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Green roofs for stormwater mitigation in Hong Kong

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ABSTRACT

Hong Kong often faces stormwater problems during the rainy season. The heavy rainstorm could cause flooding and serious damages to the society. To tackle this, the Government has to make large investment in drainage and flood control projects which have significant socio-economic implications. The research findings in other countries indicated that green roofs can be an effective tool to help mitigate stormwater problems. The application of green roofs in the buildings can delay the starting time of the stormwater runoff and reduce the magnitude of peak runoff and the total amount of rainwater discharged from the buildings. Also, the roof greening method in urban areas can improve the quality of the built environment and provide useful spaces for community functions.

This paper explains the major findings of a research project to study the potential of green roofs for stormwater mitigation in Hong Kong. The rainfall characteristics and stormwater issues in Hong Kong are evaluated. The basic principles of green roof systems for stormwater management are studied. In addition, laboratory test and field studies have been done to assess the effectiveness of green roofs to alleviate the stormwater problem. Finally, the strategy to develop green roofs to improve the quality of urban environment is discussed.

Keywords: Green roofs, stormwater mitigation, Hong Kong.

1. Introduction

Like many urban cities in the world, Hong Kong is facing a range of environmental problems. An important one is related to stormwater runoff, which is ameliorated by variations in the climate in recent years (Mok, *et al.*, 2006). Climate change is expected to result in more frequent occurrence of extreme temperatures and precipitation events. Urban areas tend to exacerbate these problems because vegetation is often replaced by impervious surfaces for the urban land uses and development (Bass and Baskaran, 2003).

Stormwater runoff could cause problems in water quantity and quality and during extreme rainfalls, it can lead to flooding and erosion. Impermeable surfaces increase the flow of runoff during a storm event leading to the flooding. Mentens, Raes and Hermy (2006) pointed out that green roofs could be as a useful tool for mitigating the rainwater runoff problem in urban areas. Since vegetated surfaces are highly permeable, they can help reduce the amount of stormwater and attenuate the stormwater peak. Also, vegetation can reduce the urban heat island (UHI) effect. During the last two decades, a large amount of research has been done in Germany and other developed countries on the reduction of rainwater runoff for different types of roof greening. However, there is a lack of research information for the other parts and regions of the world.

This paper explains the major findings of a research project to study the potential of green roofs for stormwater mitigation in Hong Kong. The rainfall characteristics and stormwater issues in Hong Kong are evaluated. The basic principles of green roof systems for stormwater management are studied. In addition, laboratory test and field studies have been done to assess the effectiveness of green roofs to alleviate the stormwater problem. Finally, the strategy to develop green roofs to improve the quality of urban environment is discussed.

2. Stormwater Problems in Hong Kong

The general climate and topography of Hong Kong are described. The effects of heavy rainfall are explained.

2.1 Climate and Topography of Hong Kong

Hong Kong is located at the mouth of Pearl River Delta near the South China Sea and has a sub-tropical wet-and-dry climate. The mean annual rainfall ranges from around 1300 mm at Waglan Island to more than 3000 mm in the vicinity of Tai Mo Shan. About 80% of rain falls occur between May and September. August is the wettest month; its average monthly rainfall is 391.4 mm. Moreover, May to August is hot and humid season with occasional showers and thunderstorms. Whenever there is a tropical cyclone, the weather is usually fine and extremely hot; but isolated thunderstorms sometimes occur in the evenings. When cyclone comes closer, winds will increase and rain will become heavy and widespread causing subsequent landslides and flooding.

The topography of Hong Kong is characterized by uneven uplands and precipitous slopes. The landforms in the east are steep and rugged, while landforms in the west are mostly obtained from reclamation, thus they are generally low lying and subdued. In northern New Territories, they are spacious areas of flat land. Due to the features of landforms, places like Sheung Wan in Hong Kong West, Tai Po in northern New Territories suffer from flooding in rainy season, as the storm waters from steep slopes accumulate in the low lying area.

2.2 Effects of Heavy Rainfall

Mok, *et al.* (2006) showed that the rainfall over different regions of Hong Kong was generally on a rising trend ranging from 34 mm to 103 mm per decade (see Fig. 1). The rate was higher over urban areas than the New Territories, offshore islands and high grounds. It is believed urbanization is one reason for the rainfall's increasing trend and the regional variation in Hong Kong. The urban heat island effect also enhances convective activity and the increase in concentration of suspended particulates from urban activities favours the formation and development of rain-bearing clouds.

Heavy rains overload the stormwater drainage systems; rainwater can no longer dissipate naturally through ground infiltration and so increases surface runoff causing flooding and other serious problems. For example, when the heavy rains unleashed flooding in June 2008, roads and air traffic were shut down throughout the territory of Hong Kong.

Moreover, heavy rains can weaken a slope through saturation. When stability of a slope changes from a stable to an unstable condition, landslide may occur. Because Hong Kong is very densely populated, in the past, the heavy stormwater has caused many landslips and flooding, damage to properties and even loss of lives.

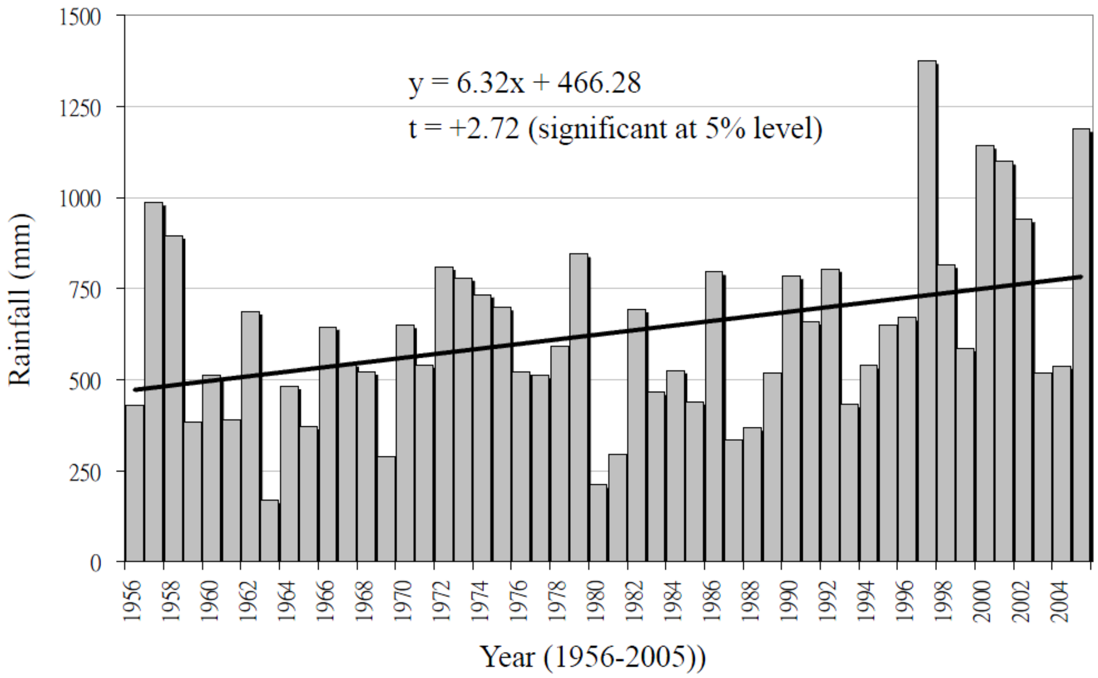


Fig. 1 Time series showing the annual rainfall difference between the Urban region and Offshore region in Hong Kong (Urban minus Offshore). The solid line indicates the linear trend over the period between 1956 and 2005 (Mok, *et al.*, 2006)

3. Stormwater Benefits of Green Roofs

Green roof systems could provide many environmental and social benefits (Hui, 2006), such as reduction of cooling loads and mitigation of urban heat island. They can also significantly reduce stormwater runoff (Dunnett and Kingsbury, 2008), and thus the cost of retaining stormwater in underground tanks and tunnels (Peck, *et al.*, 1999).

3.1 Basic Principles

Basically, a green roof (see Fig. 2) consists of a vegetation layer, a substrate layer and a drainage layer. It has the potential to deal with heavy rain problems; rainwater can be absorbed by the soil and the plants and transpired back to the atmosphere by "evapotranspiration" (it is the sum of total evaporation from vegetated surfaces and transpiration). The maximum amount of water can be removed from an area as quickly as possible. In fact, the stormwater benefits offered by green roofs include increasing retention, delaying the runoff peak, and decreasing the peak rate of runoff from the site. These benefits, in combination with the limited open space in cities, make green roofs a good method for easing the pressure on stormwater sewer systems. Also, green roofs intercept stormwater before it runs off a roof, and where water can be temporary stored, infiltrate and evaporate (DeNardo, *et al.*, 2003).

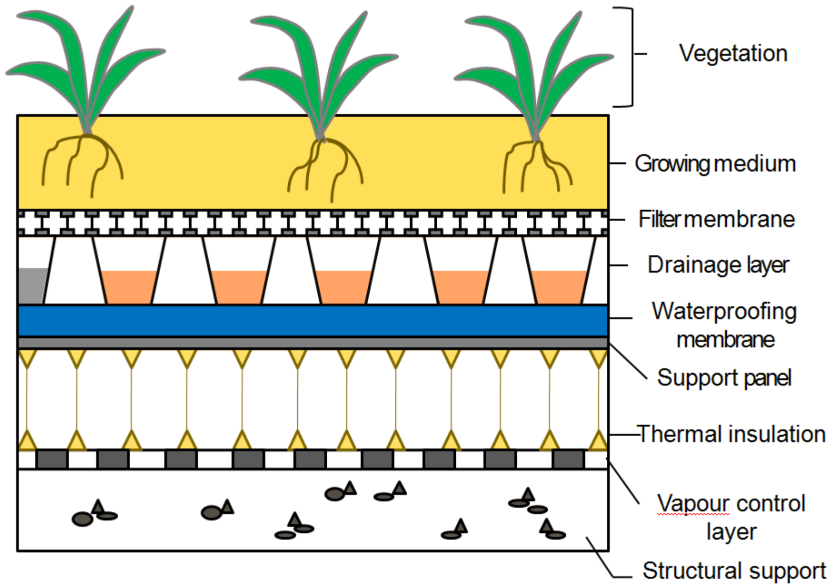


Fig. 2 Typical structure of extensive green roof

Hydrologic modeling demonstrated that widespread green roof implementation can significantly reduce peak runoff rates, particularly for small storm events (Carter and Jackson, 2007). Vegetated green roof systems not only reduced the amount of stormwater runoff, they also extended its duration over a period of time beyond the actual rain event (VanWoert, *et al.*, 2005). Therefore, green roof can delay the start of runoff and the peak flow. If designed properly, green roofs can retain water, as much as 90%, thereby significantly reducing storm water runoff and playing an important role in reducing the risk of flash flooding.

3.2 Actual Stormwater Runoff

The actual amount of reduction in stormwater runoff could vary from case to case. Bliss (2007) found that the absorption of rainwater by the substrate and plants reduces the peak flow rate and total volume of runoff by 5% to 70%. The performance is affected by storm duration, total rainfall amount and soil moisture prior to the storm. DeNardo, *et al.* (2003) showed from their field data an average 40% reduction in runoff from the green-roofed buildings; whereas Deutsch, *et al.* (2005) indicated 65%-85% reduction of roof runoff. It is interesting to note the research findings of Köhler, *et al.* (2001) that urban water retention by greened roofs in temperate (Berlin, Germany) and tropical climate (Rio de Janeiro, Brazil) are 50-75% and 65%, respectively.

4. Theory Analysis

To study carefully the potential benefits, a green roof hydrology model was constructed to simulate stormwater retention (Bass and Baskaran, 2003). The key parameters are analyzed and discussed below. As a green roof is a special type of catchment in terms of soil type, depth and vegetation, the model was based on the simulation of major hydrological processes.

4.1 Mass Balance Model

A mass balance system is used to evaluate the input and output parameters of a green roof (see Fig. 3). The model predicts that runoff will not begin until the field capacity of the system is exceeded. After this point, runoff will occur as determined by the first-order rate function. If rainfall exceeds runoff, the storage capacity of the green roof will continue to be filled. When the maximum water-storage capacity is attained, runoff will equal to rainfall.

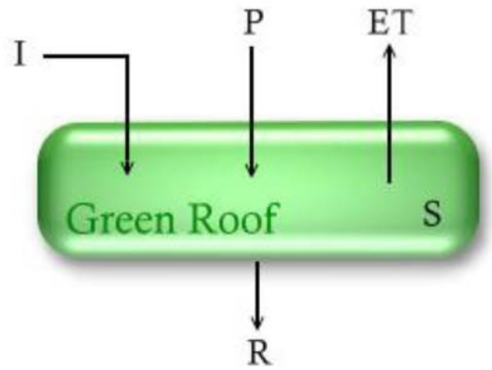


Fig. 3 Mass balance model of a green roof

The equation to describe the situation, modified from Deutsch, *et al.* (2005), is as follows.

$$R = P + I - ET - \Delta S \qquad (1)$$

where R = Rainwater runoff
P = Precipitation (rainfall)
I = Irrigation (artificial)
ET = Evapotranspiration
ΔS = Change in storage

When there is heavy rain, irrigation can be neglected. The change in storage is the water retention of different layers.

4.2 Evapotranspiration

Evapotranspiration (ET) is the volume of water lost into the atmosphere through plant respiration (through the stomata in leaves) and soil evaporation. It is a plant-mediated process and is also the most complex parameter in the mass balance equation. The degree of evapotranspiration depends on the type of plant, composition of substrate, type of drainage layer and moisture mat. Calculation of ET is affected by various weather elements including air temperature, relative humidity, solar radiation and wind speed. Rezaei, *et al.* (2005) used a greenhouse to control the environmental conditions and measure and predict ET from some extensive green roof plant species. They found that the evapotranspiration rate increases during summer months and decreases during winter months.

4.3 Water Storage

Several layers of a green roof system are responsible for storing natural rainfall (see Fig. 2). The stored water provides moisture to roots of plants, maintaining blooming plants on the roof. Besides, a major function of the layers is to reduce the volume of rainwater flowing into the sewage system. The most common water storage layers are soil, drainage and retention layer and moisture retention mat. Drainage layer plays an important role in storing water among the layers, however, they have close relationships with each other. In rainy days, the substrate is highly porous. Once the substrate is saturated, the excess rainwater filters into the drainage later and over into the moisture mat right below the drainage layer. After rainy days, the substrate dries out through plant usage and evaporation. The water stored into layer previously diffuses up into the substrate. Once the drainage layer has dried out, water in the moisture mat diffuses up through the holes in the drainage layer right above it.

4.4 Rainwater Runoff

Water runoff from roof top is caused by precipitation. Volume of rainwater runoff can be reduced by storage of retained rainwater in the green roof system. Fig. 4 shows a graph of rainwater runoff from a conventional flat roof and an extensive green roof. It can be seen that the time of water runoff has been delayed. Furthermore, not only the amount of runoff has been reduced, also the peak runoff has been alleviated (Dunnett and Kingsbury, 2008).

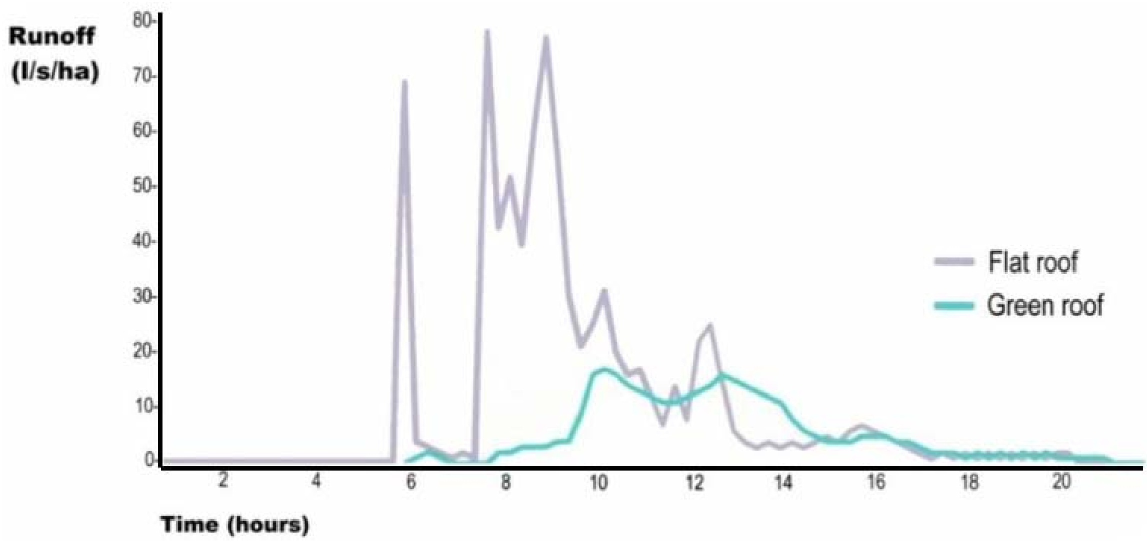


Fig. 4 Runoff from a conventional flat roof and an extensive green roof (Dunnett and Kingsbury, 2008) (adapted from a research in Germany)

Surface runoff is the water flow which occurs when water retention layers are all saturated, achieving the maximum water storing capacity, and rate of rainfall is large than that of runoff, then excess water starts to flow over the surface during heavy rain. Soil on the vegetation layer may be rinsed away by surface runoff. In a serious case, it will cause flooding. To ease the surface runoff, green roof can be designed to have a certain degree of roof gradient, leading the water to the channel.

5. Laboratory Tests and Field Studies

The test method to determine the water and media retention of drains layers used in green roof systems can be found in ASTM (2005). The drain layers retain water and media in cup-like receptacles on their upper surface (see Fig. 5). Examples include shaped plastic membranes and closed-cell plastic foam boards.

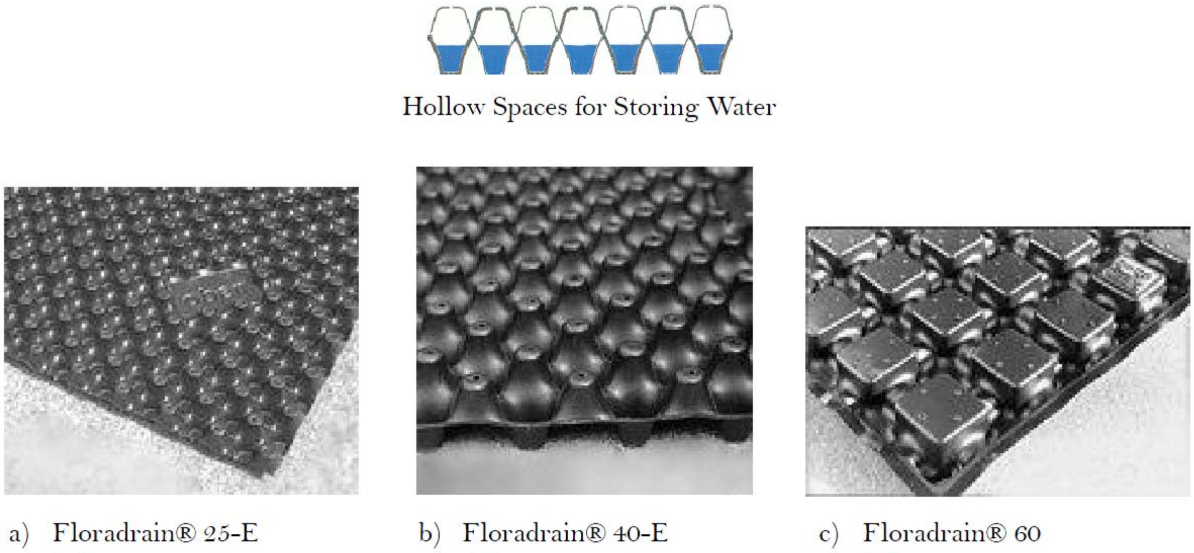


Fig. 5 Different types of drainage layer (Alumasc, 2007)

5.1 Laboratory Tests

The experimental set up for testing green roof modules and materials is shown in Fig. 6. Artificial rain (created from the circulating pump) is used for the testing and various components of green roof systems can be examined using this equipment.

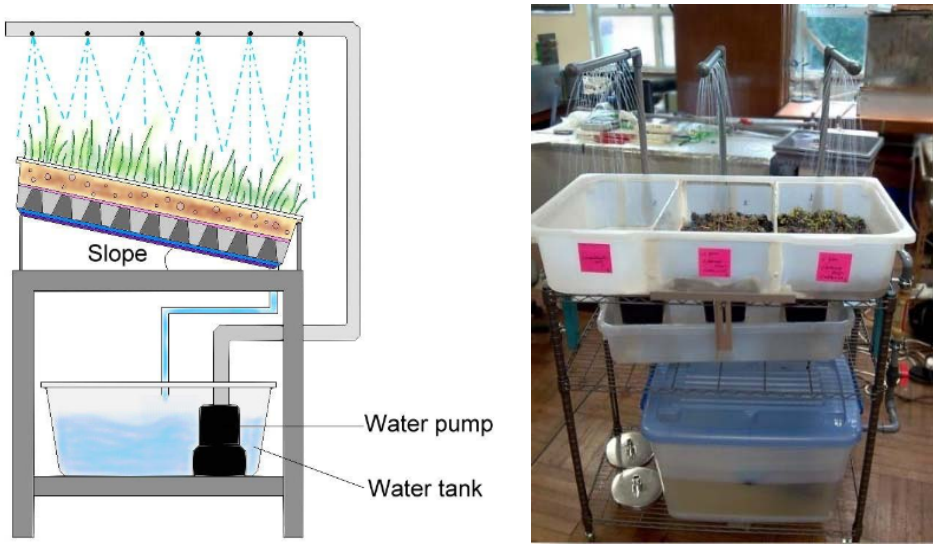
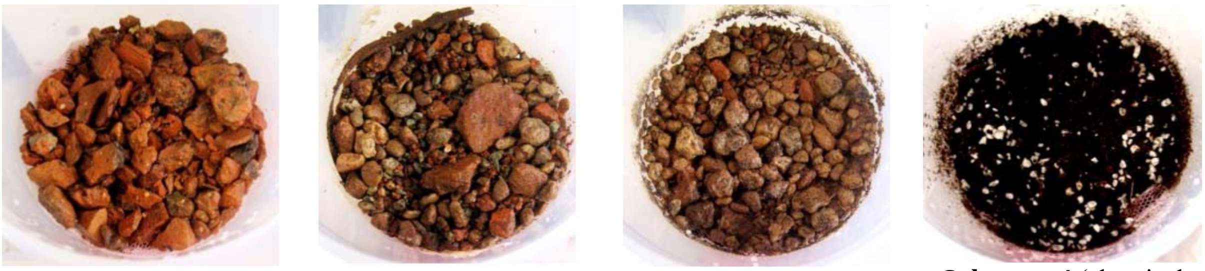


Fig. 6 Experimental set up for testing green roof modules and materials

(a) Investigation of soil/substrate

To investigate the properties of the soil/substrate commonly used for extensive green roofs in Hong Kong, four types of soils were tested in the laboratory. The substrates are placed inside circular plastic containers with some holes at the bottom and a filter inside (see Fig. 7). The depth of the soils is 7 cm. 300 millilitres of water were showered to the substrate in each trial. A summary of the test results and findings is given in Fig. 7.



Substrate 1 (crushed brick): the highest drainage ability, but the poorest storage ability

Substrate 2 (crushed brick and stones): high drainage ability, but cannot store water

Substrate 3 (crushed stones): high drainage ability, but cannot store water

Substrate 4 (chemical plant growing soil); high water storage ability, but poor drainage ability

Fig. 7 Four types of substrates under test

It is found that crushed stones and bricks (Subtrates 1 to 3) cannot be used for storing water. However, if the green roof requires good drainage to prevent water ponding, then these types of soils will function well. The chemical soil (Substrate 4) can support the vegetation and provide nutrient to them; it also has good water storage capability.

(b) Investigation of modular green roofs

To examine the components of modular green roofs, tests were performed using the experimental set up as shown in Fig. 6. There are three sections in the test unit (each about 20 cm x 50 cm) (see Fig. 8). The module on the right hand side is a green roof system with drainage and retention layer. The module in the middle is a system without drainage and retention layer. The module on the left hand side is the control to represent a conventional flat roof. The time and volume of runoff were tested under two situations: red rainstorm signal (> 50 mm in an hour) and black rainstorm signal (> 70 mm in an hour). It is found that the drainage and retention layer has significant effect on the alleviation of peak runoff.

Fig. 8 Testing of modular green roof components

5.2 Field Studies

A pilot green roof project was developed by HKU researchers at a primary school in Wong Tai Sin (Hui and Chan, 2008). The place for installing the green roof is an assembly hall (see Fig. 9) and the total greening area is about 238 m^2 (17 m x 14 m). Field studies were carried out on this green roof to evaluate the practical design issues and performance. Because of limitation of the structural loading on this roof, the weight of the green roof systems must be kept to a minimum. The shallow extensive green roof is mainly using sedum plant species that need very little soil and can survive under the hot summer in Hong Kong.

a) Overview of the green roof b) Sedum plant used on the green roof

Fig. 9 Green roof project in a primary school

Observations of the green roof during the rainy season in 2008-2009 indicated that the rainwater storage of the green roof is not large because only thin drainage layer and substrate layer are used. When heavy stormwater came (for example, during the typhoon attacks), surface runoff might occur on the surface of the green roof. At the beginning, when the sedum roots have not yet firmly grown in the soil, some soil on the vegetation layer has been rinsed away by surface runoff. But after a few months when the sedum roots have developed in the substrate layer, the situation has improved and the soil will not be rinsed away.

On-going research is now being designed to set up the measuring instruments for rainfall analysis on this green roof. The research will assess the runoff from the green roof and compare this with the runoff from a bare roof area. This could help evaluate the actual effects of the green roof on total and peak rainwater flows.

Bengtsson (2005) has carried out research in Sweden to study the peak flows from thin sedum-moss roof. It is found that neither slope nor length seems to significantly influence the runoff distribution. This implies that the vertical percolation process through the vegetation and the soil dominates the rainfall-runoff process. The presence of a drainage layer below the soil results in somewhat faster runoff compared to when there is no drainage layer, and thus results in an increased runoff peak.

6. Key Factors Affecting Water Storage Capacity

Water storage capacity is the range of available water that can be stored in soil. And this amount of water is available for growing crops on the vegetation layer. Maximum capacity is often used for identifying water storage capability of materials used in the layered superstructure in compacted condition. Besides, it can be used to indicate the water content of a substrate upon previous saturation with water (FLL, 2004).

There are a lot of elements affecting the water storage capacity of a green roof. The most significant components are the thickness and composition of substrate layer, type of plants of vegetation layer, type of drainage layer and moisture mat, and the degree of roof slope (Monterusso, *et al.*, 2004).

6.1 Substrate Layer

The substrate is an essential part of a green roof system. The appropriate structure and mix of substrate is vital to the long term health of the plants (see Fig. 7). The ability of substrate to store water depends on its thickness and its moisture content immediately prior to a rainfall event (Monterusso, *et al.*,2004). Bass and Baskaran (2003) found that when the substrate or growing medium was dry, it was able to retain 8 mm of water during a rain event. It is expected that green roof systems with a deeper soil and more vegetation would have even higher stormwater reduction potential.

The annual rainfall-runoff relationship for green roofs is strongly determined by the depth of the substrate layer (Mentens, Raes and Hermy, 2006). The rainfall-retention capability on a yearly basis may range from 75% for intensive green roofs (median substrate depth 150 mm) to 45% for extensive green roofs (median substrate depth 100 mm). Besides good water retention, the substrate should also provide compaction resistance to retain good drainage within the substrate. This is because if too much water remains in the substrate, plants may be deluged. In addition, the requirement for water retention is also affecting the depth, mix and structure of the substrate.

6.2 Vegetation Layer

The role of vegetation composition on green roof function, with particular regard to rainwater runoff is studied by Dunnett, *et al.* (2008). They pointed out that green roof vegetation can influence hydrological performance in a number of ways: through interception and evaporation of rainfall by the vegetation canopy and plant surfaces, through uptake and storage of water in plant tissues, and through transpiration of water from the plant back to the atmosphere.

In addition to factors such as climatic conditions, rainfall type, substrate qualities and aspect, vegetation characteristics such as canopy structure, density and architecture (related to rate of flow of water down stems), the water-holding capacity of plant tissues and of plant litter can influence the amount of rainfall that is intercepted, stored and returned to the atmosphere. Our current understanding about the plant physiological process is still limited at present.

6.3 Drainage and Retention Layer

Drainage and retention layer is one of the key internal factors. This layer can store water in porous aggregate, in containers or reservoirs (see Fig. 5). The water storage capacity mostly depends on the size of the containers or reservoirs. The type of drainage and retention layer to be used depends on the green roof system and/or the structure loading of the roof. For example, a drainage and retention layer with small containers is suitable for light weight extensive green roofs; a layer with large reservoirs can be a multi-functional system for intensive or semi-intensive green roofs.

On the other hand, to increase the drainage ability and reduce the green roof thickness, the drainage and retention layer can be placed reversely (see Fig. 8). The holes are now at the lower part. This increases the rate of drainage. However, the water storage capacity of the system will be decreased and mainly relies on the storage ability of substrate layer.

6.4 Slope of the Roof

Getter, Rowe and Andresen (2007) has tried to quantify the effect of slope on extensive green roof stormwater retention. They found that at four slopes (2%, 7%, 15%, and 25%) an average retention value of 80.8% was obtained. Mean retention was least at the 25% slope (76.4%) and greatest at the 2% slope (85.6%). VanWoert, *et al.* (2005) discovered that the combination of reduced slope and deeper media clearly reduced the total quantity of runoff.

The infiltration capacity of the porous soil decides the water storage capacity and influences the resistance of water to flow into deeper layers. Investigations in the past showed steep slope plots yield more runoff than those with gentle slopes and the quantity of runoff decreases with increasing slope length. This may be due to lower flow velocities and subsequently a longer time of concentration, that is the time needed for water to reach the outlet of drainage (Critchley and Siegert, 1991).

6.5 External Factors

The external factors include rainfall duration and rainfall intensity. As mentioned before, underflow starts when part of the maximum water capacity of the system is reached. Once the rain starts, the infiltration capacity depends furthermore on the moisture content prevailing in a soil. In addition, the moisture content in the system decreases with the rainfall rate. The rate of underflow finally equals the rainfall rate and the initial high capacity decreases with time if the rain continues. The capacity reaches a constant value as the soil profile becomes saturated.

On the other hand, the average size of raindrops increases with the rainfall intensity. At high rainfall intensity, the kinetic energy of raindrops causes a breakdown of the soil aggregate and soil dispersion with the consequence of driving fine soil particles in to the upper soil pores when raindrops hitting the soil surface. This leads to the formation of a thin but dense layer at the soil surface, reducing the infiltration capacity as well as the water storage capacity.

Using computer simulation and site data, Hilten, Lawrence and Tollner (2008) has revealed that rainfall depth per storm strongly influences the performance of green roofs for stormwater mitigation. They also showed that green roofs are highly effective for small storms; for larger storms, green roofs can act to extend runoff duration thereby reducing surge normally evident with impervious surfaces. This is consistent with the research findings by Teemusk and Mander (2007) who showed that greenroof effectively retained light rain; in the case of a heavy rainstorm (12.1 mm), the greenroof can delay the runoff for up to half an hour, but cannot fully retain it.

7. Discussions

The ability of a green roof to retain stormwater and limit the amount of fertilizer in the effluent flow is an important characteristic of a properly installed green roof system (Monterusso, *et al.*, 2004). Determining these performance characteristics of green roof systems provides information to facilitate the assessment of related engineering aspects, such as structural design requirements, mechanical engineering and thermal design requirements, and fire and life safety requirements (ASTM, 2005). Water capture is also useful in assessing irrigation requirements for green roof designs. Information about the unit media retention volume is required to predict the quantity of material that will be needed to construct a green roof with a specified total thickness.

7.1 Runoff Water Quantity and Quality

Runoff water quantity and quality from green roof systems have a direct impact on the urban ecosystem processes (Teemusk and Mander, 2007). Since urban runoff can also contain high levels of heavy metals and nutrients, the runoff water from urban impervious surfaces will not only increase the risk of flooding but also threat water resources through pollutants (Bliss, 2007). It is important to check and monitor the water quality.

In some situations, it is possible to integrate green roof with a rainwater recycling and storage system (this rainwater storage system includes a storage tank which is used to refill the flush water tank of a building). One of the advantages of installing green roof with rainwater storage system is the quality of rainwater collected from green roof is higher than that from a man-made conventional roof (Bass and Baskaran, 2003). This is because the leaves and roots of plants in the vegetation layer and the soil have the ability to filter numerous contaminants from water that flows through the system. Besides, some metals such a cadmium, copper, lead and zinc can also be taken out from rainwater though the green roof system.

7.2 Potential of Green Roofs in Hong Kong

Since green roofs have the potential to retain stormwater on the roof surface and lower the thermal loading on buildings, the greatest environmental benefits from green roofs might be achieved in subtropical climates (like Hong Kong) characterized by high temperatures and intense rain events (Simmons, *et al.*, 2008). With such a hydrologic performance, it is believed that green roofs are effective tools for mitigating stormwater problems in Hong Kong. It has the abilities to store a portion of stormwater within the system diminishing the volume of rainwater runoff and to delay the starting time of runoff. This can help alleviate the loading of the stormwater sewer system, minimizing the chance for flooding to occur.

Nevertheless, the effectiveness of the green roof systems depends on the scale and design. The impact that widespread green roof application could have on the water hydrology in the city of Hong Kong should be studied carefully. Hydrologic models might be set up and used for developing the stormwater mitigation programme (Carter and Jackson, 2007). There is a need to quantify the benefits of green roofs so that effective policies can be designed and implemented (Deutsch, *et al.*, 2005).

For high-density urban cities like Hong Kong, modular green roofs could be an effective solution (Hui and Chan, 2008). Analysis of stormwater retention and detention of modular green roof could help us understand their characteristics and limitations (Prowell, 2006).

7.3 Final Remarks

Green roofs are effective at reducing overall flow volumes, but they were not so good at reducing storm flow peaks (Mentens, Raes and Hermy, 2006). It is clear that roof greening alone will never fully solve the urban runoff problem and it needs to be combined with other runoff reduction measures (e.g. storage reservoirs in urban green or under infrastructure, rainwater cisterns, an increase of green areas).

Simmons, *et al.* (2008) found that green roofs can retain significant amounts of rainfall, this is dependent on the size of the rain event and design and can fail if not designed correctly. As green roofs vary so much in their design and performance, they must be designed according to specific goals rather than relying on assumed intrinsic attributes.

8. Conclusions

Hong Kong often faces stormwater problems during the rainy season. The heavy rainstorm could cause flooding and serious damages to the society. To tackle this, the Government has to make large investment in drainage and flood control projects which have significant socio-economic implications. It is crucial to consider effective strategies for the stormwater management.

Stormwater can be managed through storage, infiltration and retention. The research findings in other countries indicated that green roofs can be an effective tool to help mitigate stormwater problems. The application of green roofs in the buildings can delay the starting time of the stormwater runoff and reduce the magnitude of peak runoff and the total amount of rainwater discharged from the buildings. Also, the roof greening method in urban areas can improve the quality of the built environment and provide useful spaces for community functions.

There are many different types of green roof systems and most of them contain several layers which have the ability to store water. The most important layers include the substrate layer, vegetation layer, drainage and retention layer, and moisture mat. They work in an effective manner to reduce the volume of stormwater runoff leaving the roof surface and delay the starting time of runoff.

At present, our knowledge about green roof benefits and designs is still limited. More research investigations are needed to study the measures in the local context. It is hoped that effective green roof systems can be established very soon to mitigate the stormwater problems in Hong Kong.

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