Discussion about initial runoff and volume capture ratio of annual rainfall
Kun Zhang, Wu Che, Wei Zhang and Yang Zhao

ABSTRACT

In recent years, runoff pollution from urban areas has become a major concern all over the world. But there exists a worldwide confusion about how much stormwater should be captured for the purpose of runoff pollution control. Furthermore, the construction cost and pollution control efficiency are closely linked with the size of stormwater facilities, which is then related to the first flush (FF) phenomenon and volume capture ratio of annual rainfall (VCRa). Based on this background, analysis of the random and changeable characteristics of the occurrence of FF was carried out first, which was proved to vary with catchment characteristics and pollutant types. Secondly, the distribution of design rainfall depth toward 85% VCRa in China and its causes have been analyzed. Thirdly, the relationship between initial runoff and VCRa has been studied at both conceptual and numerical levels, and the change rule of VCRa along with design rainfall depth in different regions has been studied. The limitation of initial runoff has been illustrated from the perspective of runoff characteristics of single rainfall events in the first part, and from the perspective of regional differences in the two subsequent parts.

Key words | first flush, initial runoff, volume capture ratio of annual rainfall (VCRa), water quality volume (WQV)

INTRODUCTION

Initial runoff is a concept which is based on single rainfall events, while volume capture ratio of annual rainfall (VCRa) is a value based on annual rainfall statistics. Both of them are linked with the calculation of water quality volume (WQV), which is the basic parameter for sizing stormwater facilities.

There are various methods to calculate WQV, such as one-inch rule and half-inch rule, as well as rainfall capture rule. Half-inch rule and one-inch rule embody the concept of initial runoff, but many research studies have shown that it is too arbitrary to calculate WQV by such a fixed value. The WQV calculated by it always has limited universality (Chang et al. 1990; Sharifi et al. 2011), and a lot of watershed managers and researchers have questioned its scientificity (Bertrand-Karjewiski et al. 1998; CWP 2005; Kaspersen 2008). To overcome this problem, regional variations are taken into account in the rainfall capture rule by using the criterion of VCRa, but how to obtain suitable design rainfall depth of VCRa based on local situations remains a problem against the background of no related technical guidance and research in some developing countries like China.

Background information should be clarified first. First flush (FF) is a specific phenomenon of apparently greater discharge rate of pollutant mass or concentration in the beginning part of runoff volume compared to the later part (Sansalone & Cristina 2004), which is caused by transportation of sediments on catchments or in pipes. Initial runoff is a derived empirical concept and parameter aimed at better controlling highly polluted runoff based on FF, and it is not a widely used concept globally compared with FF. Many researchers have tried to find criteria for FF benchmarking (Bach et al. 2010), for example the 40/20, 60/20 and 80/30 FF definitions (Saget et al. 1996) and MMF10/20/30 quantitative indicators, and then to quantify the appropriate value of initial runoff (Alias et al. 2014), the half-inch rule being a good example. However, the results always vary, and little consistency has been obtained by various researches (Bertrand-Karjewiski et al. 1998; McCarthy 2009; Che et al. 2011; Guo et al. 2012; Zhang et al. 2015).
For this reason, VCRa has been increasingly used as a key criterion for sizing stormwater facilities, which takes regional differences into consideration. However, the national code of China is still using 4–8 mm to quantify the size of storage facilities instead of VCRa (MOHURD & AQSIQ 2014), and some guidelines in the USA and other countries are also using initial runoff-related criteria, like half-inch (Gustafson et al. 2009). Thus, without systematic research on relationships between initial runoff and VCRa, the distribution of design rainfall depth in different climatic regions, and the causes of regional distributions, planners and designers will be confused about whether to use initial runoff criteria (4–8 mm, half-inch, etc.) or the design rainfall depth. Getting a deeper understanding about initial runoff and VCRa and their relationships will help us in better knowing the main reason why the initial runoff criterion does not have wide applicability, and the main points of obtaining suitable design criteria in different regions.

This paper has analyzed the uncertainty of FF and initial runoff, the geographical distribution of VCRa and its design rainfall depth in China, as well as the numerical relationship between initial runoff and VCRa. Relationship analysis was realized through regarding initial runoff as the comparatively small value of design rainfall depth and looking from the perspective of annual rainfall statistics. Furthermore, the concept of volume capture ratio of events (VCRE), pollution capture ratio of events (PCRE), and pollution capture ratio of annual rainfall (PCRa) has been proposed, which is to further clarify the relationship between initial runoff and VCRa. All of these works are aimed at giving people a deeper understanding about the enormous regional difference in design rainfall depth in one country and the limitation of one fixed rainfall capture criterion, and promoting the idea of obtaining design criteria of stormwater facilities based on VCRa.

**MATERIALS AND METHODS**

**FF coefficient b**

FF coefficient b comes from a dimensionless empirical equation (Philippe & Ranchet 1987), which is based on the mass-based FF principle and M–V curve, as follows:

\[
M(t) = V(t)^b
\]

where \(V(t) = \int_0^t Q(t)\,dt/\int_0^t Q(t)\,dt\), which is the ratio of the total runoff at time \(t\) to that of the total volume runoff of the event; \(M(t) = \int_0^t Q(t)C(t)\,dt/\int_0^t Q(t)\,dt\), which is the ratio of the total pollutant mass at time \(t\) to that of the total pollutant mass of the event; \(Q(t)\) is the flow rate at time \(t\); \(C(t)\) is constituent concentration at time \(t\); and \(b\) is the FF coefficient indicating the difference/gap between the M–V curve and the bisector line; \(b < 1\) indicates the occurrence of FF, and \(b > 1\) indicates the occurrence of end flush.

The monitoring data of \(b\) used for uncertainty analysis come from 131 rainfall events in 12 sites all over the Auckland city, which was monitored by Auckland Region Council (ACC), Auckland City Council (ACC) and Metwater during 2000 to 2009 (Shamseldin 2011). The monitoring sites include three in-lot small catchments, four relatively more complex catchments, and five manholes within pipeline systems. The major reasons for choosing these monitoring data are the diversity of monitoring sites and good continuity of monitoring, which make the results convincing enough.

In order to analyze the uncertainty of FF and initial runoff, three key issues were studied: firstly, the general distribution of FF coefficient \(b\), whereby the monitoring data of \(b\) were sorted in ascending order, cut into several sections by spacing of 0.2, and then approximated by a Gaussian function; secondly, the characteristics of FF in various underlying surfaces; and thirdly, the characteristics of FF of various pollutant types, considering catchment characteristics and pollutant types, two principal factors globally accepted as influencing FF. To this end, the monitoring data of \(b\) were classified by catchment and pollutant types, and a catchment type versus \(b\) scatter plot and pollutant type versus \(b\) scatter-box mixed chart were produced for analyzing characteristics of FF.

**Daily precipitation data used for calculation of VCRa**

Independent of the previous section, the rainfall data used for drawing a distribution map of design rainfall depth, and for producing curvilinear graphs of design rainfall depth and VCRa stem from rainfall monitoring data of 52 Chinese cities in a recent 30 year period (1983–2012) (snowfall is excluded), which are available from the China Meteorological Data Sharing Service System.

The procedure of calculation and analysis is briefly listed as follows.

First, the day-to-day 24 h precipitation data from 1983 to 2012 were sorted in ascending order after excluding...
rainfall events whose 24 h rainfall depth $\leq 2$ mm. After that, the annual rainfall depth of a certain design rainfall depth can be obtained. It contains two parts: (1) for rainfall events whose 24 h rainfall depth is less than the design rainfall depth, the annual rainfall depth is calculated by its actual 24 h rainfall depth; (2) for rainfall events whose 24 h rainfall depth is greater than the design rainfall depth, the annual rainfall depth is calculated by that design rainfall depth. The ratio of the sum of these two parts to annual precipitation can be calculated, and the result is the VCRs of a certain design rainfall depth. The equation can be seen as follows:

$$VCRa(\%) = \frac{\sum h_{i,D} + \sum h_{D,D} > D}{P} \times 100\%$$ (2)

where $P$ is annual precipitation (mm), $h_D$ is the design rainfall depth (mm), $h_i$ is the actual 24 h rainfall depth of each rainfall event (mm); $i$ is the sequence number of rainfall events after sorting 24 h rainfall depth in ascending order, and $D$ is the particular sequence number corresponded to the design rainfall depth.

After finishing the calculation of VCRa of various design rainfall depths of different cities, China can be partitioned into six zones by the measure of design rainfall depth toward 85% VCRa. Each zone has its own range of design rainfall depth toward 85% VCRa objective, so regional differences and the distribution pattern of design rainfall depth can be studied clearly.

The objective of 85% VCRa was proposed because research has shown that 85% VCRa can capture a significant number of storms without attempting to treat the small percentage of much larger storms, which is expensive to treat and rare in occurrence (Shamseldin 2010). In addition, this value is also widely adopted by some states in the USA. For example, manuals of New York City (CWP 2010), Kansas (MARC 2008) and Vermont (VANR 2002) adopted 90% VCRa criteria, and federal projects in the USA are required to control 95th percentile rainfall event, whose design rainfall depth is really close to that of 85% VCRa (USEPA 2009).

Furthermore, using design rainfall depth as $x$-coordinate, and VCRa as $y$-coordinate, the curvilinear graphs of representative cities of each zone partitioned above can be produced by marking each zone with different colors. Each zone has its own data range, including upper limit, lower limit and median value. The data range of design rainfall depth and VCRa of different regions in China can be seen in Table 1.

### RESULTS AND DISCUSSION

#### Uncertainty analysis of FF and initial runoff

The result of Gaussian function fitting of FF coefficient distribution is clearly shown in Figure 1. Therein, the fitting equation is:

$$y = 0.00211 + \left( \frac{0.19373}{0.76539 \sqrt{\pi} } \right) e^{-\left( \frac{x - 1.03193}{0.76539} \right)^2}$$ (3)

where $y$ indicates the frequency of occurrence below certain value of $b$; $x$ represents $b$; and PI represents the circumference ratio, which is approximately equal to 3.14159.

Equation (3) and Figure 1 represent a good approximation of the general distribution of $b$ to Gaussian function with 0.90087 adjusted $R$-squared of the fitted curve. The median point is located at $x_c = 1.03193$, which indicates a slight end flush for the whole study area generally. Furthermore, the full width of half maximum (FWHM) is 0.90118, and it is calculated that almost 70%

### Table 1 | Data range of design rainfall depth and VCRa of different regions in China

<table>
<thead>
<tr>
<th>Region</th>
<th>Value range</th>
<th>Representative city</th>
<th>30%</th>
<th>50%</th>
<th>70%</th>
<th>85%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone A</td>
<td>Lower limit</td>
<td>Gulmod</td>
<td>1.4</td>
<td>2.3</td>
<td>3.6</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>Turpan</td>
<td>1.6</td>
<td>2.5</td>
<td>4.1</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>Upper limit</td>
<td>Jiuquan</td>
<td>2.3</td>
<td>4.0</td>
<td>6.2</td>
<td>9.4</td>
</tr>
<tr>
<td>Zone B</td>
<td>Lower limit</td>
<td>Urumchi</td>
<td>2.5</td>
<td>4.5</td>
<td>7.7</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>Tonghe</td>
<td>2.9</td>
<td>6.4</td>
<td>12.0</td>
<td>20.4</td>
</tr>
<tr>
<td>Zone C</td>
<td>Lower limit</td>
<td>Harbin</td>
<td>3.4</td>
<td>6.7</td>
<td>12.7</td>
<td>22.2</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>Ganzhou</td>
<td>4.7</td>
<td>8.4</td>
<td>17.9</td>
<td>29.8</td>
</tr>
<tr>
<td>Zone D</td>
<td>Lower limit</td>
<td>Beijing</td>
<td>4.8</td>
<td>9.6</td>
<td>19.4</td>
<td>33.6</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>Nanning</td>
<td>5.7</td>
<td>12.0</td>
<td>23.5</td>
<td>40.4</td>
</tr>
<tr>
<td>Zone E</td>
<td>Lower limit</td>
<td>Guangzhou</td>
<td>6.1</td>
<td>13.3</td>
<td>25.0</td>
<td>44.0</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>Ganyu</td>
<td>6.8</td>
<td>14.0</td>
<td>28.3</td>
<td>51.5</td>
</tr>
<tr>
<td>Zone F</td>
<td>Lower limit</td>
<td>Haikou</td>
<td>7.4</td>
<td>16.7</td>
<td>32.5</td>
<td>54.0</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>Yangjiang</td>
<td>10.9</td>
<td>21.5</td>
<td>44.0</td>
<td>84.6</td>
</tr>
</tbody>
</table>
of $b$ centers in the range of 0.6–1.4, of which about 58.7% center in the range of 0.8–1.2.

To study further the uncertainty of FF caused by catchment characteristics, the data of $b$ are classified into groups by gauging stations, and the result is shown in Figure 2.

For the three in-lot small catchments, FF exists in 83.3% of all the rainfall events ($b < 1$), and strong FF exists in 37.5% events ($b < 0.5$). However, the ratio of FF is only 55.2% and 46.3% for the remaining four more complex catchments and five pipeline systems, respectively, and the number of strong FF only accounts for 13.8% and 6.8%, which is apparently smaller than that of in-lot small catchments. In addition, it is obviously observed that the distribution is very intensive for in-lot small catchments but more dispersed in more complex catchments and pipeline systems.

Apart from that, the variation of FF characteristics among different pollutant types also clearly shows the
uncertainty of FF. The same monitoring data of $b$ were classified into groups by different pollutant types, which is shown in Figure 3.

It is clear that the general distribution of $b$ among different types of pollutants is very close: most of the dots are located in the area around 0.5–1.5, which matches well with the pattern of Figure 2. However, there do exist differences between them; the fluctuation range of $b$ of total suspended solids, *E. coli* and enterococci are obviously greater than that of dCu, total dissolved nitrogen, total dissolved phosphorus and fluoride.

Studies from the US National Stormwater Quality Database (NSQD) revealed the similar fact. According to 417 rainfall events monitored and 22 pollutants examined, the results showed that no FF existed in 45% of samples. Furthermore, the percentage of the occurrence of FF varies with catchments. It is about 70% in commercial areas, 60% in residential and public areas, 45% in industrial areas, and only 0% in big open spaces (Maestre & Pitt 2005).

Altogether, the place-specific and pollutant-type-specific characteristics of FF have been reflected. It is hard to decide whether FF exists and how much volume of rainwater should be captured in single rainfall events. Although a comparatively high pollution control rate can be obtained in strong FF cases, the proportion of these specific cases is small, the volume captured is limited, and the pollution controlled is hard to guarantee. So capturing the first portion of rainwater is still not enough for capturing total runoff pollution in most circumstances, especially for large-scale areas.

It is worth noting that, although factors like gradient conditions, particle characteristics, accumulation of pollutants, rainfall intensity, and rainfall volume have not been further discussed, all of them have been implied in $b$: $b$ is the symbolic expression of all these factors.

**The geographical distribution of design rainfall depth in China**

Because of the undeniable existence of the uncertainty of FF, controlling only initial runoff is apparently not a guaranteed way for controlling runoff pollution, compared with capturing total runoff volume. However, the exact volume that should be captured is not clear, as it varies between different areas.

In order to have a clearer understanding about regional differences and distribution characteristics of VCRa and its design rainfall depth in China, mainland China was partitioned into six zones by the measure of design rainfall depth toward 85% VCRa. Therein, the design rainfall depth for 85% VCRa is $<$10 mm in A zone, 10–20 mm in B zone, 20–30 mm in C zone, 30–40 mm in D zone, 40–50 mm in E zone, and $>$50 mm in F zone. The general distribution map is shown in Figure 4.

It is easily found from Figure 4 and Table 1 that the design rainfall depth toward 85% VCRa shows an increasing trend from northwest to southeast of China generally, and is only 5–20 mm in northwestern arid and semi-arid regions.
(A and B zone), like Xinjiang, Tibet, Inner Mongolia and Qinghai province, but gradually increases to 20–40 mm in central regions, like Beijing, Hubei and Jiangxi province, and to 45–85 mm in southeastern coastal regions (E and F zone), like Hainan. Guangdong and Guangxi province.

The causes behind this phenomenon are complex. Through in-depth analysis, the dominant causes can be concluded as follows.

First, the proportional relation among rainfall events of different intensities is the primary one. Statistics show that the higher the percentage of heavy rainfall (daily precipitation >50 mm) and the lower the percentage of small and medium-sized rainfall (daily precipitation <25 mm) in annual precipitation, the greater the design rainfall depth is. Compared with average annual precipitation and climatic type, this element has greater influence. It can be seen in two aspects. Firstly, even if regions belong to the same climate type, and have similar average annual precipitation, their design rainfall depth will differ quite a bit if the percentage of heavy rainfall varies a lot, such as in Wanyuan and Shanghai, Beijing and Harbin. Oppositely, even if regions belong to different climate types with various average annual precipitation, the design rainfall depth will be close if the percentages of heavy rainfall or small and medium-sized rainfall are close, such as in Beijing and Shanghai, Lhasa, Ganzi and Urumchi. Secondly, the climatic, geographic and geomorphic characteristics also have close connection to the distribution of design rainfall depth. According to the survey, boundaries between monsoon and non-monsoon area, and between arid and humid regions, are extremely close to the boundary between B and C zones. Zones, C, D, E and F lie in areas affected by monsoon climate and typhoon, where heavy rainfalls are always caused by frontal surface, cyclone, low vortex-shear line and typhoon. In contrast, A and B zones lie in the northwestern region and Qinghai-Tibet Plateau, where the conditions that usually cause heavy rainfall, e.g. cold front, local heat convection, plateau shear line and plateau groove, are relatively less frequent (Li et al. 2015). Therefore, the quantity and frequency of heavy rainfall in northwestern regions are less than in southeastern regions, comparatively. This is considered to be an equally important element leading to the regional difference and distribution of VCRa and its design rainfall depth in China. Obviously, although the distribution characteristics vary among different countries, the theories behind these causes are of universal applicability.

### Relationship analysis between initial runoff and VCRa

The relationship between initial runoff and VCRa can be analyzed from both conceptual and numerical perspectives.

For the conceptual part, initial runoff is inter-related with four concepts, which are VCRE, VCRa, PCRe and PCRa. For single rainfall events, initial runoff is the runoff generated at the beginning part of the events, the ratio of which to rainfall volume is the VCRE. Moreover, the relationship between initial runoff and PCRe is related to event-based FF phenomenon and the characteristics of the M–V curve except for the value of initial runoff and rainfall volume of single events.

Unlike these two concepts, the annual runoff volume is the accumulative total of runoff volume in single events; so the relationships between initial runoff and VCRa and PCRa are not only linked to single events but a reflection of the rainfall, climatic and geographical conditions of a certain region, which have been shown in the previous section. Initial runoff is like a linking component among these four concepts. The inter-relationships among them can be seen from Figure 5 below.

For the numerical part, the issues of whether controlling initial runoff is sufficient for obtaining a satisfactory VCRa value, how much VCRa can be obtained in different regions, and the change rule of VCRa along with design rainfall depth should be studied. To this end, the curvilinear graph between design rainfall depth and VCRa in six zones is depicted in Figure 6.

It is worth mentioning that the understanding of initial runoff differs in different countries. In China, the most well-known and basic standard of initial runoff is 4–8 mm, which has been put forward in a national code, whereas
half-inch (12.7 mm) and one-inch (25.4 mm) have been widely used in other developed countries, especially the USA. These three representative design rainfall depths are marked as vertical dotted lines in Figure 6.

Figure 6 displays that the VCRa of a certain rainfall depth in various places differs greatly. The corresponding VCRa of 4–8 mm initial runoff can reach 70–80%, even 90% in A zone, which represents northwest extreme arid regions of China, while the VCRa of the same design rainfall depth (4–8 mm) is only 10–20%, and 30–40% in F zone and C zone, which symbolize southeastern coastal areas and central regions.

Apart from that, the degree of regional differences of VCRa are also closely linked with the value of design rainfall depth. Compared with 4–8 mm, the VCRa of half-inch and one-inch design rainfall depth are much higher, and the regional differences are smaller. The VCRa of half-inch and one-inch are 70–90% and 90–95% in northwestern areas (A and B zones), and 30–50% and 55–70% in southeastern coastal areas (E and F zones). In fact, when design rainfall depth is less than 8–10 mm, the regional difference (gap between curves) is becoming greater with the increase of design rainfall depth. It reaches maximum around 8–10 mm and diminishes when larger.
However, no matter how high the design criterion is, regional differences always exist and cannot be neglected. The value of design rainfall depth is closely linked to local rainfall, geographic and geomorphic characteristics which should be kept in mind when formulating runoff pollution control strategies and constituting technical standards. This is true not only for China, but also for other countries.

CONCLUSIONS

The influence of uncertainty of FF and initial runoff, the distribution of design rainfall depth in China, and the conceptual and numerical relationships between initial runoff and VCRa are systematically analyzed in this paper.

In uncertainty analysis of FF and initial runoff, the distribution of FF coefficient b matches the Gaussian formula very well, and its place-specific and pollutant-type-specific characteristics were reflected.

A distribution map of design rainfall depth toward 85% VCRa in China was produced, which gave us a clearer look at the dramatic difference between areas. The proportional relation between rainfall events of different intensities and the climatic, geographic and geomorphic characteristics are regarded as the main causes of the distribution of design rainfall depth.

Furthermore, the conceptual relationship between initial runoff and VCRa, VCRc, PRCr and PRCa, the numerical relationship between value of initial runoff and VCRa, and the change rule of VCRa and its regional differences along with design rainfall depth were analyzed. The VCRa of initial runoff criteria was proved to be limited, especially in southeastern areas, and the regional difference of VCRa was proved to be increasing when design rainfall depth was smaller than 8–10 mm, and diminishing when larger.

The analysis above will be beneficial to finding more economical and efficient ways to capture runoff pollution, and to formulating scientific and feasible runoff pollution control strategies on a case-by-case basis, especially for developing countries which are on their first steps to exploring stormwater management methods and techniques.

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