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Storm water runoff concentration matrix for urban areas

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Abstract

The infrastructure (roads, sidewalk, commercial and residential structures) added during the land development and urbanisation process is designed to collect precipitation and convey it out of the watershed, typically in existing surface water channels, such as streams and rivers. The quality of surface water, seepage water and ground water is influenced by pollutants that collect on impervious surfaces and that are carried by urban storm water runoff. Heavy metals, e.g. lead (Pb), zinc (Zn), copper (Cu), cadmium (Cd), polycyclic aromatic hydrocarbons (PAH), mineral oil hydrocarbons (MOH) and readily soluble salts in runoff, contribute to the degradation of water. An intensive literature search on the distribution and concentration of the surface-dependent runoff water has been compiled. Concentration variations of several pollutants derived from different surfaces have been averaged. More than 300 references providing about 1300 data for different pollutants culminate in a representative concentration matrix consisting of medians and extreme values. This matrix can be applied to long-term valuations and numerical modelling of storm water treatment facilities.

Keywords: Storm water runoff; Surface water; Ground water; Heavy metals; Organic contaminants

1. Introduction

The infrastructure (roads, sidewalk, commercial and residential structures) added during the land development and urbanisation process is designed to collect precipitation and convey it out

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of the watershed, typically in existing surface water channels, such as streams and rivers. Urban storm water runoff contains pollutants which can impact the quality of surface water, seepage water and ground water. Heavy metals, e.g. lead (Pb), zinc (Zn), copper (Cu), cadmium (Cd), polycyclic aromatic hydrocarbons (PAH), mineral oil hydrocarbons (MOH) and readily soluble salts in runoff, are partly regarded as hazardous to water (Pitt et al., 1994). The distribution or concentration of these pollutants depends on the characteristics of the surface, and the dry and wet atmospheric depositions (Förster, 1996b, 1999).

The *characteristics of the surface* is qualified by material composition of the surface, type and degree of utilization, weathering processes, development age, surface slope, exposure and spatial location. Urban surface storm water runoff can be divided in three main types:

- partly sealed surfaces (such as overgrown soil in backyards, urban green spaces and porous paving),
- impermeable roof surfaces and
- impermeable road surfaces.

Furthermore, specialised land uses such as storage and trade centres in commercial and industrial areas, agricultural property and airports may contribute additional pollutant loading such as nutrients from agricultural property or deicer from airports. These special-use properties must be studied individually to determine specific pollutant loading. Storm water falling on partly sealed surfaces generally partly infiltrates directly in the subsurface.

Urban storm water runoff is comprised of different substances with different hazard potential. Behind macro-pollution, such as major ions with high concentration, trace elements with low concentrations can be found. Trace elements are micro-pollution and may posses high hazard potential.

Dry atmospheric deposition is the direct transfer of dust, aerosol and gas from the atmosphere to the ground and plant surfaces (Georgij et al., 1983). Particles with a higher density fall to the ground; particles with a lower density stay in suspension or rise to higher atmospheric strata. Dry atmospheric deposition forms a residue on the land surface and is washed into waterways as a concentrated injection of pollutants. This is called the first flush. The *wet atmospheric deposition* is due to rain, snow, fog, dew and frost, which contain substances leached out of the atmosphere. The substances deposited on surfaces emanate from natural and anthropogenic sources and concentrations have seasonal and long-term variations. Anthropogenic substance concentrations show spatial variations. For example, on leeward sides of industrial zones, higher concentrations are expected. According to the atmospheric transport mechanism, substances can show varying dispersion widths.

Rainwater yields major ions like sulphates (SO_4), chloride (Cl), ammonium (NH_4), nitrates (NO_3) and phosphates (PO_4) in measurable concentrations. The concentration of nitrogen (N) and phosphorus (P) compounds is ecologically negligible compared to organic substances. Sulphur oxides (SO_x), nitrogen oxides (NOx) and Cl from combustion installations generate acids affecting the pH value of storm water. In the last ten years the average pH value of rainwater in Germany increased from 4.4 to 5.1. During a storm water event the mobilisation of substances is not constant, and exhibits sometimes a first-flush behaviour. The pH value increases during the first 2 mm of the storm water event and afterwards decreases asymptotically. The electrical conductivity (EC), representing the total amount of dissolved ions, shows the same behaviour. Also, the EC correlates with the storm water intensity. Because of the low pH value, heavy metals such as Pb, Zn, Cu, Cd, nickel (Ni) and chromium (Cr) in the storm water partly occur as dissolved substances. In fact, the heavy metals originate as dust particles from combustion plants, iron and steel industry, non-ferrous metal industry, waste incineration plant, cement industry, glass industry and vehicle traffic. In addition to inorganic pollutants, storm water runoff also contains organic pollutants. Leaves, bird excrement, flowers and pollen are examples of organic macro-pollution, while dust particles from combustion of fossil fuels are examples of organic micro-pollution in the rainwater. It must be mentioned that PAH, pesticides and halogenated hydrocarbons, etc. also appear; but they are not investigated sufficiently. Naphthalene, fluorene, phenanthrene, fluoranthene and benzopyrene dominate the 16 priority PAHs, as per the US-EPA (1976) (Shu and Hirner, 1997). PAH concentrations in storm water runoff increase with the storm water intensity.

Impermeable *roof surfaces* differ in material, age, slope, exposure and location. New roof surfaces often represent a pollution sink until maximal load capacity is reached. The pollutants, which settle on the roof, wash off and become storm water components. The amount of dry atmospheric deposition in the runoff water, as well as the degree of weathering processes, depends on the slope, exposure and location of the roof. The distribution and concentration of major ions in roof runoff is similar to rainwater. Different metal materials are used for roof surfaces; for example, Cu and Zn are used as roof covering, gutters and down pipes; aluminum (Al), Pb and other metals are also used in roofing materials. All these materials release heavy metals as corrosion products. The corrosion processes are enhanced because of the low pH value of the rainwater. Under central European climate conditions Cu roofs have emission rates of 1.1 g/m^2 per year (Priggemeyer et al., 1998; Odnevall Wallinder, 1999); at the same time Zn roof emit 3.0 g/m^2 per year (Korenromp and Hollander, 1999). Similar data were observed in Paris by Gromaire et al. (2001). However certain amounts of heavy metals are fixed in the patina; for example, 30 to 40% of the corrosion product remains in the patina of a Zn roof, while 75 to 80% remains in the patina of a Cu roof (Leuenberger-Minger et al., 2002). The development of the patina depends on the SO_4 concentration of the atmosphere, pH value of the rainwater, exposure and slope of the roof and condensation (during wet phases). Because of decreasing SO_4 concentrations and increasing pH values, the heavy metals erosion rate decreases significantly. The appearance of organic macro-pollution like leaves, bird excrements, flowers and pollens is site- and season-specific and therefore hard to quantify. The biological oxygen (BOD_5) and chemical oxygen (COD) demands increase with a lichen and moss cover. One third of the total suspended solids (TSS) are organic substances (Büchner and Opfermann, 1989). The concentrations of PAH are higher than for rainwater because of longer dry atmospheric deposition phases. A reasonable classification for runoff water purposes can only be developed based on specific roof materials (Bannermann, 1994). First of all, different roof materials emit different heavy metals; secondly the texture of different roof material causes different retention, different runoff behaviour (different discharge coefficient) and different weathering processes (chemical milieu, temperature, surface roughness, settlement of micro-organisms). Most roofs in Germany consist of clay-based tiles and concrete but fibre-cement, roofing fabric, glass and plastics are also used. Metal roofs of Cu and Zn with Pb materials, as well as metal gutters and metal down pipes, are found more often in urban areas. Green roofs (extensive or intensive cultivation) held an exceptional position, because the runoff is retained and cleaned by passively filtering through the engineered soil layers.

Runoff pollutant concentrations of impermeable *road and parking surfaces* differ with traffic density, wind drift, duration and intensity of storm water events, duration of dry weather period and state of traffic technology. Pollutants in road runoff water result from dry and wet atmospheric deposition as well as from the road and traffic itself (Golwer and Schneider, 1979, 1983; Golwer and Zereini, 1998; Glenn et al., 2001). Only 5 to 20% of the pollutants emitted from traffic reaches runoff water (BUWAL, 1996); the remaining part drifts in the immediate vicinity by wind and spray action. Pollutant sources from the road and traffic include road surface abrasion, tyre abrasion, brake pad abrasion, drip loss (fuel, gear oil, grease, brake fluid, antifreeze, etc.) and corrosion products (Klein, 1982; Harrison and Wilson, 1985; Ball et al., 1994, 1996; Sansalone and Buchberger, 1996). Road surface abrasion depends on the condition and texture of the road surface. Tyre abrasion determines pollutants like rubber, soot and heavy metal oxides with Zn, Pb, Cr, Cu and Ni, while brake pad abrasion determines, in particular, Ni, Cr, Cu and Pb (Muschack, 1989). Furthermore, iron (Fe) from brake drums also appears in storm water runoff. Gases and aerosols result from engine combustion, as do Pb compounds and soot. Emissions of vehicles vary with the available technology. Heavy metals also can be found in additives (Sieker and Grottker, 1988). Sodium chloride (NaCl) is the main ingredient of de-icing salts used in the period from October to April on roads. The salts contain up to 10% of calcium chloride ($CaCl_2$), calcium sulphate ($CaSO_4 \cdot 2H_2O$), magnesium chloride ($MgCl_2 \cdot 6H_2O$) and magnesium sulphate ($MgSO_4$, Krauth and Klein, 1982). The quantity of salt used in Germany is between 10 g/m^2 and 40 g/m^2 of road surface. A road with two lanes and asphalt cover gives an abrasion of 10,000 kg per kilometre per year. The abrasion of tyres is calculated by Brunner (1975) at 0.12 kg per kilometre per 1000 vehicles per year. An approximation of the brake abrasion according to Lux (1986) is 15 kg per 10^6 vehicles per kilometre. *Inorganic substances* in traffic-affected runoff are potassium (K), calcium (Ca), magnesium (Mg), Al, silicon (Si), Fe, manganese (Mn), Cl, hydrogen carbonate (HCO_3), P and N components (Hvitved-Jacobsen and Yousef, 1996). Trace occurrences include arsenic (As), Pb, boron (B), Cd, Cr, Cu, Ni, titanium (Ti), vanadium (V), Zn and, more recently, platinum (Pt), palladium (Pd) and rhodium (Rh) from catalytic converters (Lord, 1978; Golwer and Schneider, 1982, 1983; Muschack, 1989; Gäth et al., 1990; Innacker and Malessa, 1991; Berbee et al., 1999; Dierkes and Geiger, 1999; Baun and Arnbjerg-Nielsen, 2001). The particulate portion of heavy metals in storm water runoff depends primarily on the amount of suspended solids in the water (Herrmann et al., 1998), which correlates with the traffic density. Highest heavy metal concentrations in road dust were found in particles with diameters smaller than 20 μm (Kazemi, 1989). Extensive investigations of the "Nationwide Urban Runoff Program (NURP)" in the United States in the 1980s identified Cu, Pb, and Zn as the toxic heavy metals in road runoff (US-EPA, 1983). Platinum group elements from catalytic converters have greatly increased in importance during recent years. Their bio-availability is not at all clear but Sures and Zimmermann (2001) demonstrated that palladium was bio-available in the aquatic environment. Experimental studies show a palladium emission of 9 ng per driven kilometre, that means that an estimated load of about 187.2 kg was emitted in Germany during 1996. In road dust, highest concentrations of 0.73 mg/kg were determined (Beyer et al., 1999). Recent investigations show an increase of platinum group elements concentrations (Hees et al., 1998; Zereini and Alt, 1999; Schäfer et al., 1999).

Organic substances mainly originate in drip losses from vehicles (such as oils, gasoline, brake fluid, de-icing substances). Other sources are the abrasion of tyres and combustion engine emissions. Hydrocarbons are the greatest pollutant component in runoff. Oils and fuels consist mainly of aromatic and aliphatic hydrocarbons, together with sulfur, oxygen and N compounds (Kirchner, 1986). Drip losses of vehicles were reduced during recent decades. Besides these fluidal emissions, PAHs are created by the inefficient engine combustion and are then transported in gaseous form by the atmosphere. When bound to small particles, they are washed by rainfall and become pollutants in storm water runoff. PAHs consist of a varying number of benzene rings, and compounds with more than 3 rings are often carcinogenic or mutagenic. The emission of

PAHs is highest for starting and accelerating vehicles and lowest for vehicles at constant speed (Joneck and Prinz, 1996). They are also emitted by heating and industrial processes. PAHs are of low solubility and can only be dissolved by MOH and humic acids.

The *wash off behavior* of heavy metals from asphalt and concrete roads was investigated by a number of authors, with one of the most complex studies done by Kern et al. (1992). The wash off of metals is a complex process that is influenced by regional dust amounts, storm water intensities, duration of storm water events, duration of dry weather periods and the formation of the drained surface (Xanthopoulos and Hahn, 1989). The dissolved part of the heavy metals mainly originates in storm water (wet deposition). Therefore, the concentration of dissolved metals is stable during a runoff event (Kern et al., 1992). The dissolved part in runoff is low compared to the particulate fraction. Only after short, dry weather periods the dissolved metal constituents become more important, because the dry weather build-up is not very high then. Heavy metals coming from traffic activities are mainly found as particulate matter in runoff and exhibit a typical first-flush behavior (Kern et al., 1992; Sansalone and Buchberger, 1997). It must be mentioned, that different metals show a different behavior, for example zinc shows generally higher dissolved parts in runoff that lead, so these conclusions are not generally valid for all types of metals.

The objective of this study was to develop an international matrix of runoff relevant parameters for the surfaces (land use) that have the highest impact in the urban environment. The bandwidth of concentrations and representative average concentrations for surfaces should be identified. This work was the base for a pilot study in the context of research project specified in Coldewey and Geiger (2004). The *results* of this study were used to carry out long-term valuations and numerical modelling of storm water treatment facilities like swales or trenches that allow storm water infiltration to reduce pollutant loads in storm sewers and receiving waters.

2. Methodology

Table 1 contains an overview of the *type of surfaces* considered in this study. After analysing the available data the number of identified drained surfaces was reduced to get representative classes with similar pollutant loads in the urban area. To compare the types of surfaces with those given in the German regulations (ATV, 1990; ATV-DVWK, 2000; DWA, 2005), the classifications of the regulations are also given in Table 1. It can clearly be seen that the two German regulations comprise different classifications. However, surface types 7 and 8 of DWA (2005) are not considered because of lack of data. To find representative concentrations for the most common impermeable surfaces it is furthermore necessary to separate the surfaces initially into three classes depending on the land use. Rainwater, runoff from roofs, and runoff from trafficked areas were identified. The utilization of the different surfaces assigns the distribution and concentration of different pollutants in the runoff. For example, roads or roofs can be constructed out of concrete, but runoff from roads has a greater content of heavy metals and hydrocarbons than roofs. That is why the strategy of the German regulation is not suitable for this study. The resulting tables (Tables 1 and 4) address 12 types of drained surfaces (as listed in Table 1). Those are rainwater (1), roof without zinc gutters and downpipes (2), roof with zinc gutters and downpipes (3), green roof (4), copper roof (5), aluminum roof (6), zinc roof (7), cycle and pedestrian way (8), yard (9), car park and residential street (10), main road (11), and motorway (12). Surfaces with special uses like storage and trade centers in commercial and industrial areas, agriculturally used yards and airports, were not considered in this study, because the composition pollutants must be determined for each of those special uses.

Table 1
Types of relevant drained surfaces

Type	Drained surface	Main input	Classification to M 153 (ATV-DVWK, 2000)	Classification to A 138 (ATV, 1990; DWA, 2005)
1	Rainwater on unpaved areas (gardens, grassed areas, cultivated land)	Wet deposition	F1	1
2	Roof runoff, tiles, concrete, fiber cement, bitumen, glass without zinc gutters and downpipes	Dry deposition, wet deposition	F2	2
3	Roof runoff, tiles, concrete, fiber cement, bitumen, glass with zinc gutters and downpipes	Dry deposition, wet deposition	F2	3
4	Green roof, intensive-or extensive	Nutrient form substrate	F1	1
5	Copper roof	Dry deposition, wet deposition, copper	F2	11
6	Aluminum roof	Dry deposition, wet deposition, aluminum	F2	11
7	Zinc roof	Dry deposition, wet deposition, zinc	F2	11
8	Pedestrian and cycle way, yard	Dry deposition, wet deposition, drip losses	F3	4
9	Car park	Dry deposition, wet deposition, corrosion products, drip losses, abrasion	F3, F5, F6	5, 10
10	Service road	Dry deposition, wet deposition, corrosion products, drip losses, abrasion	F3	6
11	Main road	Dry deposition, wet deposition, corrosion products, drip losses, abrasion	F4, F5, F6	9
12	Motorway	Dry deposition, wet deposition, corrosion products, drip losses, abrasion	F6	12

Determining the pollutant loading from car parks is potentially problematic, because data from that land use consists of only a couple of investigations. Traffic densities on the individual parking spots are low. Even in high-use parking areas, such as supermarkets, a vehicle change can only take place up to 4 times an hour. Therefore, traffic densities on single parking spots may not exceed 48 vehicles/day, which is very low compared to streets and roads. Drip losses may be higher on parking areas, but the pollutant concentrations are often over-rated because of the lack of data.

To determine the *bandwidth of representative concentrations* of pollutants, an extensive literature search was conducted. Different publications contain a variety of data that are explained in the following section. Measurement values of single samples were not considered in the analysis. A certain series of single values of one storm water event can be transformed to an event mean concentration (EMC), which represents the average concentration of a single runoff event (Fig. 1). Sometimes, only load data were available. In those instances, the total load of one pollutant was divided by the total volume of runoff to yield a pollutant concentration. Those EMCs are suitable for the bandwidth of concentrations of single events. Events with different runoff characteristics can be compared.

Building the *representative average concentration* of several EMCs for different storm water events can give representative matrix that can be used for long-term predictions and also to predict

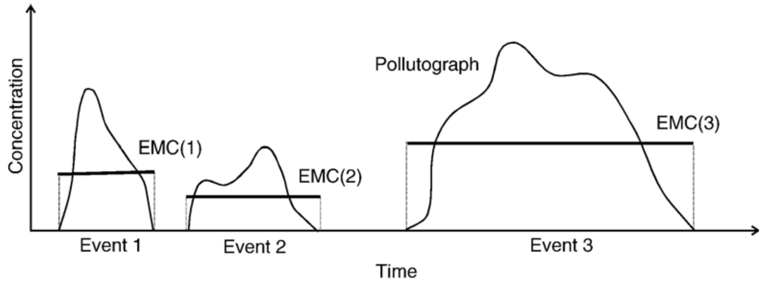

Fig. 1. Pollutograph of three runoff events explaining the event mean concentration (EMC) for single events.

annual loads. The correlation between concentrations of one single sample, EMCs (which are sometimes load weighted) and representative average concentrations of whole investigations, are given in Fig. 2. Publications were chosen that were based on measurement campaigns with a sufficient quantity of analysed samples. Thus, concentrations of single water samples were not taken into account.

Each EMC was checked with regard to trustworthiness (e.g. data amount, data plausibility and method documentation), individual or multiple measurements, sampling time (use of catalytic converter) and geographical position (industrial or developing country). If concentrations diverged from typical bandwidths of concentrations, they were not considered. So results cannot be influenced significantly by extreme concentrations. The resulting values of each type of surface were tested for normal distribution using the Kolmogorov–Smirnov-Test (Chakravarti et al., 1967) for continuous variables to check the possibility of using statistical tests for the data. Zinc was the only parameter that yielded a normal distribution. All other pollutants showed right skewed distributions. For this reason, the medians were built from the data and the arithmetic means were rejected.

For each of the 12 surface types listed in Table 1 the parameters from Table 2 were obtained. These parameters are all current environmental pollutants. The *data basis for the different parameters* is unequal for 264 possible combinations. EC and pH values were reported in nearly

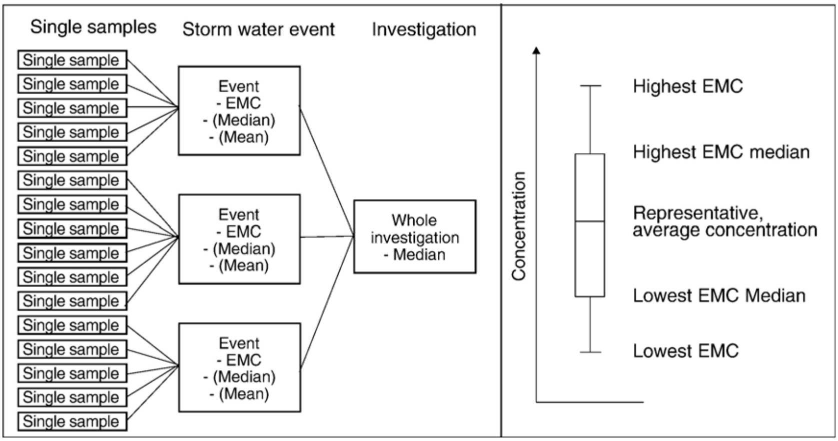

Fig. 2. Relationships of analysed data.

Table 2
Basis of data for different parameters

Parameter		Unit	Basis of data
Physico-chemical parameters			
1	EC	µS/cm	Good data basis for all types of surfaces
2	pH	–	Good data basis for all types of surfaces
Sum parameters			
3	TSS	mg/l	Good data basis for all types of surfaces
4	BOD_5	mg/l	Average data basis
5	COD	mg/l	Average data basis
Nutrients			
6	P_{tot}	mg/l	Average data basis
7	NH_4	mg/l	Average data basis
8	NO_3	mg/	Average data basis
Heavy metals			
9	Cd	µg/l	Above average data basis for all surface types
10	Zn	µg/l	Above average data basis for all surface types
11	Cu	µg/l	Above average data basis for all surface types
12	Pb	µg/l	Above average data basis for all surface types
13	Ni	µg/l	Poor data basis, average data basis for trafficked areas
14	Cr	µg/l	Poor data basis, average data basis for trafficked areas
Main ions			
15	Na	mg/l	Poor data basis, Average for rain
16	Mg	mg/l	Poor data basis, Average for rain
17	Ca	mg/l	Poor data basis, Average for rain
18	K	mg/l	Poor data basis, Average for rain
19	SO_4	mg/l	Poor data basis, Average for rain
20	Cl	mg/l	Poor data basis, Average for rain
Organic substances			
21	PAH	µg/l	Single compounds also included, average data basis
22	MOH	mg/l	Poor data basis, average data basis for trafficked areas

all publications, while TSS values were also found in most of the studies. However, fewer values were given for COD and BOD_5. Most observations apply for P_{tot}, NH_4 und NO_3. The main focus of most research projects was heavy metals like Cd, Zn, Cu and Pb because of the high environmental relevance of those pollutants. Fewer data were found for Ni and Cr. Major ions like K, Mg, Ca, SO_4 and Cl were measured — especially in rainwater samples. Only a few values exist for roof and traffic-area storm water runoff. Single compounds of the PAH according to the US-EPA list are available for nearly all surfaces. MOH values were determined mostly for trafficked areas.

The data base of Tables 2, 3 and 4 is taken from Axt et al. (1986), Barraud et al. (1998), Black (1980), Boller (1995), Boller and Häflinger (1996), Borneff (1996), Brechtel (1989), Büchner and Opfermann (1989), Bullermann and Klein (1996), Chang and Crowley (1994), Chebbo et al. (1999), Dam van et al. (1986), Dannecker et al. (1989), Dierkes (1999), Drapper et al. (2000), Driscoll et al. (1990), Förster and Herrmann (1996), Förster (1996a, 1993), Freitag et al. (1987), Fritzer (1992), Galloway et al. (1982), Galvin and Morre (1982), Geiger et al. (1999), Georgij et al. (1983), Gieska et al. (2000), Golwer (1985), Golwer and Schneider (1979, 1983), Good

Table 3
Bandwidth of EMCs of parameters and pollutants: rainwater, runoff from roofs, and runoff from trafficked areas

Parameter		Unit	Rainwater		Roofs		Trafficked areas with low density		Trafficked areas with high density	
			Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Physico-chemical parameters										
1	EC	µS/cm	28	223	25	269	n.a.	n.a.	108	2436
2	pH	–	3.9	7.5	4.7	6.8	6.4	7.9	6.4	7.9
Sum parameters										
3	TSS	mg/l	0.2	52	13	120	74	74	66	937
4	BOD_5	mg/l	1.0	2.0	4.0	16.1	n.a.	n.a.	2.0	36.0
5	COD	mg/l	5	55	n.a.	n.a.	n.a.	n.a.	63	146
Nutrients										
6	P_{tot}	mg/l	0.01	0.19	0.06	0.50	n.a.	n.a.	0.23	0.34
7	NH_4	mg/l	0.1	2.0	0.1	6.2	n.a.	n.a.	0.5	2.3
8	NO_3	mg/l	0.0	7.4	0.1	4.7	n.a.	n.a.	0.0	16.0
Heavy metals										
9	Cd	µg/l	0.1	3.9	0.2	1.0	0.2	0.5	0.3	13.0
10	Zn	µg/l	5	235	24	4880	15	1420	120	2000
11	Cu	µg/l	1	355	6	3.416	21	140	97	104
12	Pb	µg/l	2	76	2	493	98	170	11	525
13	Ni	µg/l	1	14	2	7	n.a.	n.a.	4	70
14	Cr	µg/l	2	8	2	6	n.a.	n.a.	6	50
Main ions										
15	Na	mg/l	0.22	20.00	n.a.	n.a.	n.a.	n.a.	5.0	474.0
16	Mg	mg/l	0.03	0.33	n.a.	n.a.	n.a.	n.a.	1.0	1.4
17	Ca	mg/l	1.10	67.13	1.00	1900	n.a.	n.a.	13.7	57.0
18	K	mg/l	0.46	0.65	n.a.	n.a.	n.a.	n.a.	1.7	3.8
19	SO_4	mg/l	0.56	14.40	n.a.	n.a.	n.a.	n.a.	5.1	139.0
20	Cl	mg/l	0.20	5.20	n.a.	n.a.	n.a.	n.a.	3.9	669.0
Organic parameters										
21	PAH	µg/l	0.04	0.76	0.35	0.60	n.a.	n.a.	0.24	17.10
22	MOH	mg/l	0.29	0.41	0.108	3.14	n.a.	n.a.	0.51	6.50

Key: n.a. = not available.

(1993), Göttle (1978), Gromaire et al. (2001), Gromaire-Mertz et al. (1999), Grottker (1987), Haraldsson and Magnusson (1983), Harrison and Wilson (1985), Hellmann et al. (1976), Herrmann and Kayser (1997), Hütter et al. (1998), Kern et al. (1992), Kiss et al. (2001), Klein (1982), Krauth and Klein (1982), Kronsbein and Rahm (1999), Ligocki et al. (1985), Lygren et al. (1984), Manoli et al. (2000), McVeety and Hites (1988), Muschack (1989), Nadler and Meißner (2001), Odnevall Wallinder et al. (1999), Paulsen (1984), Prat and Adams (1979), Priggemeyer (1998), Quek and Förster (1993), Remmler and Hütter (2001), Rennert et al. (1998), Ritter (1995), Ruppert (1975), Rushton (1998), Sansalone and Buchberger (1995, 1996, 1997), Shu and Hirner (1997), Sieker and Grottker (1988), Steuer et al. (2001), Swartjes (1990), Thomas and Greene (1993), Winter (1993), Wüst et al. (1994), Xanthopoulos (1992), Xanthopoulos and Hahn (1989), Yousef et al. (1987).

Table 4

Representative average concentration of 22 pollutants in 12 types of surface runoff

			Rainwater	Roof runoff						Runoff of trafficked areas				
			1	2	3	4	5	6	7	8	9	10	11	12
Parameter		Unit	Gardens, grassed areas, cultivated land	Roof runoff, tiles, concrete, fiber cement, bitumen, glass without zinc gutters and downpipes	Roof runoff, tiles, concrete, fiber cement, bitumen, glass with zinc gutters and downpipes	Green roof (intensive or extensive)	Copper roof	Aluminium roof	Zinc roof	Pedestrian and cycle way, yard	Car park	Service road	Main road	Motorway
Physico-chemical parameters														
1	EC	µS/cm	🟩 50	🟩 141	🟩 141	🟥 71	🟥 141	🟥 141	🟥 141	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟨 470	🟨 414
2	pH	_	🟩 5.0	🟩 5.7	🟩 5.7	🟥 7.5	🟥 5.7	🟥 5.7	🟥 5.7	🟥 7.4	🟥 7.4	🟥 7.4	🟨 7.4	🟥 7.4
Sum parameters														
3	TSS	mg/l	🟩 12	🟩 43	🟩 43	🟦 n.a.	🟥 43	🟥 43	🟥 43	🟥 7.4	🟥 150	🟥 150	🟨 163	🟨 153
4	BOD_6	mg/l	🟥 2	🟨 12	🟨 12	🟦 n.a.	🟥 12	🟥 12	🟥 12	🟦 n.a.	🟥 11	🟥 11	🟨 11	🟥 32
5	COD	mg/l	🟨 19	🟨 66	🟨 66	🟦 n.a.	🟥 66	🟥 66	🟥 66	🟥 70	🟥 70	🟥 70	🟨 105	🟨 107
Nutrients														
6	P_{tot}	mg/l	🟨 0.09	🟨 0.22	🟨 0.22	🟦 n.a.	🟥 0.22	🟥 0.22	🟥 0.22	🟦 n.a.	🟥 0.18	🟥 0.18	🟥 0.29	🟨 0.20
7	NH_4	mg/l	🟩 0.80	🟩 3.39	🟩 3.39	🟥 1.30	🟥 3.39	🟥 3.39	🟥 3.39	🟦 n.a.	🟥 0.1	🟥 0.1	🟥 0.9	🟨 0.5
8	NO_3	mg/l	🟨 1.54	🟩 2.78	🟩 2.78	🟥 0.59	🟥 2.78	🟥 2.78	🟥 2.78	🟦 n.a.	🟥 2.78	🟥 2.78	🟨 5.00	🟥 2.52
Heavy metals														
9	Cd	µg/l	🟩 0.7	🟨 0.8	🟨 0.8	🟥 0.1	🟥 0.8	🟥 0.8	🟥 1.0	🟥 0.8	🟥 1.2	🟥 1.6	🟩 1.9	🟨 3.7
10	Zn	µg/l	🟩 80	🟨 370	🟨 1851	🟥 468	🟥 370	🟥 370	🟨 6000	🟥 585	🟥 400	🟥 400	🟩 407	🟩 345
11	Cu	µg/l	🟩 11	🟩 153	🟩 153	🟥 58	🟨 2600	🟥 153	🟨 153	🟥 23	🟥 80	🟥 86	🟩 97	🟩 65
12	Pb	µg/l	🟩 9	🟩 69	🟩 69	🟥 6	🟥 69	🟥 69	🟨 69	🟥 107	🟥 137	🟥 137	🟩 170	🟩 224
13	Ni	µg/l	🟨 2	🟥 4	🟥 4	🟥 3	🟥 4	🟥 4	🟥 4	🟦 n.a.	🟦 n.a.	🟥 14	🟨 11	🟥 27
14	Cr	µg/l	🟨 3	🟨 4	🟨 4	🟥 3	🟥 4	🟥 4	🟥 4	🟦 n.a.	🟦 n.a.	🟥 10	🟨 11	🟨 13
Main ions														
15	Na	mg/l	🟨 2.14	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟥 18	🟦 n.a.	🟨 108	🟥 194
16	Mg	mg/l	🟥 0.18	🟦 n.a.	🟦 n.a.	🟥 7	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟥 1	🟥 5
17	Ca	mg/l	🟨 7.50	🟥 10	🟥 10	🟥 78	🟥 10	🟥 10	🟥 10	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟨 31	🟥 37
18	K	mg/l	🟥 0.56	🟦 n.a.	🟦 n.a.	🟥 7	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟥 4	🟦 n.a.	🟥 2	🟥 5
19	SO_4	mg/l	🟨 5.46	🟨 46.71	🟨 46.71	🟦 n.a.	🟥 46.71	🟥 46.71	🟥 46.71	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟨 15	🟨 39
20	Cl	mg/l	🟨 2.26	🟨 7.74	🟨 7.74	🟦 n.a.	🟥 7.74	🟥 7.74	🟥 7.74	🟦 n.a.	🟦 n.a.	🟦 n.a.	🟨 106	🟨 159
Organic substances														
21	PAH	µg/l	🟨 0.39	🟨 0.44	🟨 0.44	🟦 n.a.	🟥 0.44	🟥 0.44	🟥 0.44	🟥 1.00	🟥 3.50	🟥 4.50	🟨 1.65	🟥 2.61
22	MOH	mg/l	🟨 0.38	🟨 0.70	🟨 0.70	🟦 n.a.	🟥 0.70	🟥 0.70	🟥 0.70	🟥 0.16	🟥 0.16	🟥 0.16	🟥 4.17	🟥 4.76

n.a. = not available.

🟦 No data.

🟥 <5 data.

🟨 5-15 data.

🟩 >15 data.

Resulting tables were developed from this data base. The bandwidth of concentrations (Table 3) and representative average concentrations for 22 surfaces (Table 4) are presented below.

The plausibility of the concentration matrix was verified at the end of the study. The concentration values (in mg/l) were compared to total load values (in mg/m^2·year) in the German literature. Therefore, the concentrations were multiplied by the average precipitation in Germany of 837 mm/year (equivalent to 837 l/m^2). The average storm water runoff from roof areas was reduced to 753 mm/year due to an average discharge coefficient of 0.9 (DWA, 2005). For trafficked areas, runoff was reduced to 670 mm/year due to an average discharge coefficient of 0.8. The total loads of pollutants with their maxima and minima are described in Klein (1982), Brechtel (1989), Huth et al. (1995), Boller and Häflinger (1996), Rennert et al. (1998), UBA (1999). The converted representative average concentrations in Table 4 lie in the centre of the bandwidth of the total loads except for Pb (caused by unleaded fuel). Although the concentrations show high variations the total annual loads are plausible.

3. Results and discussion

Table 3 contains an overview of the bandwidth of the EMCs for rain, roof runoff and runoff of trafficked areas with low and high traffic densities.

- EC can be identified as leading parameter. Values rise from between 28 µS/cm and 223 µS/cm in rainwater to over 25 µS/cm to 269 µS/cm in roof runoff and to values between 108 µS/cm and 2436 µS/cm for trafficked areas with high traffic densities.
- pH values of single surfaces vary with the material of the surface. Generally the lowest pH value of rain was between 3.9 and 7.5 and was highest from traffic-related surfaces, ranging from 6.4 to 7.9. This is from the carbonated-based road surfaces.
- For TSS the bandwidth varies from between 0.2 mg/l and 52 mg/l in rainwater, to values between 66 mg/l and 937 mg/l for trafficked areas. This is caused by tyre abrasion on the traffic-related surfaces.
- BOD_5 demand rises from highest concentrations of 2.0 mg/l in rainwater up to 36 mg/l for trafficked areas. There is a similar trend for COD.
- Nutrient concentrations show an increase from rainwater to roof runoff. For P_{tot} and NH_4, the concentrations decrease towards trafficked areas. This is caused by moss and lichens on the roofs and bird excrement. Because NO_3 is a transformation product, it shows a reversed behaviour and increases in concentration as NH_4 concentration decreases.
- For heavy metals, an increase of the concentrations from rainwater to trafficked areas can be seen. The two exceptions were roofs with zinc gutters and downpipes and metal roofs made out of Cu and Zn. For these surfaces the heavy metal concentrations are higher than for trafficked areas.
- For major ions, the data base is only useful for rainwater. Only Na and Cl were analysed in trafficked areas because of the use of de-icing salts.
- Values for hydrocarbons (PAH and MOH) were found for all surfaces, but the data basis is only average.

The representative average concentrations for each of the 12 surfaces are shown in Table 4. Medians of the data base are used. Parameters which are not influenced by the material or traffic density were transferred from similar surfaces. Thus those surface types show the same values in

Table 4. If the data base was too small, concentration were estimated according to the surfaces in the adjacent rows. The scale of EMC data is represented by colour coding.

4. Conclusions

Different roof materials and different traffic densities have different effects on pollutant distribution and concentration. With regard to different roof materials, heavy metals show significant differences that depend on the materials' impact on the pH value. On all roofs, the dry atmospheric deposition implies a slight increasing pH value. Green roofs have the lowest amount of heavy metals in the runoff, except for Zn. Metal roofs, such as Cu and Zn, have the highest impact on the heavy metal concentration in the roof runoff; in addition, Cu and Zn concentrations are the highest from all observed surfaces. Concerning different traffic density on road surfaces, the motorways show the highest concentration of pollutants for 13 parameters (BOD_5, COD, Cd, Pb, Ni, Cr, all major ions and MOH). Nevertheless, main roads show highest concentration for six parameters (EC, TSS, P_{tot}, NH_4, NO_3 and Cu). Service roads show the highest PAH concentrations and pedestrian and cycle ways, as well as yards, show the highest Zn concentrations.

Storm water runoff in urban areas can influence the quality of surface water, and can potentially carry pollutants into seepage water and ground water. The surface water bodies receive the storm water runoff directly through the local urban drainage system. The seepage water is influenced by the centralised and de-centralised infiltration of storm water in the subsurface. The ground water is influenced by the seepage water, which is affected by the pollution retention capacity of the subsurface soil. Furthermore, the quality of ground and surface water is related to their interaction processes. For estimation and comparative investigation of the degree of environmental hazards on surface water, seepage water and ground water, the use of an international concentration matrix is recommended.

The qualitative effects of storm water infiltration (infiltration via swales, trenches or wetlands) on soil, seepage water and ground water can be investigated with long-term numerical modelling (Zimmermann et al., 2005). Therefore, retention capacity of the material and the soil under the infiltration devices should be determined with batch and column tests. In these tests the material, soil and polluted water in defined representative compositions and concentrations (see Table 4) should be mixed. The concentration matrix can also be used for development and optimisation of storm water treatment facilities. Dierkes et al. (2005), Göbel et al. (2006) developed a pollution control pit in such a way. A hydrodynamic separator associated with a multi-stage filter was verified concerning the retention capacity for pollutants from roof and road surfaces to reduce the amount of pollutants leaving the site and entering surface water directly.

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