMM model input parameters (e.g., subcatchment width, subcatchment slope, dstore-imperv, d_{WQv}, etc.). The sensitivity analyses did not identify any parameters that would materially change capture volume performance.]

Modeling pervious areas in SWMM introduces a great deal of uncertainty if the modeler does not have runoff data to calibrate the model to (sometimes even with calibration data). To minimize uncertainty related to runoff from pervious areas, two strategies were employed:

1. where it fit the goals of the modeling exercise, models employed watersheds that were 100 percent impervious; and
2. rather than modeling pervious area using one of the infiltration options, pervious areas were modeled as impervious area at a ratio of $A_{impervious} = 0.05^{*} A_{pervious}$, consistent with the volumetric runoff coefficient assigned pervious area (Rv = 0.05) in Equation 2. For example, for a hypothetical 4-acre site with 50% imperviousness, the SWMM subcatchment would be modeled as $A_{impervious\text{-}model} = A_{impervious\text{-}actual} + (0.05^{*} A_{pervious}) = 2.0 \text{ Ac} + (0.05^{*}2.0 \text{ Ac}) = 2.1 \text{ Ac}$.

Two SWMM modeling exercises were conducted. The objective of the first exercise was to quantify the volume captured across a range of imperviousness using the WQv criteria ($P_{WQv} = 0.75$ inches; $Rv = 0.0858i^3 - 0.78i^2 + 0.774i + 0.04$) in the current CGP (Ohio EPA, 2013) to see how the volume captured compared to the goal of 90% average annual runoff volume captured. For this exercise, watersheds with drainage areas that were 20, 40, 50, 60, 80 and 100% impervious were modeled to determine the percentage of volume captured by dry and wet extended detention basins following design criteria in the Rainwater and Land Development manual (ODNR, 2006).

The objective of the second exercise was to quantify the P_{WQv} necessary to result in 90% average annual runoff volume captured. For this exercise, it was assumed Equation 2 would be adopted and the WQv would be calculated according to Equation 1. Hypothetical 100% impervious watersheds ($Rv = 0.05 + 0.009^{*}I = 0.95$) were modeled for each of four BMPs (dry extended detention basin, wet extended detention basin, permeable pavement with infiltration, and bioretention) which had the WQv sized for each of four different P_{WQv} (0.75, 0.85, 0.90 and 1.00 inches) for a total of sixteen separate modeling runs. The modeled watersheds for the extended detention basins were 4 acres whereas the modeled watersheds for the bioretention and permeable pavement were 1 acre.

Results - SWMM Runoff Modeling Analysis

Using SWMM models to simulate the hydrologic routing of runoff through post-construction stormwater BMPs designed for the WQv event gives a more accurate representation of runoff volume "captured" and treated by the BMP than does a simple statistical analysis of precipitation data (Novotny, 2003). An advantage of using continuous simulation driven by historic rainfall data is the volume captured reflects measured rainfall and runoff patterns that account for variability in precipitation depth, duration and intensity, as well as back-to-back runoff events (James, 2005).

Working from the premise that appropriately-selected, well-designed BMPs are capable of 90% TSS removal for runoff that discharges through the BMP's treatment mechanism (extended detention, filtering, infiltration, etc.), it was stipulated that capturing 90% of the annual runoff volume would result in 80% TSS reduction:

Total TSS Reduction = Percent Runoff Volume Captured * Percent TSS Removal from Volume Captured
90% Runoff Volume Captured * 90% TSS Removal = 81% Total TSS Reduction

The estimated average annual routed runoff volume captured by wet and dry extended detention (ED) basins designed to current Ohio EPA (2013) criteria ranged from 71% at I = 50% (wet ED basin) to 83% at I = 100% (dry ED basin, Figure 11). When multiplied by the assumed 90% TSS removal efficiency (for wet ED basin only), the resulting estimated average annual TSS reductions ranges from 64% at I = 50% to 73% at I = 100% (Table 5), well below the goal of 80% TSS removal on an average annual basis.

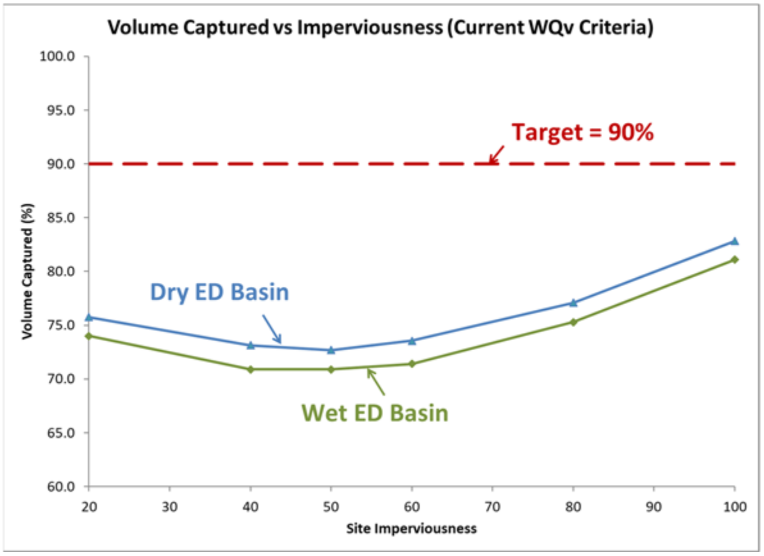


Figure 11. Average annual runoff capture volume as a function of imperviousness; current CGP post-construction WQv criteria (Ohio EPA, 2013).

Imperviousness (%)	**Average Annual Runoff Capture Volume %**	**Estimated TSS Reduction (Assuming BMP Effectiveness = 90%) %**
20	74.0	66.6
40	70.9	63.8
50	70.9	63.8
60	71.4	64.3
80	75.3	67.8
100	81.1	73.0
Goal	90.0	80.0

Table 5. Average annual runoff capture volume and estimated TSS reduction as a function of imperviousness for wet extended detention basins sized for current CGP post-construction WQv criteria (Ohio EPA, 2013).

SWMM was used to run a series of simulations of four different post-construction BMPs to determine the routed stormwater runoff volume captured when each practice was sized for the WQv with Rv following Equation 2 for four different P_{WQv} (0.75, 0.85, 0.90 and 1.00 inches). The results of these sixteen (16) simulations are presented in Table 6. Assuming 90% TSS removal for the captured runoff volume, model results can be extended to estimated average annual TSS load reduction as a function of P_{WQv} (Table 7, Figure 12)[1].

WQv P Depth (in)	**Dry ED Basin %**	**Wet ED Basin (EDv=0.75*WQv) %**	**Permeable Pavement %**	**Bioretention %**
0.75	84.6	82.8	85.8	88.9
0.85	88.1	86.3	87.9	90.6
0.90	89.0	87.7	88.9	91.3
1.00	91.2	89.4	90.5	92.7

Table 6. Average annual percent routed capture volume as a function of P_{WQv}.

[Note: Rv determined by Equation 2.]

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[1] TSS removal estimates for dry extended detention basins were not included in Table 7 because research suggests the TSS removal efficiency of dry basins is typically 60-70%, well below the 90% removal efficiency assumed for the more effective BMPs (CWP, 2007; Leisenring et al., 2014). It is recommended that Ohio EPA evaluate TSS removal performance of dry extended detention basins, and explore pretreatment, in-basin treatment enhancements, and/or increasing the WQv for this practice to bring it in line with other approved options.

WQv P Depth (in)	Dry ED Basin[1] %	Wet ED Basin (EDv=0.75*WQv) %	Permeable Pavement %	Bioretention %
0.75	-	74.5	77.2	80.0
0.85	-	77.7	79.1	81.5
0.90	-	78.9	80.0	82.2
1.00	-	80.5	81.4	83.4

Table 7. Estimated average annual TSS load reduction as a function of P_{WQv}.

[Note: Assumed percent TSS removal from volume captured = 90%.]

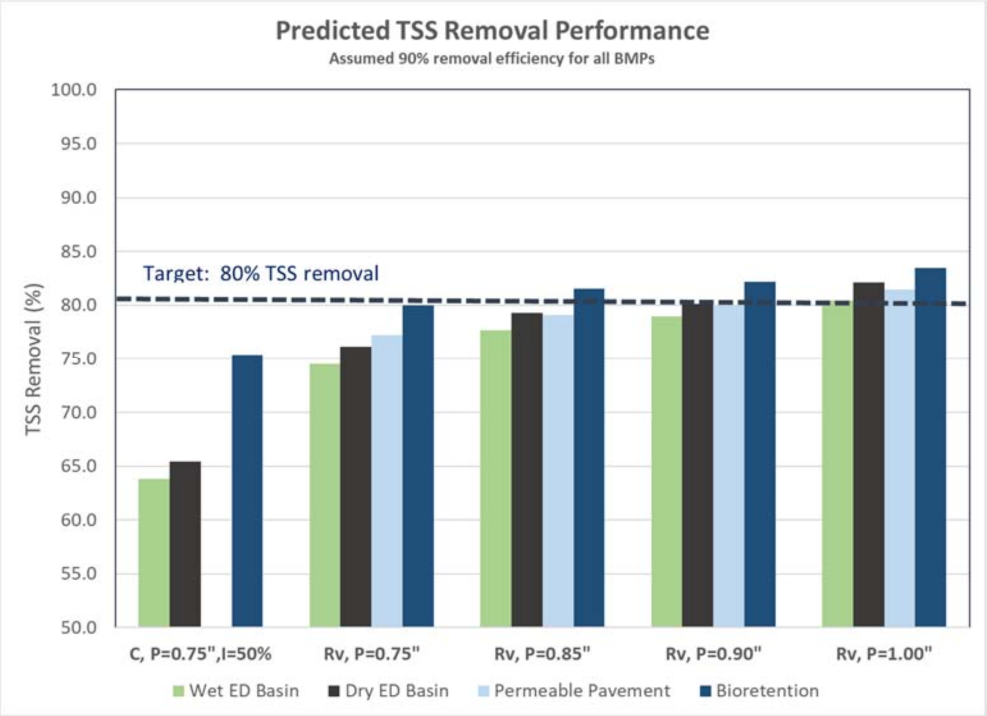

Figure 12. Predicted TSS removal performance based on Rv and P_{WQv}.

Discussion

A number of factors suggest that the values arrived at by this analysis are not conservative – i.e., this analysis is likely to over predict performance. Those factors include:

- The 90% performance assumption does not account for improperly designed, constructed or maintained BMPs.
- As noted above, dry extended detention basins – the most frequently utilized post-construction BMP in Ohio – do not exhibit TSS removal effectiveness on par with the other listed BMPs.

- Soil degradation associated with site development was not taken into account in the SWMM modeling. The excess runoff associated with soil degradation results in lower capture of runoff volume, resulting in bypass of more untreated runoff volume and lower TSS removal.
- Statewide trends in increased precipitation depth and intensity over time resulted in capture volume more than 2% lower in the most recent half (1981-2013) than in the first half (1948-1980) of the precipitation record.
- Columbus precipitation data was used to estimate volume captured and annual TSS removal because of its correspondence to statewide averages. Volume captured would be lower, and TSS removal less, for southern and southwest Ohio due to higher frequency of events greater than the WQv.

It is recommended that Ohio EPA consider these factors when selecting P_{WQv}.

Conclusions/Recommendations

Ohio EPA has set the threshold for NPDES permit compliance at 80% TSS load removal from post-construction stormwater runoff on an average annual basis. This means that a post-construction stormwater BMP must (1) control a large enough water quality volume and (2) provide highly effective TSS removal to remove 80% of the TSS mass (loading) from stormwater runoff. Because a suite of post-construction BMPs (wet extended detention basin, wetland extended detention basin, permeable pavement with or without infiltration, and bioretention) are capable of 90% TSS removal of the volume treated, a 90% capture volume target was set for average annual stormwater runoff.

The estimated average annual routed runoff volume captured by wet extended basins using current Ohio EPA post-construction criteria results in estimated average annual TSS reductions ranges from 64% to 73%. Similar capture volumes for dry extended detention basins and permeable pavement suggest current criteria in the CGP do not provide the stated goal of 80% TSS reduction on an average annual basis, and modifications to the Rv and P_{WQv} should be made.

Based on our evaluation, we recommend the following changes to the post-construction WQv criteria in the CGP:

- utilize $Rv = 0.05 + 0.009*I$
- increase the WQv precipitation depth (P_{WQv}) to 0.90 inches.

These updates, combined with estimated total suspended solids (TSS) removal efficiencies of 90% for selected extended detention (wet basin, constructed wetland basin, media filter) and infiltration best management practices (BMPs) accepted for general use (Table 2; Ohio EPA, 2013), result in removal of 80% of average annual TSS.

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