Chapter 5
Metals: Occurrence, Treatment Efficiency and Accumulation Under Varying Flows

Godecke-Tobias Blecken, Katharina Tondera, Heléne Österlund and Maria Viklander

Abstract Metals were the first priority pollutants to be widely investigated in stormwater. In solid phase, they are often attached to very fine particles. The dissolved fraction creates considerable environmental problems as it is the most bioavailable fraction. Hence, removal of both fine and dissolved particles plays a major role in the treatment of polluted runoff. Ecotechnologies specifically designed to remove metals should be able to address different treatment mechanisms. However, the exhaustion of sorption capacity reduces the lifespan of treatment facilities. Additionally, metal concentrations fluctuate extremely—spatially, seasonally and over time—which poses another challenge for further increasing removal efficiencies. While soil- or sand-based systems should be designed in a way that the filter material can be exchanged, newer developments such as Floating Treatment Wetlands show promising removal capacities as the installations bind metals in sludge sediments, which can be removed from time to time. The different treatment mechanisms, aforementioned developments and techniques as well as their removal capacities will be discussed in this chapter.

Introduction

Metals from various sources are commonly found in stormwater (and to a lesser extent in wastewater) discharges and have long been in focus when stormwater impacts on receiving water bodies and/or water quality treatment demands are assessed and discussed. Early research evaluating stormwater quality has recog-

G.-T. Blecken (✉) · H. Österlund · M. Viklander
Urban Water Engineering, Luleå University of Technology, Luleå, Sweden
e-mail: godble@ltu.se

K. Tondera
Stormwater Research Group, University of the Sunshine Coast, Maroochydore, Queensland, Australia
e-mail: ktondera@usc.edu.au

K. Tondera
Institute of Environmental Engineering, RWTH Aachen University, Aachen, Germany

K. Tondera et al. (eds.), *Ecotechnologies for the Treatment of Variable Stormwater and Wastewater Flows*, SpringerBriefs in Water Science and Technology,
https://doi.org/10.1007/978-3-319-70013-7_5

nised metals to be of certain importance. Wilber and Hunter (1975) emphasise that 'heavy metal concentrations (in stormwater runoff) were found to vary significantly throughout runoff events and from storm to storm'. This chapter will describe and discuss these variations and treatment technologies, which have been extensively evaluated with a focus on their metal treatment capacity.

Treatment Mechanisms

One main characteristic of metals which significantly affects removal processes is their distribution between the dissolved and particulate phase. A common way to estimate this distribution is by passing them through filters with a pore size of 0.45 μm and dividing them into the fractions as shown in Fig. 5.1. In a geochemical context, the dissolved fraction is commonly divided into colloidal and genuine dissolved fractions (Ingri 2012). Colloids, unlike particles, do not settle but remain in solution. The surface of colloids is often negatively charged, causing positively charged metal ions to bind to it. The ions and molecules present in free form without binding to colloids or particles are referred to as a true or authentic dissolved fraction. This is also the most bioavailable fraction since it can be taken up by aquatic plants and organisms, which also means it has increased toxicity (Ingri 2012; Campbell 1995).

Important factors that affect the solubility of metals and mobility are pH values and dissolved organic matter (DOM, such as humic and fulvic acids) and the access to particle surfaces for them to attach to. Generally, the solubility is higher at low pH values (Ingri 2012).

In stormwater quality studies, often both total and dissolved (i.e. <0.45 μm) fractions are analysed. This enables researchers to calculate the particulate fraction by subtracting the dissolved from the total concentration. The distribution between these fractions can vary substantially, not only between different metals but also within a runoff event and between different sites and seasons. For instance, investigations on the distribution of metals from runoff of five German highways by Dierkes (1999) revealed that

- 51–90% of Cd (mean 70%),
- 28–55% of Cu (mean 42%) and
- 14–51% of Pb (mean 36%).

are in the dissolved phase (<0.45 μm). Boogaard et al. (2014) found even broader ranges and mean values of approximately 60% for Cd and for Cu

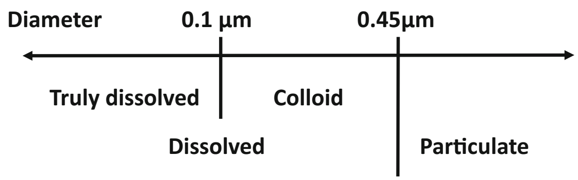

Fig. 5.1 Metal fractions in stormwater (simplified scheme: H. Österlund)

(range ~20–90%), 55% for Ni (20–95%), 70% for Pb (10–99%) and 80% for Zn (10–90%). As already mentioned in Chap. 2, these particles are bound in large proportions to particles with a grain size of less than 90 µm or even 60 µm (Xanthopoulos 1990; Boogaard et al. 2014). Hence, treatment installations should ideally be at least capable of retaining fine suspended solids.

Metals in Stormwater from Separate Sewer Systems and Combined Sewer Overflows

One important source for metals in stormwater is vehicular traffic. Further, metals also leach from surfaces in the urban environment, such as roofs, lampposts, barriers, facades, etc. or are of geogenic origin. Their composition in runoff changes over time, e.g. substitutes used in industrial products, such as the replacement of lead in fuel over the last two decades.

As listed in Chap. 1, the concentrations found in stormwater often vary during single events (e.g. due to first flush effects or varying rain intensities during the event that transports different fractions), between different events (e.g. due to varying antecedent dry periods, seasonal variations and varying rain characteristics), seasons and between different catchments (due to different catchment characteristics).

Seasonal Variations

In a study in northern Sweden, significantly higher concentrations in snowmelt runoff have been observed in March and April (Cu: 37–199 mg/L, Pb: 16–80 mg/L; Zn 105–791 mg/L) compared to runoff from rain events in May and June (Cu: 30–45 mg/L, Pb: 14–19 mg/L, Zn 130–169 mg/L) (Westerlund et al. 2003). In this study, concentrations of both metals and suspended matter in stormwater are higher in snowmelt runoff than during rainy periods. In snowmelt runoff, relatively high concentrations of Cu, Pb and between 16 and 80 mg/L were measured. This can be explained by the long period of contaminant accumulation in the snow; these contaminants are then released during a relatively short period. In a study in Germany, similar results have been confirmed by Helmreich et al. (2010), who showed significantly higher metal and total suspended solids (TSS) concentrations in winter runoff compared to the summer season. Reasons given by the authors were the use of sand and gravel for anti-slip applications, which increases wear and tear on road surfaces and vehicles.

Besides concentration variations, metal characteristics may also change. During winter in cold or temperate climates, de-icing salts are applied regularly, which, for instance, affects metal partitioning towards the dissolved phase (Marsalek et al. 2003). Higher percentages of dissolved pollutants can affect the performance of treatment technologies (Søberg et al. 2017).

Variation Between Catchments

The quality of stormwater depends on the surface characteristics of the catchment and the anthropogenic activities in or around the catchment (Eriksson et al. 2007). The contamination of stormwater with metals in urban catchments largely depends on the use of building materials, on the one hand, and the presence of frequently used roads, on the other hand. Studies have shown that runoff from metal roofs may have higher concentrations of, e.g. Cu and Zn than road runoff while other metals such as Cd, Pb, Ni and Cr are higher in road runoff (Göbel et al. 2007). In general, areas with direct connection to traffic and runoff from industrial and commercial areas often exhibit relatively high pollutant concentrations (Pitt et al. 1995; Czemiel Berndtsson 2014).

Although a correlation between the traffic density and the concentration of metals in road runoff is often assumed, Kayhanian et al. (2012) could not prove such a correlation in a literature review on road runoff worldwide. They showed, however, differences between the concentrations in North America, Europe and Asia, which prove that a local aspect has to be considered. The authors also mention the influence of preceding dry phases and the catchment area, as mentioned in Chap. 1.

Site variations may also vary for different pollutants. Gasperi et al. (2014) analysed pollutants in stormwater from three different areas. They found different Cu, Cr, Ni and Zn concentrations in these areas while they did not detect any differences in Cd and Pb concentrations, although the land use in the areas was different.

Variations Over Time

In general, it is quite difficult to compare the ranges of concentrations found in road runoff since the sampling points vary in the different studies, as can be found in literature reviews. However, many publications refer to investigations made in the middle of the 1990s or even earlier. The age of these studies is important, since metal concentrations have shifted over the decades; the ban on leaded gasoline in most countries has reduced lead concentrations in runoff significantly (Kayhanian et al. 2012; Ayrault et al. 2014). Future trends of stormwater quality changes depend on how treatment facilities perform during their lifespan. However, simulating these developments over time involves quite high uncertainties (Borris et al. 2016). Changes in climate, building materials and building design, environmental regulations and the use of unknown substances today may affect stormwater quality in the future.

Table 5.1 shows ranges of road runoff concentrations from different sources, which only include values published after 2005 given the fact that runoff composition has changed during the next last decades. In general, all values vary over two

Table 5.1 Concentrations in urban runoff (μg/L), published after 2009

Source/Catchment	Value(s)	Cd	Cu	Ni	Pb	Zn	Reference
Highway runoff							
Road high density, 57,000 vehicles7d-1, Munich, Germany (63 sampled events over a period of 2 years)	Min-max	<0.5–4.8	24–604	4.2–403	<5.0–405	128–3470	Helmreich et al. (2010)
	Median/mean	<0.5/<0.5	155/191	35/55	43/56	592/847	
Road load density	Mean	–	11	–	34	315	Li et al. (2012)
Separate sewer system							
Residential area	Min-max	0.1–0.4	3–15	1–10	1–8	5–140	Hvitved-Jacobsen et al. (2010)
	Mean ± SD	–	38 ± 28.4	2.9 ± 2.0	–	212.4 ± 145.1	Gasperi et al. (2014)
	Mean ± SD	–	14.9 ± 11.3	3.1 ± 2.3	–	126.3 ± 87.1	
	Min-max	–	11–87	0.9–13	0.2–10	33–400	Valtanen et al. (2014)
	Min-max	–	0.3–28	0.4–30	0.1–9.8	0.02–156	
Industrial	Mean ± SD	–	34.6 ± 29.2	6.6 ± 4.5	–	239.8 ± 169.8	Gasperi et al. (2014)
Commercial	Min-max	0.1–0.5	4–31	1–11	1–19	8–92	Hvitved-Jacobsen et al. (2010)
Mixed	Min-max	–	1.8–129	0.7–125	0.2–68	7.3–703	Valtanen et al. (2014)
	Min-max	–	1.8–656	0.7–122	0.2–98	7.3–1937	
	Min-max	0.1–0.5	6–120	3–190	1–33	10–300	Hvitved-Jacobsen et al. (2010)
Roofs	Mean	–	8	–	31	778	Li et al. (2012)
Combined sewer system							
Mixed area	Median ± SD	0.24 ± 0.02	27.0 ± 2.6	18.0 ± 1.3	26.0 ± 3.1	220 ± 15	Raclavska et al. (2015)
	Min-max	–	86–134	–	46–175	658–1137	Gasperi et al. (2014)

to three magnitudes. Due to the high variations, no clear overall trend can be derived, even if similar sampling locations are compared.

In terms of CSO, to date, there are only few discharge measurements available before the flow volume enters the river. In most cases, researchers concentrate on an increase of the pollutants in the receiving surface water body by measuring upstream and downstream of a discharge point or in the river sediment. Table 5.1 presents results of some measurements taken in combined sewer systems or at their outlets. Since the sampling points and the catchment are not completely comparable, it is only possible to deduct general trends. Variations between minimum and maximum are within one magnitude. The values are in general also comparable to those from separate sewer systems and highway runoff despite the different composition of CSO.

Treatment Systems

Stormwater Ponds and Basins

As described in Chap. 2, the removal mechanisms of stormwater ponds rely mainly on sedimentation. Given that fine sediments show relatively higher metal concentrations (Sansalone and Buchberger 1997; Liebens 2002), sediment close to the inlet tends to have lower metal concentrations (Karlsson et al. 2010). As mentioned above, the coarser forebay sediment may show a lower toxicity.

Table 5.2 gives an overview of data on metal concentrations in stormwater pond sediments published between 2010 and 2017. As can be seen, similar to the metal concentrations in the stormwater itself, the range found in the dry matter (DM) is quite high.

Dissolved substances are only reduced in shallow, planted areas, comparable to ponds with FTWs (see Chap. 2). For instance, a Swedish study demonstrated considerable removal of dissolved metals in a stormwater pond (Cd: 73%, Cu: 58%, Pb: 41% and Zn: 64%). However, this is still far lower than the removal of particulate metal [between 85 and 92%, (Al-Rubaei et al. 2016)]. In studies from USA and Sweden, stormwater pond influent and effluent concentrations of dissolved metals were in the same range (Stanley 1996; Pettersson 1998).

Also, when the metal contamination is assessed in sediment accumulated in ponds, only looking at the total metal content can be misleading since metals may be present in different fractions and, thus, potentially available to different degrees. Sequential extraction procedures reveal the metal fractionation by distinguishing between the five fractions: exchangeable (I), carbonate-associated (II), Fe–Mn oxide-associated (III), organic matter/sulphide-associated (IV) and residual (V). Metals in fractions I to IV are potentially bioavailable since they can be released

Table 5.2 Overview of metal concentrations measured in sediment from stormwater ponds (mg/kg DM), published after 2009 (partly based on Søberg 2014)

Source/Catchment	Value(s)	Cd	Cu	Pb	Zn	Reference
Highway/nature	Min-max	0.4–0.6	200–250	40–60	800–100	Karlsson et al. (2010)
Residential/ industrial	Min-max	0.8–1	50–150	60–80	20–700	Karlsson et al. (2010)
Commercial/ residential	Min-max	1.1–1.7	403–581	133–179	579–825	Karlsson et al. (2010)
Commercial/ residential	Min-max	0.5–1.7	138–406	47–109	427–1069	Karlsson et al. (2010)
Industrial	Mean for inlet; middle; outlet	<0.5; <0.5; <0.5	3293; 3137; 1625	220; 198; 83	1361; 1051; 760	Isteniç et al. (2012)
Residential	Mean for inlet; middle; outlet	<0.5; <0.5; <0.5	133; 171; 129	10; 10; 6	234; 240; 190	
Residential	Mean for inlet; middle; outlet	<0.5; <0.5; <0.5	45; 6; 4	22; <2; <2	378; 82; 26	
25 Swedish municipal ponds	Min-max	0.1–2.3	3–109	3–60	14–597	Al-Rubaei et al. (2017)

from the sediment if the ambient conditions change (e.g. after excavation during maintenance, see the following text). For instance, a recent study from Sweden (Karlsson et al. 2016) shows—for sedimentation ponds and tanks as well as for storm drain sediment—that the majority of Cd, Cu, Pb and Zn and a significant amount of Ni were in potentially mobile forms. This fact must be considered during pond maintenance (sediment removal, drying/de-watering/disposal) to prevent metal from being released. Similar results were reported in various studies (Marsalek and Marsalek 1997; Camponelli et al. 2010; Lee et al. 1997).

In winter, an ice cover on the sediment pond reduces oxygenation of the pond water (e.g. by wind) (German et al. 2003), which can affect metal partitioning. Additionally, road salt used in cold climates affects the metal partitioning between particulate and is dissolved: if road salt is present in stormwater, a higher percentage of the metals is in the dissolved phase (Søberg 2014). Since ponds mainly remove metals in particulate form, the overall metal treatment performance may decrease.

Constructed Wetlands

Surface-Flow Constructed Wetlands

Since metals are often bound to particles and since wetlands capture such particles to a great extent (Sansalone and Buchberger 1997), wetlands remove a significant reaction of total metals thanks to their sedimentation process. Resuspension of the captured metals has to be avoided (Zhang et al. 2012). In comparison to ponds, wetlands provide more heterogeneous morphology including dense vegetation; therefore, treatment of fine particles and/or dissolved metals is potentially more effective than in ponds.

In an extensive literature study and meta-analysis, Carleton et al. (2001) investigated factors affecting the stormwater quality treatment performance of constructed wetlands (CWs). The review published data from 49 wetlands in 35 studies. In combination with results of other studies, the removal rates achieved are illustrated in Fig. 5.2.

The figure underlines that, similarly as for ponds, the metal treatment efficiency reported in different studies varies significantly depending on a wide range of factors. In general, however, the figure corroborates the assumption of Birch et al. (2004), who conclude that a mean removal of Cd, Cu, Pb and Zn of approximately 60% can be achieved. In studies done in 1997 and 2012/13 in Bäckaslöv, Växjö (Sweden), metal removal exceeding 80% was observed (Semadeni-Davies 2006; Al-Rubaei et al. 2016), which is in the upper range of the data included in the meta-analysis done by Carleton et al. (2001). The study of Al-Rubaei et al. (2016)

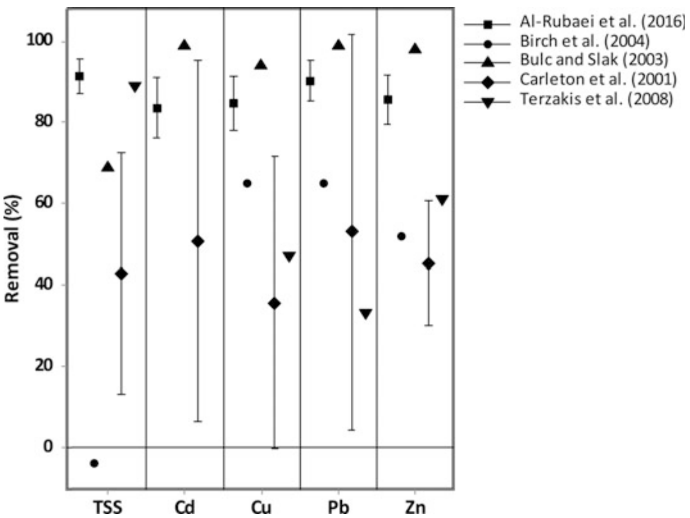

Fig. 5.2 Interval plot (95% confidence interval bar) of removal percentages achieved in constructed stormwater wetlands

also included dissolved metals. Their outflow concentrations were significantly below the inflow concentrations. Removal rates were between 55 and 80%. In the combined pond–wetland system evaluated in this study, the wetland increased the removal of the dissolved metals significantly compared to the removal in the pond only, underlining the importance of more advanced treatment processes for dissolved contamination removal.

Floating Treatment Wetlands

Since the treatment in stormwater ponds relies on sedimentation to large extent, the treatment of dissolved metals (and other compounds) in stormwater ponds may be insufficient. Accordingly, retrofitted Floating Treatment Wetlands should improve their treatment performance. After such pond retrofitting, the metal and sediment removal significantly increased [TSS, particulate Cu, and particulate Zn by 40% and dissolved Cu by 16% (Borne et al. 2013)]. Reasons for that are an increased direct plant uptake (Borne et al. 2013; Ladislas et al. 2013, 2015), bacterial/biofilm uptake (Borne et al. 2014), increased sorption [e.g. to organic matter (Borne et al. 2014)] and precipitation processes due to higher humic content, lower dissolved oxygen and more neutral pH value (Borne et al. 2013). In a study in New Zealand, some release of metals was observed in the spring, especially of Cu, due to organic matter degradation and, and thus the export of dissolved organic matter from the pond (Borne et al. 2014).

Subsurface-Flow Constructed Wetlands

Since most metals entering media-based systems are particle-bound, mechanical filtration of the incoming stormwater sediment also removes substantial loads of metals (and other particle-bound pollutants). Thus, the efficiency of TSS and particle-bound metal removal is correlated which was shown by Hatt et al. (2008) for vertical-flow stormwater wetlands (see section Bioretention filters). Studies on systems for horizontal-flow wetlands used for stormwater or CSO treatment are missing; however, the general processes in media-based systems are the same. Dissolved metal removal varies more since it is affected by diverse factors that influence soil and metal interactions. The main metal retention processes in soil are adsorption (including metal-OM complexation and cation exchange), surface precipitation and fixation (mainly to clay minerals) (Alloway 1995). Key soil properties controlling these processes are, among others, pH, OM content, clay mineral content and oxidation reduction potential (Bradl 2004). Besides these geochemical processes, plant metal uptake plays a less significant role (Read et al. 2008; Søberg et al. 2014a; Muthanna et al. 2007a) and is less important since the plants are not usually harvested. However, vegetation in media-based systems plays an important role in maintaining the infiltration capacity, facilitating treatment indirectly (e.g. by effects on microbial communities in the filter) and providing aesthetical values and/or (urban) biodiversity.

Bioretention Filters

From approximately 2000 onwards, numerous studies have been published on how well stormwater bioretention filters remove pollutants. A summary of inflow and outflow metal concentrations reported in selected studies is given in Table 5.3. Cadmium concentrations were only investigated in two studies with inflow values between 4.6 and 5.6 mg/L and removal efficiencies between 66 and >99.5%.

Table 5.3 Biofilter inflow and outflow concentrations of metals (μg/L) from selected studies. (diss. dissolved concentrations; non-veg. non-vegetated; In. inflow concentrations; Out.: outflow concentrations) (partly based on Søberg 2014)

Filter type	Value(s)	Cu		Pb		Zn		Reference
		In	Out	In	Out	In	Out	
Field scale	Total, mean	56.8	1.9	41.4	10.2	98.3	20.6	Glass and Bissouma (2005)
Field scale	Total, mean/range	10	3–4	58	<2–4	107	44–48	Davis (2007)
Field scale	Total, mean	–	–	–	–	72	17	Hunt et al. (2008)
Field scale	Total, mean/range	10	4–6	6	2–3	100	13–30	Hatt et al. (2009)
Field scale	Total, mean	60	5	110	7	330	13	
Field scale	Total, mean	19	16	6	3	71	12	Li and Davis (2009)
Field scale	Total, mean	13	9	<2	<2	15	3	
Field scale	Total, mean	16	6.3	17	4.5	120	47	Chapman and Horner (2010)
Field scale	Dissolved, mean	3.6	2.9	<1	<1	49	26	
Field, with submerged zone highway	Total, mean	20	52	80	22	130	280	Li et al. (2014)
Field highway	Total, mean	20	62	80	5	130	310	
Field, residential	Total, mean	60	5	110	7	330	13	Hatt et al. (2009)
Carpark, 3 filter cells	Total, mean	10	6	6	2	100	13/15/30	
Sludge as filter medium	Total, mean	241	4.5	90.3	0.2	1127	2.1	

The total metal removed by bioretention filters often exceeds 80–90% (Hatt et al. 2009; Muthanna et al. 2007b; Read et al. 2008; Sun and Davis 2007).

As for most compounds removed by bioretention filters (see, e.g. Chap. 2) the processes and properties are, to varying degrees, affected by ambient conditions, e.g. the drying/wetting pattern, ambient temperatures, road salt in the runoff, the pollutant concentrations in the runoff and the runoff intensity (Hatt et al. 2007b; Blecken et al. 2009; Søberg et al. 2014b; Muthanna et al. 2007a; Denich et al. 2013; Bratieres et al. 2008), the filter design (e.g. water saturated zone, different filter materials) (Dietz and Clausen 2006; Davis et al. 2009; Hatt et al. 2006; Fassman et al. 2013) and, with minor effect, the plant species utilised (Read et al. 2008).

Although dissolved metal removal has been shown to vary far more than the quite stable total metal removal, only the total metal removal has been investigated in most biofilter studies (see Table 5.1). Dissolved metal removal has been considered in fewer of the investigations (Muthanna et al. 2007b; Read et al. 2008; Hatt et al. 2007a; Sun and Davis 2007; Søberg et al. 2014b). In pilot-scale stormwater biofilters, Muthanna et al. (2007b) found removal rates of dissolved Zn up to 70%, whereas leaching was observed for both dissolved Cu and Pb. In a laboratory study investigating biofilter columns at three different temperatures, Blecken et al. (2011) found lower removal efficiencies (24–66%) for dissolved Cu and Pb compared to Zn and Cd (99%), and a negative correlation between temperature increase and removal of dissolved Cu and Pb. In a study about temperature and salt influence on metal removal in laboratory pilot-scale bioretention filters, Søberg et al. (2014a) found high removal of dissolved Zn and Cd (>90%), whereas removal of dissolved Cu and Pb was less efficient, ranging from −1345 to 71% being deteriorated by the presence of salt, particularly in connection with high temperature.

Although some findings indicate that dissolved metal removal is significantly lower than total metal removal and, in particular, Cu leaching was observed (Hatt et al. 2007a; Chapman and Horner 2010; Muthanna et al. 2007b), biofilters seem to have potential to provide adequate dissolved metal treatment if filter material with specific sorption properties is used (Sun and Davis 2007; Hsieh and Davis 2005). An efficient removal of dissolved metals has also been reported for bioretention filters where sandy soils with only little organic content are used as filter material (e.g. Blecken et al. (2011) reported removal rates of >99% for dissolved Zn and Cd and >60% for dissolved Cu when using filter material with 90% sand). Numerous studies have further tested various filter materials to enhance metal treatment. Examples are zeolites and peat (Färm 2003), blast furnace slag, chitosan, crab shell, peat, sawdust and sugar cane (Vijayaraghavan et al. 2010), limestone, shell sand, zeolite, and olivine (Wium-Andersen et al. 2012). Many of these results are derived from short-term laboratory studies; when these results are transferred to praxis, it is important to consider long-term behaviour of the material (e.g. breakdown and release of associated pollutants over time). When choosing filter materials for bioretention systems, one thus has to compromise between infiltration rate, adsorption capacity and support of plant growth.

Typically, metals do not ingress far into the filter material, but are trapped on or near the top of the filter due to both mechanical removal and sorption processes (e.g. Davis et al. 2001; Grotehusmann et al. 2017). Grotehusmann et al. (2017) found that metals accumulate on the filter surface and in the first 10–15 cm of the filter layer in correlation with how much calcium carbonate ($CaCO_3$) is available, which is often added as additional layer on top of the filter surface at the large-scale sites investigated in Germany. Although in general, high inflow values of $CaCO_3$ onto the filter could also lead to building up a carbonate layer, due to the hydraulic conditions on the filter surfaces, it is usually limited to areas close to the inflow and did not result in overall clogging of the filter surface. However, when $CaCO_3$ is added as additional surface layer or mixed into the filter material, the additive itself may not be contaminated with heavy metals, e.g. lead (Grotehusmann et al. 2017). The high metal removal in the upper layer facilitates filter maintenance since merely scraping off the top layer may remove a high proportion of accumulated metals from the system, and thus postpone the need to replace the whole filter media (Hatt et al. 2008).

Some field investigations predicted that the accumulation of fine stormwater sediment on top of the filter material and in the upper layers reduces the hydraulic conductivity relatively quickly, sometimes even within several months, and leads to clogging (Li and Davis 2008). However, Grotehusmann et al. (2017) could not confirm this in large-scale investigations on filters designed according to German standards. The main reason for this finding was oversized filter layers which led to low long-term loads of fine sediments.

During winter in cold or temperate climates, pollutant concentrations are particularly high, and de-icing salt often affects metal partitioning towards the dissolved phase (Marsalek et al. 2003; Oberts 2003). The presence of salt has been shown to substantially influence the ability of stormwater biofilters to remove metals. The latter is particularly pronounced for dissolved metals (Søberg et al. 2014b). Søberg et al. (2014b) found that ion exchange by Na^+ was probably entirely responsible for the leaching of dissolved Pb from the filter material.

In winter, plant metal uptake is generally inhibited by salt in stormwater runoff (Fritioff et al. 2004) and low temperatures generally reduce biological activities. Søberg et al. (2014b) examined the impact of temperature, salt and a submerged zone on metal uptake in three native (Northern Sweden) wet/drought tolerant plant types: *Juncus conglomeratus*, *Phalaris arundinacea* and *Carex panacea*. They found a generally higher metal uptake at low temperature. Their results suggested that the three plant species were not particularly affected by different temperatures and/or the presence/absence of a submerged zone in the filter and/or salt in stormwater. This indicates the potential to use the investigated plant species for targeted cold climate biofilter design. Additionally, Denich et al. (2013) found that biofilter vegetation was capable of withstanding high salt exposure. Despite the reduced biological activity in cold seasons as described in Chap. 2, metal retention was good for both seasons with mass reductions of 90, 82 and 72% of Zn, Pb and Cu, respectively (Muthanna et al. 2007b). The latter is supported by findings of a study evaluating seasonal performance variations (Roseen et al. 2009), where seasonal contaminant removal performance was found to vary little for stormwater biofilters.

Swales and Buffer Strips

Grotehusmann et al. (2017) found out that a major part of the metals is already captured within the first 10 cm of the buffer strip leading to the swale. Since the buffer strips contain rather coarse media, the metal accumulation was also found in deeper layers (25–30 cm). The authors revealed that a major part of the retention was, thus, already provided by the shoulder, and concluded that the treatment of swale effluent, as often practiced in Germany, is not necessary.

Reported removal percentages of metals in swales vary as follows: Bäckström et al. (2006) report about 20% metal removal while Stagge et al. (2012) and Knight et al. (2013) report very efficient metal removal rates. Bäckström et al. (2006) found that the particle size distribution influences the removal efficiency: only large particles >250 µm settle in swales. In general, the pollution removal capacities for dissolved pollutants and small particles are low. Thus, Bäckström et al. (2006) conclude that, while efficient for flow retention, swales cannot produce consistently high pollutant removal.

Although swales commonly tend to be comprised of grass, they can have particular design modifications (such as wetland planting) to improve nutrient reduction (Winston et al. 2012). Metal uptake by plants can be significant. This uptake is specific to metal and plant species (Zhang et al. 2012). Most plants accumulate the metals in their roots, but also transport to the leaves occurs (Weis and Weis 2004). It is, thus, important that swales and buffer strips be harvested regularly.

References

Alloway BJ (1995) Heavy metals in soils. Blackie Academic and Professional, London, UK

Al-Rubaei AM, Engström M, Viklander M, Blecken GT (2016) Long-term hydraulic and treatment performance of a 19-year old constructed stormwater wetland finally maturated or in need of maintenance? Ecol Eng 95:73–82

Al-Rubaei AM, Merriman LS, Hunt WF, Viklander M, Marsalek J, Blecken GT (2017) Survey of the operational status of 25 Swedish municipal stormwater management ponds. J Environ Eng-ASCE 143(6):05017001

Ayrault S, Le Pape P, Evrard O, Priadi CR, Quantin C, Bonté P, Roy-Barman M (2014) Remanence of lead pollution in an urban river system: a multi-scale temporal and spatial study in the Seine River basin, France. Environ Sci Pollut Res 21:4134–4148

Bäckström M, Viklander M, Malmqvist PA (2006) Transport of stormwater pollutants through a roadside grassed swale. Urban Water J 3(2):55–67

Birch GF, Matthai C, Fazeli MS, Suh J (2004) Efficiency of a constructed wetland in removing contaminants from stormwater. Wetlands 24(2):459–466

Blecken GT, Zinger Y, Deletic A, Fletcher TD, Viklander M (2009) Influence of intermittent wetting and drying conditions on heavy metal removal by stormwater biofilters. Water Res 43:4590–4598

Blecken GT, Marsalek J, Viklander M (2011) Laboratory study on stormwater biofiltration in cold temperatures: metal removal and fates. Water Air Soil Poll 219:303–317

Boogaard FC, van de Ven F, Langeveld JG, van de Giesen N (2014) Stormwater quality characteristics in (Dutch) urban areas and performance of settlement basins. Challenges 5:112–122

Borne KE, Fassman EA, Tanner CC (2013) Floating treatment wetland retrofit to improve stormwater pond performance for suspended solids, copper and zinc. Ecol Eng 54:173–182

Borne K, Fassman-Beck E, Tanner C (2014) Floating treatment wetland influences on the fate of metals in road runoff retention ponds. Water Res 48:430–442

Borris M, Österlund H, Marsalek J, Viklander M (2016) Contribution of coarse particles from road surfaces to dissolved and particle-bound heavy metal loads in runoff: a laboratory leaching study with synthetic stormwater. Sci Total Environ 573:212–221

Bradl HB (2004) Adsorption of heavy metal ions on soil and soil constituents. J Colloid Interface Sci 277:1–18

Bratieres K, Fletcher TD, Deletic A, Zinger Y (2008) Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. Water Res 42(14):3930–3940

Bulc T, Slak AS (2003) Performance of constructed wetland for highway runoff treatment. Water Sci Technol 48(2):315–322

Campbell PCG (1995) Interactions between trace metals and aquatic organisms: a critique of the free-ion activity model. In: Tessier A, Turner DR (ed) Metal speciation and bioavailability in aquatic systems, vol 3. Wiley, Chichester, UK

Camponelli KM, Lev SM, Snodgrass JW, Landa ER, Case RE (2010) Chemical fractionation of Cu and Zn in stormwater, roadway dust and stormwater pond sediments. Environl Poll 158 (6):2143–2149

Carleton JN, Grizzard TJ, Godrej AN, Post HE (2001) Factors affecting the performance of stormwater treatment wetlands. Water Res 35(6):1552–1562

Chapman C, Horner RR (2010) Performance assessment of a street-drainage bioretention system. Water Environ Res 82:109–119

Czemiel Berndtsson J (2014) Storm water quality of first flush urban runoff in relation to different traffic characteristics. Urban Water 11(4):284–296

Davis AP (2007) Field performance of bioretention: water quality. Environ Eng Sci 24(8):1048–1064

Davis AP, Shokouhian M, Sharma H, Minami C (2001) Laboratory study of biological retention for urban stormwater management. Water Environ Res 73:5–14

Davis AP, Hunt WF, Traver RG, Clar M (2009) Bioretention technology: overview of current practice and future needs. J Environ Eng 135:109–117

Denich C, Bradford A, Drake J (2013) Bioretention: assessing effects of winter salt and aggregate application on plant health, media clogging and effluent quality. Water Qual Res J Canada 48:387–399

Dierkes C (1999) Verhalten von Schwermetallen im Regenabfluss von Verkehrsflächen bei der Versickerung über poröse Deckbelege. Forum Siedlungswasserwirtschaft und Abfallwirtschaft, Universität GH Essen, vol 14. Essen, Germany (in German)

Dietz ME, Clausen JC (2006) Saturation to improve pollutant retention in a rain garden. Environ Sci Technol 40:1335–1340

Eriksson E, Baun A, Scholes L, Ledin A, Ahlman S, Revitt M, Noutsopoulos C, Mikkelsen PS (2007) Selected stormwater priority pollutants—an European perspective. Sci Total Environ 383(1):41–51

Färm C (2003) Rening av dagvatten genom filtrering och sedimentation (Stormwater treatment by filtration and sedimentation). Svenskt Vatten, Rapport 2003–16, Swedish Water and Wastewater Association, Stockholm, Sweden

Fassman EA, Simcock R, Wang S (2013) Media specification for stormwater bioretention devices. Technical Report 2013/011 Auckland City Coucil, Auckland, New Zealand

Fritioff Å, Kautsky L, Greger M (2004) Influence of temperature and salinity on hevay metal uptake by submersed plants. Environ Pollut 133:265–274

Gasperi J, Sebastian C, Ruban V, Delamain M, Percot S, Wiest L, Mirande C, Caupos E, Demare D, Kessoo MDK, Saad M, Schwartz JJ, Dubois P, Fratta C, Wolff H, Moilleron R, Chebbo G, Cren C, Millet M, Barraud S, Gromaire MC (2014) Micropollutants in urban stormwater: occurrence, concentrations, and atmospheric contributions for a wide range of contaminants in three French catchments. Environ Sci Pollut Res 21:5267–5281

German J, Svensson G, Gustafsson LG, Vikström M (2003) Modelling of temperature effects on removal efficiency and dissolved oxygen concentrations in stormwater ponds. Wat Sci Technol 48(9):145–154

Glass C, Bissouma S (2005) Evaluation of a parking lot bioretention cell for removal of stormwater pollutants. Ecosystems and Sustainable Development V Book Series: WIT Trans Ecol Environ 81:699–708

Göbel P, Dierkes C, Coldewey W (2007) Storm water runoff concentration matrix for urban areas. J Contam Hydrol 91(1):26–42

Grotehusmann D, Lambert B, Fuchs S, Uhl M, Leutnant D (2017) Erhebungsuntersuchung zur Optimierung der Retentionsbodenfilter in NRW. (Investigation to optimize retention soil filters in NRW). Final report, Ministry for Environment, Nature Conservation, Agriculture and Consumer Protection of the German Federal State of North 289 Rhine-Westphalia (Ed.), Düsseldorf. https://www.lanuv.nrw.de/uploads/tx_mmkresearchprojects/Abschlussbericht_RBF_NRW.pdf (in German)

Hatt BE, Siriwardene N, Deletic A, Fletcher TD (2006) Filter media for stormwater treatment and recycling: the influence of hydraulic properties of flow on pollutant removal. Water Sci Technol 54(6–7):263–271

Hatt BE, Deletic A, Fletcher TD (2007a) Stormwater reuse: designing biofiltration systems for reliable treatment. Water Sci Technol 55:201–209

Hatt BE, Deletic A, Fletcher TD (2007b) Hydraulic and pollutant removal performance of stormwater filters under variable wetting and drying regimes. Water Sci Technol 56:11–19

Hatt BE, Fletcher TD, Deletic A (2008) Hydraulic and pollutant removal performance of fine media stormwater filtration systems. Environ Sci Technol 42:2535–2541

Hatt BE, Fletcher TD, Deletic A (2009) Hydrologic and pollutant removal performance of biofiltration systems at field scale. J Hydrol 365:310–321

Helmreich B, Hilliges R, Schriewer A, Horn H (2010) Runoff pollutants of a highly trafficked urban road—correlation analysis and seasonal influences. Chemosphere 80:991–997

Hsieh CH, Davis AP (2005) Evaluation and optimization of bioretention media for treatment of urban storm water runoff. J Environ Eng 131:1521–1531

Hunt WF, Smith JT, Jadlocki SJ, Hathaway JM, Eubanks PR (2008) Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, NC. J Environ Eng 134(5):403–408

Hvitved-Jacobsen T, Vollertsen J, Haaning Nielsen A (2010) Urban and highway stormwater pollution: concepts and engineering. ISBN 9781439826850, CRC Press, Taylor & Francis Group

Ingri J (2012) Introduktion i miljögeokemi (Introduction in environmental chemistry). Studentlitteratur AB, Lund, Sweden

Isteniç D, Arias CA, Vollertsen J, Nielsen AH, Wium-Andersen T, Hvitved-Jacobsen T, Brix H (2012) Improved urban stormwater treatment and pollutant removal pathways in amended wet detention ponds. J Environ Sci Health—Part A: Tocix/Hazard Subst Environ Eng 47(10):1466–1477

Karlsson K, Blecken GT, Öhlander B, Viklander M (2016) Environmental risk assessment of sediments deposited in stormwater treatment facilities: trace metal fractionation and its implication for sediment management. J Environ Eng 142(11):04016057

Karlsson K, Viklander M, Scholes L, Revitt M (2010) Heavy metal concentrations and toxicity in water and sediment from stormwater ponds and sedimentation tanks. J Hazard Mater 178(1–3):612–618

Kayhanian M, Fruchtman BD, Gulliver JS, Montanaro C, Ranieri E, Wuertz S (2012) Review of highway runoff characteristics: comparative analysis and universal implications. Water Res 46:6609–6624

Knight EMP, Hunt WF, Winston RJ (2013) Side-by-side evaluation of four level spreader-vegetated filter strips and a swale in eastern North Carolina. J Soil Water Conserv 68(1):60–72

Ladislas S, Gérente C, Chazarenc F, Brisson J, Andrès Y (2013) Performances of two macrophytes species in floating treatment wetlands for cadmium, nickel, and zinc removal from urban stormwater runoff. Water Air Soil Pollut 224(2):1408

Ladislas S, Gérente C, Chazarenc F, Brisson J, Andrès Y (2015) Floating treatment wetlands for heavy metal removal in highway stormwater ponds. Ecol Eng 80:85–91

Le Coustumer S, Fletcher TD, Deletic A, Barraud S (2007) Hydraulic performance of biofilters for stormwater management: first lessons from both laboratory and field studies. Water Sci Technol 56:93–100

Lee PK, Touray JC, Baillif P, Ildefonse JP (1997) Heavy metal contamination of settling particles in a retention pond along the A-71 motorway in Sologne, France. Sci Total Environ 201(1):1–15

Li H, Davis AP (2009) Water quality improvement through reductions of pollutant loads using bioretention. J Environ Eng-ASCE 135(8):567–576

Liebens J (2002) Heavy metal contamination of sediments in stormwater management systems: the effect of land use, particle size, and age. Environ Geol 41(3–4):341–351

Li H, Davis AP (2008) Urban particle capture in bioretention media I: laboratory and field studies. J Environ Eng 134:409–418

Li YL, Deletic A, Alcazar L, Bratieres K, Fletcher TD, McCarthy DT (2012) Removal of Clostridium perfringens, Escherichia coli and F-RNA coliphages by stormwater biofilters. Ecol Eng 49:137–145

Li YL, McCarthy DT, Deletic A (2014) Stable copper-zeolite filter media for bacteria removal in stormwater. J Hazard Mat 273:222–230

Marsalek J, Marsalek PM (1997) Characteristics of sediments from a stormwater management pond. Water Sci Technol 36(8–9):117–122

Marsalek PM, Watt WE, Marsalek J, Anderson BC (2003) Winter operation of an on-stream stormwater management pond. Water Sci Technol 48(9):133–143

McNett JK, Hunt WF (2011) An evaluation of the toxicity of accumulated sediments in forebays of stormwater wetlands and wetponds. Water Air Soil Pollut 218(1–4):529–538

Muthanna TM, Viklander M, Blecken GT, Thorolfsson ST (2007a) Snowmelt pollutant removal in bioretention areas. Water Res 41:4061–4072

Muthanna TM, Viklander M, Gjesdahl N, Thorolfsson ST (2007b) Heavy metal removal in cold climate bioretention. Water Air Soil Pollut 183:391–402

Oberts GL (2003) Cold climate BMPs: solving the management puzzle. Water Sci Technol 48 (9):21–32

Pettersson TJR (1998) Water quality improvement in a small stormwater detention pond. Water Sci Technol 38(10):115–122

Pitt R, Field R, Lalor M, Brown M (1995) Urban stormwater toxic pollutants: assessment sources, and treatability. Water Environ Res 67(3):260–275

Raclavska H, Drozdova J, Skrobankova H, Raclavsky K (2015) Behavior of Metals in a Combined Wastewater Collection System in Ostrava, Czech Republic. Water Environ Res 87(2):123–131

Read J, Wevill T, Fletcher TD, Deletic A (2008) Variation among plant species in pollutant removal from stormwater in biofiltration systems. Water Res 42:893–902

Roseen RM, Ballestero TP, Houle JJ, Avellaneda P, Briggs J, Fowler G, Wildey R (2009) Seasonal performance variations for storm-water management systems in cold climate conditions. J Environ Eng 135(3):128–137

Sansalone JJ, Buchberger SG (1997) Characterization of solid and metal element distribution in urban highway stormwater. Water Sci Technol 36(8–9):155–160

Semadeni-Davies A (2006) Winter performance of an urban stormwater pond in southern Sweden. Hydrol Processes 20:165–182

Søberg LC (2014) Metal pathways in stormwater treatment systems. Licentiate thesis, Luleå University of Technology

Søberg LC, Blecken GT, Viklander M, Hedström A (2014a) Metal uptake in three different plant species used for cold climate biofilter systems. In: Proceedings of the 13th International Conference on Urban Drainage, Kuching, Sarawak, Malaysia

Søberg LC, Viklander M, Blecken GT (2014b) The influence of temperature and salt on metal and sediment removal in stormwater biofilters. Water Sci Technol 69:2295–2304

Søberg L, Viklander M, Blecken GT (2017) Do salt and low temperature impair metal treatment in stormwater bioretention cells with or without a submerged zone? Sci Total Environ 579:1588–1599

Stagge JH, Davis AP, Jamil E, Kim H (2012) Performance of grass swales for improving water quality from highway runoff. Water Res 46(20):6731–6742

Stanley DW (1996) Pollutant removal by a stormwater dry detention pond. Water Environ Res 68 (6):1076–1083

Sun X, Davis AP (2007) Heavy metal fates in laboratory bioretention systems. Chemosphere 66:1601–1609

Terzakis S, Fountoulakis MS, Georgaki I, Albantakis D, Sabathianakis I, Karathanasis AD, Kalogerakis N, Manios T (2008) Constructed wetlands treating highway runoff in the central Mediterranean region. Chemosphere 72(2):141–149

Valtanen M, Sillanpaa N, Setala H (2014) The effects of urbanization on runoff pollutant concentrations, Loadings and their seasonal patterns under cold climate. Water Air Poll 225 (6):1977

Vijayaraghavan K, Joshi UM, Balasubramanian R (2010) Removal of metal ions from storm-water runoff by low-cost sorbents: batch and column studies. J Environ Eng-ASCE 136:1113–1118

Weis JS, Weis P (2004) Metal uptake, transport and release by wetland plants: implications for phytoremediation and restoration. Environ Int 30(5):685–700

Westerlund C, Viklander M, Bäckström M (2003) Seasonal variations in road runoff quality in Luleå, Sweden. Water Sci Technol 48(9):93–101

Wilber WG, Hunter JV (1975) Contributions of metals resulting from stormwater runoff and precipitation in Lodi, New Jersey. Urbanization Water Qual Control 45–54

Winston RJ, Hunt WF, Kennedy SG, Wright JD, Lauffer MS (2012) Field evaluation of storm-water control measures for highway runoff treatment. J Environ Eng 138(1):101–111

Winston RJ, Hunt WF, Kennedy SG, Merriman LS, Chandler J, Brown D (2013) Evaluation of floating treatment wetlands as retrofits to existing stormwater retention ponds. Ecol Eng 54:254–265

Wium-Andersen T, Nielsen AH, Hvitved-Jacobsen T, Kristensen NK, Brix H, Arias C, Vollertsen J (2012) Sorption media for stormwater treatment—a laboratory evaluation of five low-cost media for their ability to remove metals and phosphorus from artificial stormwater. Water Environ Res 84:605–616

Xanthopoulos C, Hahn HH (1990) Pollutants attached to particles from drainage areas. Sci Total Environ 93:441–448

Yu SL, Kuo JT, Fassman EA, Pan H (2001) Field test of grassed-swale performance in removing runoff pollution. J Water Res Plan Manage 127(3):168–171

Zhang Z, Cui B, Fan X (2012) Removal mechanisms of heavy metal pollution from urban runoff in wetlands. Front Earth Sci 6(4):433–444