Study on the Capacity of Extensive Green Roof to Mitigate Rainwater Runoff in Guangzhou

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Abstract. Previous studies have shown that the extensive green roof (EGR) can serve to retain the rainwater and mitigate rainwater runoff, but most of studies were in the temperate zone. Located in the hot and rainy subtropical zone, Guangzhou (GZ) is one of China's earliest cities that promote vertical greening, yet the researches on the EGR in recent years focus more on the cooling effect, substrate screening and selection tests, than on the mitigation of rainwater runoff. For this study, three EGR test platforms were set up in GZ to test the EGRs with substrate thicknesses of 30mm, 50mm and 70mm in summer of higher concentration of rainfall events. The results showed that the rainwater retention performance of the 30mm, 50mm and 70mm-thick substrates were 23.29%, 27.20% and 28.44% respectively, and the mean peak reduction 18.94%, 26.17% and 27.7%. Assume the EGR with 30mm-thick substrate is to be promoted throughout the 1,035.01 square kilometers built-up area in GZ, and the roof area accounts for about 37.25% of the built-up area, a total of 122.30million cubic meters of rainwater will then be retained during the period from May to August. This would largely help mitigate the urban waterlogging and ease the pressure of rainwater runoff on the urban drainage network.

Background and Objectives

China is witnessing a rapid urbanization process and, the development of cities brings not only great opportunities, but also tremendous challenges for urban planning and management and sustainable urban development. Among the challenges, issues resulting from by urban waterlogging have caused widespread concern in all sectors of society. China's scholars have reached a broad consensus that the objective reason for urban waterlogging is local climate change as a result of global climate change and urbanization, and subjective one the fast-increasing impermeable surfaces in the cities.

Such problems also haunted developed countries such as Germany and the United States in their urbanization process. Hall (1984) pointed out that the impermeable surfaces leaves no space for rainwater permeation; the lack of soil filtration and rainwater retention is a major contributor to the rapid increase in rainwater runoff.[1] When the peak flow exceeds the urban drainage capacity, the urban waterlogging may follow.[2] In the past three decades, green roofs have been widely utilized in developed countries including Germany and the United States to reduce rainwater runoff, and as an effective solution to offset the negative effects caused by the impermeable surfaces in urban areas.[3] Globally, quantitative studies on the capacity of green roofs to mitigate rainwater runoff in urban areas has been on the rise, providing reference for solving the similar problems in China. These studies showed that the changes to climate conditions such as air temperature, humidity, wind speed and solar radiation, have impacts on the efficiency of evaporation and transpiration and the water storage capacity of green roof; such impacts is widely accepted by the scholars conducting...
researches in temperate zone as evident. Currently, researches on the capacity of rainwater retention of the EGR are mostly carried out in countries in temperate zone. Mentens et al. (2006) and Berndtsson (2010)\[4] pointed out that hot weather restore the water storage capacity of the green roof rapidly. Berndtsson et al. (2005)\[5], Mentens et al. (2006), Spolek et al. (2008)\[6], Uhl et al. (2008)\[7], Schroll (2011)\[8] and Stovin et al. (2012)\[9] indicated that rainwater retention capacity of the EGR in summer is higher than that in winter. In these regions, the rainfall is evenly distributed all year round, and maintains a relatively high level in winter. However, Voyde et al. (2010)\[10] pointed out that in mild and rainy Auckland, climate changes have no significant influence on the rainwater retention capacity of the green roof. It is therefore fair to conclude that the capacity to mitigate rainwater runoff of the green roof varies under different climate conditions. Regrettably, only a few of such researches have been conducted in China. Liu (2008) and Zhang et al. (2015) conducted systematic qualitative and quantitative analysis of the comprehensive utilization of rainwater on the green roof in Chongqing\[11,12]; Wei (2010) measured and compared the runoff coefficients between ordinary and green roofs in Shenzhen\[13]; Wong et al. (2014) showed the significant mitigation of rainwater runoff and peak reduction by green roofs by studying the thickness of the soil substrate used for roof planting in Hong Kong (HK). GZ is one of China's earliest cities that promote vertical greening; but researches on the EGR in recent years focus more on the effect of cooling, substrate screening and selection tests, than on the mitigation of rainwater runoff.

Dunnett et al. (2007) pointed out that 40-50% of impervious surfaces in urban area are unused roofs\[14]. Most buildings in GZ have flat roofs that are mostly of concrete structure, making the addition of a EGR possible. It is indeed of profound appeal to ease the pressure on the drainage network and to divert rainwater by adding a EGR to the flat roofs in the high-density downtown areas where land resources are limited and expensive. Given the climatic conditions of GZ, where the rainy season coincides with the hot season with obvious flood period, this study takes the EGR that is of a smaller load and a wider scope of application as the research subject, aiming to provide data concerning the retention of rainwater by way of quantitative studies.

Site Description

GZ lies in low latitude and borders on the South China Sea\[15]. It features distinct maritime climate and falls within the subtropical monsoon climate zone in south Asia. In summer, the warm air flow from the sea renders the climate hot, humid and rainy; in winter, the cold wind from the northern part of continent renders the climate cold, dry and rainless. The mean annual temperature is about 22°C, record-high temperature 39.3°C, and record-low temperature -2.6°C. The mean annual rainfall is 1,872.2mm (1999-2014), of which 80% occurs during the rainy season (April-September). The mean annual number of days of precipitation is around 150, and the month with the largest mean rainfall is June (370mm)\[16].

According to the statistics of the Bureau of Water Resources of GZ Municipality, there are 297 waterlogging points, 182 of which are in the Yuexiu, Liwan, Haizhu and Tianhe districts of GZ. The main causes of the waterlogging include low standard drainage network, insufficient drainage pipe network, low-lying land, network congestion, backwater due to the external river water and construction in the city\[17]. Webster et al. (2005) and Chan et al. (2012) pointed out that, as the global climate change exacerbates typhoons and storms in terms of their frequency, intensity and level\[18,19], it is necessary to adopt more scientific and effective measures to ease the pressure on the urban drainage network, making the city safer. GZ still has a long way to go in controlling rainwater runoff and building the sponge city.

Methodology

This Study was conducted on the roof of the Building Technology Laboratory in South China University of Technology, with a total of three EGR platforms being set up for the purpose of testing their capacity to mitigate rainwater runoff. The concrete roof that accommodates the
experimental site was exposed to the weather, and treated with waterproofing measures in conventional manner. The three platforms made of stainless steel cover an area of 3 square meters (1.0m x 3.0m) each, with a drainage slope of 2%, and sit on the angle steel brackets. Each platform has an outlet from which the rainwater retained is discharged into the plastic bucket beneath. The EGR is constructed as follows from bottom to top: storage and drainage layer, filtering layer, growing substrate and plant layer. The growing substrate are 30mm, 50mm and 70mm thick respectively. The selected substrate was the nutritious one that is made from urban green waste and has been widely used for vertical greening in GZ. *Pachyphytum viride* was selected as the plant for the EGR. In the three platforms planted the same amount of *Pachyphytum viride* at the same density.

Rainfall was measured by the small US Davis Vantage VUE® placed on the roof of the laboratory building. The weather station mainly measured four parameters including temperature, wind speed, rainfall and solar radiation every 10 minutes. The measurement officially started from May 1, 2015 and ended on August 29, 2015. Collect the rainfall event data in this way, and divide them into large, medium and small rainfall events as per the previous classification standards, then calculate the percentages of the three types of rainfall events during the test period. Screen the rainfall events based on such percentages, then simulate the screened rainfall events to record the precipitation value every 10min and deduce the precipitation of the 3 sqm test platform through the Davis weather station. When it is sunny and no rainfall is recorded within 48 hours, simulate the aforesaid rainfall events with the artificial rainfall system, and evenly inject the same amount of water into three test platforms every 10min. At the same time, the overflow (i.e., runoff) from the platform when raining was collected in the plastic bucket and measured with a weight scale next to the platforms.

**Study Results and Analysis**

**Analysis of the Characteristics of Rainfall**

The rainfall events of less than 0.4mm were excluded from the experiment. In case that before a rainfall event was not over, another one happened (divided by 6h), the two successive events would be recorded as one event. Data measured during experimental period showed that there was a total depth of 1,315.80mm recorded in the 71 rainfall events. The monitored meteorological data was analyzed and compared against the historical statistics to verify its effectiveness. The monthly rainfall on the site basically coincided with the mean rainfall of the last 16 years (1999-2014) in the same period[20], which showed the experiment data regarding the capacity of the EGR to mitigate rainwater runoff in this experiment is applicable in GZ.

**Analysis of the Retention Performance of Three Substrates in Different Thicknesses**

As automatic measurement was not available in the experiment, the data could not cover all the rainfall events. During the experiment, 14 sets of data (n=14) rainfall events were selected to simulate an artificial event. The overall capacity to mitigate rainwater runoff by the three substrates in the variable group is shown in Table 1. Quantitative analysis of the retention performance of each EGR module was conducted based on the total retention capacity. The cumulative retention capacity ranged from 75.94mm to 92.70mm: 70mm-thick substrate was 28.44%, 50mm 27.20%, and 30mm 23.29%.

**Analysis of the Retention Performance under Three Types of Rainfalls**

According to characteristics of rainfall, the rainfall events can be classified as heavy, medium and light ones for the sake of analysis, which is shown in Table 2. Such classification criteria were set up referring to the previous studies (Getter et al., 2007; Speak et al., 2013; Wong et al., 2014)[11]. Based on the foregoing classification, each event could be classified into one category and the mean retention capacity could be calculated. The calculation results then showed that the mean retention capacity varied under different types of rainfalls. The total retention, being the cumulative capacity
under different types of rainfall events, also demonstrated similar performance, namely the highest retention under light rainfall events.

Table 1. Comparison of Capacity to Mitigate Runoff by Three Substrates in Different Thickness (n = 14).

<table>
<thead>
<tr>
<th>Rainfall mm</th>
<th>Duration h:min</th>
<th>Runoff/mm</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>70mm</td>
<td>50mm</td>
</tr>
<tr>
<td>0.8</td>
<td>0:30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0:40</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>3</td>
<td>1:20</td>
<td>0.13</td>
<td>0.12</td>
</tr>
<tr>
<td>5.6</td>
<td>0:30</td>
<td>0.98</td>
<td>1.07</td>
</tr>
<tr>
<td>6.8</td>
<td>0:50</td>
<td>1.21</td>
<td>1.46</td>
</tr>
<tr>
<td>9.4</td>
<td>1:10</td>
<td>2.93</td>
<td>2.69</td>
</tr>
<tr>
<td>13.2</td>
<td>1:00</td>
<td>8.12</td>
<td>8.93</td>
</tr>
<tr>
<td>14.2</td>
<td>0:50</td>
<td>10.86</td>
<td>11.05</td>
</tr>
<tr>
<td>14.6</td>
<td>1:10</td>
<td>5.49</td>
<td>5.62</td>
</tr>
<tr>
<td>18.8</td>
<td>2:10</td>
<td>16.70</td>
<td>17.10</td>
</tr>
<tr>
<td>20.8</td>
<td>1:10</td>
<td>12.26</td>
<td>11.74</td>
</tr>
<tr>
<td>52.2</td>
<td>1:10</td>
<td>42.48</td>
<td>43.35</td>
</tr>
<tr>
<td>63.2</td>
<td>2:10</td>
<td>50.34</td>
<td>19.14</td>
</tr>
<tr>
<td>101.4</td>
<td>3:20</td>
<td>81.75</td>
<td>85.03</td>
</tr>
</tbody>
</table>

Table 2. Classification of 71 Rainfall Events Recorded from May to August.

<table>
<thead>
<tr>
<th>Rainfall type (Depth range)</th>
<th>Num. of rainfall events</th>
<th>Cumulative rainfall depth (mm)</th>
<th>Cumulative rainfall Depth (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light &lt;2mm</td>
<td>15</td>
<td>15.2</td>
<td>1.16</td>
</tr>
<tr>
<td>Medium 2-10mm</td>
<td>21</td>
<td>114</td>
<td>8.66</td>
</tr>
<tr>
<td>Heavy &gt;10mm</td>
<td>35</td>
<td>1186.6</td>
<td>90.18</td>
</tr>
<tr>
<td>Total</td>
<td>71</td>
<td>1315.8</td>
<td>100</td>
</tr>
</tbody>
</table>

Analysis of the Characteristics of Two Types of Rainfall-Discharge Modes

One single rainfall event was selected as the research subject. When simulating this event, its rainfall and discharge were presented in a hydrograph to measure the peak delay and peak reduction by the EGR; the peak was defined as the first highest discharge volume in the rainfall event. For the sake of straightforward comparison, the rainfall and discharge were both in mm. All calculations of the peaks were based on the data collected in every minute to ensure correct results. This analysis took the heavy rainfall events (>10 mm) in simulation. Peak delay demonstrated the time difference between the rainfall peak and the discharge peak. Peak reduction demonstrated the reduction proportion of discharge intensity compared with the rainfall intensity at peaks. Two heavy rainfall events were analyzed as follows, each representing a type of rainfall-discharge mode: single-peak and multi-peak.

Analysis of Peak Delay of a Single-Peak Rainfall. On July 21, 2015 there was a heavy rainfall event lasting for 9 hours and 20 minutes, with the rainfall reaching 75.2mm. But due to limitations of manual operation, the measurement only lasted for 70min of the heavy rainfall section, with the total rainfall of 52.2mm that accounted for 69% of that of the entire event. To a certain extent, the measurement results could represent the characteristics of the heavy rainfall event. As shown in Figure 1, the EGRs with substrates of different thickness treatments vary in the performance to delay the peak of single-peak rainfall. Figure 1 shows that the EGR is effective in delaying the duration of the peak. 10-minute delay could reduce as high as 15.16% of the peak. In the event, the retention ranged from 14.5 to 18.61%. The peak reduction and the maximum retention of the 70mm-thick substrate could thereby be predicted. However, the number of samples at hand is too small to further support the hypothesis. Therefore, further researches are required to obtain sufficient samples for statistical analysis which could verify the hypothesis.
Analysis of Peak Delay of Multi-Peak Rainfall. From 20:10 to 23:30 on May 4, 2015 there was a multi-peak heavy rainfall event, with the total rainfall reaching 101.4mm. The highest peak appeared at 20:20 (21.4mm/10min); the second highest at 20:50 (14.4mm/10min); the third highest at 23:00pm (13.4mm/10min). When the first peak (at 20:20, 21.4mm/10min) appeared, the runoff did not reach the maximum value until 10 minutes later and the peak was reduced by 35.37% at most (70mm-thick substrate); while by the time the second peak (at 20:50, 14.4mm/10min) appeared, the runoff peak followed immediately and the peak was reduced by 23.61% at most (70mm-thick substrate); indicating that the capacity of EGR for rainwater detention and storage had decreased; when the third peak appeared, the four curves substantially overlapped with each other, meaning there was no significant peak delay. To sum up, continuous heavy rainfall greatly reduced the rainwater retention performance of EGR. See Figure 2.

Estimated Total Rainfall Retention by the EGR in the Built-up Area of GZ

Among the 1,035.01 square kilometer of built-up area in GZ (excluding Conghua and Zengcheng)[22], suppose the EGR is to be promoted in the residential land and industrial land according to the Standards of Urban Land Classification and Construction Land Planning(2011GB). Specifically, if the land for housing (60% of the residential land) and the land for public building (20% thereof), and the land for warehouse (50% of the industrial land) are taken for the promotion, it is estimated that the area available for implementation of the EGR will accounts for about 37.25% of the built-up area. If so, considering the load issue, the lighter 30mm-thick substrate is to be used for the estimation, while the capacity of the said substrate to delay and retain light, medium and heavy rainfalls are 98.57%, 73.51% and 18.41% respectively. Take the 71 rainfall events throughout the summer in 2015 as an example, and the total rainwater retained would be 317.23mm, with the total retention up to 24.11% and the volume 122.30 million cubic meters.

Conclusion and Discussion

The previous researches have shown that the factors that influence the rainwater retention performance of the EGRs with different substrate thicknesses generally include differences in climate conditions, EGR design and test methods. In this Study, the accumulative retention of the EGRs with 70mm, 50mm and 30mm-thick substrate were 28.44%, 27.20% and 23.29% respectively. Such values are relatively low compared with those of other tests as a result of the number of rainfalls, the frequent continuous rainstorms, and the humid weather in the subtropical zone. For example, in the research of Carter et al. (2006), the accumulative retention of the 72mm-thick substrate was 62%, and the mean retention 78%[23]. This research was conducted in Athens, Georgia where the annual rainfall was 1,232 mm, two-thirds of that of GZ (1,872mm). In addition, the extremely uneven rainfall distribution in GZ also contributed to the differences between the results. But the results are similar to those of the test conducted by Wang (2014) in HK (accumulative retention: 11-14%). The possible reasons for the differences in results are HK’s annual rainfall (2,400mm), and the differences in the substrate type and thickness and the

Figure 1. Analysis of the Capacity to Delay Peak of Single-Peak Rainfall by EGR.

Figure 2. Analysis of the Capacity to Delay Peak of Multi-Peak Rainfall by EGR.
Experimental design. By comparing these studies, it can be concluded that higher total rainfall, more frequent rainstorms and concentrated rainfall in a short period of time and a limited space contributes to the reduction of the overall retention.

The three substrate thickness treatments varied significantly in the mean retention capacity under different rainfall types. As the rainfall increased, the corresponding mean retention capacity decreased. The standards for classifying rainfalls adopted in this study is similar to those of VanWoert et al. (2005) and Getter et al. (2007), so are the results. Furthermore, the results of these three studies are consistent with common sense, as if rainwater is the only input into the EGR, the lighter the rainfall is, the higher the retention efficiency will be, and vice versa.

By simulating the rainfall-discharge mode of one single rainfall event in the experiment and presenting the mode in a hydrograph, the peak reduction in a heavy rainfall can be clearly observed. This indicates that the EGR can reduce the rainwater peak and the possibility of urban waterlogging. Furthermore, the multi-peak mode renders the visualization of the hydrological process of temporary storage by the EGR possible.

As this Study is in the initial stage, the test-related data still needs to be further verified and improved before being used as the basic data for urban rainwater management planning. As the initial test results showed, the mean retention of the EGR with even 30mm-thick substrate was as high as 48.04%. Suppose the EGR is to be promoted in the residential land and industrial purposes in the build-up area in GZ; then based on the rainfall from May to August of 2015, a total of 122.30 million cubic meters rainwater is to be retained, which can effectively delay the peak and therefore ease the pressure on the urban rainwater drainage network. Although rainfalls are heavy and frequent in summer in GZ, the test results have shown that even in hot weather, the EGR can still function well in mitigating rainwater runoff. Many relevant studies have shown that the retention efficiency is closely related to the substrate and its composition, design, and etc. of the EGR. Therefore, further tests and calculation are required to improve the efficiency.

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