Decontaminating effects of soil-passages for the infiltration of highway runoff

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Summary

Runoff from highways contains significant loads of heavy metals and hydrocarbons. According to German regulations, it should be infiltrated over the embankments to support groundwater-recharge. To investigate the decontaminating effect of greened embankments, soil-monoliths of highways with high traffic densities were taken. Soils were analyzed to characterize the contamination in relation to distance and depth for lead, zinc, copper, cadmium, PAH and MOTH. Lysimeters were charged in field and laboratory with highway runoff to study the effluents under definite conditions.

Concentrations of pollutants in roadside soils depend on the age of embankments and traffic density. Highest concentrations were found in the upper 5 cm of the soil and in a distance up to two meters to the street. Concentrations of most pollutants decrease rapidly with depth and distance. In lysimeter effluent lead and cadmium could not be detected. Zinc and copper were found in remarkable concentrations.

1. Introduction

Stormwater runoff from highways in Germany often is infiltrated over greened embankments. Runoff from rain and snowmelt contains significant loads of heavy metals and organic compounds. These constituents are generated by traffic activities, pavement degradation, car leakage and atmospheric deposition (MUSCHACK 1989). So highway runoff endangers roadside soils and groundwater if buffer capacities are exceeded. Even if runoff is kept by an open drainage-channel or a deep drainage-pipe parts of the runoff infiltrate into the groundwater through unavoidable leakages. As pollutant loads are closely connected to traffic density, streets with highest traffic have greatest impact on roadside soils and groundwater.

1.1. Study objectives

Main objective of the study presented is to estimate the impact of pollutants to groundwater and soil by infiltration of highway-runoff over greened embankments. Contents of heavy metals, mineral-oil-type hydrocarbons (MOTH) and polycyclic aromatic hydrocarbons (PAH), which are the main pollutants in street runoff, must be known to determine the accumulation and degradation of pollutants in the embankment-soils to archive this goal. Lysimeters filled with soil-monoliths are integrated in the embankments of five major highways in the vicinity of Essen. The sites are situated in a region with highest industrial density in Germany. Other lysimeters are charged in the laboratory with highway-runoff to estimate the purification capacity of soils from different highway embankments. Particle bound and dissolved heavy metal species are analyzed in runoff and lysimeter-effluent. The project lasts for three years.

2. Experimental methodology

An overview of the sampling-sites selected is given in table 1. Traffic densities are generally very high and vary from 52000 (B 224) to 107600 (BAB 2) vehicles per day (1995). The ages of the embankments reach from 11 (BAB 31) to 24 years (BAB 42). At BAB 2 runoff is collected in a storm sewer and only splashwater can reach the embankment. This site was chosen to study the difference between the direct infiltration of runoff and the infiltration of spray. Only BAB 42 is protected with a safety-fence. Highway BAB 2 consists of six lanes with asphalt-pavement. BAB 3 has also six lanes, but the right lanes have concrete-pavement. BAB 31, B224 and BAB 42 consist of two lanes per direction with asphalt-pavements.

Highway	City	Direction	Traffic Dens. [veh./day]	Year of construction	Date of sampling
BAB 2	Gelsenkirchen	Hannover	107600	1981	03.03.1997
BAB 3	Mülheim	Oberhausen	93700	1978	17.03.1997
BAB 31	Gladbeck	Emden	78000	1986	03.03.1997
BAB 42	Oberhausen	Dortmund	79900	1973/74	10.04.1997
B 224	Bottrop	Dorsten	52000	unknown	12.03.1997

Table 1: Sites of lysimeter-stations and soil sampling sites

The lysimeters consist of stainless steel and have diameters of 40 cm and heights of 35 cm. Soil monoliths for the lysimeters are taken from the embankments close to the highways. The cylinders were pushed into the soil using the shovel of an excavator (Fig. 1). Afterwards the soil-monoliths were dug out by hand and were taken to the laboratory where they were fixed onto the lysimeters. Pushing the cylinders into the gravel of the substructure of the highway, disturbances are expected in the edge of the lysimeters, were water can flow directly to the bottom without passing the soil. To observe the intensity of boundary fluxes, water from the peripheral zone of the lysimeters was collected separately from the central outflow (Fig. 1b).

a)

b)

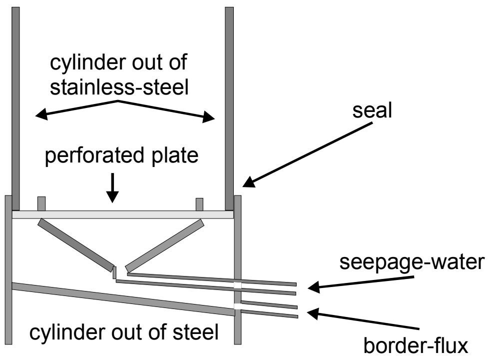

Fig. 1: a) Taking soil-monoliths at the BAB 2 in Gelsenkirchen b) schematic sketch of a lysimeter

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The soil was analyzed at depth of 0 cm to 5 cm, 5 cm to 10 cm and 10 cm to 30 cm for trace metals, polycyclic aromatic hydrocarbons (PAH) and mineral oils (MOTH). Additional samples were taken at different distances from the road, to characterize the influence of splashwater to the soil.

2.1 Field experiments

The lysimeters containing the monoliths were integrated in the embankments. Boxes for collecting the effluent were installed behind the lysimeters. Every two weeks total effluent of the lysimeters was collected and analyzed for its concentrations of pollutants. Quality of surface-runoff was measured separately.

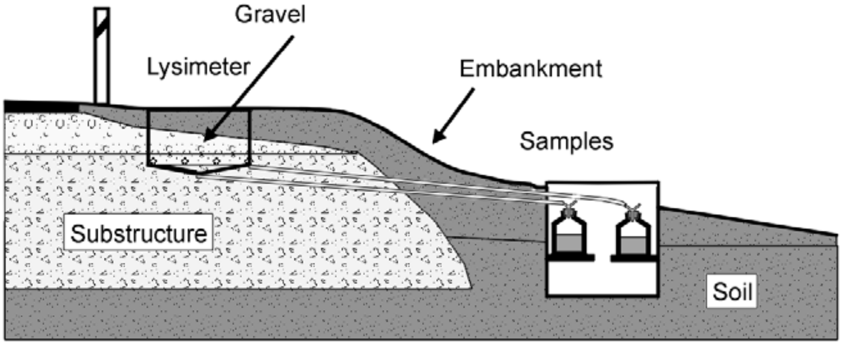

Fig. 2: Schematic crossection of lysimeter installation and sampling

2.2 Laboratory experiments

Two lysimeters from each site were taken to the laboratory, where highway-runoff was infiltrated for sixth month under definite conditions. Runoff was taken from a detention pond receiving highway runoff. Runoff was stored in tanks of stainless steel. It was mixed by electric stirrers to guarantee homogenous water quality during the tests. Every day three liters of runoff are sprinkled to each lysimeter to charge the lysimeters with pollutants faster than in reality. Effluent is kept by PE-bottles and the volume is measured. Once a week effluent is analyzed to the concentrations of lead, cadmium, zinc, copper and physcio-chemical-parameters.

3 Discussion of first Results

Results of soil analysis and laboratory-studies are presented. Data of the effluent of the lysimeters in the field-study are still incomplete. Results are expected end of 1998 after a measuring-period of one full year.

3.1 Soil analysis

The soil samples were analyzed for pH-value, grain-size distribution, content of carbonate, PAH, MOTH, lead, copper, zinc and cadmium.

3.1.1 Characterization of the soils

The build up of the embankments is similar at each sampling site. Gravels of the substructure are overlaid by a 10 cm to 15 cm thick layer of a sandy, high permeable soil. PH-values in the soils vary from 7.3 to 7.4, so effects of acidification as a result of low pH in the rain were not found. The reasons for the high pH-values are the content of carbonates in the road-surface. Rainfall is buffered before runoff reaches the embankment and infiltrates. Organic contents of the soils vary from 7.2 % to 10.2 %. Car-

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bonate contents are between 0.9 % and 5.6 %. Hydraulic conductivities reach from $2 \bullet 10^{-4}$ m/s to $1 \bullet 10^{-5}$ m/s. All soils show high densities of roots and bioturbation, so that preferential flow must be addicted.

PH-values of the substructure are higher than in the soils. They vary from 7.5 to 7.7. Organic contents reach values between 1.5 % and 3.3 %, which is lower than in the top-soils. Carbonate contents reach 71,6 %.

3.1.2 Heavy metals

Total contents of heavy metals in soils were extracted by HCl and HNO_3 and detected by ICP-AES. Heavy metal contents are generally high. Highest values were found at BAB 42 and BAB 2, which refer to the traffic densities and the age of the embankments. Highest zinc-contents up to 1600 mg/kg were found at BAB 42, that are caused by the safety-fence at this site. The high concentrations of metals at BAB 31 can not be related to the traffic density or age. Here probably contaminated soils were used for embankment-construction.

Generally concentrations decrease rapidly by distance and depth. In 10 cm to 30 cm in most cases only 7 % to 25 % of metals of the upper 5 cm of soil were found. Reduction is less for cadmium. Lead, zinc and copper normally show high gradients in the soils, while cadmium reduction is less pronounced. The first two meters distance of the street show highest concentrations. In a distance of 10 m the concentrations decrease to 7 % for copper, about 30 % for lead and zinc and 45 % for cadmium. Main reason for the decrease is the contribution of spray coming from the road.

To detect bioavailable contents of heavy metals, which are only part of total concentrations, an EDTA-extraction after BCR-regulations was made (Ure et al., 1993). All soil samples were tested to the available contents. EDTA-extractable concentrations show excellent correlations to total contents with coefficients of 0.95 for cadmium up to 0.98 for lead and zinc (Figure 3). Lead and copper show the lowest mobile part of the metals with 51 % and 54 % EDTA-extractable contents. Zinc and Cadmium are available for plants with 70 % and 79 % of total content.

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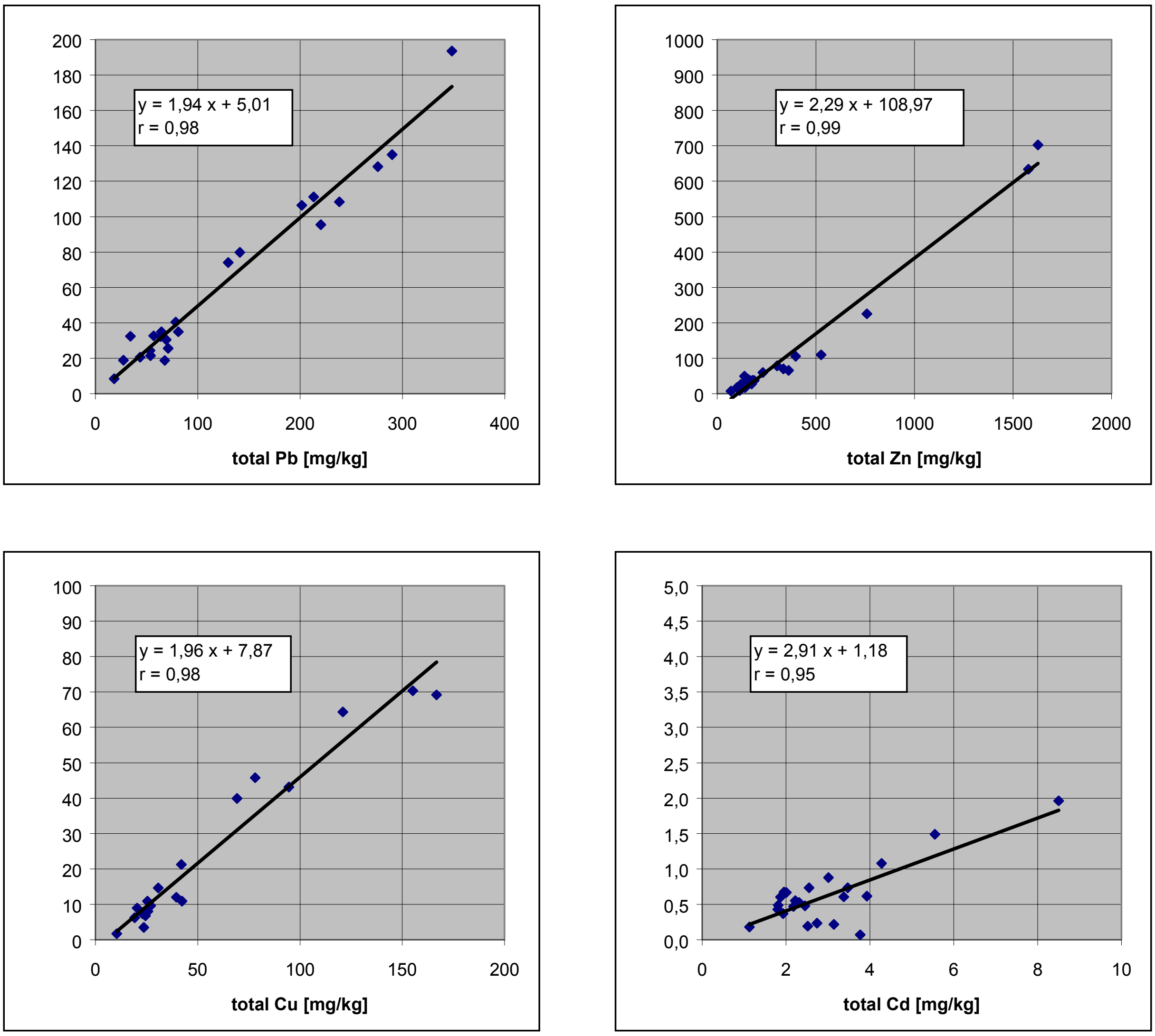

Fig. 3: Correlations between total amounts and EDTA-extractable amounts of heavy metals in roadside soils

3.1.3. Polycyclic aromatic hydrocarbons

PAH were extracted by toluole, seperated by high performance liquid chromatography (HPLC) and detected by fluorescence-detector. 16 PAH according to the list of the EPA were analyzed.

Concentrations of total PAH reach highest values at BAB 42 with 23,0 mg/kg. Lowest concentrations were found at BAB 31 and B 224 which show the lowest traffic densities. A strong relationship of PAH-values to the age of the embankments and traffic densities can be recognized. PAH-concentrations decrease with the depth. At three sites the contents decrease to values smaller than 1.7 mg/kg from 10 cm to 30 cm. At BAB 2 and BAB 3 this development can not be seen. The possible explanation can be found in an mix up of the soil at this two sites. In a distance from 3 to 10 years upper 10 cm of roadside soil were taken out to secure drainage of the street. Generally PAH were filtered effectively in the upper 10 cm of the soil, because of their particle-bound occurrence. With increasing distance from the road PAH contents decrease rapidly.

Highway	Depth	Distance	Pb	Zn	Cu	Cd	PAH	MOTH
	[cm]	[m]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]
BAB 2	0-5	0,5	239	527	413	3,9	6,7	150
	5-10	0,5	202	361	78	3,5	11,3	110
	10-30	0,5	34	99	31	2,7	5,3	57
	0-5	0,3	213	398	121	3,4	16,6	190
	0-5	2	220	336	95	3,0	9,4	74
	0,5	5	141	231	42	2,0	9,4	62
	0-5	10	65	155	27	1,8	2,1	36
BAB 3	0-5	2	81	174	25	2,0	5,3	200
	5-10	2	69	141	20	1,9	7,0	73
	10-30	2	67	114	11	1,1	5,0	23
BAB 31	0-5	0,75	276	759	268	4,3	< 2,1	28
	5-10	0,75	130	303	69	2,6	< 2,1	23
	10-30	0,75	54	112	24	2,5	< 1,6	12
BAB 42	0-5	2	290	1580	167	5,6	23,0	510
	5-10	2	348	1630	155	8,5	16,9	220
	10-30	2	27	138	23	3,1	< 1,6	60
B 224	0-5	0,75	71	187	40	2,2	2,5	160
	5-10	0,75	53	120	42	2,5	< 1,9	25
	10-30	0,75	18	69	24	-	< 1,7	21

Table 2: Concentrations of heavy metals (total contents), PAH and MOTH in roadside soils at different distances and depth

The contents of some PAH-species in the embankments are significant higher than contents of samples taken from a reference site away from the highways in Bochum. Increased values were found at Benzo(a)Pyrene, Pyrene, Benzo(a)Anthracene, Benzo(b)+(k)-Fluoranthene and Ideno(1,2,3-cd)Pyrene. The highest deviations were found at Fluoranthene and Benzo(g,h,i)Perylene. This two species are very close connected to the street runoff. Nearly all PAH show higher concentrations in the roadside soils than in the reference sites. To quantify the influence of the urban area to the runoff, differences of IP/B(g,h,i)P were calculated (Lahmann et al. 1984). The coefficients in the soils vary from 0,85 to 1,3. Most coefficients are higher than 1, which indicates the influence of urban heating. Only street influenced sites show values below 0,8. At all measuring-sites air-quality is dominated by the urban environment.

3.1.4. Mineral Oil-type Hydrocarbons (MOTH)

MOTH were extracted by 1,1,2-Trichlortrifluorethane from the soil-samples and detected by fluorescence-spectroscopy up to the German Guidelines (DEV-H 18). Highest concentrations were detected an BAB 3 and BAB 42, depending on the high traffic densities. At BAB 42 values reach 510 mg/kg near the street.

Concentrations decrease rapidly with distance to the street, because the hydrocarbons originate mostly out of leakage, and they are not transported by air. In a distance of 10 m from the street concentrations decrease up to 24 %. The decrease with the depth is much clearer than for the other pollutants. This depends on the biodegradation of the hydrocarbons in the soil. Especially in summer degradation takes place very quickly. Modern cars do not exhaust as much oil as older ones, so oil-concentrations in runoff are expected to decrease, which has positive effects on the roadside soils.

3.2. Runoff quality

Surface runoff was sampled every two weeks at the five lysimeter-sites and additionally at a detention-pond of BAB 43 in Haltern, where water for laboratory studies was taken from. All samples were filtered at 0,45 μm to separate the dissolved metals from the particular species. Results are given in table 3. In comparison with other studies, lead concentrations decrease in runoff because of the use of unleaded fuel. Zinc concentrations are higher, which is a result of safety-fences. Copper and Cadmium concentrations show the same range than in other studies, because copper is mostly emitted by brakes and cadmium out of tires. No important changes have been made in the last few years, that reduce these metals in runoff.

Highest contents of dissolved matter was found at cadmium. Nearly 85% of cadmium are dissolved in highway-runoff. Because of its high toxicity and its high mobility it is the metal with the highest eco-toxicological potential. Lead was found in runoff with only 10 % dissolved matter. Because of the low dissolved part it is better filtered at infiltration and can not be easy taken from the roots of the plants. Copper and zinc show contributions between lead and cadmium.

	Total metals				Dissolved metals			
	Zn	Cu	Pb	Cd	Zn	Cu	Pb	Cd
	(mg/l)	(μg/l)	(μg/l)	(μg/l)	(mg/l)	(μg/l)	(μg/l)	(μg/l)
BAB 43	0,8-3,0	80-130	10-20	0,8-3,6	0,3-1,3	17-56	n.d.-10	n.d.-0,7
BAB 31	-	40-150	4-60	0,5-1,0	-	20-80	n.d.	n.d.-0,6
BAB 42	0,7-41,0	60-70	10-40	1,7-3,3	0,2-23,1	30-60	n.d.	n.d.-2,4
B 224	0,2-0,8	60-160	n.d.-4	0,7-7,6	0,1-0,6	20-50	n.d.	n.d.-1,8
n.d. = not detectable								

Table 3: Heavy metals in highway runoff after 20 weeks measurement

3.3. Quality of seepage water

18 lysimeters were tested in the laboratory, to detect pollutants in the effluent. The test was carried out for 6 months. To protect the grass on the lysimeters, plant-specific lamps were installed. The concentrations of heavy metals in runoff are quoted in table 3. Zinc concentrations are higher than in other studies, which is probably an effect of the safety fence.

Lysimeter-effluent was analyzed once a week. PH-values vary between 7.4 in the lysimeters of BAB 2 and 7.7 in the lysimeters of B 224. Rising redox had no influence on metal concentrations. In the beginning boundary fluxes in the lysimeters were high, because of the disturbances of the edges of the soil-monoliths caused by sampling. After 4 weeks boundary regions were probably clogged by fine particles, so that water passed the lysimeters homogeneously.

		runoff	B 224	BAB 2	BAB 3	BAB 31	BAB 42
pH		7,3	7,7	7,4	7,5	7,6	7,6

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Pb	[µg/l]	17	< 5	< 5	< 5	11	8
Zn	[µg/l]	1250	44	101	69	274	107
Cu	[µg/l]	140	31	50	38	40	50
Cd	[µg/l]	1,4	< 0,4	< 0,4	< 0,4	< 0,4	< 0,4

Table 4: Mean-concentrations of heavy metals in runoff and lysimeter-effluent

A typical development of the effluent is given in figure 4. PH-values remain weakly alkaline. Redox is rising from 30 mV in the beginning to 370 mV at the end, which is an effect of rising redox at runoff. Zinc and copper concentrations are not rising during the test. Lead-concentrations sometimes are found at the detectable limit, while cadmium could not be observed at all. No breakthrough of metals could be found. There are no big differences between the five chosen soils in the test. Differences in soils of the selected sampling-sites seem to have no important effect on leachability of the trace metals.

The effectivity of the soils for retaining the trace metals is high. During the test more than 95 % of cadmium load is retained. The effectivity for zinc is between 84 % and 94 %, while 77 % to 98 % of lead were trapped in the soils. In case of zinc at lysimeter 2 for example 375 mg of zinc were infiltrated, while only 23,7 mg were detected in effluent. Only retention for copper with 43 % to 61 % is much lower, which is caused by the high organic content in the soils. Copper is organically complexed and leaches to the groundwater.

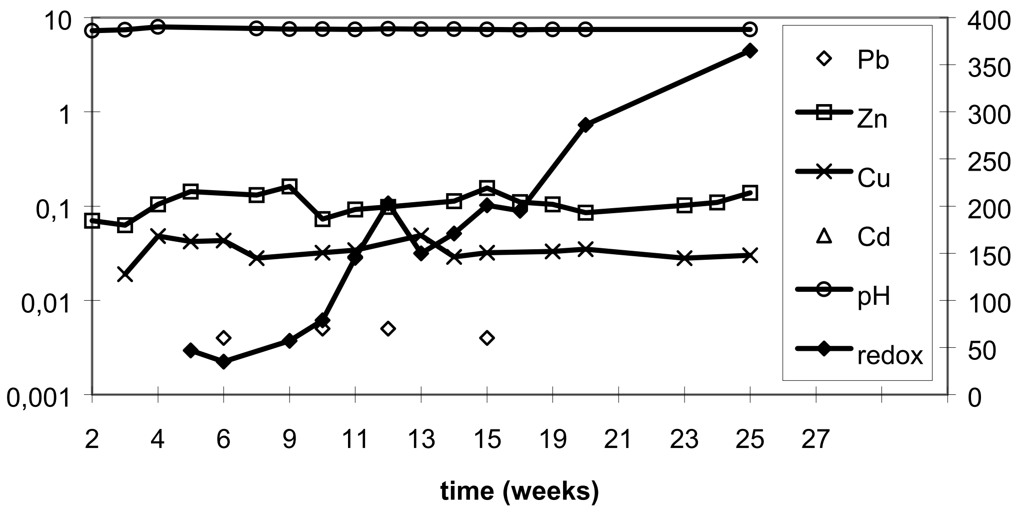

Fig. 4: Development of metals, pH and redox in effluent of lysimeter 2 (BAB2), cadmium was not detectable

The high effectivity of the soils on the one hand belongs to the high part of particle bound species, especially for lead, that is filtered by the infiltration in the first centimeters of the soil. On the other hand the dissolved species are adsorbed effectively in the soils. High adsorption takes place when pH-values are weakly alkaline. A lowering of pH could mobilize parts of the metals, especially cadmium. Buffer capacities of the roadside soils are still high, so water is decontaminated effectively by the soil passage.

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By comparing measured concentrations with defined criteria for drinking water, permissible limits of the German guidelines are not exceeded for any metal. Highest zinc-concentrations for example reach 0,27 mg/l, while 5 mg are allowed in the regulations.

4. Conclusions

Roadside soils are heavy affected by traffic-activities. Highest concentrations in soils were found for lead and zinc. Zinc concentrations are high, when safety fences escort the street. Pollutants in runoff lead to a significant built-up of pollutants in soils. Buffering capacities of the soils are still high, because of high contents of organic matter and almost neutral to weakly alkaline pH-conditions at all sampling sites. Leaching of metals is limited, but because of accumulation especially cadmium could be transported into depth by time and varying chemical-milieu. Breakthrough of metals is not expected in the near future, but to prevent groundwater in the long run, soils have to be removed after a certain period when buffer capacities are exceeded. Changing pH-values as a result of rain acidity endanger groundwater near the streets.

PAH accumulate in the upper 10 cm of the soils because of low biodegradation, but they are known to sorb well in soils. Mineral oil type hydrocarbons are degraded more effectively, so that concentrations decrease rapidly by depth.

Highest mobility of trace metals was found for cadmium and zinc in soils and in runoff. Nearly 85 % of cadmium are in dissolved species. In the soils about 65 % of cadmium is EDTA-extractable and mobile. Great quantities can be taken from the roots of the plants. Better conditions were found for lead, which has only 10 % dissolved species in runoff and only 10 % are EDTA-extractable in the soils. Cadmium was not detectable in lysimeter effluent. Zinc shows concentrations from 44 mg/l to 274 mg/l and copper from 31 mg/l to 50 mg/l. Concentrations do not exceed European and German permissible limits for drinking water quality, because the soils act as effective pollutant traps. Differences in the investigated roadside soils do not show great impacts on the purifying-efficiency of the embankments.

Acknowledgement

This study is financed by the Bundesanstalt für Straßenwesen (BASt).

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