WAER QUALITY CAPTURE VOLUME FOR STORMWATER BMP and LID DESIGNS


ABSTRACT

This paper summarizes the methodology and procedure developed for determining the Water Quality Capture Volume (WQCV) for stormwater BMP and LID facility designs. WQCV is directly related to the local rainfall pattern, watershed imperviousness, and drain time applied to the BMP/LID facility. The performance of a BMP facility is evaluated using the rainfall-runoff continuous simulation that computes the long term runoff volume-based and event-based capture ratios using the principle of water volume balance among rainfall amount, hydrologic losses, runoff volume captured in the BMP facility, and bypass flow. For a regional study, the procedure associated with the continuous simulation can produce optimized design values for WQCV. Typically, but not always, the optimal runoff volume and event capture ratios vary between 80 and 90%. This WQCV design and analysis procedure is more robust than the one used to estimate the WQCV's using the regression equations outlined in ASCE Manual of Practice No. 87 and WEF Manual of Practice No. 23. The computer model, WQ-COSM, was also developed as a freeware for evaluating the performance of a BMP facility or producing regional design charts. The model accepts the standard hourly and 15-minute rainfall data format provided by the National Climatic Data Center. Hourly data are typically available for major metro areas in the United States for a period of 20 to 60 years.

Key Words: Stormwater BMP, LID, water quality capture volume, drain time, sedimentation, detention pond, retention pond.

INTRODUCTION

Since 1977, the Clean Water Act (CWA 1977) is the federal law the United States governing surface water pollution control. The act sets the criteria to mitigate releases of any form of pollutant (i.e., dissolved and suspended) into waters of the USA. The impact of 1977 CWA on urban planning is revealed in the development of new approaches that include storm water best management practices (BMP) and low impact development (LID) designs (EPA Reports 1983, 1986). Correspondingly, urban drainage systems are expanded into a 3-layer cascading flow system that include a micro system designed for water quality enhancement, a minor system designed for dealing with 2 to 5-yr flooding water through street gutters, and a major system sized to mitigate the 50- to 100-yr extreme events through natural waterways, man-made channels, streets, detention systems, etc. Figure 1 presents an example illustrating how this 3-layer cascading flow system is blended into a street layout.

A micro system is sized to capture and to treat the runoff volumes generated from the directly connected impervious areas under small, frequently occurring rainfall events while the minor and major systems follow the conventional approach to cope with the 2- to 100-yr and larger extreme events. During a significant storm event, the micro-system basin intercepts the initial storm water runoff volumes from impervious surfaces immediately upstream. What is not intercepted overtops the basin and flows to the street gutter(s), downstream storm sewers, channels and receiving waters. Many creative concepts for stormwater BMP and LID have been converted into micro system designs using sub-base filtering and infiltrating processes, including sand filters, infiltration basins, rain gardens, bio-swales, retention ponds, wetlands, extended detention basin etc. (EPA National Menu for Stormwater BMP 2011).
A common practice in storm water management is to incorporate stormwater quality BMPs and their water quality control basins (WQCB) into flood mitigation systems. In doing so, the operation of such a urban drainage system provides a full-spectrum control that range from small to extreme rainfall events (Guo 2009, Guo and Cheng 2008). The challenge in the design of stormwater full-spectrum control system lies in how to select the design events for the micro, minor, and major levels of protection. The rudimentary question is how big a BMP facility is big enough to treat storm water while at the same time how small to make it to be cost effective. This tradeoff presents a new challenge to stormwater professionals.

Recommendations on how to size stormwater BMP facilities vary greatly, including the 1-year 24-hour storm, the 80 to 95th percentile storms, the runoff depth of 25.4 mm (one-inch) from the new development areas etc. (International BMP Database, 2010). Similarly, there are several empirical and regulatory methods in use for the selection of WQCB storage volume, varying from a high standard to capture the runoff depth of 76 mm (3 inches) for LID designs in the Washington D.C. areas (UFC-LID 2004) to the cost effective approach using water quality capture volume (WQCV) for BMP designs in the Denver region (UDFCD Vol 3 2011). Although these empirical methods appear inconsistent, they all agree that the WQCV shall be in the same magnitude as the street flush volume or the 3 to 6 month event. As a result, there is an urgent need to have procedures that can systematically relate the field experience of urban runoff volume to local rainfall patterns. For design events with a return period of less than one year, approaches using annual data series are not applicable. As a result, it is necessary that the rainfall analysis for BMP/LID designs shall switch from extreme value methods to the analyses of complete data series.

In 1996, a long-term event-based simulation scheme was derived to select the WQCV based on the optimized runoff capture ratio (Guo and Urbonas 1996). Using 30 to 40 years of continuous rainfall recorded in the Cities of Seattle WA, Sacramento CA, Phoenix, AZ, Denver, CO, Cincinnati, OH, Tampa, FL, Boston MA, and Little Rock, AK, a set of regression equations were derived and then recommended for sizing stormwater BMP facilities (ASCE Manual, 1998). Although these empirical formulas were further examined by the statistical model using the exponential distribution, it is clear that the event-based simulation approach does not best represent a continuous runoff time series flowing through the proposed BMP/LID facility (Guo and Urbonas 2002a and 2002b).

In this study, a rainfall-runoff continuous simulation technique was developed to first convert a long-term continuous rainfall series into a continuous runoff series, and then to route the incremental runoff depths as a time series through the BMP/LID facility to calculate the long term runoff capture ratios. As expected, the more the capture volume such a facility has, the higher the runoff capture ratio will be. The optimal design magnitude for BMP facilities can then be derived using the principle of diminishing returns. This procedure has been coded into a computer model: Water Quality Capture Optimization and Statistics Model (WQ-COSM) which is a freeware available at WWW.Urbanwatersheds.org and WWW.UDFCD.org.
CONVERSION OF RAINFALL INTO RUNOFF VOLUME

Rainfall data are often recorded at a rain gage as a point value. When the tributary area is small (<25 square km), the point rainfall depth can represent the source of runoff without a depth-area adjustment (NOAA Hydro-40, 1984). A continuous rainfall record is composed of individual events separated by a dry period. A rainfall event separation time of six hours is recommended to identify individual rainfall events (Driscoll et al. 1989). With a pre-selected rainfall event separation time, a 30 to 40-year rainfall record can be divided into thousands of individual events. For each single event, its rainfall duration is divided into several time steps according to the pre-selected time increment used in the numerical simulations as:

\[ N(i) = \frac{T(i)}{\Delta t} \]  \hspace{1cm} (1)

Where \( T(i) \) = duration for \( i \)-th rainfall event, \( N(i) \) = number of time steps, and \( \Delta t \) = time increment such as one hour or 15 minutes for each time step used in computations. The hydrologic abstraction for each event includes soil depression and infiltration losses. Soil infiltration rates can be quantified using the rational method or Horton’s soil infiltration formula, depending on the modeling convenience (WQ-COSM 2011). If the lumped model is preferred, the runoff coefficient can be chosen based on the watershed imperviousness percent. The incremental soil infiltration loss is estimated as:

\[ \Delta F(i,j) = (1 - C) [p(i,j) - p_i] \quad \text{where} \quad 1 \leq j \leq N(i) \]  \hspace{1cm} (2)

Where \( \Delta F(i,j) \) = \( j \)-th incremental soil infiltration loss during \( i \)-th rainfall event in depth per watershed area, \( C \) = runoff coefficient selected based on watershed imperviousness percentage \( p(i,j) \) = incremental rainfall depth at \( j \)-th time step, and \( p_i \) = incipient runoff depth such as 2.0 to 2.5 mm as recommended (EPA report 1986). If the detailed modeling technique is preferred, the storm runoff from a watershed can be divided into two independent flows from the pervious and impervious sub-areas respectively. Each sub-area has its own depression and infiltration losses calculated at each time step as:

\[ \Delta F(i,j) = \left[f_c + (f_o - f_c) e^{-\alpha(j\Delta t)}\right] \Delta t \quad \text{where} \quad 1 \leq j \leq N(i) \]  \hspace{1cm} (3)

Where \( f_c \) = final infiltration rate, \( f_o \) = initial infiltration rate and \( \alpha \) = soil infiltration decay factor. During a continuous simulation process, the recovery of these parameters used in the loss functions is linearly modeled as a cycle over a user defined period such as 1 to 14 days, depending on the local climate condition (Rossman 2005). For instance, in arid climates a drying time of 1 to 3 days would be appropriate, while 7 to 14 days would be more appropriate in a climate with cool temperatures and much rainfall. Eq 3 describes how the soil column becomes saturated over time. Integration of Eq (3) represents the soil antecedent moisture deficit as:

\[ F(i,j) = f_c \times j \Delta t + \frac{(f_c - f_o)}{\alpha} \left[1 - e^{-\alpha(j\Delta t)}\right] \quad \text{where} \quad 1 \leq j \leq N(i) \]  \hspace{1cm} (4)

Where \( F(i,j) \) = infiltration amount at \( j \)-th time step during \( i \)-th event in depth per watershed. The numerical procedure for modeling hydrologic losses is to firstly fill up the antecedent soil moisture deficit (EPA SWMM 2011). As soon as the accumulated rainfall amount exceeds Eq (4), the depression loss begins to be filled up. Numerically, the array of incremental depression loss is determined step by step through the early incremental rainfall depths as:

\[ d(i,j) = \max \{0, \min[(p(i,j) - F(i,j)), D]\} \]  \hspace{1cm} (5)
\[ d(i, j) = \max \{0, \min \left[ \sum_{k=j}^{j-1} p(i, k) - F(i, j) - \sum_{k=1}^{j-1} d(i, k), \ D - \sum_{k=1}^{j-1} d(i, k) \} \} \text{ for } 2 \leq j \leq N(i) \quad (6) \]

Where \( d(i, j) \) = \( j \)-th incremental depression loss during \( i \)-th event in unit depth per watershed area, \( d(i, 1) \) = initial depression loss, \( p(i, 1) \) = first incremental rainfall depth in \( i \)-th event, \( F(i, 1) \) = initial infiltration loss, \( k \) = \( k \)-th time step to fill up depression loss, and \( D \) = watershed depression loss such as 10 mm (0.4 inch) for pervious area and 2.5 mm (0.1 inch) for impervious area (UDFCD 2001). Eq (5) defines the initial incremental depression loss. Under a mild rainfall event, \( p(i, 1) < F(i, 1) \), Eq (5) leads to \( d(i, 1) = 0 \) while an intense event, Eq (5) may result in \( d(i, 1) = D \). Likely, \( d(i, 1) \) lies between these two extreme conditions. Eq 6 generates the array of incremental depression losses, \( d(i, j) \), after the antecedent soil moisture deficit has been satisfied. After having the depression storage areas been completely filled up, the incremental depression loss for each time step is reduced to zero; and the incremental runoff depth will be produced as:

\[ r(i, j) = \max \{0, \sum_{k=1}^{j} p(i, k) - F(i, j) - \sum_{k=1}^{j} d(i, k) \} \text{ for } 1 \leq j \leq N(i) \quad (7) \]

in which \( r(i, j) \) = \( j \)-th incremental runoff depth for \( i \)-th rainfall event. Eq 7 implies that the watershed surface remains dry until the accumulative rainfall depth becomes greater than the sum of depression and infiltration losses.

**RUNOFF ROUTING THROUGH A WQCB**

The key factor for flow routing through a WQCB is the drain time. For detention and retention BMPs, the selection of drain time is closely related to the sedimentation process in the WQCB. If sediment characteristics are not known, a 12-hour settling time is recommended for a wet WQCB and a 24-hr settling time is recommended by Waugh, et al (2002) for a dry WQCBs. At the same time UDFCD (2011) recommends a 40-hr drain time for dry extended detention basins. As a result, the drain time for an extended detention basin can typically range from 24- to 48-hr, depending on the local design criterion. Drain times for a surcharge WQCB nested in a retention system typically range from 12 to 24 hr (UDFCD 2011). Drain times of 12 hr are recommended for LID designs such as rain gardens and infiltration swales, while drain times of 24 hr are recommended for sand filters (Urbonas, 1999). With the pre-selected storage volume and drain time, the average release rate for the proposed WQCB is calculated as:

\[ q = \frac{P_p}{T_d} \quad (8) \]

Where \( q \) = average release rate in depth per time, \( P_p \) = WQCB’s brimful storage volume in depth per watershed area, and \( T_d \) = drain time. Throughout the \( i \)-th event, the basin is loaded with the incremental runoff depth for each time step as:

\[ P_v(i, 1) = \min [0, P_v(i - 1) + r(i, 1) - q\Delta t] \quad (9) \]

\[ P_v(i, j) = \min [0, \min \{P_v, P_v(i, j - 1) + r(i, j) - q\Delta t\}] \text{ where } 2 \leq j \leq N(i) \quad (10) \]

Where \( P_v(i, j) \) = accumulated storage volume in WQCB, and \( P_v(i - 1) \) = residual volume from the previous event. Eq (9) sets the \( i \)-th initial condition for flow routing through the WQCB. Eq (10) warrants that the maximum accumulated storage volume does not exceed the basin size and the minimum volume is not less than the dry condition. After the rainfall event ends, the basin continues being drained as:
\[ P_0(i) = \max[0, P_r(i), N(i)] - \sum_{k=1}^{k+1} kq\Delta t] \quad (11) \]

Numerically, Eq (11) will be operated till the WQCB becomes emptied or the next event comes, whichever comes first. Between two events, all hydrologic loss parameters are refreshed through the user-defined recovery cycle.

During the i-th flow routing process, the WQCB either had a complete interception if the event produces a runoff volume less than the WQCB’s maximum capacity or the WQCB is overtopped with an untreated or partially treated bypass flow. The maximum runoff treatment capacity in a WQCB is no more than its brim full volume plus the water volume flowing through the WQCB during the storm event as:

\[ P_m(i) = P_p + q \times T(i) \quad (12) \]

Where \( P_m(i) \) = maximum runoff treatment capacity for i-th event in depth per watershed area.

\[ R_c(i) = \min \{P_m(i), \sum_{j=1}^{j=N(i)} [r(i, j) + q \times \Delta t] \} \quad 1 \leq j \leq N(i) \quad (13) \]

Where \( R_c(i) \) = treated runoff volume in depth per watershed and \( P_p(i) \) = initial water volume at the beginning of i-th event. Eq 13 means that the runoff capture volume for i-th rainfall event is either the runoff volume flowing through the WQCB or the maximum WQCB’s treatment capacity, whichever is smaller. Applying Eq (13) to the entire rainfall record, the overall runoff volume capture ratio (RVCR) is calculated as:

\[ R_v = \frac{\sum_{i=1}^{i=M} R_c(i)}{\sum_{i=1}^{i=M} \sum_{j=1}^{j=N(i)} r(i, j)} \quad (14) \]

Where \( R_v \) = runoff volume capture ratio (RVCR), and \( M \) = number of individual rainfall events in the continuous rainfall record. Eq (14) gives a fair assessment on the WQCB’s performance if the rainfall record is not skewed with extreme events. In fact, it is likely that several large events in the data base can numerically dominate the outcome from Eq (14). To avoid a bias analysis, the runoff event capture ratio (RECR) is also developed to count the number of events that were completely captured with no bypass flow. For the entire rainfall record, the overall RECR is defined as:

\[ m(i) = 1 \text{ if } \sum_{j=1}^{j=N(i)} [r(i, j) + q \times \Delta t] \leq P_m(i) \text{ or } m(i) = 0 \quad (15) \]

\[ R_v = \frac{\sum_{j=1}^{j=M} m(i)}{M} \quad (16) \]

Where \( m(i) \) = counter for i-th event, \( M \) = total number of events in record, and \( R_v \) = runoff event capture ratio (RECR).
A WQCB is designed to capture and to treat runoff from the small urban runoff events and relatively small catchments. During Runoff volume will be captured and treated up to WQCB’s capacity and then overtopping will occur. Usually, the overtopping flows carry diluted or partially treated sediment loads. In practice, the RECR is more meaningful than the RVCR. This is because the bulk of urban pollutants, including sediment are transported by frequent, small events, into natural water bodies. The design of a micro system is best aimed at the targeted water quality enhancement rather than the flood mitigation provided in the minor and major systems to deal with extreme storm events that create significant drainage and flooding problems, but it would be prohibitively expensive to capture and treat.

**DETERMINATION OF WQCV FOR BMP DESIGNS**

To construct a design chart for WQCV at a site, repeat the above-described procedure for a range of WQCB storage volumes. Both RVCR and RECR can be calculated as a rising curve as the storage volume increases. Figure 2 is an example derived for the Denver region, Colorado. The watershed imperviousness for Figure 2 is set to be 50%. The drain time of 12 hours is used to generate 1869 individual events from the 40-year continuous hourly rainfall data recorded at the Stapleton Airport rain gage. The soil losses are described with \( f_0 = 76 \text{ mm/hr} \) (3 inches/hr), \( f_c = 12.5 \text{ mm/hr} \) (0.5 inch/hr) and \( \alpha = 3 \text{ per hour} \), and \( D = 10 \text{ mm} \) for pervious area, and \( 2.5 \text{ mm} \) for impervious area. The distribution of RECR is calculated and plotted in Figure 2. The x-axis represents various basin storage volumes normalized by the index rainfall depth. The index rainfall depth is chosen as a cut-off value to exclude very large events in the rainfall data base (EPA SWMM5). In general, the 99.5th percentile rainfall depth can serve this purpose. Both RECR and RVCR represent the non-exceedance probability curve that increases from zero to unity. Before the break-even point as shown in Figure 2, the curve begins with sharply increasing returns and then ends with flat diminishing returns. As a result, the break-even point is recommended as the water quality capture volume (WQCV) for the design of stormwater BMP and LID basins.

![Figure 2 WQCV Developed for Denver Area with 50% Imperviousness and 12-hr Drain Time](image)
WQCV depends on watershed’s imperviousness and WQCB’s drain time. For a selected drain time, the same procedure used in Figure 2 can be repeated for a range of imperviousness percentages. As shown in Figure 3, the RECR-based design chart is developed for Denver’s WQCV using 12-, and 24-hr drain times. The average RECR is 0.87 for the 12-hr curve and 0.85 for the 24-hr curve. Of course, similar WQCV design curves can be produced for any metropolitan areas using the computer model: WQ-COSM.

![RECR-based WQCV for Denver Area, Colorado](image)

Figure 3 Denver’s Water Quality Capture Volumes Developed for 12- and 24-hr Drain Times

CONCLUSION

Like many BMP projects, this research study has been a continuous effort, starting in 1987. Extensive rainfall and runoff field data were analyzed over the last twenty five years under supports of Urban Watersheds Research Institute and Urban Drainage and Flood Control District, Denver, Colorado. This paper presents a procedure to derive the localized Water Quality Capture Volume (WQCV) for stormwater BMP and LID designs. The latest development in the continuous rainfall-runoff modeling techniques modifies the regression formulas and design charts outlined in ASCE Manual of Practice No. 87 and WEF Manual of Practice No. 23.

Although the rainfall event separation time is recommended to be 6 hours (Driscoll et al, 1989), the local design requirement may have a different criterion. From the operational point of view, set the rainfall event separation time equal to WQCB’s drain time to warrant that flow routing begins with an empty basin. When sedimentation is the primary pollutant removal mechanism, WQCB’s drain time is often selected to be not shorter than the settling time to allow the targeted solids to be effectively trapped. Derivation of WQCV is a procedure to relate the urban runoff volume to the local rainfall pattern and then routing this runoff through a WQCB. WQCV depends on watershed’s imperviousness and the BMP/LID basin’s brim-full drain time. The longer the drain time is, the higher the WQCV will be. The capture ratio at the point of diminishing returns typically, but not always, varies between 80 and 90% for both the event-based or
volume-based approaches. At the same time, the RVCR-based WQCV can demand significantly more storage volume than the RECR-based WQCV while the added environmental benefits of the increased size of the BMP/LID facility have not been yet determined and appear to be of marginal value. This is because urbanization impacts on geomorphic and ecological response in receiving waters are closely related to the increased frequency of small runoff events, rather than the large events that have produced flooding flows before urbanization.

The lengthy computational procedure has been coded into a window-based computer model: Water Quality Capture Optimization and Statistics Model (WQ-COSM). WQ-COSM is a freeware available at www.udfcd.org and at www.urbanwatersheds.org. The model accepts the standard hourly and 15-minute rainfall data format provided by the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/climate/stationlocator.html). Hourly data are typically available for most municipal areas in the United States for a period of 20 to 60 years and 15-minute data for most major metro areas for periods of 15 years. The computer model, WQ-COSM, is an effective tool that provides a consistent basis to develop site or region-specific WQCV analyses and design charts using the local rainfall records.

REFERENCES


EPA SWMM (2011), Stormwater Management Model supported by EPA. http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/


APPENDIX II
C= runoff coefficient
D=watershed depression loss
d(i,j)= j-th incremental depression loss in unit depth per watershed area,
d(i,1)= initial depression loss,
f_i= final infiltration rate,
f_0= initial infiltration rate
F(i,j)= infiltration amount at j-th time step during i-th event in depth per watershed
F(i,1)= initial infiltration loss,
K= k-th time step
M= number of individual rainfall events in the record
m(i)= counter for i-th event,
N(i)= number of time steps fro i-th rainfall event,
P_p = WQCB’s brim full storage volume in depth per watershed area,
P_m(i)= maximum runoff treatment capacity for i-th event
p_i= incipient runoff depth
\( p(i,j) \) = incremental rainfall depth at \( j \)-th time step,
\( p(i,1) \) = first incremental rainfall depth in \( i \)-th event,
\( P_v(i,j) \) = accumulated storage volume in WQCB,
\( P_v(i,j) \) = accumulated storage volume in WQCB,
\( P_v(i-1) \) = residual volume from the previous event
\( q \) = average release rate in depth per time,
\( R_v(i) \) = treated runoff volume in depth per watershed
\( R_v \) = runoff volume capture ratio (RVCR)
\( R_v \) = runoff event capture ratio (RECR).
\( r(i,j) \) = \( j \)-th incremental runoff depth for \( i \)-th rainfall event
\( T_d \) = drain time.
\( T(i) \) = duration for \( i \)-th rainfall event,
\( \alpha \) = soil infiltration decay factor.
\( \Delta t \) = time increment used in computations.
\( \Delta F(i,j) \) = \( j \)-th incremental soil infiltration loss during \( i \)-th rainfall event in depth per watershed area