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# Extensive Green Roofs: first step towards sustainable urban drainage system design in Hong Kong

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## ABSTRACT

One of the major purposes in adopting the sustainable urban drainage system (SUDS) design is the restoration of green space or pervious surface that is lost during city development. In the highly congested Hong Kong urban districts, roof areas represent some of the most underutilized spaces. Installing extensive green roofs on top of such buildings could be an effective way to accomplish this goal. Additionally, beyond the drainage related functions such as stormwater runoff reduction, runoff quality improvement and aesthetic enhancements, green roofs can provide numerous other environmental and economic benefits, which have been studied extensively overseas. However, installing a green roof costs more than a conventional flat roof, and practices recommended by foreign guidelines may not be suitable for the subtropical climate in Hong Kong. Comprehensive studies using experiments and numerical models are needed to obtain local data for developing reliable green roof guidelines that apply to Hong Kong's unique climate condition and building environments.

In this study, actual extensive green roofs were designed and constructed in Sha Tin Sewage Treatment Works (STSTW) to study green roof runoff quality and quantity and other key issues of green roof design and construction, including loadings, wind safety and waterproofing. Moreover, 36 test plots, each simulating a 150mm thick extensive green roof system, were built for laboratory investigations of the significance of the factors affecting runoff mitigation. They are plant types, plant growth, types of soil substrate, rainfall intensities, roof slopes, and soil moisture contents.

The performances of the runoff retention and detention of extensive green roofs were found to be closely related to the aforementioned factors. In the event of 30mm/hr rainfall intensity (i.e. amber rainstorm warning signal in Hong Kong), the tested extensive green roof systems have an average retention rate of 31.9-53.5% and an average peak runoff delay time of 21-35 minutes. Results obtained from runoff quality analysis were in line with foreign extensive green roof studies. The findings of the study greatly contribute to the design of green roof system and guideline establishment.

## 1. INTRODUCTION

Typical urban surfaces and drainage systems are designed to concentrate and dispose stormwater as quickly and efficiently as possible. In return, huge drainage facilities are constantly needed to accommodate the flood risks posed by every heavy storm. Large amount of runoff water that is contaminated by the city surface enters the sea in each first flush. Also, the impermeable surface disturbs the ecological balance that groundwater cannot be replenished by rainwater through infiltration, and natural live forms cannot survive on dry concrete and asphalt. All these problems exacerbate with the growth of population and urbanization.

To counter these environmental impacts, a sustainable urban drainage system (SUDS) targets to restore the natural habitat by using techniques such as greening, stormwater runoff mitigation and pollution control [1]. As a source level control, an extensive green roof system is a component of SUDS, and is particularly suitable for Hong Kong as it requires less additional space compared to other SUDS components. The runoff mitigation performance of a green roof has been reviewed in many overseas studies [2,3] along with many other environmental and economic benefits such as cooling effect. While this greening design is gaining popularity in Hong Kong, research on green roof runoff regarding the unique subtropical climate of Hong Kong is not yet available. In this study [4], the runoff mitigation performance of an extensive green roof system is examined quantitatively using field measurements and laboratory experiments. The runoff was also analyzed to determine the pollution level comparing to the runoff from a traditional roof.

## 2. METHODOLOGY

### 2.1. Part 1 – Field Measurements of the STSTW Green Roofs

The studied extensive green roof is located on the rooftop of the Sludge Thickness House Extension (STHE) in Sha Tin Sewage Treatment Works (STSTW). The installation was completed on January 2012, and experiments and measurements started since then. Total area of the STHE green roof is about 600m$^2$. The rooftop is partitioned into five independent lots, each designed to represent a specific roof system for performance comparison. Figure 1 below shows the design layout and the configuration of Lot1 to 5:

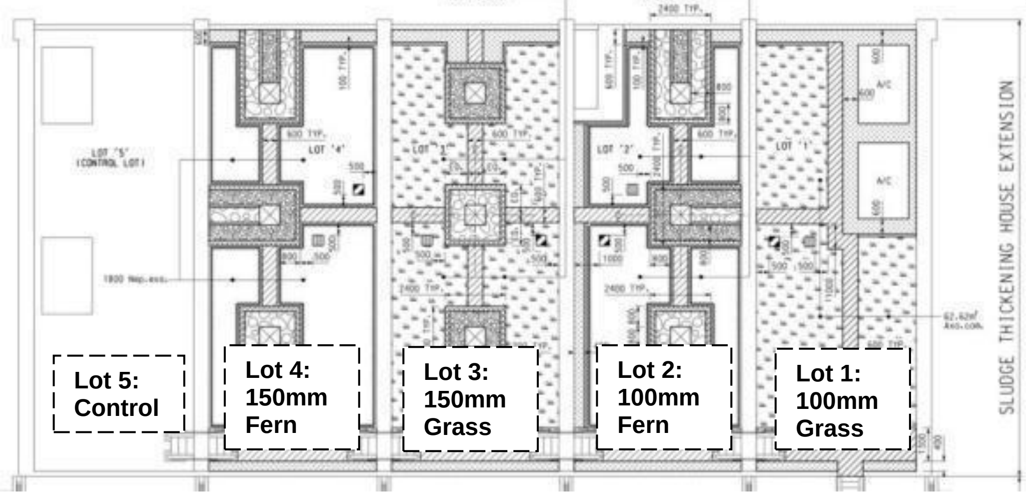


Figure 1: Green Roofs of STHE

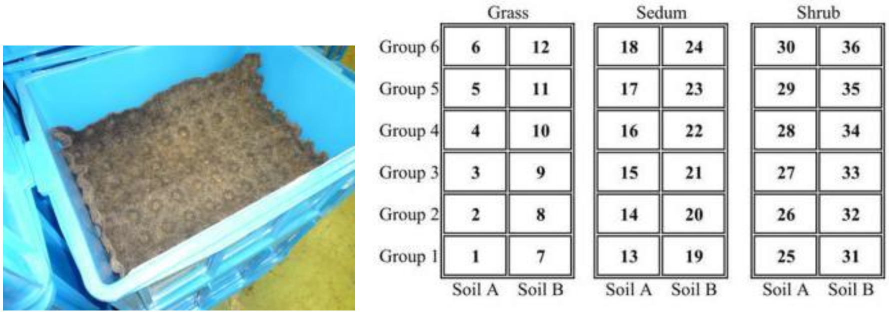
Evaluation of the performance of an extensive green roof on stormwater runoff mitigation is one of the major missions of this study. By using the five separated lots on the STHE roof, combinations of vegetation choices and substrate thicknesses (Lot1-4) were tested, and easily compared to the conventional rooftop represented by Lot5. For this purpose, each of the five lots was connected to an individual v-notch weir chamber where runoff rate can be measured and runoff water samples can be collected.

### 2.2. Part 2 – Laboratory Runoff Experiments

Laboratory runoff experiments were carried out to investigate the stormwater mitigation performance of different green roof systems (i.e. plant types, substrate mixes, substrate depths, and slope), under different scenarios (i.e. antecedent moisture condition, rainfall intensity, and plant age after establishment). For this experiment, 36 test plots were prepared in August 2012. Three plant species were chosen to represent respectively grass, sedum and shrub type vegetation cover: *Zoysia matrella*, *Sedum lineare*, and *Veronica serpyllifolia* as shown below in Figure 2.

Figure 2: (left to right) *Zoysia matrella* (馬尼拉草/台北草), *Sedum lineare* (佛甲草) and *Veronica serpyllifolia* (水藍星/小婆婆納)

Growth medium is another parameter being investigated in the laboratory experiments. Two soil mixes were used: Soil A is by volume 1:1 mixture of river sand and high quality peat moss. Soil B is a commercial potting soil with peat moss and other composts. Figure 3 (left) shows the actual test plot which is a 0.6 x 0.45 x 0.4m plastic container with an inspection window on one side; a drainage-and-filter layer for free drainage; 150mm soil substrate carefully and evenly added to avoid unnecessary compaction; and lastly, vegetation layer planted in the soil. Each soil and plant combination was replicated into six groups as shown in Figure 3 (right), and each group was analysed two months apart for the investigation of the age of the systems.



| | Grass | | Sedum | | Shrub | |
|---|---|---|---|---|---|---|
| | Soil A | Soil B | Soil A | Soil B | Soil A | Soil B |
| Group 6 | 6 | 12 | 18 | 24 | 30 | 36 |
| Group 5 | 5 | 11 | 17 | 23 | 29 | 35 |
| Group 4 | 4 | 10 | 16 | 22 | 28 | 34 |
| Group 3 | 3 | 9 | 15 | 21 | 27 | 33 |
| Group 2 | 2 | 8 | 14 | 20 | 26 | 32 |
| Group 1 | 1 | 7 | 13 | 19 | 25 | 31 |

Figure 3: Photo of box container and green roof layer (left), and combinations of plots (right)

Nine scenarios were studied for each group of test plots as listed in Table 1:

Table 1 List of Laboratory Runoff Experiment Scenarios

| Scenario No. | (rainfall, slope, no.of days after irrigation) |
|---|---|
| 1 | 10mm/hr, 1°, **1 day** |
| 2 | 10mm/hr, 1°, **3 days** |
| 3 | 10mm/hr, 1°, **7 days** |
| 4 | 10mm/hr, **3°**, 1 day |
| 5 | 10mm/hr, **6°**, 1 day |
| 6 | **30mm/hr**, 1°, 3 day |
| 7 | **50mm/hr**, 1°, 3 day |
| 8 | **70mm/hr**, 1°, 3 day |
| 9 | **100mm/hr**, 1°, 3 day |

In the experiment, the rainfall duration was set to be 1 hour, and the runoff measurement continued for another 45 min after rainfall stopped. The rainfall simulation setup included two types of sprinkler, one for larger events (100 and 70mm/hr) and the other for smaller events (10-

50mm/hr). A robot car design was used for the small events to achieve an even raindrop distribution (Figure 4).

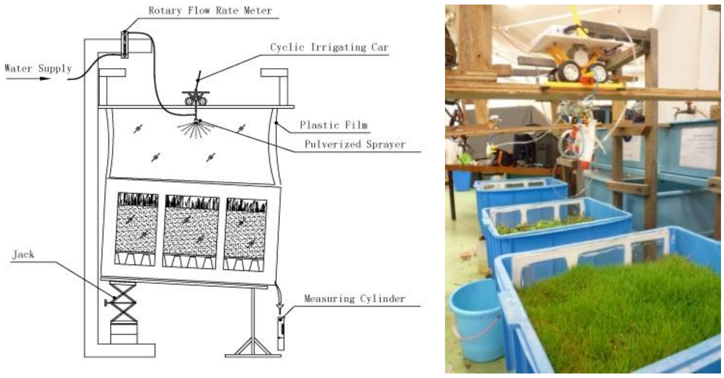


Figure 4: Rainfall Simulation Setup with Robot Car Design: Drawing (left) and Photo (right)

In this study, the retention volume is defined as the difference between total rainfall and total runoff volume. In the rainfall volume measurement, although the flow rate was calibrated each time, small variations were inevitable. To account for this uncertainty, percentage retention (% retention) was used, which is defined as the ratio of retention volume over rainfall volume. By doing so, the results from different trials and scenarios can be compared directly and easily.

Peak flow delay is defined as the difference between the peak runoff from control roof and that from a green roof, under the same experiment scenario, with a 5% range of tolerance in selecting the peak.

### 2.3. Part 3 – Runoff Water Quality Analysis

Runoff water samples were collected from the STSTW trial green roof 2012 and 2014. As described in previous sections, the green roof site is located on the STHE building and is divided into five lots (Lot 1–5), representing four extensive green roof systems (Lot1-4) and a traditional flat roof as the control (Lot 5). To avoid contamination from the pipes, sampling began 3 minutes after the first appearance of runoff. The samples were tested for the following water quality parameters using the corresponding methods as shown in Table 2:

Table 2 Summary of Runoff Quality Parameters and Methods Used

| Parameter | Method/Equipment |
|---|---|
| Total and dissolved copper | Flame atomic absorption spectrometry; Dissolved metal filtering using 0.45µm syringe filter; 3030E. nitric acid digestion (Standard Methods 21st edition) |
| Total and dissolved lead | |
| Total and dissolved zinc | |
| Total suspended solids | Filtering by 0.45µm membrane filter and dry weighing |
| Biochemical oxygen demand | 5210B. 5-day BOD test (Standard Methods 21st edition) |
| Reactive phosphorus | Hach DR/890 Colorimeter |
| Ammonium nitrogen | |
| Nitrate nitrogen | |
| Nitrite nitrogen | |
| pH | pH meter |
| Residual chlorine | Hach Pocket Colorimeter |

## 3. RESULT AND DISCUSSION

### 3.1. Part 1 – Field Measurement

One of the field rainfall-runoff measurements was conducted on 23rd July 2012 when Typhoon Vicente was approaching Hong Kong.

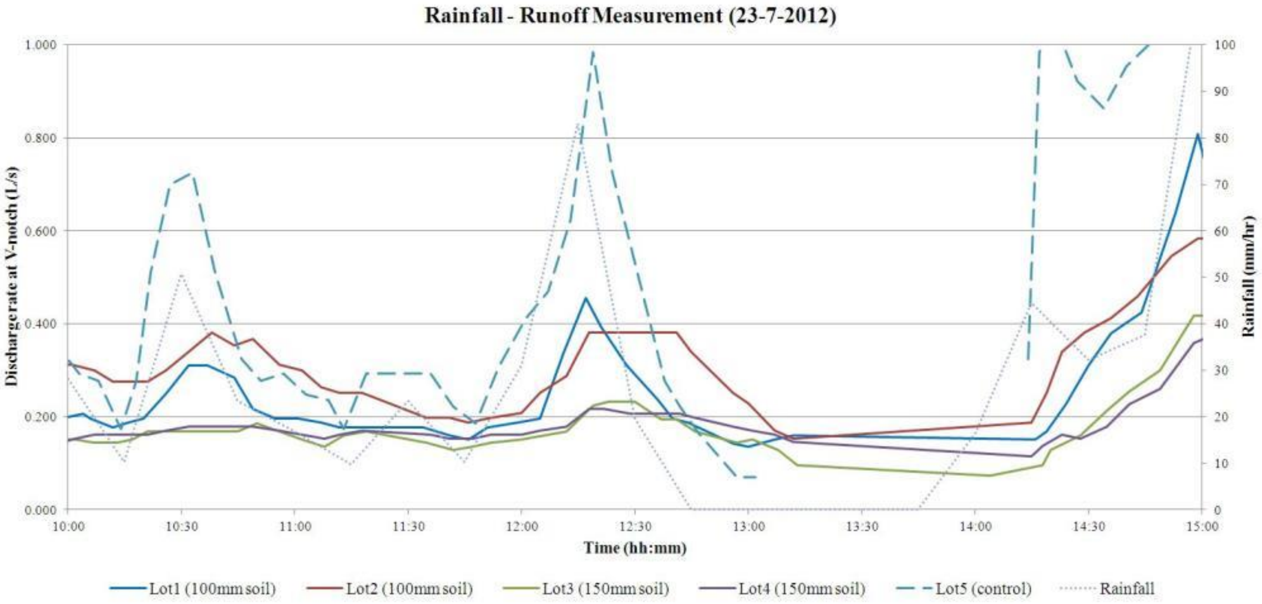


Figure 5: Runoff Measurement of Rainfall Event 23-7-2012

As shown in Figure 5, the runoff rate from the Lot5 control roof (thick dotted line) had significantly higher and earlier peaks after each round of rainfall (fine dotted line), comparing to the runoff rates from the green roofs. This difference can also be observed between the thinner (Lots 1 and 2) and the thicker green roof systems (Lots 3 and 4). In the figure, the runoff rates of Lots 3 and 4 (green and purple curves) were constantly lower and inert to rainfall, unlike in Lots 1 and 2 (blue and red curves), until the third rainfall event at about 14:30 hr. The difference between the two types of vegetation was however not as clear. A point worth mentioning is that water ponding during rainfall events was serious, which means the amount of retention measured may not be completely due to the green roof systems but also other structures on the rooftop.

### 3.2. Part 2 – Laboratory Experiment

Runoff Mitigation Performance among Groups

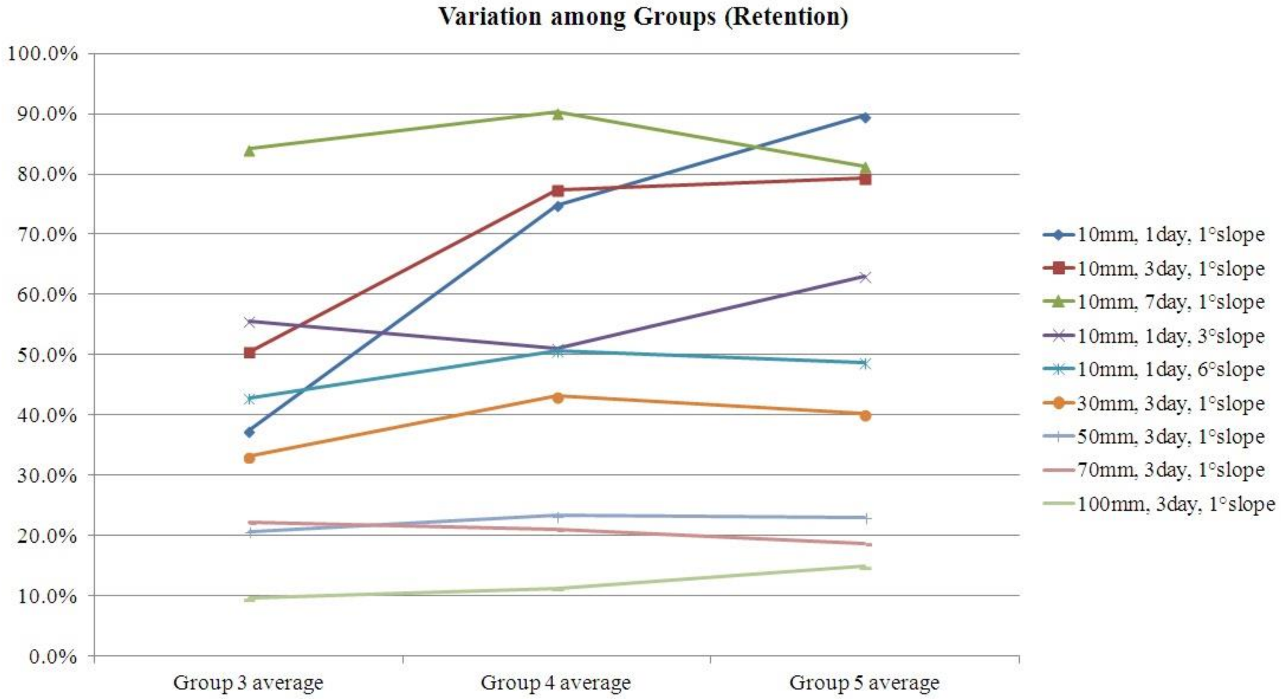


Figure 6: Retention Performance Comparison among Groups

Figure 6 shows the variation of retention rate among Group 3 to Group 5. Group 1 and 2 were removed due to the indoor storage condition during experiment period which did not favour plant growth.

It was observed that the runoff mitigation performance of Group 4, obtained in the hot and dry autumn 2013, increased significantly comparing to the results of Group 3. In Group 5 which was completed in winter 2013, performance dropped or remained stable. It suggests that the improvement in Group 4 was not due to the age of the test plots, but the antecedent conditions such as weather, irrigation and plant health. Based on this observation, results from all groups were averaged, and further analysis would focus on variations among test scenarios.

Retention in Different Scenarios

Table 3 Average %Retention by the Test Plots under Various Rainfall Intensities

| Rainfall Rate (mm/hr) | 10 | 30 | 50 | 70 | 100 |
|---|---|---|---|---|---|
| Ave. %Retention (Green Roof) | 69.6% | 38.9% | 22.4% | 20.6% | 12.0% |
| %Retention (Control) | 16.1% | 7.0% | 6.9% | 7.1% | 1.6% |
| Difference in %Retention | 53.5% | 31.9% | 15.5% | 13.5% | 10.4% |

From the laboratory experiment results summarized in Table 3, retention (as well as peak flow delay, to be discussed later) performance reduces with the increase of rainfall intensity as expected [2,3]. In condition “1° roof slope and 3 days after irrigation”, the average retention rate in 10mm/hr rainfall is 53.5%. The average retention rate in 30mm/hr is 31.9%.

According to the HKO rainstorm database in the past 16 years (i.e. 1998-2013) [5], 92% of the rainfall events in Hong Kong were below 30mm/hr. In addition to intensity, rainfall pattern is also important to green roof retention performance. It was found that within the rain season from April to September, the average number of days between rainfall events varied from 3.77 to 7.45 days. This range is higher than the 3-day “no-irrigation” interval of our experiment scenario, suggesting the possibility of a higher retention rate in real situation.

Therefore, an average retention rate of about 31.9 - 53.5% for a 150mm extensive green roof system can be expected in Hong Kong’s climate, assuming minimal irrigation. This range is also comparable to the results from other extensive green roof studies [6, 7, 8].

Peak Flow Delay Time in Different Scenarios

Table 4 Average Peak Flow Delay Time in Various Rainfall Intensities

| Rainfall Rate (mm/hr) | 10 | 30 | 50 | 70 | 100 |
|---|---|---|---|---|---|
| Ave. Peak Flow Delay Time (±5% in calculation of peaks) | 35min | 21min | 11min | 10min | 10min |

Similar to the retention performance results, detention time decreased with the increase of rainfall intensity, as shown in Table 4. As mentioned in the methodology section, peak flow delay time represents the gap between the moments of maximum rainfall rate and maximum runoff rate. The results (e.g. 35min. for 10mm/hr scenario) may appear longer than the 10min delay determined in several studies [9, 10, 11]. However, this result and this experiment design would be important to examine the maximum potential of different green roof systems in terms of runoff mitigation ability.

### 3.3. Part 3 – Runoff Quality Analysis

Water quality analysis results are summarized in Table 5:

Table 5 Green Roof Runoff Quality Analysis Results and Comparison

| **Parameter** | **Inflow** | **Green Roofs** | **Control Roof** |
|---|---|---|---|
| Total suspended solid (g/L) | 0.003 | 0.010 - 0.042 | 0.010 |
| Nitrite nitrogen (mg/L) | 0.091 | 0.049 – 0.105 | 0.062 |
| Nitrate nitrogen (mg/L) | 0.8 | 0.55 – 1.15 | 0.75 |
| Ammonium nitrogen (mg/L) | 0.04 | 0.01 – 0.07 | 0.03 |

| | | | |
|---|---|---|---|
| BOD (mg/L) | 0.18 | 0.09 – 0.42 | 0.25 |
| Reactive phosphorus (mg/L) | 0.12 | 0.18 – 0.35 | 0.11 |
| Residual chlorine (mg/L) | 0.03 | 0.03 – 0.04 | 0.03 |
| pH | 6.16 | 6.76 – 6.99 | 6.87 |
| Total Cu (mg/L) | 0.006 | 0.006 – 0.014 | 0.019 |
| Total Pb (mg/L) | 0.08 | 0.04 – 0.07 | 0.12 |
| Total Zn (mg/L) | 0.004 | 0.000 – 0.102 | 0.228 |

The result from the runoff water quality analysis is two-sided. On the negative side, values of the parameters including total suspended solid, BOD, nitrogen and phosphorus are higher in the green roof runoffs than in the inflow and control roof runoff. This result is predictable and is mentioned in other studies, as part of the excessive nutrients, small soil particles and organic matters from the green roof system will always be carried away by the runoff. Among Lot1-4, Lot 4 has particularly small values in several tests (i.e. BOD, nitrogen and phosphorus tests), which is probably because of the rainfall simulation experiments that were mainly conducted on this lot.

On the positive side, there are parameters that are lower in the green roof runoffs or remained unchanged, such as acidity (pH), copper, zinc, lead and residual chlorine. This result is also comparable to other runoff quality studies, which suggest that extensive green roofs are not sources, if not sinks, of heavy metals [7, 12], and that green roofs can neutralize mild acid rains [12, 13]. Among Lot1-4, there is no significant trend regarding the pollutant retaining performance. The values of residual chlorine in the inflow and runoffs were very similar.

## 4. CONCLUSION

This paper reveals the quality and quantity of the stormwater runoff from real experimental extensive green roofs so as to determine the applicability of using extensive green roofs as a part of the sustainable urban drainage system in Hong Kong. As regards runoff quantity mitigation, results from field measurements and laboratory experiments show that an extensive green roof system with 15cm substrate thickness is an effective device to retain and detain stormwater runoff. Under a 10mm/hr rainfall event, which is the most common in Hong Kong, the average retention rate of the green roof system is 31.9-55.5% better than that of a traditional concrete rooftop. Similarly, the average peak runoff delay of the green roof is 21-35 minutes longer. Substrate thickness, roof slope, and irrigation scheme are important parameters controlling the retention and detention performance of a green roof system, while the age of the system and the plant choice are not as significant given the plant growth is healthy and sustainable.

As regards runoff quality, results show that total suspended solid, organic matters and soil nutrients slightly increased in green roof runoff, comparing to the inflow and the control roof runoff. However, acidity and heavy metal contents (i.e. lead, copper and zinc) decreased in green roof runoff samples. The results are similar to the findings in other foreign green roof runoff quality studies, which agree that green roof is effective in neutralizing small acid rains and is recommended for mitigating stormwater. It is also important to use fertilizers and irrigation water responsibly (e.g. using slow release fertilizers and rain sensor) to minimize pollution to the downstream. The results in this study signify that extensive green roofs are an imperative component of SUDS design in Hong Kong.

## 5. ACKNOWLEDGEMENT

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