An overview of methods of calculating storage volume for low impact development and other stormwater facilities

H Chen¹, X Y Chang² and N She¹,²,³

¹China Machinery International Engineering Design and Research Institute Co., Ltd., Changsha, 410007, China
²School of Environmental Science and Engineering, Guangzhou University, 510006, China

E-mail: nianshe@gzhu.edu.cn

Abstract. This review compares the methods of calculating storage volume in “Technical Guide for Sponge City Construction – Construction of Low Impact Development Stormwater System (Trial)” with other volumetric methods in BMPs. Water Quality Volume (WQv) capture and low impact development (LID) in the United States. The purposes of the comparison are to extend the methodologies relating to the evolution of stormwater management and to provide broad references to establish a reasonable design and evaluation standard for Sponge City Construction in China.

1. Introduction
The most controversial issue in the “Technical Guide for Sponge City Construction – Construction of Low Impact Development Stormwater System (Trial)” (hereinafter referred to as the Guide) probably is the total runoff volume control. The controversy is focused on whether or not the total runoff control rate is a reasonable goal for sponge city construction. Some scholars also questioned the total runoff control rate as an indicator for engineering design and performance evaluation from the perspective of hydrology. Most of these disputes occurred earlier in the professional forums of the internet. To clarify the confusion, several papers were published to explain the derivation process of the control rate in details [1,2]. Wang Hong et al [3] also overviewed the hydrological based stormwater management goals, and clarified the differences between China and the United States on the total runoff control rate. Regarding to the terminology of “runoff control rate” in the Guide, the online discussion was quite intense, but the final results tended to reach the consensus. The conclusion is that the total runoff control rate is actually the rainfall control rate [4], which is similar to the Water Quality Control Volume (WQv) in the BMP design in the United State.

However, when it comes to the sponge city planning, engineering design, construction, and performance evaluation, few people have questioned the rationality, application limitations and deficiencies of the volumetric method of the Guide. From the perspective of engineering implementation, the volumetric method determines the size of the LID facility, which is directly related to the amount of investment and the degree of difficulty for the implementation. These factors affect the residents’ daily life, especially in the high-density communities. So, it is necessary to understand the volumetric method used in the Guide and compare it with other volumetric methods used by the United States in BMPs, LIDs, and green stormwater infrastructures (GSI). The objectives of this paper are to understand the rationales behind each method, so that the planning, engineering
design and evaluation of the sponge city projects are more rationalized. In the process of analysis and comparison, several key conceptual misunderstandings and several terminology confusions are sorted out. These misunderstandings and confusions have had occurred in the stormwater management for a long time.

2. Overview of the volumetric methods

2.1. The background of the volumetric methods in the guide

Two volumetric methods in the Guide are adapted directly from the detention facility design in China’s “Outdoor drainage design specification” (GB50014) [5] and “Rainwater control and utilization engineering design specification” (DB11/685) [6]. The most popular one is given below.

\[ V = 10H\varphi F \]  

where, \( V = \) Detention volume (\( m^3 \)), \( H = \) Rainfall depth corresponding to the total annual runoff (mm), \( \varphi = \) composite runoff coefficient and \( F = \) catchment area (\( hm^2 \)).

It can be seen that from equation (1) that the rainfall depth \( H \) is evenly distributed in the catchment area, so that the detention volume of the LID facility on the site is equal to the total runoff generated from the catchment given a design storm event. The total runoff is irrelevant to the duration of rainfall event, the concentration of time, the flow path, the slope of the catchment and the characteristics of the land use. The composite runoff coefficient in equation (1) is a weighted average of different land use runoff coefficients. This composite runoff coefficient works only when the runoff from each land parcel flow out independently. This obviously contradicts to the LID design principles, which maximize the flow path and connect the impervious area to pervious area as long as it is feasible. In this way some of runoff is infiltrated and intercepted during the conveyance. So, the runoff generated by the site is not necessarily relatively independent. Moreover, the runoff generated by the green space generally does not produce pollutions. If this part of the runoff is also included in the LID detention volume, it would oversize the LID facility and cost more than needed.

Another volumetric method in the Guide is based on the flow runoff coefficient, which refers to the ratio of runoff to rainfall over a period of peak flow [7]. This coefficient is mainly used to calculate the maximum diameter of the drainage pipes, or the detention volume for the flood mitigation. If this method is used to calculate the LID detention volume, it will be oversize the LID facility larger than that based on the composite runoff coefficient.

In general, the runoff coefficient is referred to the amount of runoff to the amount of rainfall received. It can be event based, or annual based, or average based on multiple years. The depth \( H \) in equation (1) has no direct relationship with the composite runoff coefficient. Therefore, it is questionable to use equation (1) to design LID facilities, and it is necessary to explore other volumetric methods for LID designs.

2.2. The volumetric methods in stormwater BMPs

Best Management Practices (BMPs) refer to methods of controlling and mitigating the adverse impacts of development and redevelopment. The term has been gone through an evolution since early 20th century. The word BMP originated in the early 20th century that was used to support certain functions of industrial and domestic wastewater treatment systems such as training and maintenance of operators. In the late 20th century, the practitioners began to use BMPs such as detention ponds and wetlands to treat stormwater runoff. In the Clean Water Act (CWA) passed by the US Congress in 1972, several references were made to the use of BMP [8-10]. During late 1970s to 1980s BMPs had been defined as structural and non-structural stormwater control measures to reduce runoff, peak flow and non-point source pollution. In 2003, the BMP was expanded to cover stormwater control, soil erosion control and integrated stormwater management decision-making system [11].

The early BMP design was based on the “Critical Storm Method (CSM)”. The critical storm event is referred to 1-yr to 100-yr storm event. So, the storage volume of BMP is calculated based on the
detention volume of the peak flow. For example, Ohio State’s BMP design requires that the peak flow of 1-yr, 2-yr, 5-yr until 100-yr storm event after the development must equal or less than the peak flow before the development [12]. Other states such as New Hampshire requires that the peak flow discharged into the river after the development of the site should not greater than the peak flow of 2-yr/24-hour storm event before the development [13]. Therefore, the rational formula of BMP design uses the composite flow runoff coefficient associated with the peak flow [14]. The rational formula for the peak flow is given as

\[ Q = CIA \]  

where \( Q \) = peak flow (cfs), \( I \) = intensity of design storm (in/hr), \( C \) = rational runoff coefficient, and \( A \) = catchment area (acre).

After calculating the hydrograph of peak flow using equation (1), the storage volume of BMP is

\[ V = QD \]  

where \( V \) = BMP storage volume, \( D \) = duration of storm event.

By comparing equation (2) with the volumetric method based on the flow runoff coefficient in the Guide, it was found that they are exactly the same. But the applications are quite different. In the United States, the rational formula is used to design detention facility only, while in the Guide it is used for LID facility design.

2.3. Water quality volume

Since the early BMP design used the CSM, it caused many problems in practice. First of all, the design goal of BMP is to target the infrequent storm events requiring the peak flow after the site development not exceeding that before the development. This directly leads the over design for BMP facilities, including large outfalls, shorten hydraulic retention time, so that the BMP cannot effectively remove pollutants such as TSS. Generally, the wet pond requires 6-12 hours to remove TSS. The retention time required to remove TSS for dry pond takes at least 24 hours. In addition, according to the CSM, the frequent occurred small storm will pass the BMP to erode the river channel and banks, causing damage to the habitats. In response to these shortcomings of the early BMP, researchers had proposed small storm BMPs that intercept and control 90%-95% of the rainfall events. Therefore, the BMP volume required to intercept and control the runoff generated by 90%-95% of the rainfall events is referred to as the Water Quality Volume (WQv).

WQv is related to rainfall depth, runoff coefficient and catchment area. The formula of calculating WQv looks the same as the rational method equation (2), but the difference is in the runoff coefficients. In the following paragraph a detail description of how the runoff coefficient of WQv is derived will be given.

When it comes to the derivation of the runoff coefficient for WQv, the Nationwide Urban Runoff Program (NURP), the only national urban runoff research project launched by the US Environmental Protection Agency (US EPA) from 1979 to 1983, is the scientific foundation. The NURP studies found the relationship between the runoff coefficient of the catchment area and the impervious surface as shown in figure 1 [15], which provides a scientific basis for WQv, LID and GSI volume calculation. The relationship in figure 1 is not entirely true because the data from four of the 16 cities in the NURP study was deliberately deleted, as the data for these four cities does not match the relationship in figure 1. Does this indicate that there are other kind relationships between stormwater runoff and impervious surface? Many scholars were encouraged by the initial discovery and conducted extensive research on the relationship between stormwater runoff and impervious surface [16]. They found that stormwater runoff is related to the size, shape, slope, and impervious surface of the basin or catchment area [17]. The coverage of the impervious surface is the most sensitive [18] element.

Based on the relationship between impervious surface and runoff coefficient discovered in the NURP study and taking account of other factors such as climatology, meteorology, geology and hydrology, regression-based formulas were derived from monitoring data. For example, the formula
equation (4) was derived using linear regression from multiple sites in New York, Maryland and Pennsylvania [19].

\[ C = 0.05 + 0.009i \]  

(4)

The runoff coefficient developed for Ohio State is a third order polynomial [20]

\[ C = 0.85i^3 - 0.78i^2 + 0.774i + 0.04 \]  

(5)

where \( C \) is the runoff coefficient as usual, \( i \) is the percentage of impervious surface.

So, the WQv can be calculated using rational method with the derived runoff coefficient.

\[ WQv = C \frac{P \times A}{12} \]  

(6)

where, \( P \) = depth of design rainfall, \( A \) = catchment area. The dimension of WQv is Acre-Feet. Note that 1 Acre-Feet = 1 Acre x 1 foot, which is equal to 1233.48 m\(^3\) in metric system. The reason of mention Acre-feet is due to help readers to understand literatures from the US.

In addition to the impervious surface, other factors such as particle settling time in BMP are also taken in account. San Francisco’s WQv formula is [21].

\[ WQv = a \frac{C \times P \times A}{12} \]  

(7)

\( a \)-value is listed in table 1.

| Retention Time | Correct Coefficient a |
|----------------|-----------------------|
| 12             | 1.312                 |
| 24             | 1.582                 |
| 48             | 1.963                 |

It can be seen from equation (4)- equation (7) that the WQv in Ohio, New York and San Francisco are different under the same rainfall depth, catchment area and impervious surface coverage.

2.4. Volumetric method for LID

The term low impact development (LID) refers to systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of rainwater in order to manage stormwater on site such that the hydrological regime post the development is almost the same as pre
development. The hydrological regime generally refers to runoff temperature, flow, total runoff, and time of concentration. This definition was finally adopted by the US Environmental Protection Agency [22]. According to this definition, LID proposes a new site development concept. Unlike BMP, which only controls peak flow or WQv, LID requires that the hydrological regime post construction should keep the same as pre development (generally pre development is referred as forest or green space coverage).

Although the requirement of hydrological regime post development must be closed to pre development in LID design, there is a few quantitative methods exists to evaluate how well a developed site meets the LID goal of replicating pre-development (or target) hydrology. In general, there are two types of methods: volumetric method and model method. The volumetric method considers that LID and runoff volume match are achieved when the volume of runoff leaving the site after development is less than or equal to the volume of runoff before development. For example, in North Carolina the assessment of LID design is based on the comparison of runoff from the site before and after development (centralized facilities are not counted). In general, the runoff leaving the site after development must be less than or equal to the volume of runoff before development [23]. In Washington State, hydrological models were used to evaluate the site design. Before the land development permit is issued, the developer must run 30 years of continuous rainfall simulation for the site before and after the development. The total runoff and peak value must meet the pre-development requirements. The City of Seattle even considered 158 years of continuous rainfall simulation in large-scale development projects, taking into account climate change [24]. Since the focus of this paper is on volumetric methods, modeling method will not be discussed here.

The most common calculation method for calculating the storage volume required for the site LID is the SCS-CN Method. The runoff curve method is an empirical model proposed by the US Department of Agriculture’s Soil Conservation Bureau. The method is simple. Only one composite parameter, the number of runoff curves (CN), which reflects the characteristics of the underlying surface of the catchment, can be used to calculate the runoff of the basin. Therefore, it is widely used in many countries and regions. The details of the method can be found from “Hydrology in National Engineering Handbook. Supplement A, Section 4, Chap.10, Soil Conservation Service(R). USDA, Washington, 1985: 10.5” [25].

SCS-CN method was initially derived by Mockus [26] in 1954.

\[
\frac{F}{S} = \frac{Q}{P} \tag{8}
\]

where \(Q\) is the depth of runoff, \(P\) is the depth of total rainfall, \(S\) is potential maximum retention after runoff begins, and \(F\) is actual retention after runoff begins.

In most cases, a certain amount of rainfall is abstracted. The three important abstractions for any single storm event are rainfall interception (Meteorological rainfall minus throughfall, stem flow and water drip), depression storage (topographic undulations), and infiltration into the soil. The curve number method lumps all three abstractions into one term, the Initial abstraction \(I_a\).

If initial abstraction is considered, then

\[
F = P - I_a - Q \tag{9}
\]

The formula was modified by Mockus [27] in 1964. The final formula of SCS-CN is given by

\[
I_a = 0.2S \tag{10}
\]

\[
Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{11}
\]

\[
S = \frac{1000}{CN} - 10 \tag{12}
\]
where, CN is called SCS Curve Number, or curve number.

CN is a spatial parameter that is attributed to the influence and contribution of many environmental factors (soil, land use, vegetation, slope, etc.). The determination of the CN values is based on soil permeability and land use properties. The soil is divided into four categories A, B, C and D according to the permeability. The curve number method was originally developed for the agricultural watershed, but with the development of urbanization, the curve number method has been gradually revised and adopted for most cities, especially for calculating the pre-development runoff.

Because the soil, hydrology, climate and other conditions in the eastern and western parts of the United States are very different, each state, city, and county calculate the runoff using CN associated with its own soil distribution, hydrological characteristics, and land cover. Tables 2 and 3 are the soil classification and CN values for North Carolina State [28].

Table 2. Four hydrologic soil groups as defined by the SCS (1986).

| Hydrologic Soil Groups | Soil Min Infil (mm/hr) | Soil texture               |
|------------------------|------------------------|----------------------------|
| A                      | > 7.62                 | Sand, loamy sand, sandy loam |
| B                      | 3.81 - 7.26            | Loam, silt loam            |
| C                      | 1.27 - 3.81            | Sandy clay loam            |
| D                      | 0.00 - 1.27            | clay loam, silty clay loam, sandy clay, silty clay, or clay |

Table 3. Runoff curve numbers in urban areas for the SCS method (SCS, 1986).

| Cover Description                     | Curve Numbers for Hydrologic Soil Group |
|---------------------------------------|----------------------------------------|
|                                       | A  | B  | C  | D  |
| Fully developed urban areas           |    |    |    |    |
| Open Space (lawns, parks, golf courses, etc.) |    |    |    |    |
| Poor condition (<50% grass cover)     | 68 | 79 | 86 | 89 |
| Fair condition (50% to 75% grass cover) | 49 | 69 | 79 | 84 |
| Good condition (>75% grass cover)     | 39 | 61 | 74 | 80 |
| Impervious areas                      |    |    |    |    |
| Paved parking lots, roofs, driveways, etc. |    |    |    |    |
| Paved; curbs and storm sewers         | 98 | 98 | 98 | 98 |
| Paved; open ditches                   | 98 | 98 | 98 | 98 |
| Streets and roads:                    |    |    |    |    |
| Paved parking lots, roofs, driveways, etc. | 83 | 89 | 98 | 98 |
| Paved; curbs and storm sewers         | 76 | 85 | 89 | 91 |
| Paved; open ditches                   | 72 | 82 | 85 | 88 |
| Streets and roads:                    |    |    |    |    |
| Paved parking lots, roofs, driveways, etc. |    |    |    |    |
| Paved; curbs and storm sewers         | 77 | 86 | 91 | 94 |
| Paved; open ditches                   | 68 | 79 | 86 | 89 |
| Newly graded areas                    |    |    |    |    |
| Pasture (<50% ground cover or heavily grazed) | 49 | 69 | 79 | 84 |
| Pasture (50% to 75% ground cover or heavily grazed) | 39 | 61 | 74 | 80 |
| Pasture (>75% ground cover or heavily grazed) | 30 | 58 | 71 | 78 |
| Meadow - continuous grass, protected from grazing and generally mowed for hay | 45 | 66 | 77 | 83 |
| Brush (<50% ground cover)             | 36 | 60 | 73 | 79 |
| Brush (50% to 75% ground cover)       | 30 | 55 | 70 | 77 |
2.4.1. **Applying CN method to LID design.** This example was taken from the Iowa Stormwater Management Manual [29], but was slightly modified by the authors.

The purpose of this case is to calculate the volume or area required for LID before and after the development. The design site area $A$ is 28 acres, which is a good pasture before the development, with a composite CN = 62. After the development, the impervious surface increased to 28%, and the composite CN increased to 68. To calculate the volume or area required for the LID, the first step is to calculate the initial interception $I_a$ before the development. Obtained from equations equations (10) and (12).

$$I_a = 0.2 \left( \frac{1000}{62} - 10 \right) = 1.22 \text{ inch}$$

The design rainfall depth according to the Iowa Stormwater Management Manual is: $P = 1.5I_a = (1.5)(1.22) = 1.83 \text{ inch}$. Substituting CN and $P$ to equation (11) to obtain the runoff difference before and after the development $d = 0.087 \text{ inch}$. So, to match the volume of runoff before the development, LID requires the storage volume $V_d/12 = 0.203 \text{ acre-foot}$. The required area $A_{LID} = V_d/6 =ug/6 = (0.087)(28)/6 = 0.41 \text{ acre}$, if the ponding depth is 6 inches. Therefore, for 1.83 inch (46.5mm) design rainfall depth, if the ponding depth of LID is 6 inches, then 0.41 acres LID can satisfy the requirement of matching the runoff before and after the development.

2.4.2. **LID performance evaluation.** The CN method can be used to evaluate the performance of the LID in addition to the volume calculation. Use monitoring data to evaluate LID facilities’ performance is currently the most commonly used method, but for bioretention facilities, in most case, cannot monitor inflows because inflows usually flow into bioretention facilities in the form of sheet flow. So, in this case, the CN method is often used to solve the CN after the LID is installed in the site using rainfall data and outflow monitoring data. The performance of the LID is evaluated by comparing CNs before and after LID installation.

From equation (12)

$$CN = \frac{1000}{S + 10} \quad (13)$$

$S$ needs to be calculated from rainfall and outflow data. Rearranging equation (11),

$$0.04S^2 - (0.8Q + 0.4P)S + P(P - Q) = 0 \quad (14)$$

Let $b = -(0.8Q + 0.4P)$, $c = P(P - Q)$, the quadratic equation (14) can be written as

$$y = Sx \quad (15)$$

where

$$y = 0.04S^2 + c$$

$$x = -b$$

given an initial value to $S$ in equation (15), the $S$ can be solved by iteratively solving the linear regression.

Finally, an example is shown here how to calculate the CN of the green roof of University of Georgia using the monitoring data [30].

The monitoring data for the Green Roof of the University of Georgia is shown in table 4.

| Date   | $P$ | $Q$ | Date   | $P$ | $Q$ | Date   | $P$ | $Q$ |
|--------|-----|-----|--------|-----|-----|--------|-----|-----|
| 2003-11-19 | 5.38 | 3.27 | 2004-06-18 | 0.66 | 0.02 | 2004-09-02 | 0.94 | 0.18 |
| 2004-02-06 | 2.69 | 1.32 | 2004-06-21 | 0.3 | 0.01 | 2004-09-06 | 8.23 | 4.43 |
| 2004-02-11 | 2.92 | 1.55 | 2004-06-22 | 0.3 | 0.03 | 2004-09-27 |
| 2004-03-06 | 0.38 | 0.01 | 2004-06-23 | 0.81 | 0.09 | 2004-10-12 |
From equation (15) iterative linear regression was used to calculate S. The result is shown in figure 2.

Substitute \( S = 4.27 \) to (3.7), \( CN = 70 \). One can see that the green roof CN is reduced to 70 from 98.

3. Conclusion
This paper reviews the evolution of urban stormwater management in the United States in the past 40 years, detailing the different volumetric methods for different stormwater management strategies and infrastructures. By comparing with the LID volumetric methods used in the Guide, we draw the following conclusions:

- The volumetric method of BMPs has changed from considering critical storm event and peak flow in 1970s to current ones that are focusing on WQv, LID and GSI. The methods serve for different stormwater management goals and have been modified for local needs. It can be seen that the choice of the methods will have great consequence on the project planning, design and cost;
- The volumetric methods developed in the United States can be classified into two categories, one is the rational method, the another is the curve number method. The runoff coefficient in the rational method is only related to the percentage of impervious surface and the residence time of the stormwater infrastructure. While, the curve number CN is a composite parameter that describes the characteristics of the underlying surface such as soil properties, land use properties, vegetation cover, and slope of catchment. This parameter can be used to calculate the runoff of the site;
- In addition to calculating the storage volume of various stormwater infrastructures, the curve number method can also be used in conjunction with monitoring data to evaluate the
performance of LID facilities. Especially if the model parameters are uncertain and the inflow to bioretention facility cannot be measured, then the curve number method is a simple and feasible method to evaluate the performance;

- It can be seen from the analysis and comparison that the volumetric method used in the Guide is too conservative for LID design. It assumes that each site is independent each other, and does not consider the connection of impervious surface and green space. One of the principles of LID is to convey the runoff from impervious surface into green space before discharging to drainage pipes, and extending the flow path as long as possible. Therefore, each site is not independent. The composite runoff coefficient in the Guide over calculated the runoff which leads to over sizing the LID facilities;

- The volumetric methods in the Guide are uniformly applied to every stormwater facility regardless it is a bioretention cell or a detention pond. As discussed in the section 2.2, detention pond or dry pond should use peak flow runoff coefficient in the rational formula. So, the method in the Guide will over design LIDs and under design BMPs.

- Through the overview of the volumetric methods, the confusions and misuse of BMP, WQv, LID and GSI are cleared. This is critical for the design goals and can avoid the misuse of these terminologies;

- The volumetric methods of the United States can be considered as alternative methods for the construction of sponge cities in China, but their parameters need to be justified for the local conditions. Therefore, it is recommended to conduct more researches in this area and establish a reasonable sponge city design and evaluation standard.

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