Description of the WQ-COSM Computer Model to Generate a Water Quality Capture Volume for Stormwater BMPs

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INTRODUCTION

Water Quality Capture Optimization Statistical Model (*WQ-COSM*) is a result of cooperative activities among the Urban Watersheds Research Institute (*UWRI*), the Urban Drainage and Flood Control District (*UDFCD*) and the Civil Engineering Department of University of Colorado Denver (*UCD*), all organizations located in Colorado. The model is a Windows-based computer program that uses recorded rainfall data from the National Climatological Data Center (*NCDC*) operated by NOAA and information about the catchment's hydrologic parameters to help the user determine the long-term ratio of runoff volume captured by a water quality capture volume (*WQCV*) to all runoff volume and the ratio of runoff events captured by a *WQCV* to all runoff events. The information produced is a table of increasing WQCV vessel sizes (i.e., basin sizes) and the vessel size for the maximized WQCV. These volumes can be used to size and design various types of stormwater treatment facilities (i.e., structural Best Management Practices (*BMPs*)) that temporarily capture runoff for treatment or infiltration.

This program replaces a DOS based program called PondRisk (ref.: Guo, James C.Y. (1992). WQ-COSM has a modern user interface and functionality that was not available in PondRisk. It computes surface runoff using continuous runoff simulation using either Rational Method or Horton's Infiltration Method and then calculates the WQCV using the resultant surface runoff.

A WQCV is an integral to any BMP that removes significant portions of pollutants from stormwater runoff and it also helps mitigate the hydrologic changes caused by urbanization. BMPs with WQCV differ from flow-through BMPs, which do not mitigate the effects of increased stormwater runoff peaks and volumes. Flow-through BMPs are primarily used to remove gross pollutants consisting of floating trash and coarse sediment, but for the most part, do not remove fine sediment and associated pollutants such as bacteria and dissolved constituents in significant amounts. A WQCV is a part of the following types of BMPs:

- As storage in an extended detention basin (i.e., dry) basin (*EDB*)
- As surcharge storage above the permanent pool of a retention (i.e., wet) pond (*RP*)
- As surcharge storage above the permanent pool of a wetland basin (*WB*)
- As storage above, or upstream of a media filter (*MF*)
- As storage above, or upstream of, a rain garden (*RG*), (often called bio-retention cell).

The size (i.e., volume) of WQCV vessel, namely the physical size of a stormwater quality detention basin, is a function of both the runoff that results over time from a given catchment and the time it

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takes to empty the brim-full WQCV vessel when there is no additional runoff entering it (i.e., its *drain time* which is the average rate of discharge from the vessel).

WQ-COSM is implemented as two programs, a user interface and the math engine. The user interface collects information from the user, generates properly formatted input files for the math engine and displays the results after the math engine has successfully processed the information in the input file. What follows is a description of what the program does to provide the WQCV information of the user, which then can be used to size the desired BMP for any catchment in the United States (or anywhere in the world for that matter). Guidance is also provided for the selection of appropriate drain/emptying times

SEPARATING RAINFALL DATA SERIES INTO INDIVIDUAL STORMS

In 1989 Driscoll, Palhegyi, Strecker, and Shelley (Driscoll et.al., 1989) submitted to U.S. EPA a draft report titled: *Analysis of Storm Events Characteristics for Selected Rainfall Gauges throughout the United States*. It contains maps of the United States showing a variety of characteristic parameters of rainstorms such as mean depth, mean storm duration, mean number of storms per year, etc. Their analysis concluded that a dry period between storms of 6-hours was sufficient and most statistically defensible to define a new storm. They also concluded that storms less than 0.1 inch (2.5 mm) in total depth produced virtually no runoff from urban areas and excluded all such storms from the data set of storms. However, that did not end the debate on what dry period defines a new storm, and there are advocates for different durations that range from 3-hours to 24-hours.

After reviewing the 1989 Driscoll's report we concurred with its recommendation of 6-hours for separating any continuous rainfall data into a record of individual storms. We also concurred with the need to filter out storms that produce no runoff, since most records throughout the United States show that almost half of all individual storms fall into this "no runoff" category. Storms that produce total precipitation depth of less than 0.10 inch (2.5 mm) are generally of no concern when sizing the BMPs. Also, depending on the region of the country, one may want to exclude precipitation data from certain periods of the year from this analysis. For example, winter months have precipitation in the form of snow which often does not produce runoff until spring and at much different rates and quantities than would be generated from rainfall. Regardless of what protocols are used to keep or exclude individual storms, it is necessary to identify and tag each incremental precipitation depth in the data set with a storm number for later use in determining the WQCV based on the number of storm events it will capture in total.

One may ask, why separate storms when determining an appropriate WQCV for use in sizing BMPs? With continuous simulation of runoff, separating the data set into individual storms and then filtering out inconsequential events is not needed. Continuous runoff volume simulation tells us what fraction of the total runoff volume is captured and what fraction of total runoff exceeds the WQCV vessel's size the period of rainfall record analyzed. However, if we want to know the number of storm events and percentages that are captured in total, we need to have a data set that identifies individual storms with overflows/bypasses.

After many years of observing the impacts of urban runoff on receiving water aquatic life we have concluded that the fraction of storms captured is much more important than the fraction of total runoff volume captured. This is because the total volume captured can be heavily weighted by a relatively few very large events. These large storms create significant drainage and flooding problems, but it would be prohibitively expensive to capture and treat. At the same time, this does not mean that runoff from larger events will not receive some treatment since some of this runoff from larger storms, ranging from most to only a fraction, is also captured and treated or infiltrated by a BMP with a WQCV.

ESTIMATING SURFACE RUNOFF

Surface runoff can be estimated in a number of ways, ranging from simple to quite complex. Although the more complex methods generally require the use of more input parameters, there is no assurance that they produces more accurate results because of the need by the user to make many assumptions on the exact values of parameters to use. The UWRI incorporated two methods in WQ-COSM to estimate WQCV, namely the Rational Method and the Horton's Infiltration Model.

The **Rational Method** is simple and uses a runoff coefficient to convert a rainfall depth to a runoff volume. It merely says that, after the initial retention loss is satisfied, runoff occurs and is equal to the product of rainfall and the runoff coefficient, as described by Equation 1.

$$P_r = C \cdot \left(P_t - P_i\right) \qquad (1)$$

in which, P_r = runoff volume in watershed inches (mm),

C = watershed runoff coefficient,

P_i = incipient runoff depth in inches (mm) low end rainfall filter in WQ-COSM, and

P_t = precipitation over the watershed in inches (mm).

Horton's Infiltration Method requires the hydrologist to separate the *effective* impervious area from the previous area. For the impervious area, runoff begins to occur once the depression losses are satisfied, after which runoff volume is equal to rainfall. For pervious areas, the hydrologist needs to account for the initial and final infiltration rates and to estimate how rapidly initial infiltration rate decays to its final value. Once the rainfall rate (intensity) exceeds the infiltration rate pervious depressions begin to fill. Runoff occurs after the infiltration and depression losses are exceeded. After rainfall ends, drying of all surfaces begins and the initial infiltration losses and retention storage losses begin to be reclaimed. How much of the initial infiltration losses and retention losses are reclaimed depends on the *drying time* that the hydrologist deems to be appropriate. Depending on the region of the United Sates, drying times typically range from 1 to 14 days.

Equation 2 is the classic expression for Horton's Equation, but in practice the integrated form of this equation is used to estimate what portion of rainfall that lands on pervious surfaces actually becomes surface runoff.

$$f = f_o + \left(f_i - f_o\right) e^{-at} \qquad (2)$$

in which: f = infiltration rate (in/hr or mm/hr),

f_o = final infiltration rate (in/hr or mm/hr),

f_i = initial infiltration rate (in/hr or mm/hr),

e = natural logarithm base,
a = decay coefficient (1/hour),
t = time (hours).

For continuous simulation, hourly (and sometimes 15-minute) precipitation data (available in comma separated value format) for all regions of the United States can be obtained from the National Climatic Data Center (NCDC, http://www.ncdc.noaa.gov/oa/climate/stationlocator.html). Hourly data are typically available for much longer periods (typically exceeding 20 years or more), but these data need to be scrutinized for completeness and for questionable rainfall depths before use. The data that are found to be acceptable can be used in a continuous simulation model to estimate surface runoff for each time step. Figure 1 illustrates how the rainfall, losses and runoff accumulate for two successive storms. For the second storm in this illustration, the degradation of runoff loss was partially recovered by the drying time.

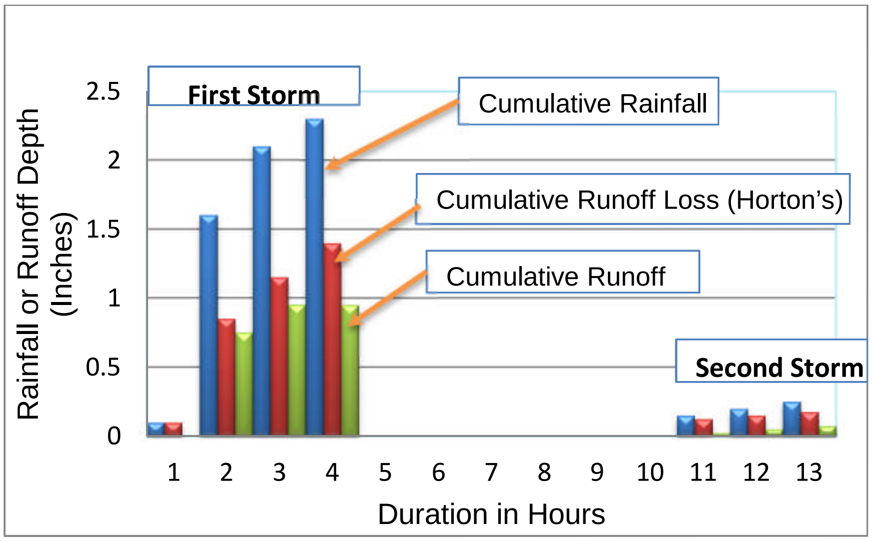

Figure 1. Example of cumulative rainfall, rainfall losses and runoff for two successive storms.

Next, the runoff data series is processed through a storage model (i.e., the WQCV vessel) to determine what fraction of the runoff volume from each storm is captured and what fraction bypasses it. In addition, a record is kept of whether the storm was fully captured by the vessel or not and if fully captured, that storms is added to the number of fully captured storms.

WQCV DRAIN TIME

Defining the rate at which the WQCV vessel is to be drained is very important and is defined as the time it takes the brim-full WQCV vessel to completely empty (i.e., its *drain time*). Drain time is defined by the person designing the facility and is based on the type of BMP used or by the effects on receiving waters that need to be mitigated. For example, the drain time for WQCV of an EDB typically ranges from 24- to 72-hours, depending on local requirements. drain times for the surcharge WQCV of a RP typically range from 1- to 12-hours, the faster time providing virtually no mitigation of flow increases due to urbanization.

Drain times for MFs and RGs depend on the surface infiltration rates of the filter or growth media and/or the capacity of the underdrains. When new, the infiltration rates for a MF and for the sandy growth media of a RG is very high and can exceed 24 inches (600 mm) per hour. But, as these facilities age and fine sediment accumulates on their surface, infiltration rates can drop to ½ inch (12 mm) per hour or less as illustrated by Figure 2. For practical reasons, allowing for some degradation in surface infiltration rates and to provide for a long life of the installation before surface rehabilitation is needed; the authors suggest using a 24-hour drain time to size the WQCV vessel above a MF and a 12-hour drain time above a RG. The surface infiltration rate of the RG is expected to degrade more slowly than that of a media filter because the plant roots tend to reopen some of the clogged pores in the media. Drain times will also determine the surface area these types of facilities need, since their surface is estimated as the volume of the WQCV vessel divided by its design depth.

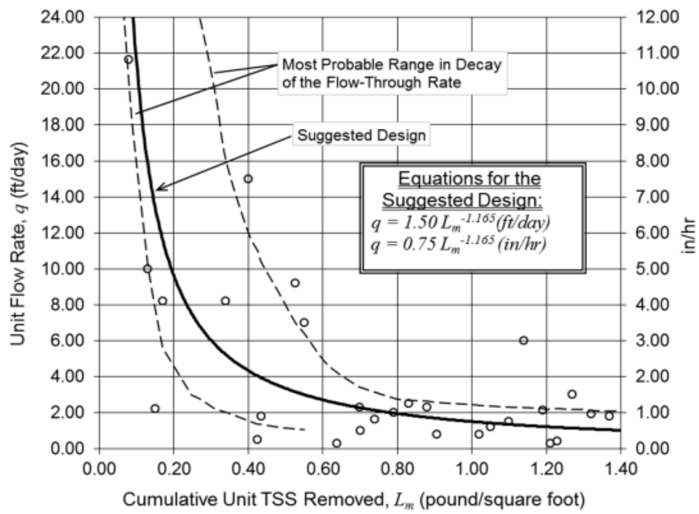

Figure 2. Infiltration rate decay at a Lakewood, Colorado sand filter test site. (Ref.: Urbonas, 1999 and Urbonas, 2002)

ROUTING RUNOFF THROUGH THE WQCV VESSEL

After the runoff volume for each time step in the filtered rainfall data set has been defined, it is routed through a series of WQCV vessels of increasing volume increments at a pre-selected drain time. Water discharges out of the WQCV vessel either through an outlet pipe, through an underdrain, through infiltration into the soil or through a combination of infiltration and underdrains. Equation 3 describes this routing process mathematically, while Figure 3 illustrates this process schematically.

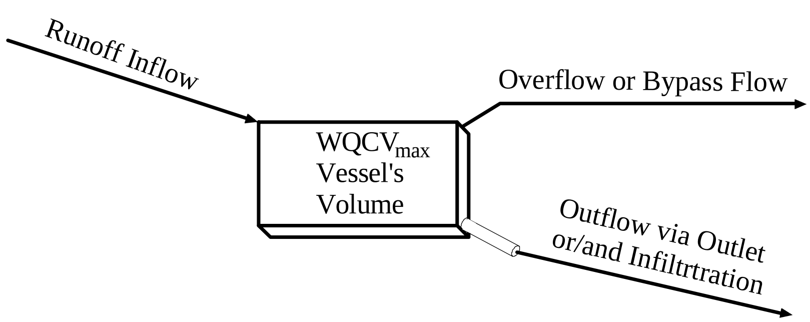

Figure 3. Schematic of the routing process through a WQCV vessel.

$$The\ greater\ of\ (WQCV_{max})\ \text{or}\ (WQCV_t = WQCV_{t-\Delta t} + V_{in\ t} - V_{out\ t}) \quad (3)$$

in which, $WQCV_t$ = Water Quality Capture Volume at time t,
$WQCV_{t\text{-}\Delta t}$ = Water Quality Capture Volume at time the end of the previous time step,
$V_{in\ t}$ = Inflow volume during the time step t,
$V_{out\ t}$ = outflow volume during the time step including overflows
(namely, $WQCV_{max} / T_d$ in which T_d = drain time), and
$WQCV_{max}$ = the maximum physical volume of the WQCV vessel.

If the cumulative runoff volume being stored within the WQCV vessel during the storm does not exceed the maximum capture volume (i.e., $WQCV_{max}$) for the incremental WQCV vessel size being tested, the runoff volume for that event is considered to be entirely captured and treated. If the runoff during a storm causes $WQCV_{max}$ to be exceeded, some of the runoff overflows/bypasses the vessel. The incremental volume that overflows/bypasses is added to the cumulative total overflow volume. Mathematically this is expressed as,

$$P_{tr} = \sum_{j=1}^{j=N} P_{rj} \quad (4)$$

$$P_{to} = \sum_{j=1}^{j=N} (P_{rj} - WQCV_{max});\ for\ (P_{rj} - WQCV_{max}) > 0, otherwise = 0 \quad (5)$$

in which P_{tr} = cumulative runoff volume in inches (mm),
P_{to} = cumulative overflow/bypass volume of runoff in inches (mm),
P_{rj} = runoff volume during the runoff event increment j in inches (mm),
($j = j^{th}$ storm event runoff increment in the record and
N = the total number of storm event's runoff increments in the record).

Using these relationships, we define the *Runoff Volume Capture Ratio* (R_v)for the entire period of rainfall record as

$$R_v = 1.0 - \left({}^{P_{to}}/_{P_{tr}} \right) \quad (6)$$

in which, R_v = runoff volume capture ratio.

In addition, the number of storm events that exceed $WQCV_{max}$ are counted by the software. Thus, for a continuous record with a total of N_s runoff producing storm events, the total number of runoff events that have an overflow/bypass is used to define the *Event Capture Ratio*(R_n), which can be expressed as

$$R_n = 1.0 - \left({}^{N_{to}}/_{N_s} \right) \quad (7)$$

in which, R_n = runoff event capture ratio,
N_{to} = total number of storm events where runoff exceeded $WQCV_{max}$ and
N_s = total number of storm runoff events.

Figure 4 illustrates how the runoff from the two sequential storms described earlier in Figure 3 are captured. At the start, the entire $WQCV_{max}$ amount is available to capture runoff. Because this is a large storm, the runoff from it fills the WQCV vessel within the first hour and all runoff that follows overflows/bypasses the vessel. At the end of the storm event the vessel continues to empty and begins to regain its WQCV capacity. When the second much smaller storm begins six hours later, the vessel has regained part of its original capacity and is able to intercept the runoff from the first three hours of runoff, but not the entire runoff volume during the fourth hour and a small amount of overflow/bypass occurs. The overflow/bypass volume is added to the total cumulative overflow/bypass volume account and both storms are added to the total count of storms that had overflows/bypasses occur. Had the second storm occurred 12 hour after the first one, there would have been enough WQCV capacity in the vessel to fully capture it.

Thus, continuous simulation of the rainfall/runoff process and how it affects the amount of water stored in the $WQCV_{max}$ vessel gives us a complete picture of how the WQCV BMP is functioning over extended periods of time. Long-term averages of hydrologic and hydraulic performance can be expressed, along with the accompanying effects on water quality and geomorphic effects.

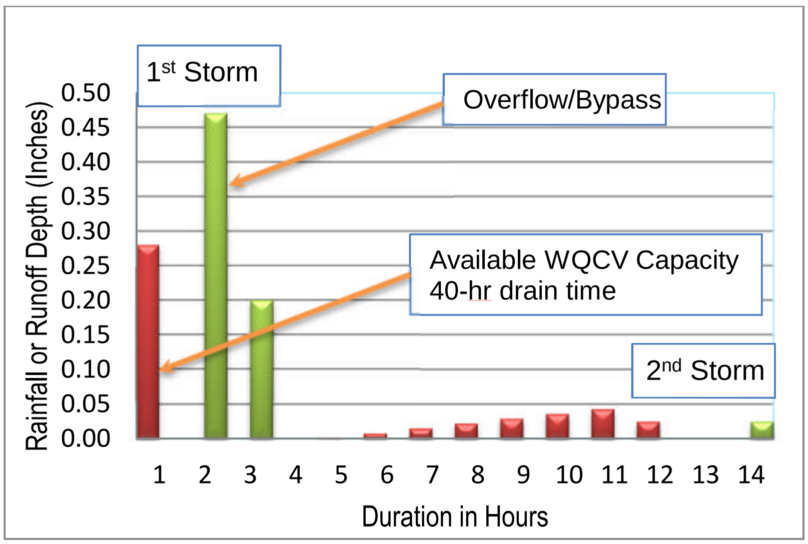

Figure 4. Illustration of $WQCV_{max}$ vessel's capacity and overflows for two successive storms.

FINDING THE POINT OF DIMINISHING RETURNS

The concept of finding the point of diminishing returns in the sizing of BMPs and their WQCV was suggested by Urbonas, Guo, and Tucker in 1990 (Urbonas, et.al., 1990), which was based on protocols developed by Pechter (Pechter, 1978). This was followed by Guo in the development of software to find this point, which was referred to at that time as the point of Maximized WQCV (Guo, 1992). This concept was further developed and tested by Guo and Urbonas using continuous rainfall data at a wide variety of locations in the United States (Guo and Urbonas, 2002).

Since then, continuous simulation procedures were refined and the authors reexamined this topic. They developed simple software for UWRI, namely WQ-COSM mentioned earlier and described next. An important feature of WQ-COSM is a procedure that identifies where the point of diminishing returns (i.e., maximized WQCV) occurs. Up to that point, incremental increases in WQCV vessel size result in corresponding favorable returns in terms of incremental increases in the fraction of the total volumes of runoff and the total numbers of storms completely captured (i.e., no overflow or bypass). Beyond that point, incremental increases in WQCV result in rapidly diminishing returns in the fraction of total volumes and number of storms captured. Figure 4 illustrates this phenomenon, which was found to occur at all rain gage records examined at a number of locations in United Sates.

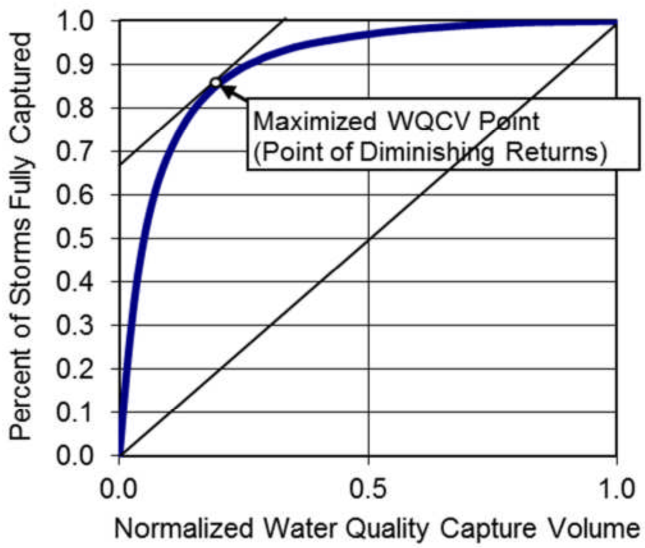

Figure 4. Point of Diminishing Return, namely the Maximized WQCV. (Urbonas, et.al., 1990)

In order to find this point of diminishing returns, all incremental values of WQCV were normalized by dividing each of them by the WQCV that fully captures all of the runoff volume or storm events generated by the rainfall-runoff model. To avoid a few very large events from dominating the averages and skewing the results, a WQCV value equal to a very large percentage of the maximum possible WQCV (say 99.5%), can be used, which was defined as P_m. This normalizing value is used to screen out extreme rainstorm events that can produce disastrous flooding. Equation 8 illustrates how each WQCV increment is normalized to determine this normalized volume based on runoff volumes.

$$WQCV_n = \left({}^{WQCV_i}\!\big/_{P_m} \right) \tag{8}$$

in which, $WQCV_n$ = the n^{th} WQCV normalized by P_m,

$WQCV_i$ = the i^{th} WQCV increment being tested for volume capture,

P_m. = the WQCV that captures practically all of the runoff volume.

Once all of the WQCV test increments have been normalized, either the percent capture of total runoff volume or the percent of all runoff events fully captured can be plotted as previously illustrated in Figure 4 and the maximized point found. The maximized WQCV occurs where the slope of the curve is equals to one.

WATER QUALITY CAPTURE OPTIMIZATION AND STATISTICS MODEL (WQ-COSM)

Performing the necessary calculations for the sizing and optimization of a WQCV for any BMP can be a daunting task, even with the use of spreadsheets. This task is easy to perform using the WQ-COSM freeware. As mentioned earlier, it has two continuous runoff volume simulation options (i.e., Rational Method and a Horton's Infiltration's method, similar to that used in EPA SWMM 5). It can use 15-minute and 60-minute (i.e., 1-hour) comma separated NCDC rainfall data. The user can exclude specific seasons (i.e., snow season) or specific periods such as periods of rainfall data with errors or periods of missing data from being analyzed.

The user needs to specify the consecutive dry period used to identify a new storms (default = 6-hours), the days of drying period to fully recover Horton's initial infiltration and depression losses (default = 3-days), and the emptying time for the WQCV (default = 24-hours). In addition, the user can specify the lowest value of total rainstorm depth to process in order to filter out non-runoff producing storms (default = 0.08 inches or 2 mm), and also the upper WQCV percentile to exclude large outlier storms (default = 99.5%) from the WQCV calculations. Additionally, the user needs to identify a NCDC comma separated data file and tell the software in which directory the data file is located.

The program has three output options: (1) Water Quality Capture Volume and Statistical Summary that contains rainfall and runoff statistics and a complete list of increasing WQCV values, including the Maximized WQCV, with information on how much total runoff volume and number of storms each increment captures. This information is provided in two ways. One is based on both the *Runoff Volume Capture Ratio* and the other on the *Event Capture Ratio*. (2) Precipitation and Runoff Statistical Summary, and (3) Complete record of storms and their total rainfall depths, durations, separation times, etc. All output is in a HTML format that can be viewed by Internet Explorer™ and other web browser software and can be copied and pasted into Excel™, MS Word™ and other types of files. In addition, the user can request an electronic file to be generated in a comma separated format, identical to the printed version provided in option 3 above that can be imported into any spreadsheet or other software for further analysis by the user.

EXAMPLE OF AN APPLICATION

As an example for this paper, we examined a 50% impervious catchment with clayey soils in the Denver, Colorado region (i.e., most common condition there) using 60-years of data from the Denver Rain Gage NCDC 1-hour data collected between 08/02/1948 and 12/28/2009. We used a 6-hour period of no precipitation to separate hourly data into individual storms and then filtered out all storms with a total of less than 0.1 inches (2.5 mm) as non-runoff producing events. The upper limit for sizing the WQCV was 99.5% to exclude very large rainfall events. A total of 2,163 individual runoff producing storms were identified over the 60-year period, of which only 10 storms exceeded the 99.5% exclusion limit.

We ran the software to find the maximized WQCV for an extended detention basin with a 40-hour drain time. The Horton's runoff options was used with parameters for clayey soils assumed to have initial infiltration rate of 3.0 inches (76 mm) per hour which rapidly decays to 0.5 inches (12 mm) per hour, a 0.1 inches (2.5 mm) impervious depression loss and 0.4 inches (10 mm) pervious depression losses. The Maximized WQCV was found to be 0.28 watershed inches (7.1 watershed mm) based on *Runoff Volume Capture Ratio* (*RVCR*) and 0.23 watershed inches (5.8 watershed mm) based on *Event Capture Ratio* (*ECR*). The *Runoff Volume Capture*

Ratio maximized volume fully captured 82.7% of all the runoff volume and 88.9 of all runoff events in total, while the *Event Capture Ratio* maximized volume fully captured 85.7% of all storms and 77.1% of all runoff volume (see Figure 5).

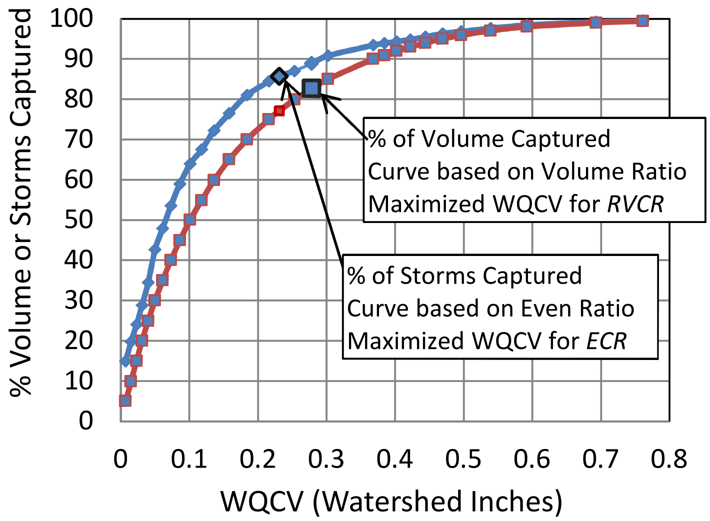

Figure 5. WQCV vs. Percent Storms and Runoff Volume Captured for Example Problem.

The difference in the maximized WQCV vessel size between the two is almost 22%, which means that the extended detention has to be 22% larger and will take up that much more land space if the *Runoff Volume Capture Ratio* is used as the basis for the sizing of BMPs that control runoff volume. It will also cost more to construct and maintain in order to capture little more runoff volume from very large flood producing runoff events. Also, to implement a 95% runoff capture standard that is based on the *Runoff Volume Capture Ratio* requires an additional 55% to 60% larger volume and correspondingly larger surface area for any BMP, with a proportionate increases in capital, maintenance, and eventual rehabilitation costs. What is rarely understood is that if this standard was applied to an example EDB with a 40-hour drain time, the result would be counterproductive. In fact, a large number of small runoff events will pass through the BMP with a significantly reduced detention time, resulting in reduced pollutant removals from large percentage of runoff events because the release rates would be higher to accommodate the larger volume needed for the 95% RVCR standard.

CONCLUSIONS

When designing a stormwater quality control facility system, one needs to balance the runoff capture capability, effectiveness in protecting receiving waters and life-cycle facility costs, including construction, maintenance, and eventual rehabilitation. A WQCV is an integral part of BMPs such as extended detention basins (dry), retention ponds (wet), wetland basins, media filters and rain gardens. The simple maximization techniques developed by the authors is one method to help the designers balance these concerns.

However, the authors recognize that localities may have different standards that need to be followed and have developed continuous simulation software, WQ-COSM, for the Urban Watersheds Research Institute that can generate not only the maximized WQCV but a list of

WQCV sizes along with their corresponding percentages of total runoff volume and events captured in total. In keeping with the Institute's mission, this handy, easy to use software costs nothing to download and use. It can be accessed through the UWRI website at www.urbanwatersheds.org or through the UDFCD website at www.udfcd.org under downloads. Finally, the authors recommend using the *Event Capture Ratio*, rather than the *Runoff Volume Capture Ratio*, as the most appropriate method for the sizing of all BMPs that have a WQCV and control the volume of stormwater runoff. This approach recognizes that it is the population of storm runoff events that occur frequently that is the driving force behind most geomorphic and aquatic habitat impacts attributed to urbanization, and it is not the very few events that produce disproportionally large volumes of runoff and cause flooding and serious economic damages.

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REFERENCES

Driscoll, E.D., Palhegyi, G.E., Strecker, E.W., and Shelley, P.E. (1989). Analysis of Storm Events Characteristics for Selected Rainfall Gauges throughout the United States (draft report), U.S. Environmental Protection Agency, November.

Guo, James C.Y. (1992). *PONDRISK Computer Model for Determination of Maximized Detention Volume*, Department of Civil Engineering, University of Colorado at Denver, Denver, CO.

Guo, James C.Y. and Urbonas, Ben. (2002). *Runoff Capture and Delivery Curves for Storm Water Quality Control Designs*, ASCE J. of Water Resources Planning and Management, Vol 128, Vo. 3, May/June.

Pechter, R. (1978). *Design of Stormwater Retention Basins*, NORDSFRSK Report, Seminar on Detention Basin, Marsta, November 7-8. (In German)

Urbonas, B., Guo, Jim C.Y., Tucker, L.S. (1990). *Maximization of Stormwater Quality Volume*, Urban Stormwater Quality Enhancement, Proceedings of an Engineering Foundation Conference held in October 1989, Davos, Switzerland, published by ASCE, Reston, MD.

Urbonas, Ben R. (1999). *Design of a Sand Filter for Stormwater Quality Enhancement*, Water Environment Research, Volume 71, Number1, Jan-Feb, Alexandria, VA.

Urbonas, Ben (2002). *Stormwater Sand Filter Sizing and Design - A Unit Operation Approach*, Report on field study by Urban Drainage and Flood Control District, Denver, CO.