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On-site infiltration of road runoff using pervious pavements with subjacent infiltration trenches as source control strategy

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ABSTRACT

The focus in this work was on subsoil infiltration of stormwater from parking lots. With regard to operation, reduced infiltration performance due to clogging and pollutants in seepage, which may contribute to contaminate groundwater, are of interest. The experimental investigation covered a pervious pavement with a subjacent infiltration trench draining an impervious area of 2 ha. In order to consider seasonal effects on the infiltration performance, the hydraulic conductivity was measured tri-monthly during monitoring with a mobile sprinkling unit. To assess natural deposits jointing, road bed, gravel of infiltration trenches and subsoil were analysed prior to commencement of monitoring for heavy metals, polycyclic aromatic and mineral oil type hydrocarbons. Furthermore, from 22 storm events, water samples of rainfall, surface runoff, seepage and ground water were analysed with regard to the above mentioned pollutants. The study showed that the material used for the joints had a major impact on the initial as well as the final infiltration rates. Due to its poor hydraulic conductivity, limestone gravel should not be used as jointing. Furthermore, it is recommended that materials for the infiltration facilities are ensured free of any contaminants prior to construction. Polycyclic aromatic and mineral oil type hydrocarbons were, with the exception of surface runoff, below detection limits. Heavy metal concentrations of groundwater were with the exception of lead (because of high background concentrations), below the permissible limits.

Key words | Infiltration trench, monitoring, pervious pavement, road runoff, stormwater infiltration

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INTRODUCTION

Decentralised infiltration of rain runoff from roofs as well as from traffic areas is state-of-the-art. In the recent past, different authors investigated various types of infiltration facilities in order to define the impact of water and its pollutants on the urban aquatic environment. Göbel *et al.* (2007) as well as Brombach *et al.* (2005) collected and analysed literature data of stormwater runoff quality. A common finding of both studies is the high variety of pollutant concentrations in urban stormwater. The infiltration performance of pervious pavements was investigated in detail by Illgen *et al.* (2007) in field tests and under laboratory conditions. The objective was to generate a data base that enables a phenomenological analysis of different types of pervious pavements. From Dierkes & Geiger (1999), it is known that the leaching of heavy metals in roadside soils was limited due to the high contents of organic matter and almost neutral to weakly alkaline pH conditions. Dierkes & Geiger (1999) recommend to remove roadside soils heavily affected by traffic activities after a certain period, to prevent heavy metals being transported downwards by time and varying chemical milieu. Tests with gravel or sand as filter media showed a high pollutant removal efficiency with respect to suspended solids and particulate associated pollutants. The removal efficiency was constant, even after clogging of the filter media (Hatt *et al.* 2006). The work of Achleitner *et al.* (2007) had a focus on heavy metal concentrations in soil of infiltration swales used to drain parking places of supermarkets. It was shown that the measured copper concentration exceeded the calculated maximum concentration accumulated in the soil. Varying

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characteristics of concentration distribution for different sites quoted from Hiller *et al*. (2001), for example (also cited by Achleitner *et al*. 2007), make it difficult or even impossible to determine a distinct relationship between traffic load, operating time and pollutant load. Based on the requirement of long-term monitoring to get representative results Barraud *et al*. (2002) introduced an interdisciplinary project on a stormwater infiltration basin. To enhance the quality of input data in this long-term field study backup measuring equipment was implemented. Sansalone (1999) presented a field-scale study of a partial exfiltration trench – a combination of porous pavement with a subjacent infiltration trench to treat the runoff from a highway with 140,000 passenger vehicles and 15,000 commercial vehicles per day.

The former results are not suitable to predict the hydraulic and pollutant retention efficiency of permeable pavements used for low-trafficked areas. The results of Achleitner *et al*. (2007) cannot be transferred because this study was limited to infiltration swales and dissolved pollutants were not taken into account. The pollutant load was assessed using literature data. However, the database in particular for low-trafficked areas is very poor as reported by Göbel *et al*. (2007). The results obtained by Sansalone (1999) cannot directly be used to assess permeable pavements although the investigated structure was somewhat similar to the one in this work. This is possibly due to the highly trafficked highway, which has an impact on the runoff constituents and concentrations. The objective of this work was to analyse all pollutant fluxes in an infiltration facility of a parking place with an impervious area of 2 ha to be able to make some kind of mass balances. The facility constituted an infiltration trench covered with an overlying pervious pavement made of precast concrete blocks. Water samples of rainfall, surface runoff, seepage in the infiltration trench and groundwater were considered. To evaluate the risk of inundation, the hydraulic performance was measured during monitoring.

MATERIALS AND METHODS

The monitoring took place four years after construction of the infiltration facilities. Prior to this, the jointing of a pervious paved subarea was replaced and measures like gutters, shafts among others, were installed to collect water samples. The monitoring itself lasted 20 months covering two winter and summer seasons for the purpose of considering the seasonal effect on infiltration performance and pollutant retention by means of biological activity.

Characterisation of the parking area and its infiltration facilities

The investigated parking area had an effluent effective area of 2 ha and was characterised by a continuous slope from North to South. The height difference of ground surface from North to South was roughly 2.4 m. A slope of 1.2° was calculated from North to South end (a distance of 117.5 m). Two rows of parking sites and the aisle way, which were impervious, drained into an infiltration trench (IT) located on the south side. Two adjacent lines of parking space were separated by a verge of 1.4 m width. To determine the intensity of traffic, the access was equipped with an induction loop detector. The downside to this method is that it was not possible to differentiate between different type of vehicles (e.g. passenger cars, heavy goods vehicles, etc.) in the results. Due to the low infiltration performance of the fine-sandy, silty soil, infiltration trenches were installed beneath the pervious paving to store the rain runoff until it could be infiltrated into the subsoil. The thickness of the fine sandy, silty soil layer was around 3 m. An impermeable marlstone layer can be found beneath the native soil.

To protect the infiltration trenches from clogging, they are wrapped with a geo-textile. The characteristics of the infiltration trenches investigated in this work are summarised in Table 1.

The pervious paving was made of precast concrete block pavers with dimensions of 20 cm × 20 cm × 8 cm which were separated with integrated spacers of 2.8 cm. The original jointing was limestone gravel (LG) with a grain size range from 2 to 5 mm. To investigate the impact of different materials on the infiltration capacity and pollutant retention capability, the original jointing was replaced by recycled concrete (RC) with grain sizes between 0 and 5 mm, lava (LA)

Table 1 | Characteristics of the infiltration trenches and connected effluent effective area

Filter material (–)	Length (m)	Width (m)	Height (m)	Connected area vs. Infiltration area (–)
IT2 limestone gravel 32/45	90	1.20	1.0	15
IT3 sandy gravel 0/32	96	1.20	1.0	15
IT4 limestone gravel 0/45	124	1.20	1.0	15

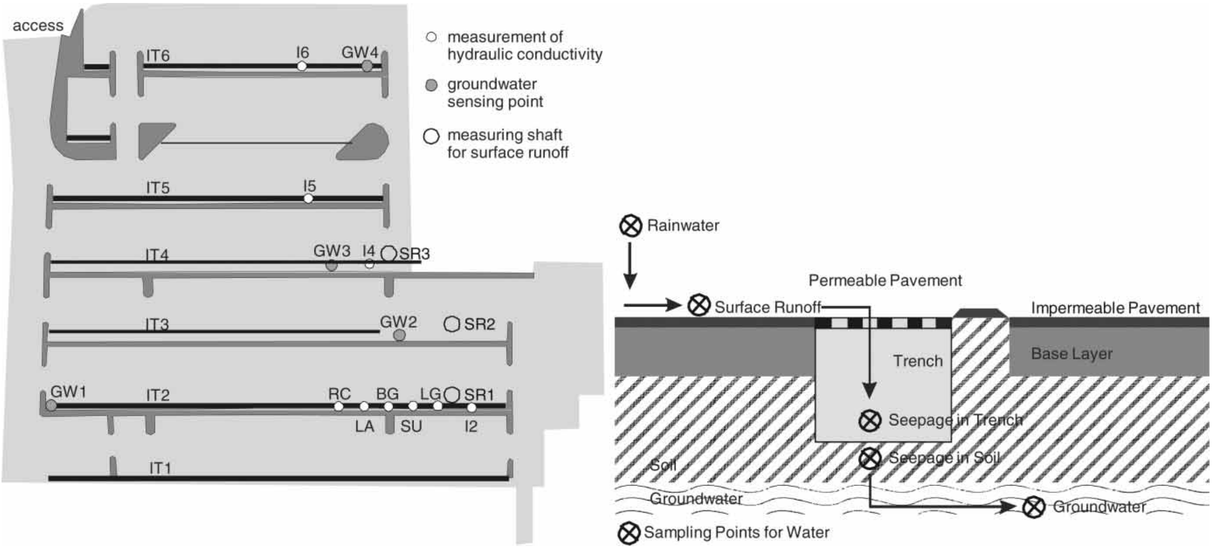

Figure 1 | Layout of the investigated parking area with measuring equipment and points (left side) and cross section of permeable pavement and infiltration trench (right side).

(grain sizes 4 to 8 mm), basalt gravel (BG) (grain sizes 1 to 3 mm) and substrate (SU) (grain sizes 0 to 5 mm) at specific sections of the infiltration trench IT2. The left side of Figure 1 shows the placement of the six infiltration trenches of varying lengths between 64 and 133 m. The construction of permeable pavement and infiltration trench in cross section can be seen on the right side of Figure 1.

Collection of water samples

Precipitation was collected in a glass bottle located near the parking area. To minimise temperature variation and UV radiation on the sample, the glass bottle was wrapped in foamed polystyrene. The rain intensity was recorded continuously using a data logger with a resolution of 0.1 mm.

At three distinctive locations, the surface runoff of 48 m^2 each was collected in a 200 L PE container situated in a sealed measuring shaft. This runoff was mixed and homogenised, to ensure representative water quality samples. The exceeding runoff volume was retained in the surrounding measuring shaft. After each sampling run, the excessive water in the shaft as well as the PE container were pumped out.

Due to the high hydraulic conductivity of the infiltration trench, the gauge for taking the samples was built into a bucket. Thereby it was possible to take samples even after the infiltration trench had fallen dry.

The seeping water, upon passing the infiltration trench, was obtained with porcelain suction cups, which were installed at depths of 5, 10 and 30 cm below the base of the infiltration trench. Each end of the porcelain suction cups was connected to a hose which could be accessed at the measurement shaft. The sampling was done with negative pressure, its maximum value being 500 hPa.

The groundwater was monitored at four measuring points. The gauge was bored to the impermeable layer of the plaster stone at depths between 3.2 and 5.2 m below ground surface. Due to the fine-grained soil, the filter pipe was encased with filter gravel. In order to avoid water from the infiltration trench from directly entering the filter pipe, its section crossing the trench was sealed with swelling clay.

Determining the hydraulic conductivity of the permeable pavement

The infiltration performance of the pervious pavement above the trench was investigated by means of steel ring filled with potable water. Infiltration rates below 1,440 mm/h were measured using a mobile sprinkling device according to the German guideline (FGSV 947 1998). A steel ring with an inner area of 0.64 m^2 was waterproofed and attached to the pavement. The sprinkling intensity was sensor-controlled by the water level inside of the steel ring. The irrigated water was continuously recorded by means of a flow-meter. Because the area inside and outside of the steel ring was irrigated simultaneously this method implies the same boundary conditions like a test conducted with a double-ring infiltrometer according to the German standard (DIN 19682-7 2007). The test was carried out for at least 50 min or until the final infiltration rate was reached. For infiltration rates above 1,440 mm/h, a steel ring with an inner area of 0.16 m^2 was filled with 10 L of water and the time needed to drain this water was kept and recorded manually. This test was repeated until the measured time was constant. Because this methodology could not avoid horizontal streamlines of fluid flow, the resulting infiltration rate was reduced by 20%. The nature of hydraulic processes in porous media implies that the infiltration performance will decrease with time until saturation and hence equilibrium is reached. In Germany areal infiltration facilities are usually designed for storm events of 10 min duration (DWA 138 2005). The guideline FGSV 947 (1998), likewise, requires an infiltration performance over 10 min. As such, the measured data is analysed with regard to the infiltration rate after 10 min and for the final state.

Analyses of water and total solid samples

All samples were prepared according to BBodSchV (1999). Water samples were analysed with regard to the heavy metals lead, copper, zinc and cadmium as per German standard DIN EN ISO 11885 (2009) by means of an inductively coupled plasma optical emission spectrometry (ICP OES). Mineral oil type hydrocarbons (MOH) were investigated in accordance with the German standard DIN EN ISO 9377-2 (2001) by means of gas chromatography (GC). The analysis of polycyclic aromatic hydrocarbons (PAH) was carried out according to the German standard DIN 38407-8 (1995) using high performance liquid chromatography (HPLC). The total solids were additionally analysed prior the monitoring to avoid influence of geogen background contamination of subsoil and packing of the infiltration trenches on the pollutant concentrations of the water sample. Heavy metal concentration of the total solids was determined with aqua regia digestion according to DIN ISO 11047 (2003).

The detection limits of the ICP OES adopted were 5 μg/L or 1 mg/kg for lead, copper and zinc as well as 0.5 μg/L or 0.1 mg/kg for cadmium. The HPLC had detection limits for PAH of 0.01 μg/L or 0.05 mg/kg and the GC for MOH of 0.05 mg/L or 50 mg/kg. In general, uncertainties should to be taken into account for the evaluation of the results. In order to minimise additional analyses of samples, its accuracy was assessed according to Zauner (1996), who introduced a simplified procedure in which the total error is the result of an error contribution due to fluctuation of concentration during the sampling preparation and analysis. Error contribution due to imprecision (e.g. applying volumetric instructions for analysis) is also considered.

RESULTS AND DISCUSSION

Temporal variation of precipitation and groundwater table

The annual precipitation during the monitoring period was insignificantly below the annual mean value of 852 mm. Of the 578 monitored days, precipitation was observed 55% of the time (this corresponds to 319 days). As one can see from Figure 2, the maximum daily precipitation was 39 mm/d. Only 12% of all wet days showed a rainfall depth greater than 10 mm/d. Precipitation with a rainfall depth lower than 2.5 mm/d occurred most frequently (in 54% of all wet days). With regard to intensity, 55% of all storm events had an average intensity between 0.9 and 1.8 mm/h (Figure 3). The rain intensity of roughly 5% of all events was between 1.8 and 3.6 mm/h. Only 2% of the storm events showed intensity above 3.6 mm/h and can be therefore characterised as heavy storm events. In addition

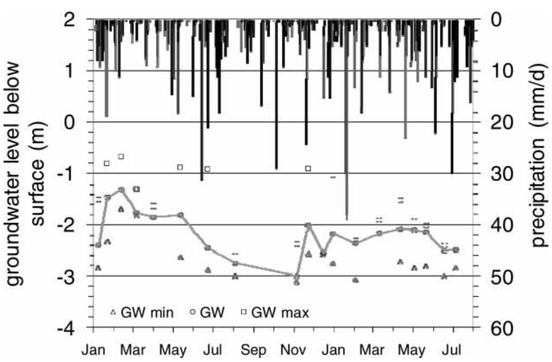

Figure 2 | Temporal variation of precipitation and groundwater table.

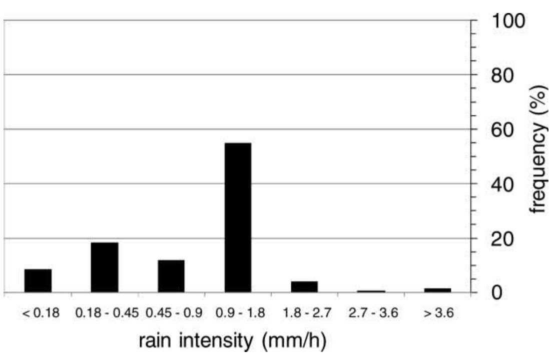

Figure 3 | Relative frequency distribution of rain intensity.

to intensity storm events can additionally be characterised by their duration. The largest proportion – namely 46% of all storm events – lasted 10 min or less. Only somewhat more than 20% of all storm events exceeded 6 h.

The groundwater level below surface was measured concurrently to sampling at the four distinctive places marked in Figure 1. This was necessary to be able to determine whether the water sampled was coming from stratum water due to storm events or from groundwater. As illustrated in Figure 2, there is no direct correlation between precipitation and groundwater level. Furthermore, the groundwater graph shows the typical characteristics for the monitored region with minimum levels in autumn and maximum levels in winter/spring. Therefore it can be assumed that the water sampled was a matter of groundwater. The depth to the water table is relevant because it defines the contact time of seepage water passing the soil filter prior entering groundwater. During monitoring, the maximum groundwater level was about 0.70 m below ground surface. Due to the remaining distance between bottom of infiltration trench and groundwater table, there was no short circuit of surface runoff and groundwater during the monitoring period.

Infiltration rate of permeable pavement during the monitoring phase

To consider seasonal effects with their impact on soil moisture and pore structure the infiltration performance was determined quarterly during the monitoring period. Except for the pavement above infiltration trench IT2 the test was conducted four times. Resulting infiltration rates of the pavement with the original jointing are depicted in Table 2. The first value indicates the average infiltration rate during the first 10 min and the second, the final infiltration rate. Due to the strong deviation of neighbouring flow meter values recorded every minute, the final infiltration rate is quoted as a median value for the last 10 min of each measurement with more or less steady-state conditions. On average, the infiltration rate ranges from 140 to 580 mm/h for the first 10 min and from 50 to 370 mm/h for steady-state conditions respectively. Even the variation of infiltration rates from the same date of measurement is, despite identical jointing, unexpectedly high. This effect can be explained only by differences in the macro pore structure responsible for the hydraulic behaviour caused by the feeding of particles from the surface runoff and from abrasion of tyres. Additionally, the hydraulic conductivity is reduced by biological clogging due to the presence of organic compounds, such as pollen and leafs. Also, the remains of plants growing within the jointing can significantly decrease infiltration rate.

Because the pavement was not swept during the monitoring period its infiltration rate was expected to decrease with operating time. It can however be seen from Table 2 that there is no obvious development of infiltration rate with operating time. Nevertheless, a kind of pattern can be found within this data which can be explained as follows: the highest infiltration rates correspond to (summer) months after longer dry weather periods. Although the jointing was visibly clogged by fine particles in the summer period, this seemed to have no impact on the infiltration performance. Due to the drying of the jointing, cracks are formed, which consequently support preferential flow. After longer periods with wet weather conditions, infiltration rate again decreases because the cracks are re-formed due to higher soil moisture content. The infiltration performance is mainly defined by the superposed preferential flow process. In order to point out the reduction of hydraulic conductivity with time, the deviation of final and initial rate is calculated for each measurement. The result is shown as a box-plot diagram in Figure 4. It can be seen that the existing jointing I2–I6 offered a high span of infiltration rates depending on both site and time of measurement. Except

Table 2 | Temporal variation of the infiltration rate of the original jointing (mm/h)

	Month	I2	I4	I5	I6
#1	March	120/30	–	–	–
#2	June	590/600	–	–	–
#3	September	60/10	2,000/1,280	140/60	90/30
#4	January	40/10	90/50	430/220	90/90
#5	March	230/140	140/10	1,700/1,340	2,240/1,230
#6	July	320/260	140/40	730/510	690/300
	Median	180/90	140/50	580/370	390/200

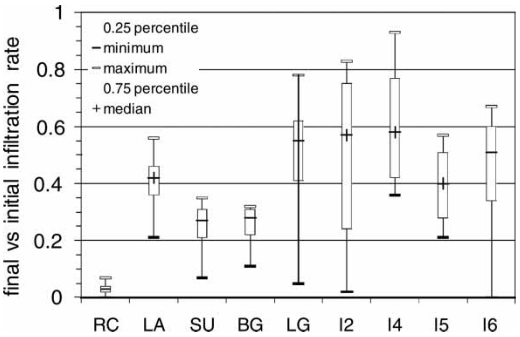

Figure 4 | Variation of final and initial infiltration rate over monitoring period.

for the limestone gravel, the newly built-in jointing showed a much smaller variation in infiltration rate. It is commonly known from intensity-duration-frequency curves that rain intensity is decreasing with time. A more or less time-independent and therefore constant infiltration rate is equivalent to a higher protection against inundation. To increase the social acceptance of water sensitive urban design, its security in terms of drainage should be just as high as conventional end of pipe solutions. Therefore, the permeable pavement has to ensure reliable drainage and prevent consequential damage due to inundation.

According to the German guideline FGSV 947 (1998), permeable pavements should be capable of infiltrating a design storm event of 270 l/(s ha) over 10 min, which corresponds to a hydraulic conductivity of 97 mm/h. Taking into account that the runoff effective area connected to the pervious area was 15 times higher, the necessary infiltration rate should be 1,455 mm/h instead of 97 mm/h. This infiltration rate was reached only for less than 20% of all measurements. Because the rain intensity of 98% of all storm events in the monitoring phase was below 3.6 mm/h, an infiltration rate above 54 mm/h can be regarded as sufficient to prevent surface runoff. This threshold value was met for all measurements. As a result, less than 2% of the storm events would cause an inundation.

Additionally, infiltration tests were concurrently conducted with the newly built-in jointing. As expected, the measured infiltration rates (summarised in Table 3) are many times higher than that of the original jointing. Even the limestone gravel (LG), which was more or less equivalent to the original jointing showed at least 4.6 (8.7) times higher infiltration rates for the final (initial) state. The recycled concrete (RC) attained by far the highest infiltration rates with a median of 14,310 mm/h (14,420 mm/h) for the initial (final) state. On top of it there was no real reduction in infiltration rate with time (Figure 4). The infiltration rate of lava (LA), basalt gravel (BG) and substrate (SU) showed the same order of magnitude ranging from 6,060 mm/h (3,770 mm/h) to 6,520 mm/h (4,630 mm/h) for the initial (final) state. However, as mentioned above, all newly built in jointings offered a more or less time-independent hydraulic behaviour with the benefit of protection against inundation. After more than one year in operation, all newly built-in jointings were fulfilling the required infiltration rate of 1,455 mm/h. Nevertheless, limestone gravel (LG) cannot be recommended for use due to its comparatively low final hydraulic conductivity which may be an indication for the reduction with increasing operation time, which is evident when comparing the values of Table 3 with the ones of Table 2. In contrast, recycled concrete (RC), lava (LA) and substrate (SU) were capable of fully draining the surface runoff without any restrictions even when the connected area was 15 times larger than the aerial infiltration area itself. Due to the short duration of monitoring and the overall operation time, it is not possible to forecast the yearly reduction of hydraulic conductivity of each jointing investigated.

Geogen contamination of road and infiltration trench material as well as of subsoil

In order to assess pollutant concentrations of the water samples it is necessary to know the geogen background contamination of materials that come in contact with seepage water. Therefore, jointing (JO), road bed (RB), infiltration trench gravel (IT#) and subsoil (BO#) were analysed prior

Table 3 | Temporal variation of the infiltration rate of the new jointing (mm/h)

	Month	RC	LA	BG	SU	LG
#1	September	14,760/14,530	1,700/740	7,530/5,300	6,520/4,860	5,510/5,240
#2	January	15,000/15,000	5,120/3,030	6,560/4,490	6,000/3,930	5,420/1,190
#3	April	12,050/12,860	10,590/12,860	6,470/4,760	5,510/5,130	2,340/1,030
#4	July	13,850/14,300	7,890/4,500	4,460/3,960	6,120/4,340	4,650/2,180
	Median	14,310/14,420	6,510/3,770	6,520/4,630	6,060/4,600	5,040/1,690

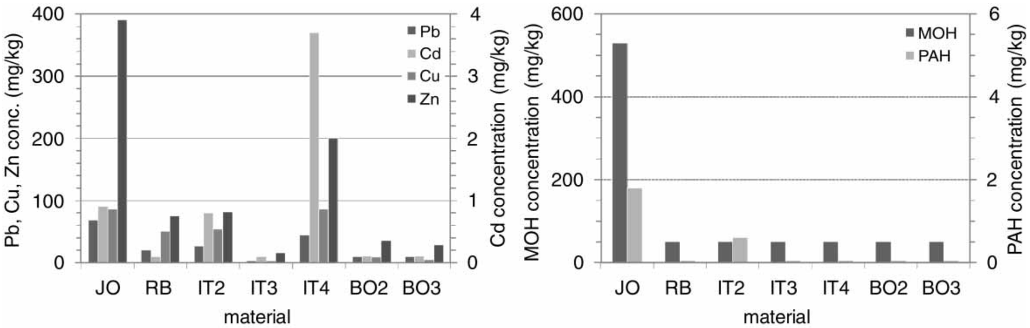

Figure 5 | Particle concentrations with regard to heavy metals (left side) and hydrocarbons (right side).

to commencement of the monitoring with respect to heavy metals lead, cadmium, copper and zinc. Additionally, these materials were analysed for mineral oil type hydrocarbons (MOH) and polycyclic aromatic hydrocarbons (PAH). Highest concentrations were detected, as expected, in jointing and roadbed as shown in Figure 5. The pollutants' origin can be traced back to abrasion products and dripping losses due to traffic. Inconsistent with the pollutant path are the high particle concentrations of the gravel built into the infiltration trenches IT2 and IT4, which may be a result of former land use in this highly industrialised area. These high concentrations have to be taken into account when assessing the water samples of the infiltration trenches in question as well as of the impacted groundwater. Furthermore, analysis for harmful substances should be carried out for materials built into infiltration facilities. Only the concentrations found for the gravel of infiltration trench IT3 seemed to follow the predicted pollutant path. The concentrations of the subsoil were below the limit values given in BBodSchV (1999).

Pollutants in precipitation, surface runoff, seepage water and groundwater

The average intensity of traffic was 358 vehicles per 24 h, with a range from 52 vehicles to 686 vehicles per 24 h. The unequal distribution can be attributed to the selected car park, which caters for a sports centre. For example the attached outdoor swimming pool is occupied whenever wind and weather permit.

Water samples of precipitation (PR), surface runoff (SR), seepage water (SW) and groundwater (GW) were collected from 22 storm events covering the monitoring period. The depth of rainfall responsible for surface runoff varied from 4 to 29 mm with a median value of 8.2 mm. Median concentrations and pH-values of the water samples are summarised in Table 4. The table also includes the limit values for seepage water of BBodSchV (1999). Additionally, the various magnitudes of heavy metal concentrations are depicted in Figure 6 to illustrate the wide range measured. The box plot diagram is restricted to lead, copper and zinc, because all other parameter were mostly below detection limits. Measured values are subsequently interpreted using average values from literature which were statistically analysed from Göbel *et al*. (2007).

The precipitation is characterised by a comparatively high pH-value of 7.2. Cadmium as well as mineral oil (MOH) and polycyclic aromatic hydrocarbons (PAH) in precipitation were below detection limits. Zinc corresponded well with average values from literature whereas lead and copper were below.

The pH of surface runoff was higher than the one of precipitation due to buffering provided by the concrete block pavers. The slightly basic pH-value ensures prevention of heavy metals mobilisation. Zinc was detected in the range of 80 to 110 μg/L, far-off the average value of 400 μg/L. Copper concentrations were about 20 μg/L, which is below average values of 80 μg/L. The minor concentrations can be explained by the low trafficked parking place. The low concentrations of mineral oil type hydrocarbons can be attributed to minor dripping losses and more efficient motors with regard to emission.

Contrary to initial expectations of pollutant path, heavy metal concentrations of water from the infiltration trench were above those of surface runoff. The answer of this phenomenon is given by the detected particle concentrations of the filter material itself. Even when concentrations in seepage water collected with suction candles were at least of same level as surface runoff, the high particle concentration has a direct impact on water quality. That is why all filter materials should be approved by autonomous testing laboratories.

Table 4 | Median concentrations and pH-values of precipitation (PR), surface runoff (SR), water in infiltration trench (IT), seepage water collected with suction candles (SC) and groundwater (GW)

	pH	el. cond. (μS/cm)	Pb (μg/L)	Cd (μg/L)	Cu (μg/L)	Zn (μg/L)	MOH (mg/L)	PAH_{EPA} (μg/L)
PR	7.2	51	5	<0.5	2.5	60	<0.05	<0.01
SR1	7.7	268	5	0.5	20	80	0.22	0.01
SR2	7.5	117	5	<0.5	20	110	0.05	0.07
SR3	7.6	147	5	<0.5	25	90	0.18	0.01
IT2	7.3	615	125	2.5	150	330	<0.05	<0.01
IT3	7.7	1,245	50	0.5	50	150	<0.05	0.16
IT4	8.9	1,949	285	22	165	1,205	<0.05	<0.01
SC1	7.3	728	5	<0.5	5	110	<0.05	<0.01
SC2	7.4	529	5	<0.5	5	80	0.26	<0.01
SC3	7.3	1,349	5	<0.5	5	115	<0.05	<0.01
GW1	6.9	1,855	5	<0.5	20	60	<0.05	<0.01
GW2	7.1	1,535	5	<0.5	5	40	<0.05	<0.01
GW3	7.7	599	50	0.5	50	345	<0.05	<0.01
Limit value	–	–	25	5.0	50	500	0.2	–

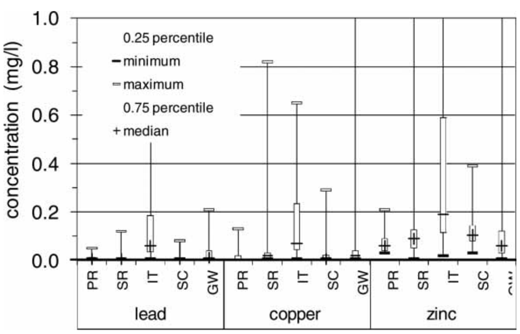

Figure 6 | Heavy metal concentrations of water samples.

In groundwater, cadmium as well as polycyclic aromatic and mineral oil type hydrocarbons were below detection limits. Copper concentration was between 5 and 50 μg/L. Zinc was measured in the span of 40 to 345 μg/L. All these values were within the tolerated concentrations given by BBodSchV (1999). Only lead concentration range was above the limiting value. This effect could not be explained as a result of the infiltration measure. It may be a result of former land use in this highly industrialised area. In general, concentrations of seepage and groundwater can be regarded as insignificant and without any impact of surface runoff polluted by traffic activities.

Of particular interest are the pollutant loads retained by the infiltration facility based on a mass-balance equation. Loads summarised in Table 5 were calculated on the basis of a surface runoff volume of 740 mm/a. Due to increased pollutant concentrations in the filter media of the infiltration trenches (see also Figure 5), heavy metal loads in seepage are listed separately. Consequently, seepage loads below infiltration trenches are also differentiated. The pollutant removal performance is dependent on the species of heavy metal. The mass removal efficiency of the investigated infiltration system was 11% for lead, 80% for copper and between 1 and 8% for zinc. As cadmium concentrations were below detection limit, results could unfortunately not

Table 5 | Heavy metal loads of the investigated parking place

	Lead (mg m^{-2} a^{-1})	Cadmium (mg m^{-2} a^{-1})	Copper (mg m^{-2} a^{-1})	Zinc (mg m^{-2} a^{-1})
Precipitation	3.7	0.4	1.9	44.4
Surface runoff	3.7	0.4	16.1	68.8
Seepage in trench	58.6 (189.8)	1.0 (14.7)	66.6 (109.9)	159.8 (802.5)
Seepage	3.3 (3.3)	0.3 (0.3)	3.3 (3.3)	63.3 (67.9)

be verified, but is consideration for future work. The mass removal performance reported by Sansalone (1999) was calculated from effluent concentrations of four rain events and varied between 45 and 75% for lead, 60 and 92% for copper and 91 and 100% for zinc. It is obvious that lead and zinc were removed significantly better by the partial exfiltration trench investigated by Sansalone (1999). This effect may be attributed to the filter media, which was silica sand covered with iron oxide. The diversity of runoff and seepage concentrations (see Figure 6) also have to be considered as these result in a wide range of removal performance.

CONCLUSION

The experimental investigation entailed a pervious pavement made of precast concrete pavers with subjacent infiltration trenches draining an impervious area of 2 ha. The infiltration trench was filled with different aggregates, including limestone gravel 32/45, sandy gravel 0/32 and limestone gravel 0/45. Because the jointing accounts for the hydraulic behaviour as well as pollutant retention capabilities, recycled concrete, basalt gravel, limestone gravel, lava and substrate were investigated. Decisive with regard to function is also the width and ratio of joints which should ensure surcharge-free drainage. The joints of the investigated pavement had a width of 0.03 m and a ratio of approximately 20%. The recycled concrete showed the best infiltration performance with almost a constant hydraulic conductivity over time. The hydraulic conductivities of basalt gravel, lava and substrate were significant lower. The variation of initial and final infiltration rate was also much higher. The highest deviation of initial and final infiltration rate and the lowest hydraulic conductivity was obtained for the originally built-in limestone gravel. Materials with a higher coarse fraction can be problematic, where transport of fine particles (which are mainly associated with pollutants) is concerned. In terms of cleaning, fine particles should be kept near the surface in order to remove them with suction cleaning. Infiltration rates of new constructions should be capable of draining surface runoff without any surcharge up to 10 years. If the specific infiltration rate drops below 97 mm/h, the jointing should be replaced by new material. Due to accumulated pollutants, the old material has to be analysed prior to recycling or land filling.

An important aspect is the pollutant retention capability because even in the event of an accident, pollutants are not allowed to enter groundwater. Coarse materials therefore cannot be recommended as jointing. From this point of view, basalt gravel of grain sizes between 1 and 3 mm, recycled concrete as well as the substrate both of grain sizes between <0.1 and 5 mm should be used. Increased concentrations of heavy metals as well as polycyclic aromatic and mineral oil type hydrocarbons could be detected in surface runoff. Seepage water and groundwater were characterised by generally low concentrations, which were below the corresponding limit values of BBodSchV (1999) except for lead. At present there was no detectable impact of the polluted surface runoff on seepage water and groundwater. The results of the water samples could be confirmed by the laboratory analysis of particle concentration. Elevated concentrations in jointing and road bed were apparent due to the accumulation of pollutants caused by traffic. Nevertheless, increased particle–bound concentrations were also obtained for the two limestone gravels built into the infiltration trenches. This raises the need to analyse all materials to be used in infiltrations facilities prior to construction in order to ensure that they are free of any degradatory contaminants.

REFERENCES

Achleitner, S., Engelhard, C., Stegner, U. & Rauch, W. 2007 Local infiltration devices at parking sites – experimental assessment of temporal changes in hydraulic and contaminant removal capacity. *Water Science and Technology* **55** (4), 193–200.

Barraud, S., Gibert, J., Winiarski, T. & Krajewski, J. L. B. 2002 Implementation of a monitoring system to measure impact of stormwater runoff infiltration. *Water Science and Technology* **45** (3), 203–210.

BBodSch, V. 1999 *German Federal Soil Protection and Contamination Ordinance – Bundes- Bodenschutz- und Altlastenverordnung (in German)*. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Bonn.

Brombach, H., Weiss, G. & Fuchs, S. 2005 A new database on urban runoff pollution: comparison of separate and combined sewer systems. *Water Science and Technology* **51** (2), 119–128.

Dierkes, C. & Geiger, W. F. 1999 Pollution retention capabilities of roadside soils. *Water Science and Technology* **39** (2), 201–208.

DIN 19682-7 2007 *Soil quality – Field tests – Part 7: Determination of infiltration rate by double ring infiltrometer*. Beuth Verlag GmbH, Berlin, Germany.

DIN 38407-8 1995 *German Standard Methods for the Examination of Water, Waste Water and Sludge – Jointly Determinable Substances (Group F) – Part 8: Determination of 6 Polynuclear Aromatic Hydrocarbons (PAH) in Water by High Performance Liquid Chromatography (HPLC) with*

Fluorescence Detection (F 8). Beuth-Verlag GmbH, Berlin, Germany.

DIN EN ISO 9377-2 2001 *Water Quality – Determination of Hydrocarbon Oil Index – Part 2: Method Using Solvent Extraction and Gas Chromatography*. Beuth-Verlag GmbH, Berlin, Germany.

DIN EN ISO 11885 2009 *Water Quality – Determination of Selected elements by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)*. Beuth-Verlag GmbH, Berlin, Germany.

DIN ISO 11047 2003 *Soil Quality – Determination of Cadmium, Chromium, Cobalt, Copper, Lead, Manganese, Nickel and Zinc in Aqua Regia Extracts of Soil – Flame and Electrothermal Atomic Absorption Spectrometric Methods*. Beuth-Verlag GmbH, Berlin, Germany.

DWA 138 2005 *Planning, Construction and Operation of Facilities for the Percolation of Precipitation Water*. German Association for Water, Wastewater and Waste, Hennef.

FGSV 947 1998 *Merkblatt für wasserdurchlässige Befestigungen von Verkehrsflächen*. FGSV Verlag GmbH, Köln.

Göbel, P., Dierkes, C. & Coldewey, W. C. 2007 Storm water runoff concentration matrix for urban areas. *Journal of Contaminant Hydrology* **91** (1–2), 26–42.

Hatt, B. E., Siriwardene, N., Deletic, A. & Fletcher, T. D. 2006 Filter media for stormwater treatment and recycling: the influence of hydraulic properties of flow on pollutant removal. *Water Science and Technology* **54** (6–7), 263–271.

Hiller, D. A., Winzig, G. & Dornauf, C. 2001 *Soil-chemical investigations of infiltration facilities as a basis for a sustainable rainwater management with respect to protect soil and groundwater (Bodenchemische untersuchungen von Versickerungsanlagen als Grundlage für eine nachhaltige Niederschlagswasserbewirtschaftung im Sinne des Boden- und Grundwasserschutzes)*. Final report (in German). University of Essen, Germany.

Illgen, M., Harting, K., Schmitt, T. G. & Welker, A. 2007 Runoff and infiltration characteristics of pavement structures – review of an extensive monitoring program. *Water Science and Technology* **56** (10), 133–140.

Sansalone, J. J. 1999 In-situ performance of a passive treatment system for metal source control. *Water Science and Technology* **39** (2), 193–200.

Zauner, G. 1996 Schwermetallgehalte und -bindungsformen in Gesteinen und Böden aus südwestdeutschem Jua und Keuper. *Hohenheimer Bodenkundliche Hefte* **31**.

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