Canadian Water Resources Journal

ISSN: 0701-1784 (Print) 1918-1817 (Online) Journal homepage: www.tandfonline.com/journals/tcwr20

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To cite this article: Daniel Roehr & Yuewei Kong (2010) Runoff Reduction Effects of Green Roofs in Vancouver, BC, Kelowna, BC, and Shanghai, P.R. China , Canadian Water Resources Journal, 35:1, 53-68, DOI: 10.4296/cwrj3501053

To link to this article: https://doi.org/10.4296/cwrj3501053

Published online: 23 Jan 2013.

Runoff Reduction Effects of Green Roofs in Vancouver, BC, Kelowna, BC, and Shanghai, P.R. China

Daniel Roehr and Yuewei Kong

Abstract: This research examines how distinct climatic conditions affect the runoff reduction functions of green roofs by comparing performance in Vancouver, BC, Kelowna, BC and Shanghai, P.R. China. To quantify the reduction in runoff volume effectuated by green roofs, both the Soil Conservation Service Curve Number (SCS-CN), crop coefficient method and the Hargreaves-Samani method are applied in calculating the annual water gains and losses of green roofs during a year of average precipitation, using local climate data such as precipitation, evapotranspiration, and temperature. Using a soil water balance model, the research also analyzes the change in soil water content of a typical green roof with a soil depth of 150 mm, and compares the potential irrigation requirements of plants with low versus high water requirements in each of the three cities. The calculation results show that the typical green roof could reduce annual rooftop runoff by 29% in Vancouver, 55% in Shanghai, and 100% in Kelowna. Furthermore, these results illustrate the important role that soil properties, soil depth, and plant selection play in maintaining growth of plants and minimizing green roof irrigation requirements.

Résumé : L'étude dont il est question ici a pour objectif d'examiner l'influence des conditions climatiques sur la fonction de rétention des eaux de ruissellement par les toits verts. Cet objectif est effectué par une comparaison de performance d'un toit vert de spécification typique dans les villes de Vancouver et Kelowna en Colombie Britannique ainsi que Shanghai en R.P. de Chine. Pour quantifier la réduction des eaux de ruissellement effectué par les toits verts, l'étude applique la "Soil Conservation Service Curve Number" (SCS-CN), la méthode "Crop Coefficients" (coefficients de cultures) ainsi que la méthode Hargreaves-Samani pour calculer les gains et pertes annuelles en eau par un toit vert pendant une année de précipitations moyennes, basé sur les donnés climatiques locales, comme les précipitations atmosphériques, l'évapotranspiration et la température. Se servant d'un modèle d'équilibre aquatique cette recherche explore d'avantage le changement du contenu d'eau d'un toit vert typique avec un substrat de croissance d'une épaisseur de 150 mm, et compare le besoin d'irrigation de plantes à haut

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Submitted December 2008; accepted August 2009. Written comments on this paper will be accepted until September 2010.

et bas niveau de demande d'eau dans chaque ville. Les résultats montrent qu'un toit vert typique pourrait réduire la quantité les eaux de ruissellement annuels de 29% à Vancouver, de 55% à Shanghai et de 100% à Kelowna. De plus, il s'avère que les spécificités du toit vert, en particulier, la qualité du sol, l'épaisseur du substrat de croissance et la séléction des plantes jouent un role important pour assurer la bonne croissance des plantes et amoindrir le besoin d'irrigation du toit vert.

Introduction

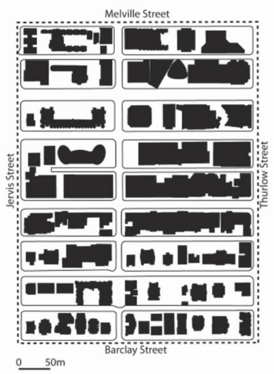
Urban population growth has caused tremendous urban sprawl and densification in many countries. In Canada, the population grew by 16% from 1991 to 2006 (Statistics Canada, 2008), which is the same rate as population growth in China during the same period (China Population, 2009). Moreover, an increasing number of citizens are now living in urban rather than rural areas. In North America, 80% of citizens live in urban areas (United Nations, 2008). In China, urban populations in major cities like Shanghai, have increased from 61.3% in 1980 to 86.8% in 2007 (Shanghai Municipal Statistics Bureau, 2008). Around the world, population growth and urban development have caused cropland, grassland, and forests to be paved over and replaced with the impervious surfaces of buildings, parking lots, streets and driveways, resulting in a myriad of environmental problems, one of which is the generation of large volumes of stormwater runoff. When green spaces are replaced by buildings and streets, rainwater can no longer infiltrate into the soil and contribute to groundwater recharge. This significant change to the urban hydrological system causes large fluctuations in the volume of stormwater runoff, often becoming extremely high during periods of rainfall and remaining very low during dry periods (Mentens *et al.*, 2006). Higher velocity runoff from impervious surfaces combined with increased runoff volume raises not only the risk of flooding and river erosion, but also the chance of overflows in combined sewer systems (T. Buck Suzuki Environmental Foundation, 2002; White, 2002). These combined sewer overflows (CSOs) can kill fish and threaten human health as sewage contains a host of heavy metals, nitrogen, phosphorus, and other toxic chemicals (T. Buck Suzuki Environmental Foundation, 2002). To cope with the problem of CSOs, urban sewer systems must be upgraded by increasing the capacity of wastewater treatment facilities or by separating sanitary sewers from storm sewers. Such infrastructure upgrades are costly and take many years to be implemented. In Vancouver, for instance, it will take 50 years to complete the separation of combined sewers across the city, at a cost of approximately $16,150,000 per year (Greater Vancouver Regional District, 2001).

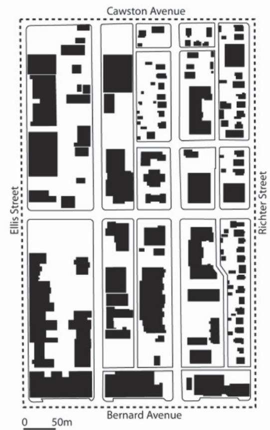
One way to mitigate stormwater impacts and improve micro-climate and biodiversity is to introduce extra vegetation and "micro" wild life habitat into cities (White, 2002; Jenks and Dempsey, 2005; Mentens *et al.*, 2006). However, the high coverage of impervious surfaces (Roehr and Laurenz, 2008; Roehr *et al.*, 2008) and high land prices in downtown areas have made the creation of vegetated green space that provides infiltration of water into subsoil very expensive. In this case, the large amount of unused rooftop area has a great potential to increase green space in cities. An analysis of a 20-hectare case study area (Figure 1) in downtown Vancouver shows that each hectare within this area has an average potential green roof area of 3,500 m^2.

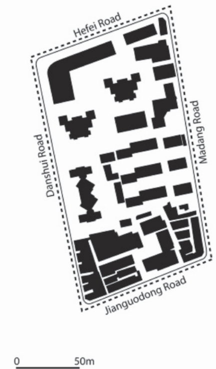
By applying green roofs to buildings, the quantity of stormwater runoff can be reduced and the quality of runoff improved (Peck *et al.*, 1999; Van Metre and Mahler, 2003). Research from Europe and North America has shown that green roofs can significantly reduce stormwater runoff volume and peak flow runoff by retaining rainwater in the growing medium (Köhler *et al.*, 2001; Dunnett and Kingsbury, 2004; Liu, 2004; Moran *et al.*, 2004; Bengtsson *et al.*, 2005; Connelly, 2006). However, the runoff reduction effects of green roofs are strongly related to local climatic conditions, such as precipitation and evapotranspiration. For example, while extensive green roofs in Berlin can retain 75% of annual precipitation (Köhler *et al.*, 2001) extensive green roofs in Vancouver can retain only 26% to 29% of annual precipitation (Connelly, 2006). For many cities interested in introducing green roofs as a stormwater management tool, the potential runoff reduction effects of green roofs remain unknown.

Through analyzing the soil water balance, the performance of green roofs can be estimated and their runoff reduction potential can be quantified.

Downtown Vancouver, BC[1]:	Downtown Kelowna, BC[2]:	Downtown Shanghai, China[3]







Downtown Vancouver, BC[1]:		Downtown Kelowna, BC[2]:		Downtown Shanghai, China[3]	
Total site area:	20ha	Total site area:	20ha	Total site area[4]:	2.2ha
Roofs area:	7ha	Roofs area:	6ha	Roofs area:	0.8ha
Average roof area per ha:	3500m^2	Average roof area per ha:	3000m^2	Average roof area per ha:	3700m^2

Notes:

1. GIS Map: City of Vancouver (http://vancouver.ca/VanMap)
2. GIS Map: City of Kelowna (http://www.kelowna.ca/website/ikelowna_map_viewer)
3. GIS Map: Shanghai Planning Bureau (www.shghj.gov.cn)
4. A typical neighbourhood is measured, as most neighbourhood in downtown Shanghai are high density and mixed with residential and commercial buildings.

Figure 1. Case study areas in three selected cities.

Vancouver, BC, Kelowna, BC, and Shanghai, P.R. China will be compared to demonstrate how local rates of precipitation and evapotranspiration influence the efficacy of green roofs in reducing stormwater runoff. Further, the paper explores the feasibility of applying green roofs to mega-cities like Shanghai to mitigate stormwater impacts. This paper applies the SCS-CN method, the crop coefficient method and the Hargreaves-Samani method to calculate stormwater runoff and the soil water balance of the proposed green roof systems, using local climatic data such as precipitation, evapotranspiration, and daily minimum and maximum air temperature. The findings of this paper may be useful to policy makers, urban planners, civil engineers and landscape architects in determining and developing the most locally-appropriate and effective green roof strategies for their cities.

Methodology

For traditional roofs, runoff rates are calculated using the Soil Conservation Service Curve Number (SCS-CN) method (U.S. Department of Agriculture, 1986). The SCS-CN method, which is also known as Technical Release-55 (tr-55), is widely used amongst engineers and watershed managers, as it provides simplified procedures for estimating runoff in small watersheds. This method is also recommended in many stormwater management manuals, such as *Stormwater Management Guidelines for the Province of Alberta* and *Stormwater Best Management Practices Manual for Georgia, New Jersey and North Carolina* (Alberta Environmental Protection, 1999; Atlanta Regional Commission, 2001; Department of Environmental Protection, 2004; Division of Water Quality, 2007).

In the SCS-CN method, urban areas are categorized by the cover type, each of which is assigned its own curve number dependent on the water transmission rate of soil. The higher the curve number, the more impervious the surface (U.S. Department of Agriculture, 1986). For example, impervious surfaces like roofs and streets have a curve number of 98, while pervious areas could range from 39 to 89. Pervious areas like lawns and parks could have a curve number of 39 if soils are well drained and grass coverage is greater than 75%, but 89 if soils are poorly drained and grass coverage is less than 50%. The runoff rate generated from traditional impervious roofs could then be calculated using Equations (1) and (2), and a curve number of 98 (U.S. Department of Agriculture, 1986).

When $P+2-200/CN>0$,

$$Q=\frac{(P+2-200/CN)^2}{P-8+800/CN} \quad (1)$$

When $P+2-200/CN<0,\ Q=0$ (2)

where Q is runoff, P is rainfall and CN is the curve number. Variables are measured in depth equivalent (inches, 1 inch = 25.4 mm).

The SCS-CN method cannot, however, be used when snowmelt runoff is included, as snowmelt cannot be estimated using SCS-CN method. Therefore, a snowmelt term (M), will be added to rainfall (P) in Equation (1) (U.S. Army Engineer Research and Development Center, 1998). In this paper, snowmelt (M) is simply considered as precipitation minus rainfall. Also, as snowmelt is influenced by daily mean air temperature, this paper assumes that snowmelt occurs only when daily mean air temperature is greater than 0°C (U.S. Army Engineer Research and Development Center, 1998). In this case, snowmelt (M) will be accumulated when daily mean temperature is less than 0°C and become runoff when daily mean air temperature is greater than 0°C. Snowmelt runoff is calculated by adding the sum of snowmelt (M) to rain, represented by P in Equation (1). Table 1 is an example of the snowmelt runoff calculation for Kelowna during a year with average precipitation (Environment Canada, 1998). As the runoff rate (Q) generated from each rainfall event can be calculated, total annual runoff can be determined by using daily precipitation data obtained from local climate stations.

Using the SCS-CN method alone has limits for the effectiveness in calculating runoff rates generated from green roofs, as it does not provide a curve number specifically for green roofs. Some research uses an experimentally derived curve number of 86 for green roofs (Carter and Jackson, 2006). However, a single curve number cannot represent all types of green roofs, as runoff would be influenced by soil depth, growing medium, and plant selection. Another critical distinction is that water retained by the growing medium of green roofs would drain into the downspout pipe as runoff rather than replenishing groundwater. To quantify the runoff rate of green roofs, this paper uses the following soil water balance (Hilten *et al.*, 2008)

$$\text{GR Runoff} = \text{I} + P - \text{ET} \pm \Delta\text{SW} \quad (3)$$

where I is irrigation, P is precipitation, ET is evapotranspiration, ΔSW is change in soil water content, and GR runoff is green roof runoff, which includes both surface overflow and water that drains out of growing medium when saturated. Variables are measured in depth equivalent. According to this soil water balance equation, runoff generated from green roofs can be considered as the sum of irrigation and precipitation minus all rainwater retained on plant surfaces (on leaves and stems) and in the growing medium.

For modelling purposes, two assumptions are made in the soil water balance model. Firstly, as the amount of rain water retained by leaves and stems is unknown, it is assumed to equal the surface depression of a traditional impervious roof. Surface depression refers to the fraction of the rainfall amount that is retained by unevenness (Mishra and Singh, 2003). In this case, the runoff rate of traditional roofs, which is calculated using SCS-CN method, can be considered as the available rainwater that can be retained by the soil and used by plants.

The amount of rainwater retained by soils is dependent on the water content of soil. Based on the properties of soil, field capacity is the amount of water held in the soil after excess water has drained away. When the growing medium reaches its field capacity, overflow will drain into the downspout pipe as runoff and end up in the city's sewer system. After all excess water has drained away, evapotranspiration of plants is the main cause of soil water content loss. It is assumed that the amount of rainwater retained by soils is equivalent to the sum of evapotranspiration during the preceding dry period. If irrigation is applied during

Table 1. Calculation example of snowmelt, Kelowna, BC

Year 1998	Precipitation (mm)	Rain (mm)	Snowmelt (mm)	Mean Temperature (˚C)	Rain+Snowmelt (mm)
1-7	6.2	2.2	0	-2.00	2.2
1-8	0.8	0	0	-5.40	0
1-9	0	0	0	-10.90	0
1-10	0	0	0	-12.60	0
1-11	0	0	0	-16.70	0
1-12	1.2	0	0	-16.00	0
1-13	5.4	0	0	-9.40	0
1-14	1.6	0	0	-5.80	0
1-15	0	0	0	-1.30	0
1-16	0	0	0	-1.10	0
1-17	0.8	0.4	13.4 [1]	0.50	13.8
Total	**16**	**2.6**	**13.4**	-	**16**

Notes:
1. Snowmelt occurs when daily mean air temperature is greater than 0˚C.
Snowmelt = Σ(Precipitation – Rain) = 16 mm - 2.6 mm = 13.4 mm

this period, the sum of irrigation will be added in the soil water balance. Therefore, the soil water balance equation is revised as

$$\text{GR Runoff} = Q + \Sigma \text{ I} - \Sigma \text{ ET} \quad (4)$$

where Q is the traditional impervious runoff, ΣI is the sum of irrigation, and ΣET is the sum of evapotranspiration during the antecedent dry period. Variables are measured in depth equivalent. Evapotranspiration (ET) of plants can be calculated by the crop coefficient method using (Allen *et al.*, 1998; California Department of Water Resources, 2000)

$$ET_c = Kc \times ET_o \quad (5)$$

where ET_c is evapotranspiration or water use of plants, ET_o is pan evaporation or reference ET for vegetation, and Kc is crop coefficient. Variables are measured in depth equivalent. For places where ET_o data are not available, the Penman–Monteith Combination equation is recommended for estimating potential evapotranspiration (ET_o) (Penman, 1948; Monteith, 1965; Allen *et al.*, 1998; Hilten *et al.*, 2008). Due to the lack of proper climatic data, the simpler Hargreaves-Samani method is used, with only a few weather parameter inputs (Hargreaves and Samani, 1985; Allen *et al.*, 1998; Hilten *et al.*, 2008). The Hargreaves ET_o in this paper is calculated using the *PMDay.xls spreadsheet*, with the inputs of latitude, daily maximum, and minimum temperature (Snyder and Eching, 2007). The Hargreaves-Samani method is shown as

$$ET_o = 0.408[0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a] \quad (6)$$

where T_{mean} is mean daily air temperature, T_{max} is daily maximum temperature, T_{min} is daily minimum temperature, and R_a is extraterrestrial radiation. 0.408 =1/λ factor converts from MJ $m^{-2}d^{-1}$ to mm d^{-1} (Allen *et al.*, 1998; Snyder and Eching, 2007). The reference surface assumed in Hargreaves-Samani method is based on the following definition:

"A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23" (Allen *et al.*, 1998).

Crop coefficient (Kc) in equation (5), ranging from 0 to 1, indicates the characteristic water use of different plant species. For example, a low water use species such as *Sedum* species has a Kc value of 0.25-0.35, while high water use species like sea pink (*Armaria maritima*) and moss rose (*Portulaca grandiflora*) have a Kc of 0.4-0.6. Turfgrass like perennial ryegrass (*Lolium perenne*) has an even higher Kc of 0.6-0.8 (City of Riverside Planning Department, 1994; California Department of Water Resources, 2000). The Kc value of plants is also influenced by density and microclimate (California Department of Water Resources, 2000). To calculate ETc of green roofs, this paper simplifies the Kc of green roofs by assuming that plants are mature and cover the entire roof area. An average Kc of 0.3 is used to represent low water use plants and 0.6 for high water use plants (City of Riverside Planning Department, 1994).

For modelling purposes, a proposed green roof system is required. An extensive green roof is usually defined as lightweight with thin soils (50-150 mm), and requires no maintenance or irrigation (Lawlor *et al.,* 2006). The greater the depth of the soil, the more water a green roof is able to retain. In this paper, a soil depth of 150 mm is used in the soil water balance model. Properties of soils like field capacity and wilting point of soils are used in the soil water balance model. Field capacity is the maximum amount of water the soil can hold, while the wilting point indicates the minimal point of soil moisture below which a plant wilts. Field capacity minus the wilting point is the water available to plants. According to previous research, the ideal green roof growing medium should be highly efficient at absorbing and retaining water, and must also be well aerated (Dunnett and Kingsbury, 2004). Clay and organic matter can improve water-holding capacity but cause poor aeration. Poorly aerated soils result in poor plant growth (Hitchmough, 1994; Dunnett and Kingsbury, 2004). This paper uses sandy loam soil for the soil water balance analysis, as research in Greece shows that sandy loam soil fosters better plant growth than other soil mixtures do (Nektarios *et al.,* 2004). Based on the soil properties defined in the *Water Balance Model* (BC Ministry of Agriculture & Lands, 2009), sandy loam soils have a field capacity ranging from 8% to 31%, a wilting point from 0% to 18%, and from 4% to 20% available water, depending on compaction and percentage of organic matter. In order to analyze the maximum potential stormwater retention effects of green roofs, a sandy loam soil with 20% maximum available water is used to calculate the soil water balance model. The hypothetical sandy loam soil is assumed to be normally compacted and mixed with 43% sand, 7% clay and 8% organic matter, and having a field capacity of 31% and a wilting point of 11% (BC Ministry of Agriculture & Lands, 2009). The proposed green roof with a soil depth of 150 mm would therefore have a field capacity of 47 mm, a wilting point of 17 mm, and an available water level of 30 mm.

Table 2 is a sample calculation of the daily soil water balance for the proposed Green Roof (GR) described above in Vancouver in September. The calculation uses rainfall data from 2006, a year with an average amount of precipitation, 1,224 mm, in Vancouver (Environment Canada, 2006). As shown in Table 2, during a drought period, soil water content will fall below the wilting point and irrigation will temporarily be required to maintain the plants on the green roof.

Once runoff rates are calculated, stormwater runoff volume can be deduced by multiplying runoff rate by surface area. Due to the differences in size of the case study areas, the average roof areas on each hectare of the selected sites (Figure 1) are calculated to compare the average rooftop runoff volume in the three selected cities. The selected case study areas are located in the downtown cores of the cities and the sites are measured from high quality aerial photos and GIS maps provided by the cities. With information about roof area and the rate of runoff generated by the roofs, total runoff can be calculated. Case study areas in Vancouver, Kelowna, and Shanghai are shown in Figure 1. A steep roof slope would result in higher rate of runoff during heavy rainfall events (> 6 mm), but would have the same runoff rate as a flat roof during light and medium rainfall events (< 6 mm) (VanWoert *et al.*, 2005). To simplify the calculation of runoff, the effect of roof slope on runoff rate is not considered in this study.

Calculated Results

Case Study Area 1: Downtown Vancouver, BC

Using the SCS-CN method and following the sample calculation shown in Table 1, the calculated runoff rate of an impervious roof is 736.5 mm per annum, when snowmelt is included. Based on the 20-hectare case study area in downtown Vancouver (Figure 1), average

Table 2. Example of daily soil water balance – low water use plants, Vancouver, BC.

Year 2006	Rainfall (mm)	Runoff *Q* (SCS-CN) (mm)	HS- ET_o (mm)	GR[1](Kc=0.3)		
				ET_c[2] (mm)	Soil water content[3] (mm)	Irrigation I (mm)
9-10	0.0	1.5	2.8	0.9	17.6	0
9-11	0.0	0.0	2.7	0.8	17.0	0.8
9-12	0.0	0.0	2.6	0.8	17.0	0.8
9-13	3.8	0.0	2.1	0.6	17.0	0.6
9-14	1.0	1.0	1.5	0.5	17.0	0.5
9-15	0.6	0.0	2.0	0.6	17.0	0.6
9-16	0.0	0.0	2.3	0.7	17.0	0.7
9-17	2.4	0.0	1.4	0.4	17.0	0.4
9-18	8.2	0.3	1.8	0.6	17.0	0.6
9-19	1.2	4.2	1.8	0.5	17.5	0
9-20	17.4	0.0	0.8	0.2	17.8	0
9-21	0.0	12.4	1.8	0.5	18.3	0
9-22	0.0	0.0	2.0	0.6	18.9	0
9-23	0.0	0.0	2.1	0.6	19.5	0
9-24	0.0	0.0	2.0	0.6	20.1	0
Total	**34.6**	**19.3**	**29.7**	**8.9**	-	**4.9**

Total Runoff (Traditional):19.3 mm
Total Runoff[4] (GR): 15.3 mm
Runoff Reduction (GR): 4.0 mm (20.7%)

Notes:
1. Green roof one with low water use plant (Kc = 0.3)
2. ETc = 0.3 × Hargreaves ETo
3. Soil Water Content = Antecedent Soil Water Content + Q – ETc. The maximum soil water content is field capacity (47 mm). When soil water content falls below wilting point (17 mm), irrigation will be required, which equals ETc minus Runoff *Q*.
4. Green roof runoff (GR-R) = $Q + \sum I - \sum ET_c$

roof surface areas account for 35% of total site area, which means each hectare of the site has an average of 3,500 m^2 of roof surface. Based on this study, a total runoff volume of 2,578 m^3 per hectare per annum would be generated from roof surfaces in the downtown area in Vancouver.

The runoff reduction of green roofs is strongly related to the evapotranspiration of plants. This study applies a crop coefficient of 0.3 for low water use plants like *Sedum* species, and 0.6 for high water use plants like sea pink (*Armaria maritime*) and moss rose (*Portulaca grandiflora*) on the proposed green roof (City of Riverside Planning Department, 1994).

According to the Hargreaves-Samani equation and using the *PMDay.xls spreadsheet* (Allen *et al*., 1998; Snyder and Eching, 2007), the calculated accumulated sum of reference evapotranspiration rates during the year 2006 was 717.1 mm. Using the crop coefficient method, the potential runoff reduction of green roofs is calculated to be 215.1 mm (29%) per annum using low water use plants (Kc=0.3) and 430.2 mm (58%) using high water use plants (Kc=0.6). Assuming an average of 3,500 m^2 of roof surfaces per hectare based on the case study site in downtown Vancouver, green roofs could prevent 753 m^3 of rainwater per annum from entering the sewer systems when planted with *Sedum* species, and 1,506 m^3 when using sea pink (*Armaria maritime*) and Moss Rose (*Portulaca grandiflora*).

Table 3. Soil water balance – low water use plants, Vancouver, BC.

Month	Available Rainwater (mm)	Evapotranspiration (mm)	Irrigation Requirement (mm) A	B
July	5.9	36.8	31.0	0
August	9.5	31.5	22.0	0
September	19.3	20.7	1.4	5.6
October	32.0	10.4	0	3.0
Total	**66.7**	**99.4**	**54.4**	**8.6**

Notes:
A: Soils (150 mm): Field Capacity (47 mm), Wilting point (17 mm)
B: Soils (150 mm) + Retention layer (50 mm): Field Capacity (97 mm), Wilting point (17 mm)

However, Vancouver is wet in winter and dry in summer. The most rainfall occurs during November, December and January, but very little evapotranspiration occurs during these months (Figure 2). Precipitation is lowest in August, when evapotranspiration rates of both low and high water use plants are the highest. Based on the calculation example shown in Table 2, the analysis of the soil water balance indicates that irrigation is needed for green roofs in Vancouver. In Vancouver's climate, only 20% of annual rainfall occurs during the summer period (April to September) when plants most need water (Environment Canada, 2006). Table 3 shows precipitation, SCS-CN runoff, and water use (ETc) of both low and high water use plants on green roofs. During the summer period, only 114.2 mm of rainwater would be collected from the roofs, but 172.1 mm of water is required by low water use plants, and 344.2 mm by high water use plants. High water use plants are therefore less appropriate for green roofs in Vancouver, as they would require more than 200 mm of additional water for irrigation in summer. Even when using low water use plants, it is necessary to ensure that the selected green roof growing medium is able to store enough water for plants to survive the summer.

Based on the proposed green roof with a 47 mm field capacity and a 17 mm wilting point, a total irrigation amount of 54.4 mm would be required by low water use plants as shown in Table 3. Using an additional retention layer to increase the capacity to 97 mm, the irrigation required by plants could be reduced to 8.6 mm. A retention layer with a filter membrane is installed over the water proofing membrane below the growing medium and can serve as a reservoir and release moisture during the dry period.

Case Study Area 2: Downtown Kelowna, BC

Compared to Vancouver, the climate of Kelowna is much drier throughout the year. As shown in Figure 3, precipitation is low in both winter and summer. In 1998 Kelowna received 370.8 mm of precipitation, an amount similar to the average annual precipitation (380.5 mm) since 1971 (Environment Canada, 1998), and was thus selected to be used in calculations for this model. Using the SCS-CN method, the calculated runoff rate of impervious roofs is 133.5 mm per annum. Based on a 20-hectare case study area in the city core of downtown Kelowna (Figure 1), the average roof surface areas account for 30% of the total site area, which means each hectare within the study site has an average of 3,000 m^2 of roof surfaces. It can thus be estimated that 400.5 m^3 of runoff per hectare per annum would be generated from roof surfaces in downtown Kelowna.

However, during the summer, both low and high water use plants have substantially higher evapotranspiration rates in Kelowna than in Vancouver (Figure 3). The Hargreaves-Samani equation indicated that the annual evaporation rate in Kelowna is

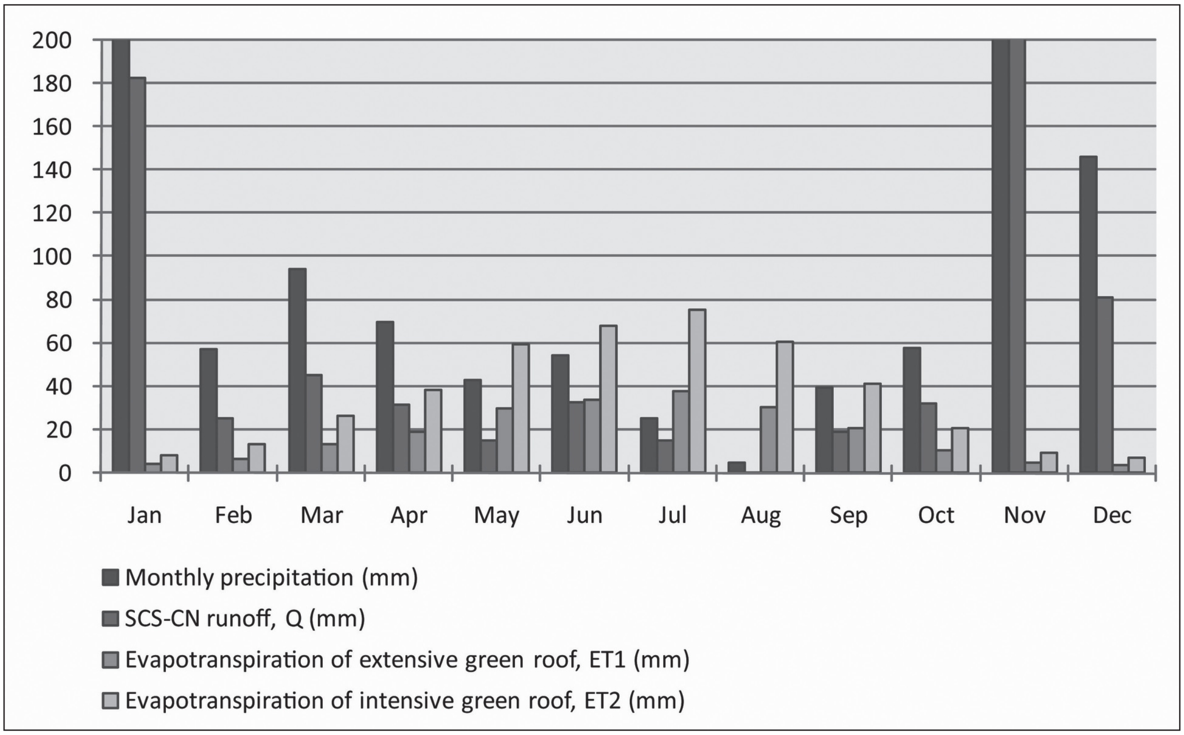


Figure 2. Precipitation, runoff, and evapotranspiration – Vancouver, BC.

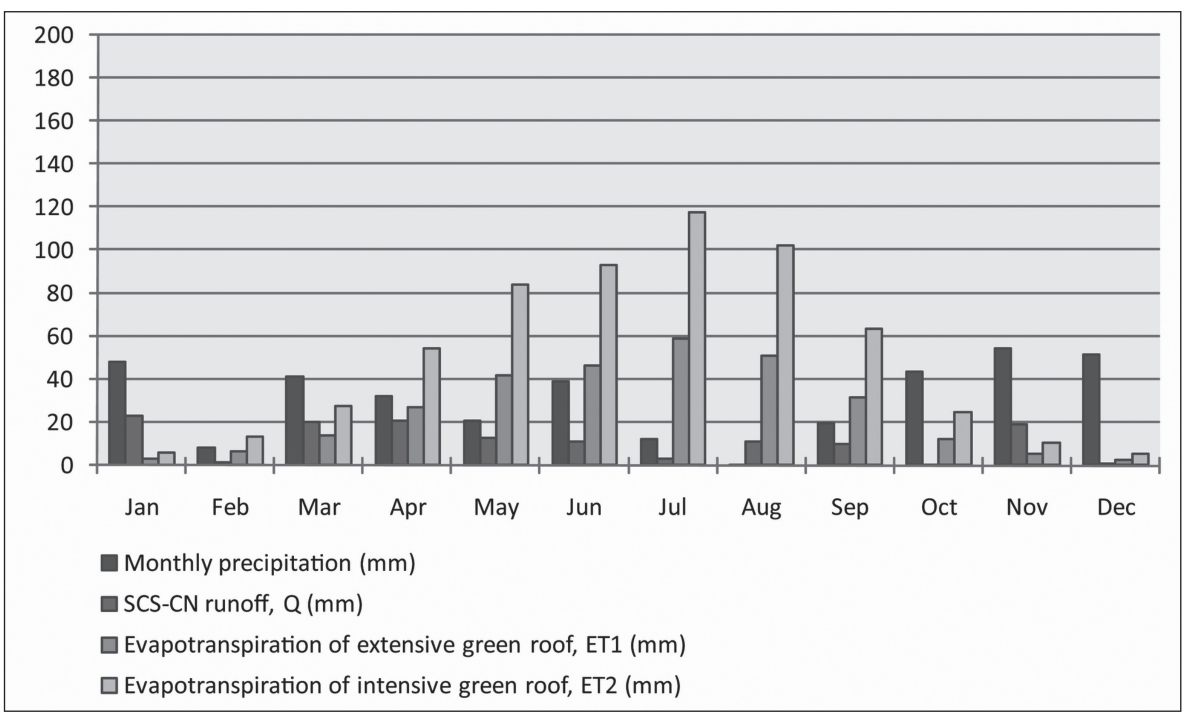


Figure 3. Precipitation, runoff, and evapotranspiration – Kelowna, BC.

1005.2 mm. According to the crop coefficient method, low water use plants (Kc=0.3) need 301.6 mm of water per year, and high water use plants (Kc=0.6) need 603.1 mm. As 301.6 mm would be required by low water use plants, but only 133.4 mm of rainwater could be collected from the roofs (44% of 301.6 mm), recommended green roof areas should not cover more than 44% of total roof areas. It would also be necessary to collect rainwater from adjacent impervious roof areas to provide adequate irrigation to the vegetated roofs, as shown in Figure 4.

The proposed green roof with a soil depth of 150 mm and 30% vegetation cover using low water use plants, would still require a total of 48.6 mm of irrigation, as shown in Table 4. If an additional retention layer is used to increase storage capacity to 97 mm, then irrigation required by plants could be reduced to 0.7 mm.

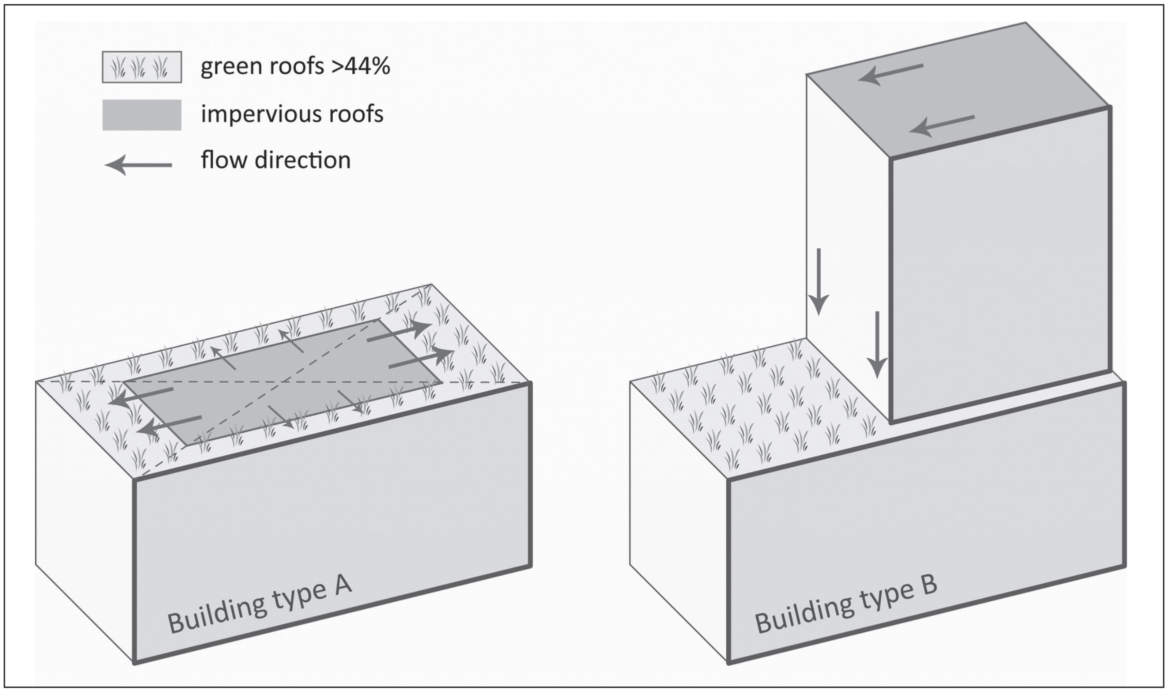


Figure 4. Scenarios of green roofs, Kelowna, BC.

Table 4. Soil water balance – low water use plants, Kelowna, BC.

Month	Available Rainwater (mm)	Evapotranspiration (mm) (greening 30% of the roof areas)	Irrigation Requirement (mm) A	B
July	4.5	25.9	21.4	0
August	0	22.5	22.5	0
September	9.3	14.0	4.7	0.7
October	17.5	5.4	0	0
Total	**31.3**	**67.8**	**48.6**	**0.7**

Notes:
A: Soils (150 mm) : Field Capacity (47 mm), Wilting point (17 mm)
B: Soils (150 mm) + Retention layer (50 mm): Field Capacity (97 mm), Wilting point (17 mm)

Case Study Area 3: Downtown Shanghai, P.R. China

The climate of Shanghai is wet and hot in the summer. In 2008, Shanghai received 1,254.5 mm of precipitation, the closest to the average annual precipitation (1,219 mm) since 2004 (Shanghai Climate Center, 2008). Using the SCS-CN method, the calculated runoff rate of impervious roofs is 887.3 mm per annum. Based on the 2.2-hectare case study area in the city core of downtown Shanghai (Figure 1), the average roof surface area accounts for 37% of the total site area, meaning that each hectare of the site has 3,700 m^2 of roof surfaces. In this case, a total runoff volume of 3,283 m^3 per hectare per annum would be generated from the roof surfaces.

Shanghai has similar annual precipitation and evapotranspiration rates to Vancouver, but most of the rainfall occurs during the summer, as shown in Figure 5. The evapotranspiration rate in Shanghai is 813.8 mm per annum (Shanghai Municipal Statistics Bureau, 2008). During most months of the year, precipitation was higher than evapotranspiration rates of both low and high water use plants (Figure 5). Calculated with the crop coefficient method, the potential runoff reduction of green roofs is 244.1 mm (28%) per annum when low water use plants (Kc=0.3) are used, and 488.3 mm (55%) with high water use plants (Kc=0.6). Through the analysis of the soil water balance, the soils of these green roofs have a field capacity of 47 mm and a wilting point of 17 mm and can therefore provide enough water for the low water use plants (Kc=0.3) (Table 5). By increasing the capacity to 97 mm with an additional retention layer, water retained on green roofs could be enough to support even high water use plants (Kc=0.6) without employing the use of an irrigation system (Table 5).

Discussion

Research has shown that green roofs can significantly mitigate urban stormwater impacts. However, climatic influences on green roofs should be carefully considered when planning and designing a green roof, as inappropriate designs can lead to additional irrigation requirements, thereby increasing water consumption, which would make green roofs less ecologically beneficial. Using an average Kc of 0.3 for low water use plants the crop coefficient method can be used to calculate the daily water use. A simple soil water balance model can further analyze whether water

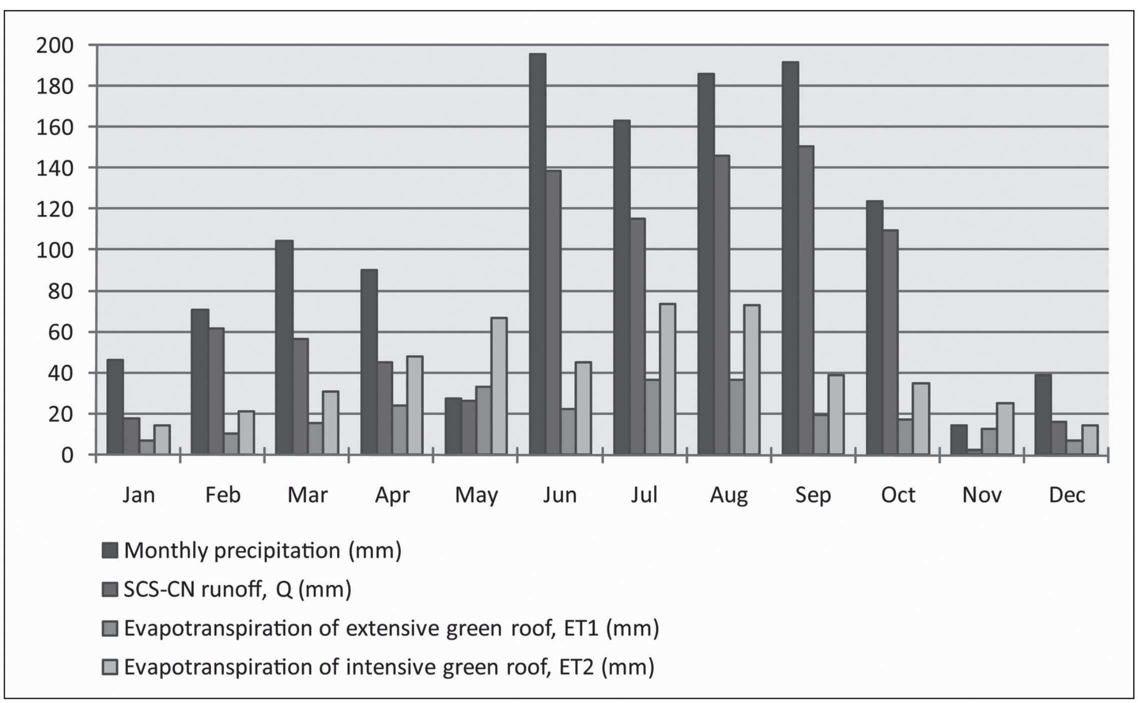


Figure 5. Precipitation, runoff and evapotranspiration – Shanghai, P.R. China.

Table 5. Soil water balance- low and high water use plants, Shanghai, China.

Month	Available rainwater (mm)	ETc1 (Kc=0.3) (mm)	Irrigation for A (mm)	ETc2 (Kc=0.6) (mm)	Irrigation for B (mm)
July	115.6	37.0	0	74.0	0
August	145.5	36.5	0	73.0	0
September	151.1	19.5	0	39.0	0
October	107.4	17.5	0	35.0	0
Total	**519.6**	**110.5**	**0**	**221.0**	**0**

Notes:
ETc1. Evapotranspiration rate of low water use plants (Kc=0.3)
ETc2. Evapotranspiration rate of high water use plants (Kc=0.6)
A: Soils (150 mm) : Field Capacity (47 mm), Wilting point (17 mm)
B: Soils (150 mm) + Retention layer (50 mm): Field Capacity (97 mm), Wilting point (17 mm)

stored in the green roof growing medium is sufficient for plant use during the drought period.

According to the results calculated for Vancouver, the proposed green roofs with a maximum soil depth of 150 mm of silt soils and low water use plants can reduce summer runoff by 95%, winter runoff by 8%, and annual runoff by 29%. This is similar to the results measured by researchers at the British Columbia Institute of Technology, which show an annual reduction of 26%, with reduction rates of 94% in summer and 13% in winter (Connelly, 2006). However, there are limits to this research, as the SCS-CN method is less accurate for small rainfall events, and the Kc value of plants can be influenced by factors such as elevation, shading, wind, water content of soils, and estimated reference evapotranspiration. The Penman–Monteith method uses more parameters and can therefore generate more accurate results. For the purposes of this paper, it is assumed that the amount of rainwater retained by leaves and stems of plants is equivalent to the surface depression storage of a traditional impervious roof, so that the SCS-CN method can be used. It is possible that mature plants with high vegetation density could retain more rainwater on leaves. This research assumes a soil depth of 150 mm, but many green roofs might actually have thinner soil, which could cause wilting of plants or lead to higher required amounts of irrigation.

Conclusions

Precipitation and evaporation play a significant role in determining runoff reduction effects of green roofs, while soil type, soil properties and plant selection influence plant health and growth and affect irrigation requirements. With annual precipitation totalling over 1200 mm, green roofs are an effective stormwater management tool in both Vancouver, BC and Shanghai, P.R. China, where they are able to reduce runoff significantly, particularly in the downtown area where there are few green spaces capable of absorbing stormwater from surrounding impermeable surfaces. Calculations of evapotranspiration rates indicate that green roofs could potentially reduce runoff by 29% to 58% in Vancouver. However, analysis of the soil water balance shows that only low water use plants would be appropriate for green roofs in Vancouver, as dry summer periods mean that little water is available to plants during the months of April through September. For green roofs with a soil depth of 150 mm and 30 mm of available water, low water use plants (Kc=0.3) like *Sedum* species would require 31 mm of irrigation in July and 22 mm in August. Assuming an average roof area of 3,500 m^2 per hectare in downtown Vancouver, 753 m^3 of rainwater per hectare could be absorbed annually by green roofs.

In Shanghai, the calculation of evapotranspiration shows that green roofs could potentially reduce runoff by 28% to 55%. As 68% of rainfall occurs during the summer, an analysis of the soil water balance indicates that both low water use plants and high water use plants would be appropriate. A soil depth of 150 mm with 30 mm of available water would be sufficient to meet the needs of low water use plants (Kc=0.3). If total available water is increased to 80 mm through the use of water retention layers, high water use plants (Kc=0.6) could be used. Therefore, to maximize the runoff reduction effects of green roofs in Shanghai, the use of high water use plants is encouraged. Assuming an average roof area of 3,700 m^2 per hectare in Shanghai, green roofs could potentially reduce stormwater runoff by 903.2 m^3 per hectare per annum using low water use plants and 1,806.7 m^3 using high water use plants.

For the city of Kelowna, where annual precipitation is less than 400 mm and the density of the city is low, bio-swales and rain gardens could be substituted for green roofs as a lower-cost stormwater management tool. The application of green roofs should be considered for other environmental benefits, such as improving air quality, mitigating Urban Heat Island effects, improving biodiversity and reducing energy demands of buildings. Green roofs should not be applied to more than 44% of total roof area, and should be designed to receive runoff generated from adjacent impervious roof surfaces to eliminate the need for irrigation with potable water.

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