First flush effect from vegetated roofs during simulated rain events

J. C. Berndtsson, L. Bengtsson and K. Jinno

ABSTRACT

Vegetated roofs are becoming increasingly popular in urban environments. Still, several aspects of their influence on various urban infrastructures are not sufficiently investigated, including the roofs' influence on runoff water quality. In this study a first flush effect in runoff water from vegetated roofs during simulated artificial rain events is investigated. Example extensive (Sweden) and intensive (Japan) vegetated roofs are studied. The first flush effect is typically occurring in urban runoff from hard surfaces and is not observed when the source of pollutants is unlimited (e.g. soil particles). Vegetated roofs would thus not be expected to exhibit a first flush effect. However, the results show that concentrations of the studied chemical compounds and elements were higher in first runoff samples than in samples taken at higher runoff depths. Analysis of the plots of normalized cumulative mass of studied runoff constituents as a function of normalized cumulative flow showed that, generally, the values are above the diagonal line with the exception of potassium (K) and dissolved organic carbon (DOC). This indicates that, with the exception of K and DOC, proportionally more mass is washed off in the earlier runoff than in the later, which can be interpreted as the occurrence of a first flush effect.

Key words | first flush effect, green roof, stormwater quality, vegetated roof

J. C. Berndtsson (corresponding author)
L. Bengtsson
Department of Water Resources Engineering,
Lund University, Box 118,
SE-221 00 Lund,
Sweden
E-mail: justyna.czemiel_berndtsson@tvrl.lth.se

K. Jinno
Institute of Environmental Systems,
Kyushu University, Hakozaki, Higashi-ku,
Fukuoka-shi 812-8581
Japan

INTRODUCTION

Vegetated roofs are becoming more and more popular in urban environments; next to Germany and Switzerland, vegetated roofs are now gaining more attention in other countries such as USA, Great Britain, Japan and Sweden. Generally, vegetated roofs can be divided into two categories: intensive and extensive; the former being established with a thick soil layer (30 cm and more) and the later with a thin soil layer (usually 3–10 cm). Intensive vegetated roofs are often referred to as roof gardens and usually require maintenance such as watering, fertilizing and weeding. Extensive vegetated roofs are commonly designed to be maintenance-free.

The reasons behind the establishment of vegetated roofs vary in different contexts but the usual ones include: reduction of urban heat island effect, aesthetics, improving the environmental image of corporations and municipalities

that own the buildings. Additionally vegetated roofs offer a number of benefits including attenuation and reduction of stormwater runoff, provision of wildlife habitat, health benefits, protecting roof fabric, and reducing cost of heating and air conditioning. It is also often expected that vegetated roofs would contribute to runoff water quality improvements as compared with hard roofs in the same localities (English Nature 2003). This expectation has its roots in the fact that total annual runoff is usually reduced with a vegetated roof as compared with runoff from a hard surface. However, there is still little evidence on how different vegetated roofs influence runoff water quality, both annual pollutant loads and concentrations during single events. Generally, vegetated roofs are not designed with an eye on improving water quality. It has been shown that fertilizers used to enhance vegetation may, in certain existing

installations and certain periods, cause runoff water quality degradation (Moran *et al.* 2005; Czemiel Berndtsson *et al.* 2006; Emilsson *et al.* 2007). This does not have to be a general case for vegetated roofs, presuming that more attention is paid to runoff water quality issues.

In this study we investigate changes of runoff water quality from vegetated roofs during simulated artificial rain events. Example extensive (in Sweden, Malmö City residential area) and intensive (in Japan, Fukuoka City downtown area) vegetated roofs are studied. The extensive vegetated roof is divided into sections; runoff from each section can be collected separately. The difference between two sections used in the experiment is that one of them is equipped with an underlying drainage layer and the other is without a drainage layer. The studied intensive vegetated roof is designed with different materials (soil, vegetation, drainage) to the extensive one. Details on the design of studied vegetated roofs are given in the Materials and Methods section.

The objective of this study is to analyze if the first flush effect is observed in runoff from different vegetated roofs. The first flush effect is a washing-off, by the initial runoff, of a large part of the pollution accumulated on hard surfaces and in the air. This effect is often typical for urban runoff from impermeable surfaces. In those cases when a source of pollutants is unlimited, like for example for weathering soil, the first flush effect is usually not observed. This is because the supply of particles is theoretically continuous during a storm event. Based on this reasoning a first flush effect would not be expected to occur in runoff from vegetated roofs. Besides, in the case of vegetated roofs, soil would be expected to function as a filter for pollutants in atmospheric deposition and, if not removing, at least delaying the discharge of pollutants and equalizing the quality of runoff. However, an artificial rain simulation study performed on an extensive vegetated roof in Sweden two years earlier (Czemiel Berndtsson *et al.* 2006) indicated, among other things, that there might be a first flush effect occurring from the studied vegetated roof. The first flush phenomenon from different vegetated roofs is further investigated in this paper. Currently no other studies of first flush from vegetated roofs have been reported.

Knowledge of the first flush effect is useful for urban runoff management and can support the use of additional treatment for the first portion of runoff which is carrying the higher pollutant loads. In those cases in which runoff water is harvested for reuse (often from roofs) and its quality is of concern, the first flush effect is crucial for the design of harvesting techniques. In cases in which a significant first flush effect appears, an initial runoff with highest concentrations of pollutants can be bypassed and harvested for uses which do not require better quality, or additional treatment can be applied. Because of the importance of a first flush effect for stormwater management this phenomenon has been of interest for a number of researchers (Bertrand-Krajewski *et al.* 1998; Deletic 1998; Larsen *et al.* 1998; Lee *et al.* 2002; Kim *et al.* 2005). The difficulty in quantifying and predicting first flush lies in the fact that it depends on local conditions and varies between storm events. First flush pollution load would depend, among others, on a length of antecedent dry period, local pollution sources (the type and size of drainage area) and the hydraulic characteristic of rain and runoff. A number of different approaches to quantitatively define the first flush effect exist. For example, the possibility to express changes of pollutant concentrations during a runoff event as a first-order law, as a function of runoff depth x, has been used as indicative of a first flush effect (Zobrist *et al.* 2000). Kim *et al.* (2005) suggest that if the fractions of washed-off mass are very high in the first 30% of runoff this indicates first flush. They suggest characterizing first flush in terms of normalized mass discharged in the first fraction of the normalized runoff volume. If, on the plot of normalized cumulative mass as a function of normalized cumulative flow the median values are above the diagonal line, there is proportionally more mass washed off in the earlier runoff than in the later runoff, which indicates first flush (Kim *et al.* 2005). The above-mentioned techniques of first flush analyses are usually applied to urban areas with an extent of impermeable surfaces. Here, the same techniques are used for analyses of first flush effect from a different system – the soil of a vegetated roof. It may be that the processes involved are different; however, it is not necessarily so. The drainage material situated under the soil layer in a vegetated roof may function as an impermeable surface, allowing pollutants to accumulate in periods between rainfall in a similar way as open impermeable urban surfaces.

In the reported investigation mains-supply water is used as the eluting water. As its chemistry is different from the

chemistry of precipitation the results of runoff quality will not be compared with runoff quality of a real rain event. However, it is useful for artificial rain simulation and first-flush studies in which input and output water quality are compared. The quality of runoff generated during real rain events from extensive vegetated roofs in Malmö, Sweden was previously studied on the same vegetated roof and the results are reported in Czemiel Berndtsson *et al.* (2006).

MATERIALS AND METHODS

Sweden

The studied extensive vegetated roofs are located in the Augustenborg residential area, in the city of Malmö (270,000 inhabitants), Sweden. The vegetated roofs were established in 2001 on existing single-storey buildings. These vegetated roofs consist of a prefabricated sedum-moss vegetation layer grown in a 3 cm thick soil substrate, a geotextile filter layer and usually some kind of a drainage layer. The soil substrate is a commercially available mixture of crushed lava, natural calcareous soil, clay and shredded peat. A bitumen membrane reinforced with a polyester layer is situated beneath the vegetated roof to protect the original roof. The roof material is described in more detail in Czemiel Berndtsson *et al.* (2006). The studied extensive vegetated roof, situated on the municipal office buildings, is divided into sections with different drainage layers and different slopes. Two of the sections (Figure 1), which are 1.25 m wide and 4 m long, with

Figure 1 | Sections SD (from the left) and S0 of the extensive vegetated roof, Augustenborg, Malmö, Sweden.

a slope of 1.5°, are used in this study. The first section is with an underlying 2 cm thick drainage layer made from crushed bricks, and the second is without a drainage layer. They are further referred to as SD and S0, respectively (S indicates study site Sweden, D – drainage layer and 0 – no drainage layer). The hydraulic field capacity of the soil, as investigated by Bengtsson *et al.* (2005) is 10 mm. The vegetated roofs were fertilized during spring 2001 and spring 2002 and there was no fertilizer added since 2003.

To investigate a first flush effect from the studied sections of the extensive vegetated roof rain simulations with mains-supply water were performed. Rain events (26 mm at an intensity 8 mm/h) were simulated manually through distributing water equally, with the use of watering cans, on vegetated roof sections (SD and S0). One runoff sample was taken at each following interval: 14 mm rain (corresponding to the beginning of observed runoff), 16 mm, 18 mm, 20 mm and 26 mm. A sample of mains-supply water was also collected. Each sample was collected in two 100 ml plastic bottles (high density polyethylene (HDPE)); half of each sample – which was later used for analyses of heavy metals – was acidified ($0.1 M HNO_3$). All the samples were refrigerated until analysis. Samples were analysed for metals (cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), potassium (K), manganese (Mn), lead (Pb) and zinc (Zn)) and nutrients (nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4—N), total nitrogen (Tot-N), phosphate phosphorus (PO_4—P), total phosphorus (Tot-P) and dissolved organic carbon (DOC)). Metals were analysed using the optical ICP AES technique with a Perkin-Elmer OPTIMA 3000 DV instrument; analyses were performed following the instrument's manuals. Analyses of NO_3—N, NH_4—N, Tot-N, PO_4—P and Tot-P were performed using a FIA 5000 instrument from FOSS-Tecator; nitrate nitrogen was analysed according to ISO 13395, ammonium nitrogen according to ISO 11732, total nitrogen according to ISO 11905, phosphate phosphorus according to ISO 15681-1 and total phosphorus was analysed according to CAS 5305 (FOSS, Customer Application Summary Note).

Japan

The ACROS building was constructed in 1993 in downtown Fukuoka City (1.4 million inhabitants), Japan. It is a 14-storey

commercial building which houses shops, entertainment facilities, restaurants and offices. Terraces with vegetation were constructed on the south side of the building (Figure 2). More than 70 different plant species have been planted in this terrace garden but many new ones have appeared in the area due to seeds spread by wind and birds. The role of garden terraces, later in this paper referred to as the intensive vegetated roof, in stormwater management has not previously been studied.

On the floors, vegetation, including trees and bushes, is planted in a 50 cm deep artificial soil layer (Figure 3). At half the height on each floor, attached to the building's outside wall, there is a concrete overhang filled with artificial soil of 40 cm depth. It provides support for bushes and smaller plants. Overhanging between floors 12 and 13 on the west side of the building, the section closest to the middle of the building was used in this study. The choice was dictated by the accessibility of this site, the possibility to sample runoff and the relatively small size of separate sections with individual drainage. The section used in the simulation experiment is 0.8 m wide and 2.75 m long. It is further referred to as roof J (J indicates study site from Japan). Drainage is made of plastic.

A commercially available *Aquasoil* used on the terraces is made of perlite – naturally occurring siliceous rock which, after being crushed and heated, produces an inorganic lightweight soil. Since perlite is a form of natural glass (contain mainly Si, Al, K and Na), it is classified as

Figure 2 │ Vegetated terraces at ACROS building (roof J), Fukuoka, Japan.
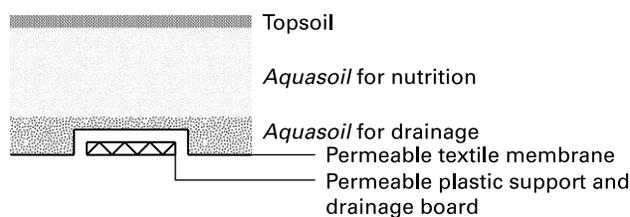

Figure 3 │ Cross section of soil layer on the study site, ACROS Fukuoka, Japan.

chemically inert and has a pH of approximately 7. Specific gravity of the *Aquasoil* used at the ACROS building is 0.65 (Takenaka Corporation 2005) and its saturated hydraulic conductivity is 5148 mm/h (AquaSoil Ikegami Inc. 2002). *Aquasoil* for nutrition and *Aquasoil* for drainage are commercially available types of modified *Aquasoil*. *Aquasoil* for nutrition is enriched in micronutrients, while *Aquasoil* for drainage is enhanced to work as an aeration and drainage layer, and both have large water retention ability and high drainage capacity when saturated.

Rain of depth 45 mm (intensity 15 mm/h) was simulated manually through distributing water equally with watering cans on the studied vegetated roof (2.2 m^2). The simulation was performed after one week without rain. During the experiment the runoff was generated after 27 mm rain. Runoff samples were collected at rain depths of 27 mm (corresponding to the beginning of observed runoff), 32 mm, 36 mm and 45 mm. A sample of mains-supply water used in rain simulation was also collected. Samples were collected in 1 dm^3 plastic bottles (HDPE) and refrigerated until they were analyzed for metals (Cd, Cr, Cu, Fe, K, Mn, Pb and Zn) and nutrients (NO_3—N, NH_4—N, Tot-N, PO_4—P, Tot-P and DOC). Analyses were performed according to Japanese standard methods listed in Table 1.

Table 1 │ Japanese standard methods for chemical analyses of water

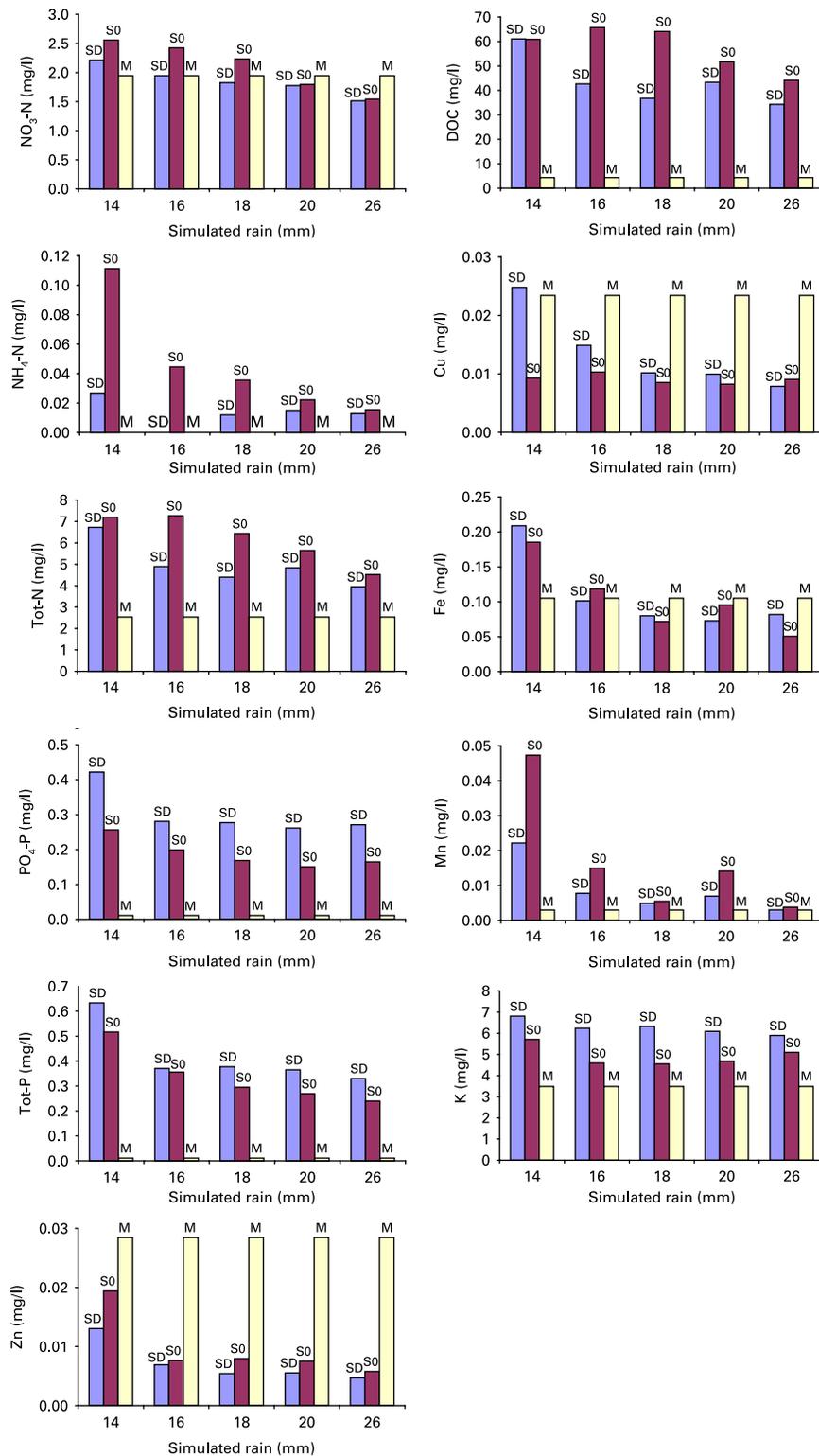| Component	Analysis method	Component	Analysis method
Tot-N	JIS K 0102 45.4	Pb	JIS K 0102 54.3
NO_3-N	JIS K 0102 43.2.3	K	JIS K 0102 49.2
NH_4-N	JIS K 0102 42.2	Zn	JIS K 0102 53.3
Tot-P	JIS K 0102 46.3.1	Cd	JIS K 0102 55.3
PO_4-P	JIS K 0102 46.1.1	Cr	JIS K 0102 65.1.4
DOC	JIS K 0102 22	Fe	JIS K 0102 57
Cu	JIS K 0102 52.4	Mn	JIS K 0102 56

Figure 4 | Concentration of metals and nutrients in mains-supply water (M) and in runoff from extensive vegetated roofs (SD – with drainage layer, S0 – no drainage layer).

RESULTS AND DISCUSSION

The results are presented in Figure 4 (study in Sweden) and Figure 5 (study in Japan). Pb, Cd and Cr are not included in Figure 4 and Pb, Cd, Cr, Mn, NH_4-N and PO_4-P are not included in Figure 5 because those compounds and elements were either not detected or detected in concentrations close to the detection limits. As changes of concentrations are discussed and not the loads the total pollutant load reduction due to runoff volume reduction within the vegetated roof is not accounted for.

The results show that, for nearly all compounds studied, on both sections of the extensive vegetated roof (SD and S0,

Figure 4) and the intensive vegetated roof (J, Figure 5), the first runoff sample collected at the beginning of runoff shows higher concentrations of the studied compounds than the samples taken at higher runoff depths. The exception is Cu in the runoff from S0, which almost does not change during the simulated event, and the concentration of DOC, which is lower in the first runoff sample than in those taken at higher runoff depths. The concentration changes follow different paths for different components and roofs (SD and S0 in Figure 4 and J in Figure 5).

The first flush effect is tested and the methods are as used by Zobrist *et al.* (2000) and as suggested by Kim *et al.* (2005).
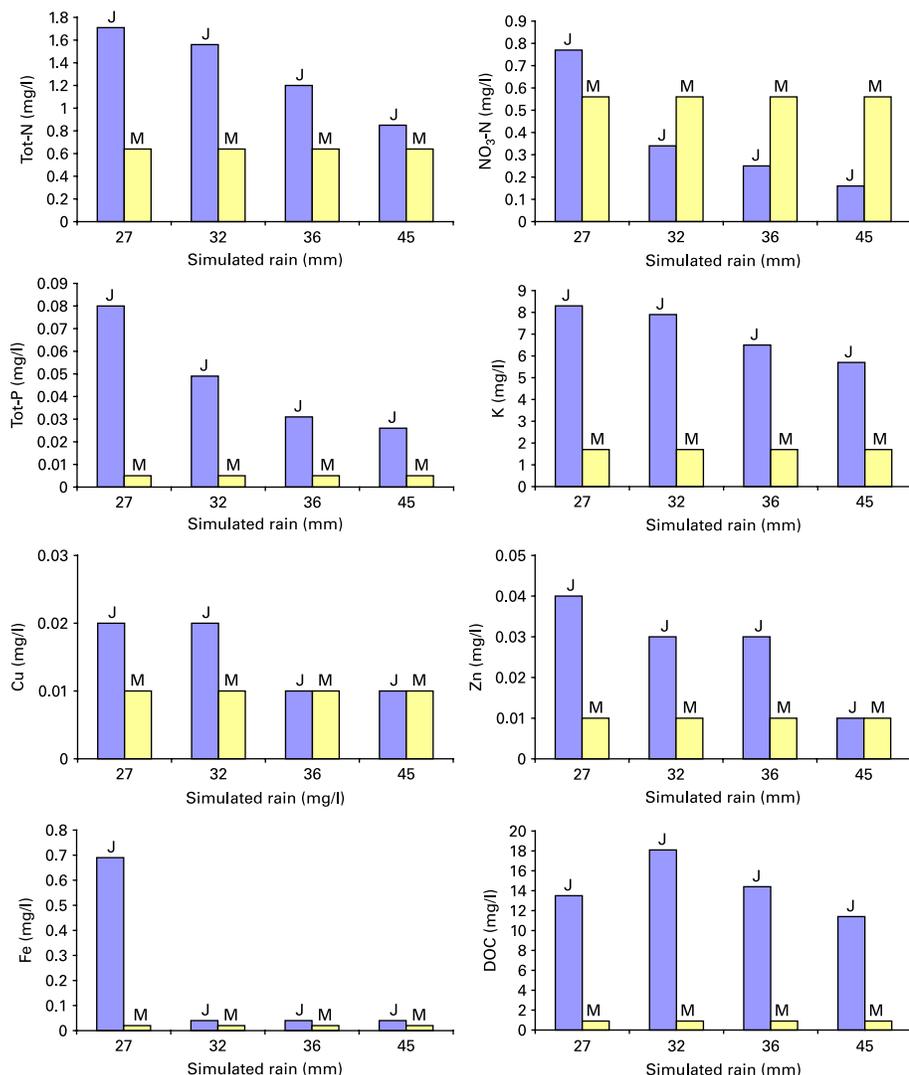

Figure 5 │ Concentration of metals and nutrients in mains-supply water (M) and in runoff from the intensive vegetated roof (J).

It is tested if the changes of concentrations of the compounds studied which were observed from the studied vegetated roofs can be expressed as a first-order law, as a function of runoff depth x. This has been used to describe the first flush effect by Zobrist *et al.* (2000):

$$\mathrm{d}c/\mathrm{d}x = -kx$$

and therefore

$$c = c_0 + c_1\mathrm{e}^{(-kx)} \qquad c - c_0 = c_1\mathrm{e}^{(-kx)}$$

where c is concentration at runoff depth x, c_0 is the leveling-off concentration (here assumed to equal the concentration in the sample at runoff depth $x = 12$ mm for SD and S0 and $x = 18$ mm for J), c_1 is an initial concentration of the decrease and k is a wash-off coefficient.

It is found, for roof SD (extensive vegetated roof with a drainage layer), that the concentration changes of Cu, Zn and Tot-P in the runoff can be expressed as a first-order law as a function of runoff depth (with R^2 of the fit exceeding 0.9), thus showing a similar first flush effect as the runoff from hard surfaces. For roof S0 (extensive vegetated roof without drainage layer) the runoff concentrations of NH_4—N, Tot-P and Zn can be expressed in the same manner, thus depicting a first flush effect. For intensive vegetated roof (J), NO_3—N and Tot-P depict a first flush effect. Concentrations of Tot-P in runoff during a simulated event from all studied roofs exhibits a first flush effect. The result of Cu concentration evolution in runoff from SD is presented in Figure 6.

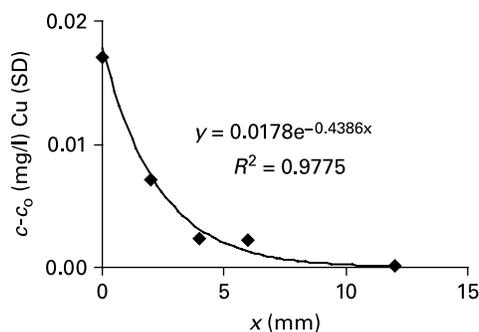It is also tested, for all studied components and roofs, if on the plot of normalized cumulative mass as a

Figure 6 | Evolution of the copper concentration in the vegetated roof (SD) runoff during the simulated rain event.

function of normalized cumulative flow the values are above the diagonal line. This would indicate that proportionally more mass is washed off in the earlier runoff than in the later (i.e. the occurrence of first flush (Kim *et al.* 2005)). It is assumed that a leveling-off concentration is that of samples taken at the runoff depth of 12 mm for extensive roofs (SD and S0) and of 18 mm for the intensive roof (J). It is further assumed that, lacking quality data for runoff at 8 and 10 mm for extensive roofs (SD and S0) and at 14 mm for the intensive roof (J), it should be as that of the last taken runoff sample (Figures 4 and 5).

The left-hand graphs in Figure 7 show discharged mass in each volume interval (14.3% of total volume). The figure shows, for example, that 0.3 (30%) of the total Fe mass and 0.24 (24%) of Tot-P is washed off in the first 14% of the runoff volume. The right-hand graphs of Figure 7 show the running total washed-off Fe and Tot-P, respectively, as a function of normalized flow. The values above the diagonal line indicate that there is proportionally more Fe and Tot-P mass washed off in the earlier runoff than in the later runoff, which indicates first flush. Such analyses performed for all studied runoff constituents indicated first flush occurring from both extensive vegetated roofs (SD and S0) for Fe, Mn, Zn, for Cu from SD and for NH_4—N from S0. A less pronounced first flush effect was also indicated for Tot-P, PO_4-P, Tot-N, NO_3—N and DOC from roofs SD and S0 and for NH_4—N from SD. The first flush effect was not observed for K from roofs SD and S0 and for Cu from S0. Analysis of runoff from the intensive vegetated roof (J) indicated the occurrence of first flush effect for NO_3—N, Tot-N, Tot-P, Fe, Mn, Zn and Cu but not for K and DOC.

The reasons behind the occurrence of a first flush effect from vegetated roofs are not well understood. The possible explanation can be that the weathering soil particles with adjacent pollutants are collected on the drainage material placed under the soil layer and in macropores within the soil layer during dry periods. These particles are washed off with the initial runoff, this then being the reason for the occurrence of the first flush effect. The comparison between concentration of runoff constituents in first runoff samples from extensive vegetated roofs with and without a drainage layer shows higher loads of PO_4—P, Tot-P, Cu, Fe and K from the roof with the drainage layer (SD). Ammonium
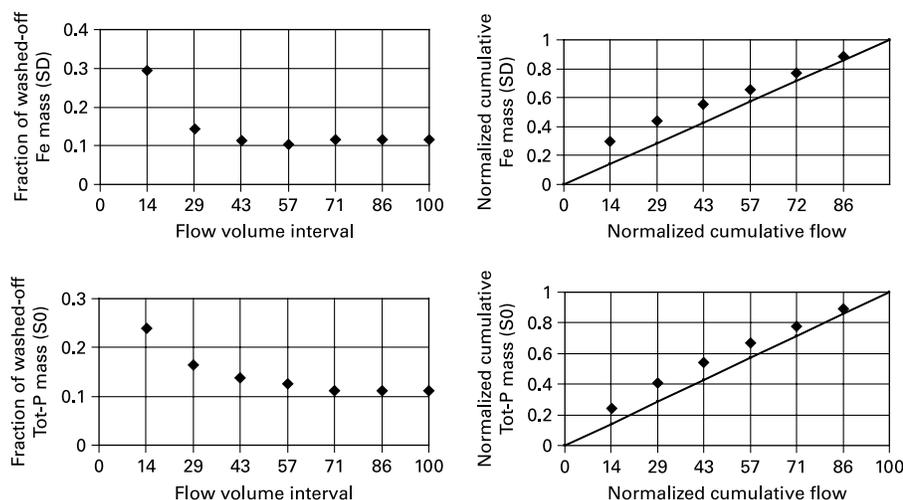
Figure 7 | Wash-off pollutant mass and volume (Fe, roof SD; Tot-P roof S0) indicating first flush effect.

nitrogen concentrations are lower in the runoff from the roof with a drainage layer (SD), which can be explained by better oxygen access to the soil with underlying drainage (supporting oxidation of ammonium nitrogen).

Comparing the results obtained in this study for extensive vegetated roofs with the results of similar rain simulations performed two years earlier (Czemiel Berndtsson *et al.* 2006) it can be concluded that, in general, the concentrations of nitrate and total nitrogen in runoff were on similar levels while concentrations of phosphate and total phosphorus in runoff are lower in the later experiment. These may indicate that phosphorus, which has been initially added with fertilizers, is gradually washed off and its leakage is decreasing with time. Initial runoff concentrations of zinc, copper and iron are lower in this study compared with earlier results; however, the concentrations of these components for deeper runoff depths are similar in both studies.

CONCLUSIONS

Higher concentrations of studied components are observed in first runoff samples than in the samples taken at higher runoff depths. Concentration changes of total phosphorus in the runoff from all studied vegetated roofs can be expressed as a first-order law as a function of runoff depth, thus showing a similar first flush effect as for runoff

from hard surfaces. For some of the studied roofs concentrations of ammonium nitrogen, nitrate nitrogen, zinc and copper can also be expressed in the same manner, thus depicting a first flush effect. The analysis of the plots of normalized cumulative mass of studied runoff constituents as a function of normalized cumulative flow showed that, generally, the values are above the diagonal line with the exception of potassium and dissolved organic carbon. This indicates that proportionally more mass is washed off in the earlier runoff than in the later, which can be interpreted as the occurrence of a first flush effect.

The reasons behind the occurrence of a first flush effect from vegetated roofs are not well understood. It is suggested that weathering soil particles with adjacent pollutants are collected on the drainage material placed under the soil layer and in macropores and washed off with the initial runoff, causing the first flush effect.

ACKNOWLEDGEMENTS

REFERENCES

AquaSoil Ikegami Inc. 2002 *Properties of AquaSoil. Product Information*. Ikegami Inc., Japan (in Japanese).

Bengtsson, L., Grahn, L. & Olsson, J. 2005 Hydrological function of a thin extensive green roof in southern Sweden. *Nordic Hydrol.* **36**(3), 259–268.

Bertrand-Krajewski, J.-L., Chebbo, G. & Saget, A. 1998 Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon. *Water Res.* **32**(8), 2341–2356.

Czemiel Berndtsson, J., Emilsson, T. & Bengtsson, L. 2006 The influence of extensive vegetated roofs on runoff water quality. *Sci. Total Environ.* **355**, 48–63.

Deletic, A. 1998 The first flush load of urban surface runoff. *Water Res.* **32**(8), 2462–2470.

Emilsson, T.U., Czemiel Berndtsson, J., Mattson, J.E. & Rolf, K. 2007 Effect of using conventional and controlled release fertiliser on nutrient runoff from various vegetated roof systems. *Ecol. Eng.* **29**(3), 260–271.

English Nature 2003 *Green Roofs: Their Existing Status and Potential for Conserving Biodiversity in Urban Areas*. English Nature Research Reports 2003, Report no. 498. English Nature, Peterborough, UK.

Kim, L.-H., Kayhanian, M., Zoh, K.-D. & Stenstrom, M. K. 2005 Modeling of highway stormwater runoff. *Sci. Total Environ.* **348**, 1–18.

Larsen, T., Broch, K. & Andersen, M. R. 1998 First flush effects in an urban catchment area in Aalborg. *Water Sci. Technol.* **37**(1), 251–257.

Lee, J. H., Bang, K. W., Ketchum, L. H., Choe, J. S. & Yu, M. J. 2002 First flush analysis of urban storm runoff. *Sci. Total Environ.* **293**, 163–175.

Moran, A., Hunt, B. & Smith, J. 2005 Hydrological and water quality performance from green roofs in Goldsboro and Raleigh, North Carolina. In: *Green Roofs for Healthy Cities Conference, Washington DC, May*. The Cardinal Group, Toronto pp. 512–525.

Takenaka Corporation 2005 *Environmentally Responsible Projects: ACROS Fukuoka*. Available at: http://www.takenaka.co.jp

Zobrist, J., Müller, S. R., Ammann, A., Bucheli, T. D., Mottier, V., Ochs, M., Schoenneberger, R., Eugster, J. & Boller, M. 2000 Quality of roof runoff for groundwater infiltration. *Water Res.* **34**(5), 1455–1462.