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Removal of heavy metals in a wet detention pond in Reykjavik

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Abstract

A wet detention pond draining a residential area in the outskirts of Reykjavik was monitored during a 12 month period starting June 1st, 2008. The goal of the project was to increase the local information on stormwater pollution and detention pond treatment efficiency. Water samples taken during five runoff events were analyzed for a range of heavy metals and particle size. The results of this study was that on average, the heavy metal content of residential surface runoff entering the Icelandic pond was low compared to ponds in similar catchments in other northern countries. The highest pollutant concentrations occurred during snowmelt and in rain events preceding a long dry period. First flush of heavy metals was observed in almost all the surface runoff events but the extent of the first flush varied between metals. Chromium, copper and nickel were found to be mainly (>50%), bound to particulates whereas zinc was <40 % particulate bound. The mean particle diameter in the inflowing runoff ranged from 10-20 µm and 68 % of the mass was bound to particles less than 20 µm. Despite the low pollution concentration in the inflowing water, the total treatment efficiency of the pond calculated based on the Event Mean Concentration (EMC) was found to be relatively high, or in the 80-90% range.

Introduction

Urban and road stormwater runoff may contain harmful pollutants, originating from e.g. motor vehicle emissions, tire and asphalt wear, road debris, roof painting and urban metal surfaces. The pollutants that are considered of major concern to human health and aquatic life are heavy metals, such as Cd, Cr, Cu, Ni, Pb and Zn, as well as organic pollutants, such as polycyclic aromatic hydrocarbons (PAH) (e.g. Brown and Peake, 2006). Both the heavy metals and PAHs have been found to be predominantly bound to particulates (e.g. Marselek et al., 2003). The load of pollutants conveyed by stormwater runoff depends on a variety of factors, such as the type and density of the drainage area, the usage of the catchment, traffic density, and the number of dry weather days preceding the runoff event (Westerlund et al., 2003).

Pollutant concentrations vary over the course of a rainstorm. Specifically, contaminant concentrations are often highest on the rising limb of a storm, prior to the peak flow rate, upon which concentrations decline fast (e.g. Li et al., 2005). This phenomenon is called "first-flush". In addition, pollutant concentrations vary with season, which is particularly true in cold climates where there is snowmelt (Hallberg et al. 2007). Snowmelt events are known to cause rather high pollutant loads as snow building up on e.g. highway shoulders tend to accumulate significant amounts of pollutants (Sansalone et al., 2002).

In order to protect sensitive receiving waters from runoff pollutants, wet detention ponds have been built worldwide (ASCE, 1992). Pollutant removal in such ponds is based on naturally occurring physical, chemical and biological processes. The removal of pollutants is mainly caused by gravitation settling enhanced by a reduction of water velocity as the runoff enters the pond (Akan, 1993). The rate of settling is determined by the particulate size, as large particles settle faster than small particles. Studies on the particulate composition of surface runoff indicate that more than 50 % of the particulate mass for samples with TSS concentrations less than 100 mg/L consists of particles less than 20 µm (Li et al, 2006). Studies also suggest that particle size distribution may not vary much with season (Greb and Bannerman, 1997).

Besides gravitational settling, chemical processes like precipitation, coagulation and sorption contribute to the removal of dissolved and colloidal bound pollutants (Durin et al., 2007). Biological processes associated with growth and respiration of aquatic plants, algae, and microorganisms cause the removal of nutrients and can also function to break down toxic organic compounds into less harmful compounds (e.g. Fatta-Kassinos et al., 2009).
Reykjavik has a number of urban rivers that are valuable for the ecosystem and recreational activities such as fishing. In an attempt to prevent possible urban runoff pollution from reaching and deteriorating these waters, several wet detention ponds have been constructed during the past seven years (Sævarsson, 2007). The

design and construction of these ponds was based on experience from neighboring Nordic countries and Germany.

Limited research exists on the temporal variability of pollutant loads in urban runoff and on the treatment efficiency of wet detention ponds under Icelandic conditions. Flow proportional sampling over the course of 14 months in 2005-2006 at the Víkurvegur pond, suggested an 83% removal of total suspended solids but only 54% removal of zinc (Gunnarsson and Sigurðsson, 2007). This study did not consider specific runoff events, but rather combined multiple events together.

Reykjavik Energy has together with the University of Iceland initiated a monitoring and research program to investigate the treatment efficiency of newly built detention ponds, with the ultimate goal of increasing local information and building a knowledge base that can help future storm water management practices in Iceland. In this paper, results from detailed sampling of five discrete runoff events over a time span of one year are presented. The time variability in heavy metal concentration in urban runoff is explored and the treatment efficiency for selected heavy metals based on an Event Mean Concentration is presented. Organic pollutants such as PAHs are not included in this study, as a preliminary analysis indicated that PAH concentrations were under detection limits (0.01-0.2 µg/L).

Methods

Site description

The research presented in this paper is based on a wet detention pond located at Vikurvegur in the outskirts of Reykjavik. While the pond is located near the crossing of a highway and a major road, its drainage area is entirely the residential area Grafarholt, located to the south of the pond (Figure 3). The pond was designed particularly to protect the nearby river Úlfarsá which is popular for salmon fishing.

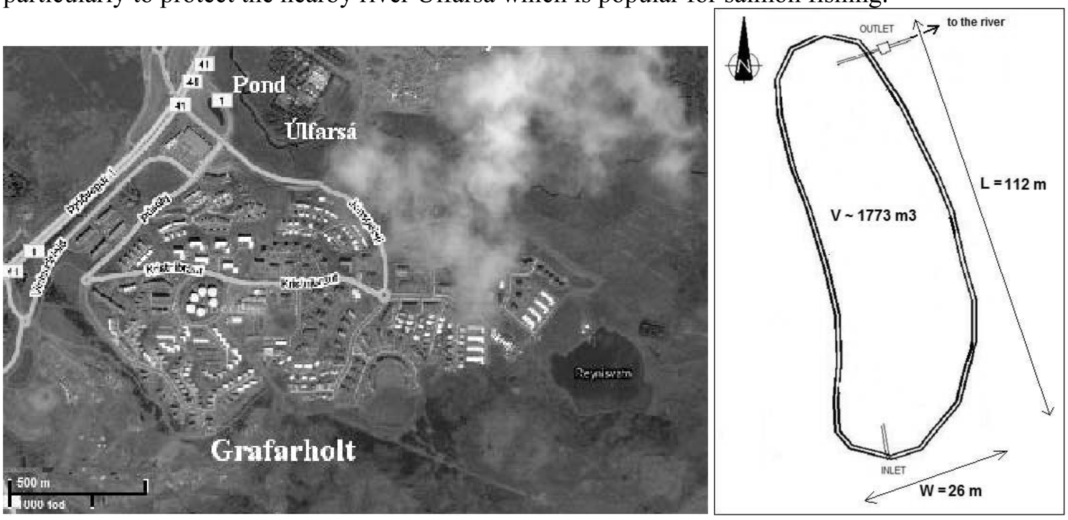

Figure 3: Study site showing the residential drainage area Grafarholt, the pond shape and dimensions, and the receiving waters river Úlfarsá (Borgarvefsjá, 2009; Mortamet, 2009).

The Víkurvegur pond is 112 m long, 26 m wide and has a permanent volume of approximately 4,000 m^3 (Mortamet, 2009; Gunnarsson and Sigurðsson, 2007).
The water inlet situated on the southern shore of the pond (Figure 3) consists of a submerged 600 mm diameter concrete pipe which goes about 10 m into the pond at the pond bottom. The outlet of the pond is situated on the far end of the northern shore, in order to prevent short circuiting of flow. During the 12 month monitoring period, aquatic vegetation was found to be sparse and localized around the pond inlet.

Rainfall and runoff rates

Precipitation intensity at 10 min intervals has been monitored by a tipping bucket rain gauge located approximately 500 m NE of the catchment area (Figure 3) since 2004 (Vista Engineering, 2009). Another five rain gauges spread all over Reykjavik operated by Vista were used to assess the seasonal variation of precipitation. Rainfall was defined as the precipitation above 0.2 mm per 10 minutes.
The volumetric flow into and out of the pond has been monitored by the Icelandic Meteorological Office on behalf of Reykjavik Energy for the past four years (Icelandic Meteorological Office, 2009). The outflow of

the pond is monitored through a water level gauge located at a V-shaped overflow structure. The inflow rate is back calculated from the outflow rate, based on the measured water level in the pond (Gunnarsson and Sigurðsson, 2007). As a result, the estimated inflow rate may exhibit short term variability associated with wind driven water level fluctuations. The time series of the inflow water was separated into discrete runoff events, which were defined as when the inflow exceeded 4 L/s preceding at minimum a 12 hours dry period (see
Table 1 below).

Water sampling and analysis

Liqui-port 2000 autosamplers maintained by the Icelandic Meteorological Office on behalf of Reykjavík Energy were situated both at the pond inlet and outlet. The autosamplers, connected to the automated flow rate measurements, were programmed to collect 1 L water samples at regular time intervals when inflows exceeded a minimum threshold rate of 4 L/s at the inlet of the pond.

Table 1: Overview of sampled runoff events.

Event	Date	Qmax (L/s)	Tot. Vol. (m^3)	Duration (hours)	Dry period (days)	Type
Summer	7.1.08	53	150	1.5	21	Short rain
Fall	9.16.08	98	1500	14	1	Hurricane remnant
Winter A	12.22.08	67	1700	18	7	Rain on snow
Winter B	2.13.09	29	410	8	17	Snow melt
Spring	5.28.09	27	240	7	2	Rain

A summary of five different runoff events discussed in this paper is presented in Table 1. In order to capture the seasonal variability discussed in this paper introduction, care was taken to capture both rainfall and snowmelt events of varying intensity and duration over a course of a 12 month period starting June 1st, 2008 (see
Table 1). The first event analyzed was a short but intensive July storm following a three week dry period. The fall event was a large individual rainstorm in another wise continuous period of rainfall. Two winter events were chosen because previous studies have shown that the heaviest pollution load occurs when it rains on snow or on frozen ground (Sansalone et al., 2002; Marsalek et al., 2003; Vollertsen et al., 2007). The spring event with comparatively low inflow rates was chosen to characterize an average runoff pattern in Iceland, as will be discussed more carefully in the results section. Each water sample was analyzed for pH, conductivity, total suspended solids as well as a wide range of compounds. In this paper, the results for heavy metals are reported. Total and dissolved heavy metal concentrations were analyzed using an ICP-MS by ALS Laboratory in Sweden. The samples from July 1, 2008 and the sample for total concentrations from September 16, 2008 were measured by an analytical method allowing the following detection limits: Pb: 0.6 µg/L; Cd: 0.05 µg/L; Cr: 0.9 µg/L; Cu: 1 µg/L; Ni: 0.6 µg/L; Zn: 4 µg/L. The rest of the samples were analyzed by a more sensitive method, allowing the detection limits of: Pb: 0.01 µg/L; Cd: 0.002 µg/L; Cr: 0.01 µg/L; Cu: 0.1 µg/L; Ni: 0.05 µg/L; Zn: 0.2 µg/L. Average concentrations were calculated as the arithmetic mean of the concentrations.

Particulate size distribution

Two ten liter samples were collected at the inflow during the summer event of July 1st, 2008. The samples were heated and the volume reduced from 10 liters to 1 liter. The concentrated water samples were analyzed using a Malvern Mastersizer 2000 owned by the Icelandic Meteorological Office. The experiment was not repeated as previous studies showed limited seasonality (Greb and Bannerman, 1997).

Treatment efficiency

Detention pond treatment efficiency (*TE)* was determined using the Event Mean Concentration *(EMC)* method. EMC is defined as a flow-weighted mean concentration of a constituent in the runoff water from a runoff event. Therefore the EMC is defined corresponding to the total transport of mass over an individual event divided by its total volume of runoff water. Three to seven samples were used in order to get a good estimate for EMC for both the inflow and outflow of the pond in accordance with Westerlund et al.(2003).

The treatment efficiency (TE) was then determined as the ratio of mass removed by the pond relative to the mass entering the pond, or

$$T.E = 1 - \frac{EMC_{out}}{EMC_{in}}$$

The treatment efficiency of the pond was calculated for all of the events presented in
Table 1 except for the summer event due to lack of flow out of the pond for that event. For the outflow of the event 9.16.08, all compounds but Cu and Zn were below the detection limit therefore only Cu and Zn are in the calculations the others were disregarded.

Results and discussion

Rainfall and runoff patterns

Our analysis of rainfall data from six rain gauges in the greater Reykjavik area from the past 5 years suggests that it rains about 10% of the time. In general, rainfall events have a long duration and mild intensity. The summer season has been the driest season in the past five years, with fewer, shorter and less intensive events compared to the other seasons. The heaviest rainfall intensities as well as the highest rainfall volume occurred in the fall and spring. This rainfall pattern is different from what is seen in many other countries. For example in Denmark a storm with 10 minutes duration and a 1-year return period has an intensity of approximately 11 µm/s (Spildevandskomiteen, 2006), while the largest 10-minutes rain intensity for the studied 6 rain gauges and 5 years was only 5.7 µm/s. This difference is probably due to the high intensity storms being caused by thunderstorms which almost never occur in Iceland (DMI, 2008).
Our analysis of the volumetric inflow to the pond suggests that 122 discrete runoff events occurred during the 12 month monitoring period. The most common runoff event generated a maximum flow rate of 15-30 L/s at the pond inlet and had duration of 16 hours. In particular, only 11% of the runoff events generated flows exceeding 50 L/s. With that in mind, the first 3 runoff events sampled (see
Table 1) represent statistically extreme events, while the remaining two events represent the most commonly occurring runoff events.

Surface runoff chemical composition

A summary of total and dissolved heavy metal concentrations at the pond inlet during the five discrete runoff events is presented in Table 2. The table shows that the average composition of the storm water runoff varies significantly between events. This variability between events is on the order of 10 for most of the metals, and the order of 100 for lead. Such a variability of factor of 10-100 is typical for stormwater runoff and has been reported for numerous sites (USEPA, 1983). The highest heavy metal concentrations occurred in the second winter storm, which was predominantly snowmelt (only 2 mm of rainfall). Elevated concentrations in snowmelt are a common finding in cold climate regions, as snow has the capacity of accumulating both road debris and vehicle emissions over some length of time (Marsalek et al., 2003). In this particular instance, the snowmelt event was preceded by a 17 day dry period, which is long enough for substantial pollution accumulation to take place.

The second highest heavy metal concentrations were measured in the summer storm. As mentioned in the rainfall pattern section, summer has been the driest season in Reykjavík these past 5 years. The event sampled was both short and intensive proceeding a 3 week dry period. Consequently, a large amount of road dust and debris was able to accumulate and be released in the storm just as in the snowmelt event. The lowest heavy metal concentrations were observed in the long, low intensity spring event. The dry period leading to that event was short, or only 2 days (see
Table 1). Interestingly, the pollutant concentrations were significantly lower than in the fall event which had an even shorter dry period. This difference may be explained by that the fall event was much more intensive, producing maximum inflow rates of 98 L/s as compared to 27 L/s in the summer (see
Table 1). Therefore, the fall event had more power to mobilize particles from road surfaces than the much less intensive summer storm. To summarize, each of the runoff event exhibits different pollutant concentration, which appear to primarily be determined by the length of the dry period leading to the event and secondarily to the intensity of the event.

Table 2: Arithmetic mean of inflow concentrations (µg/L) during the five runoff events

Event	Concentration	Lead (Pb)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Nickel (Ni)	Zinc (Zn)	N
Summer	Total	1.1	<0.05	4.89	18.3	4.35	41.2	2
	Dissolved	<0.2	<0.05	0.90	8.2	0.52	24.9	
Fall	Total	<0.6	<0.05	1.29	12.7	1.25	28.1	6
	Dissolved	0.03	0.007	0.39	6.1	0.36	20.4	
Winter A	Total	0.62	0.014	2.21	9.4	2.77	48.6	4
	Dissolved	0.01	0.008	0.67	2.6	0.51	30.3	
Winter B	Total	1.70	0.030	6.15	27.3	4.57	91.2	4
	Dissolved	0.28	0.024	2.64	9.1	0.87	53.9	
Spring	Total	0.42	0.011	0.61	7.1	0.87	33.4	3
	Dissolved	0.03	0.008	0.31	5.0	0.35	28.6	

A comparison of stormwater pollutant concentrations measured in this study to those of other neighboring countries is presented in table 3. The table reveals that the average heavy metal content of the stormwater was low compared to what has been reported for comparable catchments. The reason for this difference is not fully understood. A possible explanation is that population density, and hence pollutant source, was lower in the Reykjavík suburban catchment than in the Danish suburban catchment. Table 3also highlights that the heavy metal content of runoff from suburban residential catchments is significantly lower than that from a highway catchment.

Table 3: Comparison between average concentrations (µg/L) found in this and a previous study, and two Scandinavian catchments ([1]Icelandic Meteorological Office, 2007; [2]Vollertsen et al, 2009; [3]Malmqvist et al., 1994;).

	Iceland		Denmark	Sweden
Catchment area	**Residential**		**Residential**	**Highway**
Year of sampling	**2008/2009**	**2007[1]**	**2008/2009[2]**	**1994[3]**
Lead (Pb)	0.6	1.0	4.9	80
Cadmium (Cd)	0.014	0.038	0.08	1
Chromium (Cr)	2.23	7.66	4.0	-
Copper (Cu)	12	5	19	50
Nickel (Ni)	2.1	3.2	8	-
Zinc (Zn)	30	44	208	222
Number of samples	22	18	24	-

Tables 2 and 3 indicate that copper and zinc are the most abundant pollutants in the surface runoff entering the Víkurvegur pond. Figure 4 takes a closer look at these two heavy metals during four of the five storm events. Figure 4 shows that the total concentration of zinc (and to a lesser extent copper) in the inflowing water varied significantly over the course of each sampled runoff event. Most of the storms demonstrated a “first flush” of zinc contamination, seen by the highest metal content occurring at the beginning of the storm, prior to the peak flow. A similar behavior was observed for the dissolved fraction (data not shown). The extent of the first flush varied between metals, and some metals such as zinc did not appear to exhibit any first flush as seen from Figure 4.

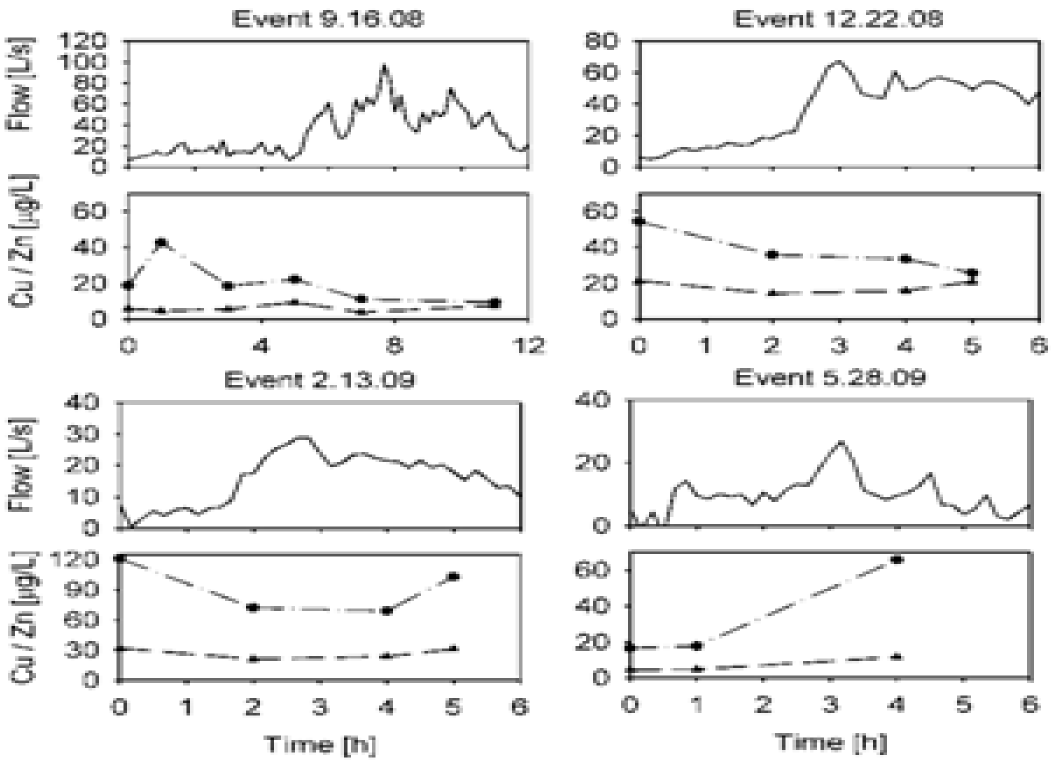

Figure 4: Time variation of copper (triangles) and zinc (filled circles) total concentrations in surface runoff during four discrete events

Particulate content

The arithmetic average total and dissolved concentrations in Table 2 can be used to derive the fraction of heavy metals bound to particulates, which can be removed through gravitational settling. Such an exercise indicates that 60-80% of chromium, copper and nickel were bound to particulates in the first four runoff events. Zinc, however, was found to have only 40% bound to particles in the same events. These four most abundant heavy metals all showed a lower particulate content in the spring storm (5.28.09). This difference is not fully understood yet, but may be related to the number of samples (only 3 taken as opposed to 4-7 in other events) and the timing of the samples. For the two remaining heavy metals with the lowest observed concentration, lead was found to be 80-90% bound to particulates, while cadmium was found to be predominantly in dissolved format. Westerlund et al. (2003) states that metals are more particulate bound during melt periods than in rain runoffs.

The mean particle diameter in the inflowing runoff in Vikurvegur pond was found to range from 10-20 µm. More specifically, 68 % of the mass was bound to particles less than 20 µm which is in direct accordance with the findings of Lie et al (2006).

Inflow v.s. outflow concentrations

As discussed earlier, heavy metal concentrations at the inlet vary considerably over the course of a storm and between storms. The heavy metal concentrations at the outlet, however, do not exhibit the same variability. This contrast in inflow and outflow concentrations is exemplified for copper in Figure 5. The total copper concentration in the outflow is approximately 4 µg/L independent of the type of event or time of year. This suggests that the pond is lowering the concentration to approximately the same level independent of the inlet concentration. This is true for both the total copper concentration and for the dissolved concentrations. This is also true for other heavy metals (not shown).

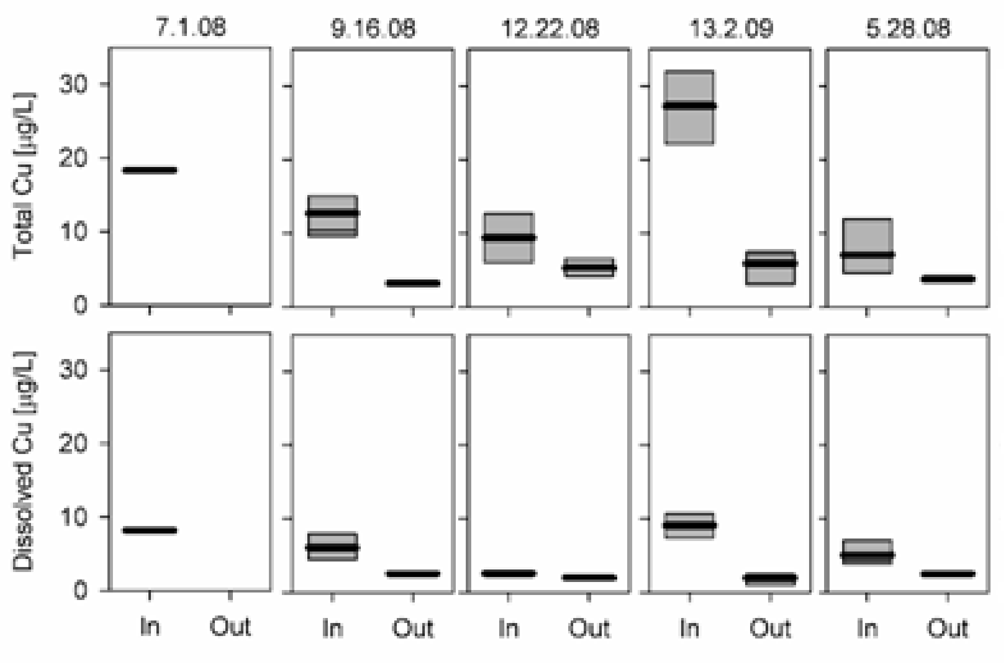

Figure 5: Inlet and outlet concentrations of copper. The boxes represent the 25% and 75% percentiles, the thin line in the boxes is the median value and the bold line is the average value.

Detention pond treatment efficiency

Table 4 presents the results of treatment efficiencies calculations using the EMC method. Results are presented as total removal, and then broken down by removal of particulate vs. dissolved heavy metals. Overall, the table presents a consistently high treatment efficiency for the runoff events which ranged from being large (Qmax > 50 L/s) to average (Qmax ~ 15-30 L/s). For all the studied heavy metals the total treatment efficiency was 80-90%. This is higher than what generally is seen for well-designed wet detention ponds, which is typically in the 50-60% range (USFHA, 1996; Debo and Reese, 2002). This efficiency is also larger than previously determined from a different method based on flow proportional composite sampling (Gunnarsson and Sigurðsson, 2007). It is interesting to note how high the treatment efficiency was despite the comparatively low pollutant concentrations in the inflow water.

Table 4: Average pollutant removal efficiency calculated from discrete runoff events

Heavy metal	Treatment efficiency (%)			Number of events
	Total	Bound to particulates	Dissolved form	
Cr	90±6	90±4	80 ±12	3
Cu	90±5	90±4	80 ±12	4
Ni	90±5	95±3	70 ±22	3
Zn	80±14	80±11	80 ±19	4

The reduction of particulate pollutants is generally better than that of dissolved pollutants, confirming that sedimentation is the main treatment process. Interestingly, the pond appears to also be treating dissolved heavy metals, which would suggest that biological and or chemical processes may also be present.

Conclusion

Pollutant concentrations present in the residential runoff water in Iceland were found to be lower than for comparable suburban watershed in a neighboring country. Despite this low pollution content, the Víkurvegur detention pond was found to efficiently remove the heavy metals present in the runoff water. Using an EMC method, the total treatment efficiency of the pond was found to range around 80-90% in all four runoff events analyzed, which varied both in intensity and chemical content. First flush was observed in the inflowing surface runoff water during most of the events analyzed, but the extent of the first flush varied between metals: In particular, metals that were mostly bound to particles like cadmium, copper and nickel showed an indication of first flush while the predominantly dissolved zinc, did not. The pollutant concentration in the outflow of the pond was rather stable compared to that of the inflow. The event with the highest pollutant concentrations was the winter event with snow melt which concurs with earlier studies in cold climate. Length of dry period prior to a runoff event was also a good indicator for elevated concentrations.

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