Infiltration of a copper roof runoff through artificial barriers

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Abstract On-site infiltration of a copper roof runoff may contribute to deterioration of the ground and ground water. To avoid such a negative effect the performance of two different technical systems, equipped with four different barrier materials, regarding copper elimination was examined in a field study. During the period March 2004 to January 2005, 16 rain events were examined. Copper concentrations between 200 and 11,000 μg/L in the roof runoff during a rain event were observed. The cover material of the roof and the drainage system were responsible for the high concentrations of copper in the roof runoff. It was evident that roof aspects facing towards the wind direction were receiving higher rainfall, thus were establishing higher copper runoff rates. The retention facilities have reached a performance of up to 97% regarding copper elimination.

Keywords Chabazite; clinoptilolite; corrosion rate; first flush; philipsite; runoff rate

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Introduction

Metals are essential to our modern world and are used in large amounts in buildings, constructions and in vehicles. Copper and zinc are commonly used in roof construction and in drain water systems in countries all over the world. Both roofing materials are considered to be maintenance free, have a long lifetime and are easily adapted to various design styles. The use of copper as a roofing material has a long tradition right back to the sixteenth century when copper sheet began to be used in Scandinavian countries, originally to prevent buildings from catching fire. Copper exposed to atmospheric conditions is subjected to a corrosion process in which clean copper transforms from salmon-pink to a progressively darkening brown and finally to the green colour, commonly known as "patina". The timescale for this corrosion process can be anywhere from 6 to 50 years (Franey and Davis, 1987). A part of the products formed through this corrosion process is released during a rain event in the roof runoff through erosion or dissolution processes. The rest is retained on the roof surface as corrosion products. Traditionally, the roof runoff is sent to sewers through which the rainwater is either directly transported to the receiving water or, in the case of combined sewer systems, is sent to waste water treatment facilities. From an economical point of view, this solution is far from being optimal because of the high costs for providing sewer and treatment facility capacity which is rarely exploited. Ecologically, the traditional urban dewatering concept is to be critically assessed as well, since it leads to two negative effects, pollution of the receiving water by direct discharge of the storm water or by sewer overflow, and lowering of the groundwater table underneath the urban area. On-site infiltration may be considered as a promising way of managing roof rainwater situations in urban areas, provided the hydrological and geological conditions allow infiltration, and provided the pollutants contained in the collected water are effectively removed before the rainwater enters the soil and the groundwater. Otherwise, the pollutants may accumulate in the soil leading eventually to

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highly contaminated sites, and may contribute to further deterioration of the groundwater quality. Major pollutants of concern are heavy metals such as copper, zinc and lead stemming from the roof material and from the piping.

To avoid such a negative effect it is proposed to pass the roof runoff through an artificial barrier before it enters the soil and the ground water (Boller and Steiner, 2002; Matsui *et al.*, 2003; Athanasiadis *et al.,* 2004a, b). The pollution removal mechanism of the barrier has to be effective under different and extreme rain weather conditions. Also, the pollutants in roof runoff may appear in enhanced concentration at the beginning of the precipitation event, whereas particularly heavy metals may remain in enhanced concentration for a prolonged period of time. The main objective of our research is to study the feasibility of the application of two different technical infiltration systems equipped with four different artificial barrier materials for the treatment of the copper roof runoff of the Academy of Fine Arts in Munich, Germany. Our target is to define the quality of roof runoff, regarding weather conditions, roof orientation and profile of rain event, the performance of the four different barrier materials under different hydraulic conditions, their sorption capacity, the possibility for on-site regeneration of the barriers materials, the risk of ground and groundwater contamination, and finally to calculate the cost of installation and maintenance of the infiltration facilities. The results obtained, so far, are presented and discussed in this paper.

Methods

Description of the field site

The Academy of Fine Arts is located in the centre of Munich, Germany (1,260,597 inhabitants). The building is surrounded by Leopold, Akademie, Türken and Georgen Street. Leopold Street is one of the main roads in Munich with a daily traffic load of cars. The traffic load of the other streets is less than 2,000 vehicles per day. The copper roof of the Academy of Fine Arts covers a total area of 4,800 m^2. The roof runoff is channelled into 10 retention facilities where each can treat the runoff of almost 500 m^2 roof surface. Four of them were chosen to be monitored; one at the west site, two at the south and one at the east. The copper panels at the west and east site are four years old. The panels at the south site are only two years old.

The retention facility from KME-Mall (RF I) at the west site is a technical infiltration system composed of a silt trap and a filtration tank equipped with a zeolith cartridge. After saturation of the barrier material, the cartridge can be replaced with a new one. The treated roof runoff is infiltrated into the ground by means of an infiltration ditch (Figure 1). The rest of the monitored retention facilities are using the technical infiltration system which has been developed by HydroCon (Figure 2). The roof runoff is channelled tangentially into the hydrodynamic separator of the filtration tank, passes through the barrier material and finally is infiltrated into the ground by means of an infiltration ditch. Since the filter medium (barrier material) could fail under extreme rain weather conditions, an emergency overflow has been arranged. At the east site (RF II) a barrier material of porous concrete, with a high concentration of $CaCO_3$, coated with iron hydroxide has been used. This medium is developed from HydroCon (Dierkes *et al.*, 2002). A mix of chabazite–philipsite has been used at the southeast site (RF III) and clinoptilolite at the southwest site (RF IV). Both barrier materials have been developed at the Institute of Water Quality Control and Waste Management of the Technical University of Munich (Athanasiadis *et al.*, 2004b; Athanasiadis and Helmreich, 2005).

As has already been mentioned the outflow of both technical systems, KME-Mall and HydroCon, is infiltrated into the ground by means of an infiltration ditch. The applied infiltration ditch is a special construction which contributes to an additional reduction of

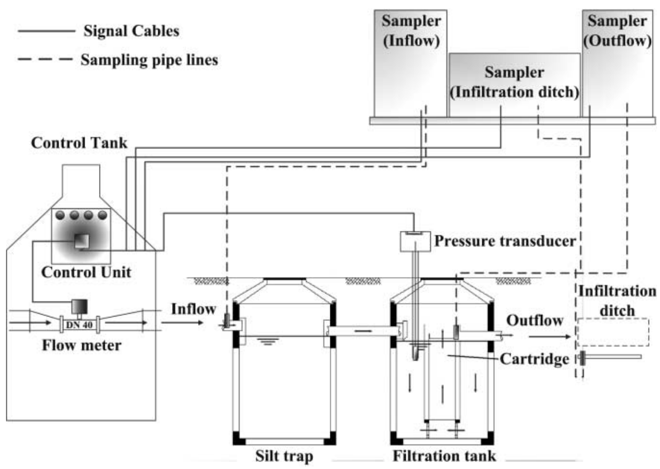

Figure 1 Technical infiltration system from KME-Mall with monitoring devices

the copper concentration. The ditch consists of a partial seeping pipe of impermeable concrete in the lower part (bottom of the pipe) and a porous concrete in the rest. The ditch is constructed from the same material used for the barrier material at the east site and it is also developed by HydroCon.

Monitoring system

As is shown in Figures 1 and 2 all retention facilities are equipped with a control tank. A control unit with a digital writer and a flow meter device are installed in every control tank.

Magnetic induction flow meter (MID). Every flow meter has been industrially calibrated in the range of 0–100 L/min and is able to function competently under rain water conditions, regarding electric conductivity down to 5 μS/cm.

Sampler (inflow and outflow). Every sampler has a capacity of 12 bottles with a volume of 2.5 L each. The sampling process lasts about two minutes and a sample of 250 mL can be collected in the bottle. The sampler temperature is arranged at 5 ± 1 °C.

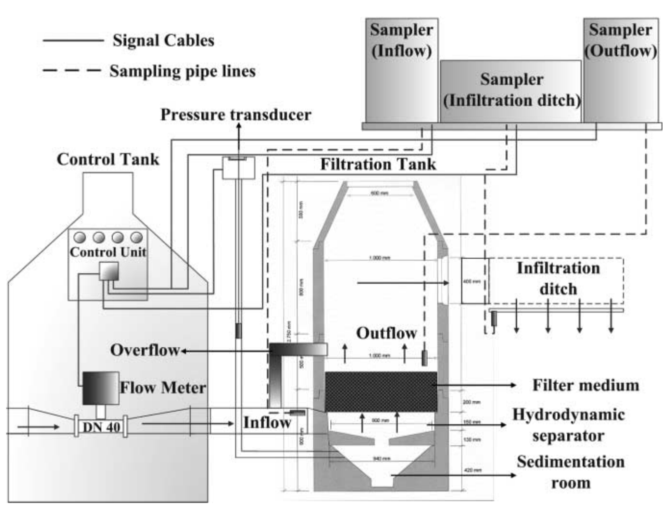

Figure 2 Technical infiltration system from HydroCon with monitoring devices

Sampler (infiltration ditch). The sampler comprises a glass bottle of 15 L and a suction pump. The pump delivers the percolation water which is collected from a halved pipe (DIN 200) installed 25 cm all the way along underneath the infiltration ditch. The halved pipe is packed with washed gravel of 7 mm grain size.

Pressure transducer. A pressure transducer is installed in every filtration tank. The load cell of the transducer is arranged 25 cm underneath the level of the infiltration ditch. The measure range of the device is between 0 and 0.25 bar.

Control unit. The control unit equipped with a digital writer controls and navigates the sampling process during a precipitation event. The signals from the flow meter, pressure transducer and from the samplers are digitally recorded (20 s interval modus).

Weather station. The rain data of every rain event, regarding rain height, rain intensity as well as air temperature, air humidity, wind strength and wind direction are recorded from the weather station of the Ludwig-Maximilians-University of Munich (LMU) which is located in Theresian Street, 200 m away from the Academy of Fine Arts.

Monitoring process. In the case of a rain event the roof runoff runs through the flow meter. If the flow velocity is faster than 1 L/min the control unit activates the samplers of the inflow and outflow. The sampler of the infiltration ditch is activated after 10 min and only when the flow velocity remains faster than 1 L/min. If the flow velocity is slower than 0.6 L/min, the control unit stops the sampling process. A flow velocity faster than 1 L/min will activate the system again and the new sampling process will use a new bottle of the sampler. For the sampler's inflow and outflow there is the potential to arrange a 4 × 250 mL sampling process in the same bottle. This means that the system can monitor a non-stop rain event for almost 96 min.

Sampling

Samples are taken from four different points. First, direct from the rain by means of a sampling device installed at the top of the roof; second, from the inflow of every retention facility; third, from the outflow of every retention facility; and finally underneath the infiltration ditch.

Analysis of samples

All samples were analysed for the following constituents using the methods described as follows:

- Total and dissolved copper was measured in acidified samples (1% suprapur HNO_3) by means of atomic absorption spectrometry. The dissolved fraction was obtained by filtration (0.45 μm cellulose nitrate filter) prior to acidification.
- pH values were measured in the laboratory with a glass electrode (WTW Sentix 60).
- The electric conductivity (EC) readings were performed by an EC electrode (WTW TETRACON 325) connected to a WTW LF 340 EC meter.

Results and discussion

The measured roof runoff volume, obtained through the flow meter recordings in the sampling period, was almost 292 m^3 at retention facility I (west site, 468 m^2 roof surface), 135 m^3 at retention facility II (east site, 468 m^2 roof surface), 98 m^3 at retention facility III (southeast site, 412 m^2 roof surface) and 157 m^3 at retention facility IV (southwest site, 412 m^2 roof surface). The runoff volume, calculated by using the rain height obtained from the weather station of the Ludwig-Maximilian-University of Munich, for a flat roof surface of 500 m^2 in the same sampling period was almost 168 m^3 (see Table 1).

It is evident that the retention facility at the west site generated more runoff than the other ones because the roof faces into the prevailing wind (west-facing) and also because it experiences less evaporation than those facing south and east. Similar observations have been reported by Ragab *et al.* (2003). There is significant impact of the orientation, inclination and height of the roof on the runoff volume in an urban environment. The application of rain data in runoff models for the prediction of roof runoff volume without taking into consideration the effects of aspect, slope and height of the roof includes a high risk and probably can lead to wrong estimations, e.g. in risk assessments, maintenance of retention facilities.

Sixteen rain events were sampled in the period March 2004–January 2005. Table 2 shows the profiles of those rain events regarding dry weather period and rain height. In the rainwater the pH varied from 6.8 to 8.0, the mean value was 7.2. The average pH value in the roof runoff of the four retention facilities was between 6.7 and 7.0. The pH is of major interest at the outflow the retention facility due to its impact on the bioavailability of copper. The lowest pH value measured in the outflow of retention facility I was 6.9 and the highest 9.7. In the outflow of retention facility II the pH varied from 7.7 up to 11.3, of retention facility III between 6.6 and 10.7 and of retention facility IV between 6.4 and 9.3. The increase of the pH value in the roof runoff after passing through the barrier material at the retention facilities I, III and IV was due to the ion exchange process (Doula *et al.*, 2002). For the high pH values at the outlet of retention facility II the high concentration of $CaCO_3$ in the barrier material responsible was. The mean pH value of the percolated water of retention facility I was 7.6, of facility II was 7.9, of facility III was 7.6 and of retention facility IV 7.4, respectively.

As was expected different amounts of copper were being washed off the roof surface during all sampled rain events. In the rainwater the copper concentration varied between 16.0 and 230 μg/L, the mean value was 74.3 μg/L. After contact with the roof material the copper concentration in the rainwater increased significantly. At the west site (RF I) the total copper concentration in the roof runoff varied between 500 and 6,980 μg/L. At the east site (RF II) the total copper concentration was between 1,010 and 11,100 μg/L, at the southeast (RF III) between 400 and 4,300 μg/L and finally at the southwest site (RF IV) between 200 and 5,910 μg/L.

As shown in Figure 3 there is a linear correlation between the copper mass washed off the roof during a rain event and the runoff volume of the rain event. In order to evaluate

Table 1 Measured roof runoff and rainfall in the period March 2004–January 2005

Month	Runoff volume (m^3) - MID				Weather station	
	RF I	RF II	RF III	RF IV	Rain height (mm)	Calculated runoff volume (m^3)
March	6.572	11.174	8.916	18.149	13.12	6.560
April	30.208	9.743	7.355	17.182	21.66	10.830
May	40.837	12.325	8.920	16.597	26.14	13.070
June	14.043	21.377	13.004	19.609	46.70	23.350
July	49.280	24.717	18.177	19.125	80.83	40.415
August	32.279	13.613	11.044	12.907	44.36	22.180
September	28.629	11.790	8.577	14.584	28.67	14.335
October	29.770	18.591	10.980	13.836	50.68	25.340
November	20.736	5.423	4.656	12.248	12.85	6.425
December	21.815	3.150	2.703	7.695	10.14	5.070
January	17.961	3.506	3.961	12.500	14.55	7.275
Total	292.130	135.409	98.293	156.737	349.7	174.850

Table 2 Profile of the sampled rain events (March 2004–January 2005)

Rain event	Date	Rain height (mm)	Dry weather period (d)
1	21/03/2004	2.39	26
2	23/03/2004	3.29	0
3	24/03/2004	10.96	0
4	05/04/2004	6.77	10
5	18/04/2004	11.16	9
6	30/04/2004	0.55	10
7	06/05/2004	0.38	0
8	12/05/2004	5.26	2
9	21/05/2004	2.94	4
10	01/07/2004	7.11	2
11	14/09/2004	8.11	1
12	22/09/2004	0.35	6
13	23/09/2004	8.45	0
14	08/10/2004	4.05	1
15	15/10/2004	2.27	4
16	18,19,20,21.10.2004	8.82	0

the impact of roof orientation on the copper runoff rate and if there are seasonal differences in the copper runoff rate, linear regression analysis was applied for all retention facilities and for all rain events sampled in spring and in autumn. In spring, the copper runoff rate at the west site (RF I) was 0.32 g/m^2, at the east site (RF II) 0.24 g/m^2, at the southeast site (RF III) 0.16 g/m^2 and at the southwest site (RF IV) was also 0.16 g/m^2. In autumn, the copper runoff rate at the west site was 0.38 g/m^2, at the east site 0.14 g/m^2, at the southeast 0.10 g/m^2 and at the south west site 0.17 g/m^2, respectively. It is evident that the copper runoff rate is significantly influenced from the precipitation volume hitting the roof surface. Therefore runoff rates are higher for roof aspects facing the wind direction. A seasonal difference in copper runoff rates could not be clearly observed.

Rain data from summer and winter are needed in order to evaluate the impact of the seasons on the copper runoff rate. Similar results have been published by Odnevall Wallinder *et al.* (2001), about runoff rates of new copper roofs. Figure 4 presents the

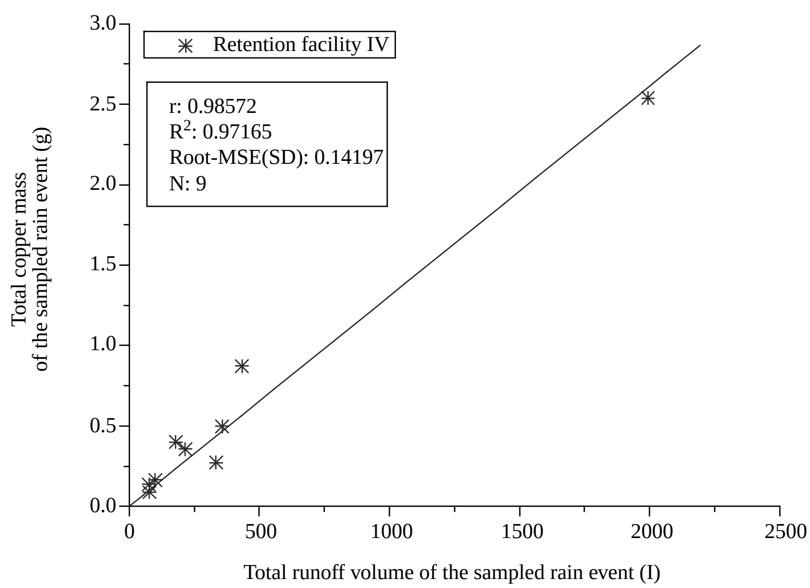

Figure 3 Linear correlation between the copper mass washed off the roof surface during a rain event and the runoff volume of the rain event, in spring

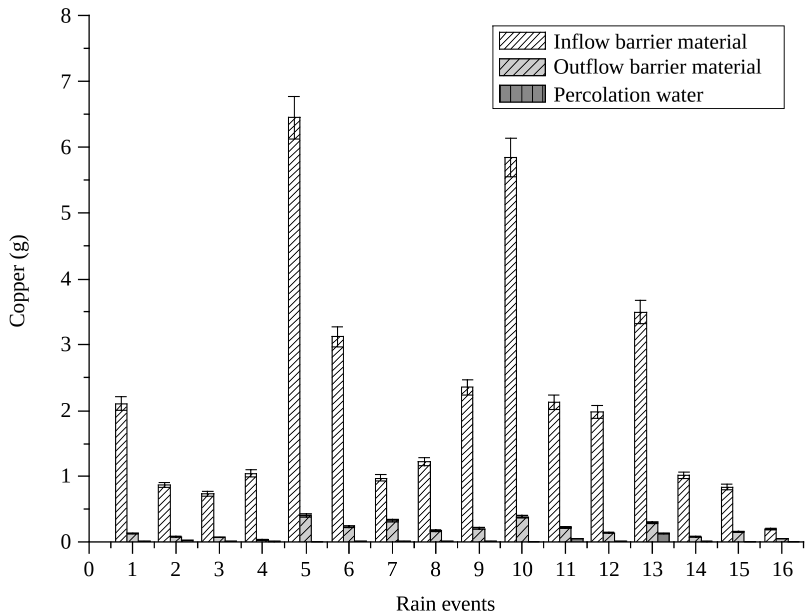

Figure 4 Performance of retention facility I regarding copper elimination

performance of retention facility I regarding copper elimination. The copper concentration in the runoff after the passage through the barrier material varied between 45.3 and 510 μg/L ($Cu^{2+}_{mean} = 240$ μg/L). In percolation water the copper concentration was between 5.6 and 85.0 μg/L ($Cu^{2+}_{mean} = 32.9$ μg/L). The application of the special infiltration ditch seems to be necessary to achieve copper concentrations in percolation water less than 50 μg/L (BBodSchV-12.07.1999-BGBI. I, S. 1554). Regarding copper

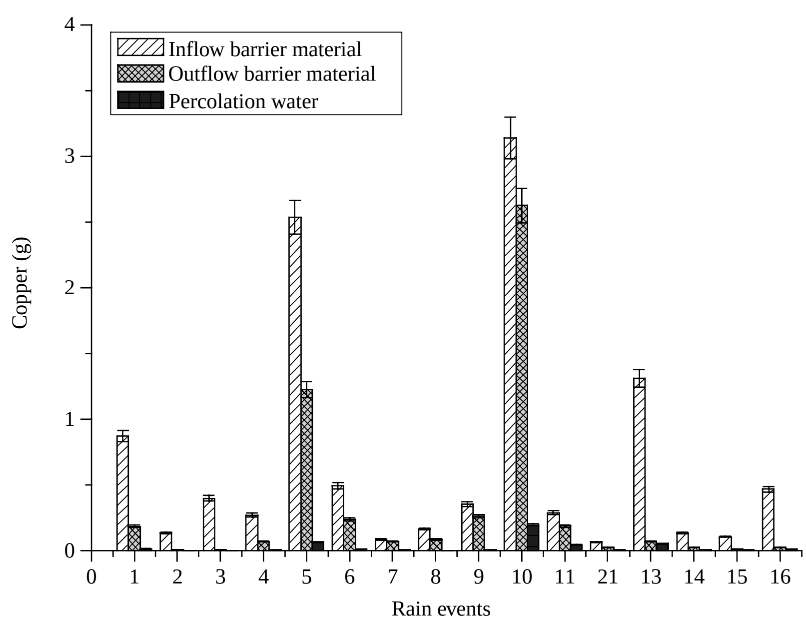

Figure 5 Performance of retention facility IV regarding copper elimination

elimination the performance of the barrier material was up to 91% and of the whole retention facility up to 99%.

Figure 5 presents the performance of retention facility IV at the southwest site with regards to copper elimination. The copper concentration in the runoff after the barrier material varied between 18.4 and 2,400 μg/L ($Cu^{2+}_{mean} = 491$ μg/L).

The unsatisfactory performance of the barrier material in some rain events, until the 11th rain event, was due to a construction failure. During heavy rain events part of the roof runoff was passing by the barrier material through the emergency overflow resulting in contamination of the treated outflow of the barrier material. After repairs were carried out at the emergency overflow of the retention facility, the copper concentration in runoff after the barrier material varied between 38.0 and 980 μg/L ($Cu^{2+}_{mean} = 161$ μg/L). The performance of the barrier material regarding copper elimination was 92%. The copper concentration in the percolation water was between 31.0 and 84.0 μg/L ($Cu^{2+}_{mean} = 53.0$ μg/L). The performance of the retention facility IV after the repair of the construction failure was 97%.

Conclusions

The results obtained can be summarised as follows:

- There is significant impact of the orientation, inclination and height of the roof on the runoff volume in an urban environment. Roofs facing into the prevailing wind direction receive higher rainfall.
- The cover material of the roof and the drainage system are responsible for the high concentration of copper in the roof runoff.
- Orientation of the roof plays a significant role on the copper runoff rate. Copper runoff rates are higher for roof aspects towards the wind direction.
- Both retention facilities were able to reduce the copper concentration from the roof runoff by a factor of up to 97%.

Regarding these results on-site infiltration may be considered as a viable way of managing storm water situations in urban areas, provided the hydrological and geological conditions allow infiltration.

Acknowledgements

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