A field study to evaluate runoff quality from green roofs

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Abstract

Green (vegetated) roofs are emerging as practical strategies to improve the environmental quality of cities. However, the impact of green roofs on the storm water quality remains a topic of concern to city planners and environmental policy makers. This study investigated whether green roofs act as a source or a sink of various metals (Na, K, Ca, Mg, Al, Fe, Cu, Cd, Pb, Zn, Mn, Cr, Ni, Li and Co), inorganic anions (NO$_3^-$, NO$_2^-$, PO$_4^{3-}$, SO$_2^{4-}$, Cl$,^-$, F$^-$, and Br$^-$) and cation (NH$_4^+$). A series of green roof assemblies were constructed. Four different real rain events and several artificial rain events were considered for the study. Results showed that concentrations of most of the chemical components in runoff were highest during the beginning of rain events and subsided in the subsequent rain events. Some of the important components present in the runoff include Na, K, Ca, Mg, Li, Fe, Al, Cu, NO$_3^-$, PO$_4^{3-}$ and SO$_2^{4-}$. However, the concentration of these chemical components in the roof runoff strongly depends on the nature of substrates used in the green roof and the volume of rain. Based on the USEPA standards for freshwater quality, we conclude that the green roof used in this study is reasonably effective except that the runoff contains significant amounts of NO$_3^-$ and PO$_4^{3-}$.

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1. Introduction

Being invented for esthetic appeal, green (vegetated) roofs are now gaining increased recognition in many countries such as Germany, Sweden, USA, UK, Japan and Singapore (Mentens et al., 2006; Berndtsson et al., 2008). Green roofs have several positive effects in the urban setting with the most important ones being their ability to retain and detain storm water (Villarreal and Bengtsson, 2005), reduce urban heat islands (Wong et al., 2003), reduce building energy consumption by cooling roofs during summer months (del Barrio, 1998), and create habitats for certain plants and animals and thereby improve urban biodiversity (Emilsson et al., 2007) and finally, their esthetic appeal. Despite constraints such as high capital and maintenance costs, green roofs have received increased attention in view of their beneficial impacts. From the storm water management perspective, green roofs can play an important role in modern urban drainage because of their ability to slow down and reduce runoff volume. High evapotranspiration from a green roof can reduce the annual runoff to less than half the precipitation (Liesecke, 1998; Knoll, 2000; Bengtsson et al., 2005). The temporal storage of water in the soil and vegetation reduces peak flow, which prolongs the time-of-concentration. A reduction in the peak flow of roof runoff implies that local urban flooding and combined sewers overflows can be considerably reduced.

An important factor which is often overlooked in previous studies published in the literature is the runoff quality from green roofs (Berndtsson et al., 2006, 2008). Theoretically, green roofs can act as pollution adsorbents and filters. However, they can also potentially contribute to the degradation of the quality of receiving waters with pollutants released from soil,
plants and fertilizers. Of the very limited literature on runoff quality assessment, green roofs are often regarded as a source of contaminants (Moran et al., 2003; Berndtsson et al., 2006; Teemusk and Mander, 2007; Berndtsson, 2010). Research conducted on vegetated roofs at Augustenborg (Malmö, Sweden) and Canoe Club House (Malmö, Sweden) has shown that vegetated roofs behave as a source of contaminants, in particular, heavy metals (Berndtsson et al., 2006). Another study on green roof in Tartu, Estonia (Teemusk and Mander, 2007) revealed that a lightweight aggregates (LWA)-based green roof has a considerable effect on the quality of runoff water. During a 9-month monitoring period on two green roofs constructed within the Neuse river basin of North Carolina, Moran et al. (2003) identified that green roof functions as a best management practice for water retention and peak flow reduction. However, water quality data indicated that higher nutrient concentrations were present in the green roof runoff than those in the rainfall and control roof runoff, respectively.

The fundamental studies mentioned above have highlighted the importance of further research on the quality of runoff from green roofs. To enhance our knowledge-base on this topic of great concern, the present study was initiated with the objective being to evaluate how local soil and commercial substrate-based green roofs function during simulated (artificial) and real rain events. To achieve this task, four pilot scale green roof assemblies were constructed and operated on a real roof in an urban setting. Four real rain events and ten different simulated rain events (5–50 mm) were studied to evaluate the runoff water quality on the basis of several physico-chemical parameters along with metals (Na, K, Ca, Mg, Al, Fe, Cu, Cd, Pb, Zn, Mn, Cr, Ni, Li and Co), inorganic anions (NO$_3^-$, NO$_2^-$, PO$_4^{3-}$, SO$_4^{2-}$, Cl$^-$, F$^-$ and Br$^-$) and cation (NH$_4^+$).

2. Experimental

2.1. Study site and roof top design

A green roof test plot was established on the EA building in June 2009 on the campus of the National University of Singapore. The roof systems were custom-designed in several 1 m × 1 m polycarbonate assemblies (Fig. 1), with the same principle as full-scale vegetated roofs. All assemblies were placed on a 4° slope to simulate common roof design. The roof runoff was collected from the lower end of the assembly through a slit (Fig. 1). The assembly consisted of three layers, the uppermost being a vegetation layer comprising of a thick growing substrate (15 cm) and plants. The second layer was a filter layer in the form of a geotextile (membrane material), which prevented small particles from being washed from the substrate layer into the drainage layer or out of the system. The third layer was a drainage layer (3 cm) in the form of pebbles (5–15 mm) (D1), or a commercial drainage element (D2).

Two types of substrates were used in the present study. The first was a local garden substrate, under the trade name “universal garden soil” (S1). Its major constituents included white peat, black peat and clay. Some of the important characteristics of the substrate include, pH (5.0–6.0), conductivity (40 mS/m), organic matter (22%), N$_{total}$ (200 mg/L), P$_2$O$_5$ (130 mg/L), K$_2$O (260 mg/L), CaO (150 mg/L), MgO (40 mg/L), SO$_4^{2-}$ (120 mg/L), Cl$^-$ (30 mg/L). The second substrate was a commercial substrate produced under the trade name DAKU (S2). This substrate is based on natural inorganic volcanic material, compost, organic and inorganic fertilizers, but the exact composition is proprietary. The substrates S1 and S2 had dry bulk densities of 243 and 1040 kg/m$^3$, respectively, and saturated wet bulk densities of 492 and 1430 kg/m$^3$, respectively. Both substrates were spread to a depth of 15 cm across the assembly. For the DAKU substrate, a commercial drainage element (D2) was used. This drainage element is specially made from pressure molded expanded polystyrene. It is especially designed to collect rain water in small compartments, thus drastically reducing the frequency of watering; and excess water can be drained off.

The selection of plant species was based on their ability to survive in low nutrient conditions, drought conditions and extreme temperature. Sedum mexicanum was selected for the present study and was obtained as 10 cm average diameter and 8 cm high plugs which were planted in the substrate at a density of 64 plugs/m$^2$. Once planted, the vegetation kept growing naturally with neither fertilization nor artificial watering. Within two months old vegetation, field experiments were conducted. Among the two substrates, S. mexicanum was

![Fig. 1 – Green roof assemblies in EA roof top in National University of Singapore (A1 – control roof; A2 – roof with universal garden soil; A3 – roof with universal garden soil along with plants; A4 – commercial assembly; S1 – universal garden soil; OO – overflow outlet; SC – sample collection; GF – geotextile fiber; DL – drainage layer) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).](image-url)
fully grown only in S1 as the universal potting soil supports most of the plant species. On the other hand, plants in S2 were unable to survive due to insufficient fertilizers and the lack of artificial watering. Therefore, S. mexicanum was grown only in S1 and data were subsequently recorded.

### 2.2. Effect of different rainfall events

To evaluate the vegetated roof’s influence on runoff quality, field experiments were conducted with different rainfall events. Four roof top assemblies were employed as part of this study (Table S1), with the first assembly (A1) comprising only concrete coat was kept as a control, and the second assembly (A2) contained concrete coat with a drainage layer and S1. The third assembly (A3) was the green roof with concrete coat, a drainage layer, S1 and vegetation. The fourth assembly (A4) was with concrete coat, DAKU substrate (S2) and a commercial drainage element. Our preliminary study indicated that at least 40 mm of water was required to generate runoff in A4. Hence, assemblies were exposed to rainfall until runoff started emerging in all assemblies. Once the runoff started, water samples were collected at the exit in 50 L pre-cleaned plastic cans at different rain events.

Rain water samples were also collected on an event basis with an automated refrigerated rain water sampler (model US-330; Ogasawara Keiki, Tokyo, Japan). This sampler collected only rain water with no interference from dust-fall. The sampler senses the first rain droplet to open the lid automatically and then collects the rain water into the sterile storage vessel inside the refrigerator (4 °C). Rain water samples were removed from the sampler at the end of each event and immediately analyzed for various water quality parameters.

### 2.3. Simulations with local utility water

To examine the potential green roof influence on runoff water quality changes during different events, rain simulations with local utility (tap) water were performed on A1, A2, A3 and A4. It is important to note that the chemistry of utility water is different from the chemistry of rain water (Table 1). Therefore, the vegetated roof runoff quality during the simulation experiments cannot be compared to the runoff quality during real rain events. The reason for conducting simulation experiments with utility water was that the volume of water required for experiments was around 200 L; because of this, local utility (tap) water were performed on A1, A2, A3 and A4.

### 2.4. Chemical analysis

All the runoff samples were immediately brought to the laboratory for the characterization of water quality parameters. For the analysis of metals and other ions, the samples were first filtered through a 0.45 μm PTFE membrane filter. For metals, the filtrate was analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES, Perkin Elmer Optima 7300 DV, Perkin Elmer Inc. USA). Anions were cation were analyzed using Dionex Ion Chromatography, equipped with AS40 automated sampler. IonPac®AS11-HC column in conjunction with IonPac®AS11-HC guard column and ASRS—ULTRA (4 mm) suppressor was used.

### 3. Results and discussion

#### 3.1. Runoff quality during simulated rain events

In the first phase of experiments, the influence of A1, A2, A3 and A4 on runoff quality was studied by simulating rainfall (5–50 mm) with the local utility water. The concentrations of different metals, other ions and important water quality indicators of simulated and actual runoffs from A1, A2, A3 and A4 at different rain events are presented in Fig. 2. Before the start of experiments, all roof assemblies were exposed to dryness for 120 h. As a result, only during 15 mm of simulated rain, runoff started from A2, but it was only dripping. Owing to the presence of only concrete layer, runoff started immediately in A1. In the case of A3, runoff began during 20 mm of rain. On the other hand, A4 showed the first sign of runoff only during 40 mm. Runoff delay in A2 and A3 was due to the water retention capacity of S1. The difference between the appearance of runoff in A2 and A3 was likely due to plants, whose roots in the substrate layer retained water and slowed the release of water from the substrate layer (S1). In the case of A4, this delay in runoff was due to the combined effect of S2 and the specially designed drainage element. It should be noted that S2 has only 35% water retention capacity, which was very well below that of S1. However, the drainage element was specially designed to hold water as discussed in Section 2.1. It also should be noted that water retention capacities of green roofs are strongly dependent on local weather conditions and prior rain events.

##### 3.1.1. pH

From Fig. 2, it is quite evident that all four assemblies (A1, A2, A3 and A4) played a significant role in altering the pH of the simulated rainfall. Both A2 and A3 initially increased the pH significantly, after which the pH decreased as the rain event progressed. This increase in pH during rain water passage through vegetated roofs indicated that there was presumably rapid neutralization of the acid deposition. This is an important environmental benefit as compared to a situation where the acidic roof runoff is directly discharged to natural water recipients (Berndtsson et al., 2009). It is worth noting that the
pH of runoff from A3 decreased gradually as the volume of rain increased and finally reached almost neutral. It thus suggests that S. mexicanum aids in stabilizing the pH of runoff to nearly neutral. In the case of A1, a reverse trend was observed i.e. an increase in pH as the rain event progressed. This increase in pH was likely due to a gradual leaching of caustic ingredients from the concrete coat. In contrast, A4 had no influence on runoff pH as no drastic change was observed.

3.1.2. Conductivity and salinity
All four assemblies enhanced the conductivity and salinity of the outflow runoffs (Fig. 2). These results also clearly indicate that the runoffs from the assemblies were more polluted in the first event compared to other events. This effect (a rapid increase in the concentration of the pollutants in the initial event followed by gradual decrease in concentration with the progress of the event) is a common phenomenon observed for urban runoffs (Lee and Bang, 2000; Davis and Birch, 2010). Dry deposition (natural fallout of atmospheric particles), weathering of building materials and wet deposition (below-cloud scavenging of atmospheric particles and gases by rain droplets) contribute to this high release of pollutants at the start of the event. However, this phenomenon was not common in green roofs because the roof material and the biological

Fig. 2 — Runoff parameters at different artificial rain events from different assemblies.
activity were expected to even the pollutograph across the rain events (Berndtsson et al., 2008). However, few studies pointed out the presence of high pollutant loading in the runoff at the beginning of the event in vegetated roofs (Berndtsson et al., 2006, 2009). The effects of subsequent rain events on the pollutant loading in the runoff observed in different assemblies, with conductivity as a typical example, are presented in Fig. 3. This occurrence is possibly due to the drainage/concrete layer in green roofs which potentially behaves as a hard surface onto which particles released from the substrate are retained and washed off with the first runoff. It is very interesting to note that among the four assemblies, A2 behaved as the highest source of pollution, followed by A3, A4 and then A1. The runoff from A1 had relatively high conductivity and salinity compared to the local drinking water/utility water. However, as the rain event progressed, the values decreased and became very close to that of the clean water at the end of 50 mm. In contrast, the runoff from A2, A3 and A4 had high conductivity and salinity even at the end of 50 mm simulated rain event.

3.1.3. Anions and cation

The results show that both A2 and A3 were high sources of NO$_3^-$, PO$_4^{3-}$ and SO$_4^{2-}$, but in different proportions. The release of F$^-$ was also observed in A1, A2 and A3. Conversely, A4 acted as a sink for F$^-$, Cl$^-$ and PO$_4^{3-}$ but a source for NO$_3^-$. None of the assemblies acted as a sink for or a source to NO$_2^-$ and NH$_4^+$. A2 and A3 showed a substantial release of NO$_3^-$, PO$_4^{3-}$ and SO$_4^{2-}$. Moran et al. (2003) reported a significant presence of total nitrogen in the runoff from two studied extensive vegetated roofs in North Carolina, USA, with the Tot-N concentrations in runoff varying between 6.9 and 0.8 mg/L with an average of 3.6 mg/L. Berndtsson et al. (2009) observed release of PO$_4^{3-}$ in runoff from an extensive vegetated roof in Augustenborg-Malmö, Sweden. Considering the runoff concentration of NO$_3^-$ obtained in the first event, A2 increased the NO$_3^-$ concentration to about 4.9 times and A3 increased the concentration to about 1.9 times more than that of the utility water. This confirms the nitrate uptake by S. mexicanum; however, no evidence of reduction to NH$_4^+$ was observed in the runoff samples. Also, the runoff from A3 after 20 mm of rain was found to contain lower concentrations of NO$_3^-$ than the utility water. This observation confirms the phytoremediation

![Fig. 3 - Conductivity profile during artificial rain events.](image-url)
potential of S. mexicanum and the potential transformation of A3 as a sink for NO$_3$- It should be noted that S1 was found to consist of 1.2 kg/m$^2$ of NPK as fertilizer. It is thus confirmed that NO$_3^-$ originated mainly from S1. An elevated release of PO$_3^{3-}$ was also observed in A2. The probable source of PO$_3^{3-}$ to runoff water from A2 was the substrate used. Similarly, Dietz and Clausen (2006) in their investigation of the performance of two rain-garden facilities in Connecticut (USA) found out that the total-P concentrations increased after passage of the rain-gardens. The PO$_3^{3-}$ pattern of A3 was similar to the results for NO$_3^-$. This result is expected as both N and P are macronutrients for plant growth. However, in contrast to NO$_3^-$, the concentration of PO$_3^{3-}$ in runoff from A3 was always higher than that in the utility water. A1, A2 and A3 showed a substantial release of SO$_4^{2-}$ (Table 1); the average concentrations of SO$_4^{2-}$ in runoff water from A1, A2 and A3 were about 1.8, 4.5 and 4.0 times more than that of the utility water. Thus, the results clearly state that substrate (S1) was a major contributor of SO$_4^{2-}$ to the runoff and a minor contribution from concrete coat should also be noted.

On the other hand, except for NO$_3^-$, the runoff from A4 was found to deviate much less from the utility water. In fact, A4 acted as a sink for F$^-$, Cl$^-$ and PO$_3^{3-}$, as it was designed to have high nutrient adsorption (or retention) capacity as per the manufacturer’s recommendation. However, the release of the high concentration of nitrate was surprising and was likely due to chemical composition of S2.

3.1.4. Metals

The results revealed that runoffs from certain assemblies were found to contain significant concentrations of metal such as Na, K, Ca, Mg, Fe, Al, and Cu (Fig. 2). Very high concentrations of these metals were observed at the beginning of the rain event, followed by a gradual decrease in the subsequent rain events (data not presented). No evidence was found to confirm the presence of significant quantities of other metal such as Pb, Cd, Cr, Co, and Mn in the runoff. There are several sources of metals in roof runoff. Atmospheric pollutants accumulate on the green roof as dry deposition as well as being washed out of the atmosphere during the course of a rain event (wet deposition) (Mason et al., 1999). In addition, the roof materials themselves may be a source of some metals. However, no study has highlighted the potential of green roofs to act as a source of various metals. Very few studies indicated the presence of some metals, but most of them were insignificant or well below permissible limits (Berndtsson et al., 2006, 2009). In this study, a substantial release of Na, K, Ca and Mg was observed in all assemblies, especially in A2 and A3. As the substrate S1 was richly loaded with these elements, the subsequent leaching was expected, especially in the presence of acidic rainfall. However, the leaching of Na, K, Ca and Mg into the runoff was so high, as it even reached 3.9, 14.0, 2.2 and 12.7 times, respectively, their concentrations in the utility water, in A2 at 15 mm of rainfall. On the other hand, the runoff from A3 contained relatively less amounts of those elements. Considering the fact that these elements are macronutrients for plant growth (Thenabadu, 1968), one can expect a decreased concentration of these elements in runoff from A3 compared to runoff from A2. In the case of A1, much less leaching of Na, K, Ca and Mg into the runoff was observed. The runoffs from A4 showed a small increase in K and Mg concentrations compared to those in the utility water. The results concerning Li clearly indicated that the element was present in significant concentrations in the runoffs of A2, followed by A3 whereas it was present in minor quantities in A1 and A4.

It is also worth noting that significant concentrations of Al and Fe were found in the runoffs of A4, followed by A2 and A3. These are important elements in soil and often present in large quantities. The increase in the concentrations of Al and Fe in the runoffs of A1 was negligible compared to the utility water. Considerable quantities of Cu were found in the runoffs of A2, followed by A3 and A4. Analyzing the metal concentrations in different assemblies revealed that the substrate (S1) acted as a source for various metals and the runoff from A2 contained highest metal concentrations compared to other assemblies. While comparing A2 and A3, the runoff from A3 always contained less concentration of metals. Some of these metals are important for plant growth; and thus the phytoremediation property of S. mexicanum responsible for the intake of metals.

3.2. Runoff quality during actual rain events

In this second phase of experimentation, the influence of A1, A2, A3 and A4 on runoff quality in real rain events was studied. Four rain events were considered for the investigation and the key parameters of these rain events and roof runoff results are presented in Fig. 4. The rainfall volumes observed during events 1, 2, 3 and 4 were 12.2, 4.2, 34.2 and 25.2 mm, respectively. For the first rain event (23/08/2009), the assemblies A2, A3 and A4 were able to retain most of the rainfall because of previous dry periods. Subsequently, due to regular rain events and the saturation of soil, all assemblies led to significant amounts of runoff. It is worth noting that runoffs from A2, A3 and A4 were significantly delayed compared to A1 and the volume of the flow was very low. However, no efforts were made to calculate the retention potential of A2, A3 and A4.

Average pH of rain water lied between 3.7 and 3.8 from different rain events. This acidic rainfall is quite common in Singapore (Balasubramanian et al., 2001; Zhong et al., 2001) and has created greater concern in recent years. As shown in Fig. 4, it is possible to neutralize the acidic pH with the aid of green roof assembly. Both A3 and A4 were able to neutralize acidic nature of rain water. On the other hand, concrete based assembly (A1) increased the pH to several folds. The runoff from A2 had high pH during initial stages, but as the rain event progressed, the pH decreased and became almost neutral. As far as the conductivity is concerned, A2 produced highest conductivity followed by A3, A1 and A4. Similar to simulated rain events, the runoff from A2 recorded highest salinity, followed by A3, A4 and A1. As shown in Fig. 4, it was clear that values of conductivity and salinity were high in event 1 and subsided as the rain events progressed.

Considering nutrients, the runoffs from A2 at different rain events were found to comprise high amounts of NO$_3^-$, PO$_3^{3-}$ and SO$_4^{2-}$ (Fig. 4). Due to the presence of plants, the runoff from A3 comprised comparatively decreased concentrations of NO$_3^-$, PO$_3^{3-}$ and SO$_4^{2-}$. It is worth noting that the nitrate concentration in the runoff from A3 was very low,
approximately 34-fold less than that of runoff from A2 during the first rain event. Very high concentrations of Ca, K, Na and Mg were found in the runoff waters collected from A2 and A3. The concentration of all these light metals decreased as the rain event progressed. Considerable amounts of Li, Fe, Al, Cu and Zn were found in the runoff waters from A2, A3 and A4.

3.3. Assessment of green roofs runoff quality

Considering that there are no standards to regulate the runoff quality from green roofs, the results obtained from this study were compared to standards proposed by the US Environmental Protection Agency for freshwaters (USEPA, 1986; 1993).
Table 2  - Comparison of runoff from green roof assembly with EPA (Environmental Protection Agency) recommended freshwater standards.

<table>
<thead>
<tr>
<th>Contaminant/parameters</th>
<th>EPA recommended freshwater standards</th>
<th>During simulated rain events</th>
<th>Exceeded limit</th>
<th>During actual rain events</th>
<th>Exceeded limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.5–9</td>
<td>6.9–8.5</td>
<td>No</td>
<td>7.0–7.5</td>
<td>No</td>
</tr>
<tr>
<td>Conductivity (µS/cm)</td>
<td>NIL</td>
<td>270.7–366.3</td>
<td>No</td>
<td>317.1–387.2</td>
<td>No</td>
</tr>
<tr>
<td>NO₃⁻ (mg/L)</td>
<td>10</td>
<td>2.6–7.3</td>
<td>No</td>
<td>0.34–0.86</td>
<td>No</td>
</tr>
<tr>
<td>PO₄³⁻ (mg/L)</td>
<td>0.05</td>
<td>42.8–66.0</td>
<td>Yes</td>
<td>19.8–40.0</td>
<td>Yes</td>
</tr>
<tr>
<td>SO₄²⁻ (mg/L)</td>
<td>250</td>
<td>52.7–71.2</td>
<td>No</td>
<td>76.7–109.2</td>
<td>No</td>
</tr>
<tr>
<td>Cl⁻ (mg/L)</td>
<td>230</td>
<td>17.3–18.2</td>
<td>No</td>
<td>10.4–15.6</td>
<td>No</td>
</tr>
<tr>
<td>F⁻ (mg/L)</td>
<td>4.0</td>
<td>2.2–3.0</td>
<td>No</td>
<td>4.1–5.6</td>
<td>Yes</td>
</tr>
<tr>
<td>Na (mg/L)</td>
<td>NIL</td>
<td>21.3–29.7</td>
<td>No</td>
<td>16.3–21.2</td>
<td>No</td>
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<tr>
<td>K (mg/L)</td>
<td>NIL</td>
<td>41.2–53.8</td>
<td>No</td>
<td>36.1–39.9</td>
<td>No</td>
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<tr>
<td>Ca (mg/L)</td>
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<td>18.6–22.6</td>
<td>No</td>
<td>30.4–34.6</td>
<td>No</td>
</tr>
<tr>
<td>Mg (mg/L)</td>
<td>NIL</td>
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<td>No</td>
<td>10.0–12.9</td>
<td>No</td>
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<tr>
<td>Al (mg/L)</td>
<td>0.087</td>
<td>0.14–0.19</td>
<td>Yes</td>
<td>0.13–0.25</td>
<td>Yes</td>
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<tr>
<td>Fe (mg/L)</td>
<td>1.0</td>
<td>0.029–0.041</td>
<td>No</td>
<td>0.043–0.113</td>
<td>No</td>
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<tr>
<td>Cu (mg/L)</td>
<td>0.013</td>
<td>0.016–0.050</td>
<td>Yes</td>
<td>0.037–0.056</td>
<td>Yes</td>
</tr>
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</table>

USEPA, 2009). Table 2 compares the EPA requirements and the quality of runoffs obtained from A3. From Table 2, it was clear that some contaminants pose serious concerns. However, as indicated by Berndtsson et al. (2006), the green roof runoff is not natural water and any influence this storm water discharge may have on a natural recipient would be dependent on the recipient’s water quality and size. Of the different ions, PO₄³⁻ content exceeded the concentrations typical for urban runoff by many folds. While the limit for NO₃⁻ is set at 10 mg/L, nitrate above 2.6 mg/L is reported to accelerate eutrophication (Bartley and Johnston, 2007). Excess N and P inputs can lead to eutrophication of natural water bodies, resulting in accelerated plant and animal productivity in these systems (Nixon, 1998). In addition to eutrophication, excessive nitrogen causes other water quality problems. Nitrates in water are potentially dangerous, especially to newborn infants, where nitrate is converted to nitrite in the digestive tract, which reduces the oxygen-carrying capacity of the blood (methemoglobinemia), resulting in brain damage or even death (Sadegh et al., 2008). Phosphorus delivered to water bodies may later be released and made available to algae when the bottom sediment of a stream becomes anaerobic, causing water quality problems (Krogstad et al., 2005). During the monitoring study on a green roof in North Carolina, Moran et al. (2003) made a similar observation in that there were higher concentrations of total nitrogen and phosphorous in the green roof runoff than those in the control roof runoff due to N and P leaching from the green roof soil media.

The concentrations of SO₄²⁻ and Cl⁻ in runoffs from the green roof assembly (A3) were generally lower than recommended limits as presented in Table 2. The abundance of Na, K, Ca and Mg were observed in all runoff samples (Table 2) owing to their presence in the substrate layer. This observation is in agreement with those from previous research reports on vegetated rooftops (Teemusk and Mander, 2007; Berndtsson et al., 2009). There is no health advisory level for K, Ca and Mg. Release of heavy metals such as Fe, Cu and Al was also observed in green roofs on several instances. Our results also indicate that green roofs leach out some nutrients such as nitrate and phosphate in runoff. This problem is a major concern and warrants further research for its implications.

During actual rain events, the effluent pH values were well in the range recommended for freshwaters.

On considering other important parameters such as the cost of construction, building weight restrictions and roof maintenance, the studied green roof assembly (A3) has its own merits and demerits. It is important to note that the cost of constructing assembly A3 is certainly lower than that of the commercial green roof assembly. However, the problem of soil leaching and some contaminant leaching should be addressed. Based on the load restrictions, A4 is lighter than A3 and A2 and also has higher water retention capacity on its own, owing to special drainage element. Considering the system maintenance, it was observed that A3 supports plant growth without any artificial fertilization and watering.

4. Conclusions

The present study investigated the runoff water quality from green roofs based on simulated and real rain events. Four distinct roof top assemblies with different components were constructed and employed for this investigation. The quality of runoff from green roofs was examined based on the concentration of inorganic ions and selected trace elements. Results revealed that green roofs showed potential in stabilizing the pH of runoff to be nearly neutral. For conductivity and salinity, green roofs act as a source by increasing the concentration of ions in the runoff. Similarly, runoffs from green roofs were found to comprise high concentrations of light metals such as Na, K, Ca and Mg. Release of heavy metals such as Fe, Cu and Al was also observed in green roofs on several instances. Our results also indicate that green roofs leach out some nutrients such as nitrate and phosphate in runoff. This problem is a major concern and warrants further research for its implications.
mitigation, if not elimination. We therefore suggest that green roofs be constructed with suitable materials such that they do not have detrimental effects on runoff quality.

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Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.watres.2011.12.050

References