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ORIGINAL RESEARCH

Effectiveness of a 19-Year Old Combined Pond-Wetland System in Removing Particulate and Dissolved Pollutants

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Abstract This study monitored the stormwater runoff quantity and quality treatment performance of a 6.8 ha 19-year old combined pond-wetland system, located in south Sweden, over one year. The mean volume reductions for 53 storm events for the pond and wetland were 40% and 28%, respectively, while the mean flow reductions were 60% and 76%, respectively. Pollutant concentrations in the influent to the wetland were highly variable. The pond-wetland system could efficiently remove an average of 91%, 80%, 94%, 91%, 83% and 92% of TSS, TP, particulate Cd, Cu, Pb, and Zn, respectively, whereas the removal of particulate and dissolved Ni was highly variable with an average of 67% ± 62% and −5% ± 41%, respectively. The removal of TN, NH_4-N and $NO_3 + NO_2$-N was highly variable with an average of 45% ± 27%, 12% ± 96% and 45% ± 43%, respectively. These removal percentages are high in comparison to other studies and underline that relatively old systems can also provide efficient treatment. Although the pond accounted for a substantial reduction of pollutant concentration, the wetland significantly enhanced both the treatment performance and the peak flow reduction. This underlines that a combined pond/wetland system is a more beneficial solution than a pond only. The pollutant removal efficiency was significantly influenced by some factors including Antecedent Dry Days, seasonal variations, air temperature, retention times, rainfall depth and duration, and peak rainfall intensity.

Keywords Urban stormwater · Constructed stormwater wetland · Combined pond-wetland · Suspended solids · Nutrients · Particulate and dissolved pollutants

Introduction

The generation of stormwater runoff in urban areas is a major challenge and an inevitable consequence of urbanization (Butler and Davies 2004; Walsh et al. 2005). High flows and high levels of pollutants (e.g. sediments, nutrients and heavy metals) can cause (inter alia) degradation and/or erosion of the receiving water, flooding and high flow rates (US EPA 1999; Swedish EPA 2000).

Often, the use of wet ponds and constructed wetlands has been adopted as a common stormwater control measure (SCM) to reduce the negative impacts of stormwater runoff on receiving water bodies (Vanloon et al. 2000; Birch et al. 2004; German and Svensson 2005). Wet ponds and constructed wetlands have been designed not only as a main treatment facility for stormwater runoff or as a regulator to control runoff peak flows and volumes (Birch et al. 2004; Greenway 2004; German and Svensson 2005), but also as an integrated community facility providing an aesthetic amenity and recreational areas (Revitt et al. 1999; Vanloon et al. 2000).

Stormwater wetlands provide a hybrid system between large retention facilities like wet ponds and green infrastructure-based technologies (utilizing vegetation and soil for stormwater

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treatment). Constructed stormwater wetlands (CSWs) are more diverse than wet ponds because they are built with a variety of different depths of water, thus improving flow retention and providing more diversified quality treatment mechanisms (Greenway 2004; Marsalek et al. 2005). A CSW's footprint is dominated by shallower water zones that promote complete coverage of the facility by emergent vegetation. In contrast to ponds (in which the treatment is largely based on sedimentation), the more diverse water-vegetation-soil matrix in wetlands provides multiple pollutant treatment mechanisms including gross solid filtration, biological transformation, and some sorption (Braskerud 2002; Greenway 2004; Vymazal 2007). To maximize the wetland performance for pollutant removal, the inclusion of a wet pond in wetland design as a pre-treatment facility is commonly recommended because wet ponds effectively trap coarser sediment, which facilitates sediment removal and disposal (US EPA 1999). Using combined pond-wetland systems achieves improved treatment efficiencies by providing enough space for particulate pollutant to settle in the pond prior to discharge into the wetland. The wetland itself provides additional pollutant removal, specifically enhancing soluble pollutant and nitrogen removal rates (Malaviya and Singh 2012).

A number of studies have evaluated removal efficiencies of CSWs; however, great variations in removal efficiency rates have been reported (Carleton et al. 2001; Braskerud 2002; Birch et al. 2004; Lenhart and Hunt 2011; Merriman and Hunt, 2014). These studies found that the pollutant treatment efficiency varies significantly depending on a wide range of factors. However, only a few studies have investigated and discussed the factors which affect the performance of CSWs that have been in operation for over 10 years (Vymazal 2011; Blecken et al. 2017).

This paper assesses the hydraulic and treatment performance of a 19-year old combined pond-wetland system relating to the removal of suspended solids, nitrogen and its compounds, phosphorus and particulate and dissolved heavy metals over four seasons. Also, this paper highlights the importance of using a sedimentation pond as a pre-treatment facility prior to discharge to the wetland. The main factors which affect the performance of this system were also identified and included season, air temperature, Antecedent Dry Days (ADDs), rainfall depth and intensity, and the duration of the storm events. Lastly, the concentrations of metals in the accumulated sediments along the pond-wetland flow path were measured and compared to the Swedish guidelines for the protection and management of lakes and watercourses (Swedish EPA 2000), and for land use (Swedish EPA 2009). These provide guidance for classifying levels of sensitivity for two different types of land use in order to assess the environmental risks presented by the dredged sediment, and thus the requirements for its safe disposal.

Materials and Methods

Site Description

Lake Södra Bergundasjön is one of the major receiving water bodies for stormwater from the city of Växjö, Sweden (approximately 61,000 inhabitants). The water quality of this lake was seriously compromised from the 1970s to the 1990s, mainly due to eutrophication (Växjö Municipality 1998). Untreated stormwater discharges were identified as a major source of pollution and therefore, in 1994, the Bäckaslöv wetland (56°52″25.0″N, 14°47″00.8″E; Fig. 1), the focus of this study, was built to reduce the pollution flowing to Lake Södra Bergundasjön. The wetland serves as the main treatment facility for the stormwater from a 320 ha catchment, as well as a recreational area and bird habitat as part of a large nature reserve. The contributing catchment area includes 130 ha of residential area (mainly single family houses and residential streets), 190 ha of industrial/commercial area (dominated by small-scale industry, wholesale establishments, car dealers, and repair shops) and several major roads with a traffic load of approximately 10,000–15,000 vehicles/day. The stormwater is collected in a separate storm sewer system connected to the CSW. The stormwater characteristics are described below.

The CSW system consists of a sedimentation pond with a water surface of 1.8 ha and average depth of 1.6 m, followed by a 5 ha meandering wetland stream (approx. 800 m long). The ratio of the CSW area to the catchment area is 0.02. Stormwater flows into the CSW through two inlet culverts of 1400 mm diameter. A 2-year storm event and base flow

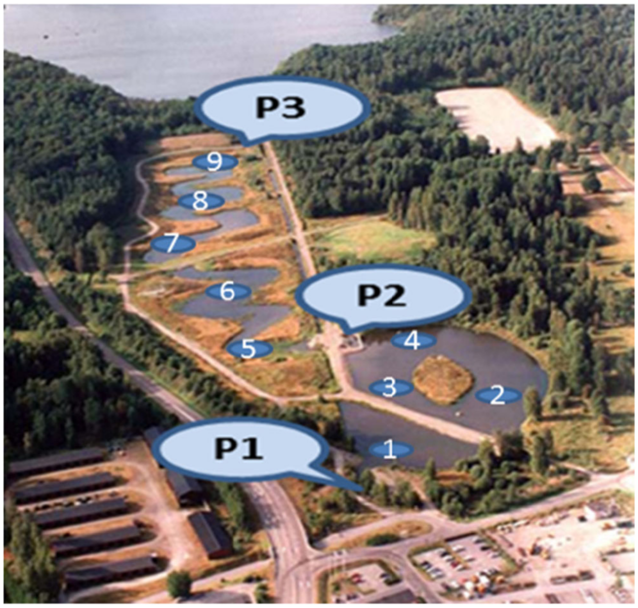

Fig. 1 Aerial view of the CSW with locations of the monitoring stations (P1, P2, and P3) and locations of the sediment sampling (1–9). Photo from Växjö Municipality

of 2500 m^3 day^{-1} were used as design parameters to define the volume of the pond (Semadeni-Davies 2006). The sedimentation pond is divided into a forebay, which provides pre-treatment of the stormwater runoff from coarse sediments, and the main pond. The pre-treated water is discharged from the pond into the wetland section via two culverts of 550 mm, each accommodating a maximum flow of 200 l/s. An overflow weir allows excess flow to discharge through a bypass pipe into the wetland. The outflow from the CSW is controlled by a weir, and then discharged to Lake Södra Bergundasjön through a ditch.

A large portion of the pond is open water. Parts are covered with Broad-leaved Pondweed (*Potamogeton natans*). Around the pond, there is a belt several metres wide where Cattail (*Typha latifolia*) is present. Further, Flowering-rush (*Butomus umbellatus*) and Water-plantain (*Alisma plantago-aquatica*) were regularly observed. The shallow sections of the meandering wetland stream are dominated by Cattail (*Typha latifolia*). Further along the wetland stream, native wetland vegetation is present, including sedges (*Carex spp.*), rushes (*Juncus spp.*), Floating Sweet-grass (*Glyceria fluitans*), and Water-plantain (*Alisma plantago-aquatica*). No detailed vegetation survey was carried out.

Throughout its 19 years of operation, the CSW and the second part of the pond have not been maintained at all. However, the (relatively coarse) sediment from the first part of the pond has been dredged out four times and stored nearby.

The average annual precipitation in Växjö is 652.6 mm, and the temperature typically varies from – 6 °C to 23 °C over the course of a year (Alexandersson et al. 1991). During the winter, de-icing and anti-slipping materials (fine macadam (0–8 mm) mixed with road salt (50 g /m^3)) are regularly applied to the streets. After the snowmelt period, these materials are removed by a mechanical sweeper.

Water Sampling

Water samples were collected at three sampling stations: P1, the stormwater inflow; P2, the water after pre-treatment in the pond; P3, the discharged water from the wetland (Fig. 1). Both continuous flow monitoring and water quality sampling were carried out. Mainstream™ Premier Fixed Area Velocity flow meters were installed at P1 and P2 to measure and record the water flow in the pipes, while an MJK 713 flow meter was installed at P3. Rainfall depth and intensity were measured using an Adcon Professional Rain Gauge with 0.2 mm resolution placed onsite. At each sampling station, all data were logged and transmitted using an A753 addWAVE GSM/GPRS. The stations were outfitted with three automatic samplers (ISCO Avalanche Portable Refrigerated Samplers at P1 and P3 and an ISCO 6712 Portable Sampler at P2) which were programmed to collect flow-weighted composite and discrete samples during storm events. The automatic samplers at P1, P2, and P3 were triggered to take samples when the flow exceeded 100 l/s every 1500 m^3, 750 m^3, and 500 m^3, respectively.

The monitoring period lasted one year (May 2013 – April 2014). During this period, a total of 53 storm events were monitored for flow measurements. Of these, 13 storm events were sampled to monitor event mean concentrations (composite sampling). The collected samples were placed in a cooler bag with ice packs and transported to a laboratory accredited by the Swedish Board for Accreditation and Conformity Assessment SWEDAC (www.swedac.se). The collection and delivery of the samples occurred within 24–48 h. All stormwater samples were analyzed for total and dissolved Cd, Cu, Pb, Ni, and Zn (measured in μg/l) using ISO 17294, TSS (mg/l) using SS-EN ISO 872, TP (mg/l) using SS-EN ISO 15681–2:2005, TN (mg/l) using SS-EN ISO 11905–1, $NO_3 + NO_2$-N (mg/l) using SS-EN ISO 13395–1, and NH_4-N (mgl/l) using SS-EN ISO 11732.

Sediment Sampling

During the summer of 2013, sediment samples were taken from four sampling locations in the pond and five sampling locations in the wetland (Fig. 1) to investigate the spatial variation of metal concentrations in sediment along the flow path of the wetland system. Five sub-samples were taken and combined at each sampling location. The resulting composite samples were then analyzed for their metal content (Cd, Cu, Cr, Pb, Ni, and Zn). From the pond, undisturbed sediment samples were taken using a 250 cm^2 Van Veen grab, while samples were taken using a plastic scoop from the wetland, since it was shallow enough to wade in. Extra care was taken when collecting the samples to avoid spilling any fines. The sediment collected was put into plastic bags which were refrigerated at about 4 °C until they were processed in a laboratory accredited by SWEDAC. Analysis was carried out using EPA methods (modified) (Determination of trace elements in waters and wastes by 200.7 (ICP-AES) and 200.8 (ICP–MS)).

Data Analysis

A paired-sample t-test was run to determine whether there was a statistically significant mean difference between flow volumes and peak flows at the pond's inlet (P1), the pond's outlet (P2) and the outlet of the CSW (P3). If the assumption of normality was violated, as assessed using Kolmogorov-Smirnov and Shapiro-Wilk tests, the data were log transformed or square-root transformed so that the residuals were normally distributed. If no transformation could resolve this issue, a nonparametric Wilcoxon signed rank test was used. A one-way ANOVA with Tukey post hoc test was used to determine if there was significant difference between the pollutant concentrations measured at P1, P2, and P3. A principal component analysis (PCA) was conducted to explore the correlations among different variables including season, air temperature, ADD, rainfall depth and duration, and peak rainfall intensity. Minitab® 17 Statistical Software was used to carry out all of the statistical tests, including a PCA at a significance level of $\alpha = 0.05$, and to construct all of the plots.

Results and Discussion

Monitored Storm Events

Of the 53 monitored storm events in total (Table 1), 13 events were sampled and analyzed for water quality. Their characteristics are shown in Table 2. These sampled events covered all four seasons and represented a wide range of operating conditions with varying ADDs (1–17 days), rainfall depths (3–24.2 mm), peak rainfall intensities (0.4–3.8 mm/10 min), rainfall durations (70–850 min) and retention times (4.5–10.5 h). A summary of all 53 rain events monitored is given in Table 1 with details in the supplementary data (Tables S1 and S2).

Hydraulic Performance

During nearly all of the 53 storm events monitored in 2013–14, outflows and peak discharges from the pond and wetland were lower than inflow volumes and peaks (Figs. 2 and 3). The pond/wetland system provided an efficient peak flow reduction (41% – 95%). A statistically significant mean difference in peak flows was found between the three monitoring stations (P1 vs. P2 and P1 vs. P3) (paired *t*-test; *p*-value =0.000). For storm flows below 700 l/s, the pond provided the majority of the peak flow reduction (Fig. 3). However, at higher flow rates, the wetland could significantly enhance the peak flow reduction, underlining the positive effect of the combined pond/wetland facility in comparison to a single pond system.

In contrast to the general peak flow reduction, the mean volume reductions were lower (40% for the pond only and 28% for the combined pond/wetland) and varied greatly between −15% and 95% for the pond/wetland system. Despite this variation, the volume reduction was statistically significant (paired t-tests P1 vs P2 and P1 vs P3: *p*-value = 0.000). For some events, a precise calculation of the flow volume reductions was difficult because the pond or wetland received new stormwater runoff before the flow had returned to baseflow conditions, particularly when the antecedent dry period was short. This partly explains the large variations in the calculated flow reduction. In contrast to the peak flow reduction, Fig. 2 shows that the pond accounted for most of the volume reduction. The efficiency of the CSW in reducing volumes is relatively low.

Table 1 Summary statistics of the monitoring period

Statistic	2013–2014	
	All	Sampled
No. of Events Collected	53	13
Mean Rainfall Depth (mm)	8.3	10.7
Median Rainfall Depth (mm)	7.4	10.6
Rainfall Depth Range (mm)	2.6–29.2	3–24.2

The findings of this study are consistent with those of Merriman and Hunt (2014), who monitored a 5-year-old CSW and reported that it exhibited a negative volume reduction of 50% for the storm events in the one-year monitoring period. This could be explained by the fact that lower available storage volume and low number of ADDs affected the hydraulic performance.

During winter, the mean volume reduction of the CSW was only 12% which is significantly lower than the 23% – 28% achieved during the rest of the year (Table 3). Similarly, the observed increase in peak flow reductions from winter to summer (70% vs. 89%) was statistically significant (Tukey post hoc analysis, *p*-value =0.000). However, this difference was due to lower peak inflows in the cold season and the peak flows at the outlet were relatively constant over all the seasons. The reduced retention capacity of the system could be due to less vegetation and thus a higher flow capacity of the system. Further, evapotranspiration is likely to be lower in cold temperatures.

Pollutant Removal

Inlet and Outlet Dissolved and Particulate Pollutants

Although inflow pollutant concentrations varied greatly, the outflow concentrations of all metals, TSS and TP were relatively consistent year-round (Table 4, Fig. 4). High mean removal efficiencies were observed for particulate Pb and TP (both exceeding 80%) as well as particulate Cd, Cu, Zn and TSS (exceeding 90%) (Table 4). In most cases, the concentrations of Cd and Pb at P2 and P3 were below the detection limits (0.02 and 0.2 μg/l, respectively). While the heavy metals entered the CSW in a mix of particulate and dissolved forms, the effluent was mostly dissolved (Fig. 4).

The TN inflow concentrations also varied greatly (Fig. 4). Despite this, the outflow concentrations of TN were always approximately 1 mg/L (Fig. 4). The comparably low TN inflow concentrations for events 7, 8, 9, and 10 were already close to that magnitude and so not reduced further. Thus, despite low outflow concentrations similar to the other events,

Table 2 The main characteristics of the sampled storm events for the period of May 2013 – April 2014

Event no.	Event date	Mean daily temp. (°C)	ADD	Rainfall depth (mm)	Peak rainfall intensity (mm/10 min)	Rainfall duration (min)	Retention time (hours)
1	9 May 2013	14.5	12	10.6	3	80	9.5
2	14 May	8.2	2	3	0.4	100	10
3	21 May	12.9	1	18	1	850	5.5
4	13 June	14.8	17	17.8	1.8	440	7
5	16 June	11.5	<1	12.8	3.2	210	4.5
6	8 August	17.6	7	14.8	3.8	150	7.5
7	1 Sep.	11	1	24.2	3.8	490	5
8	15 Sep.	14.1	3	4.4	0.6	120	7
9	28 Oct.	10.5	1	9	1	270	10
10	31 Oct.	7.9	1	4.2	0.6	80	9
11	14 Feb. 2014	0.9	2	3.2	1	70	5.5
12	25 March 2014	1.1	9	5.2	0.4	220	8
13	8 April 2014	8.9	13	11.8	2.2	140	10.5
Mean		10.3	5.4	10.7	1.7	248	7.6
Median		11	2	10.6	1	150	7.5
Min		0.9	0.9	3	0.4	70	4.5
Max		17.6	17	24.2	3.8	850	10.5
SD		5	5.6	6.7	1.3	225	2.1

the removal percentages of these four events remained low due to existing low inflow concentrations.

To put the observed removal efficiency into context, the results were compared to a metal analysis of CSW treatment performance including data from 35 studies of 49 wetland systems carried out by Carleton et al. (2001). Their data showed widely varying removal percentages (mean, minimum and maximum removal for Cd: 56%, 0% and 88%; Cu: 40%, −67% and 87%; Pb: 56%, −187% and 94%; Zn: 48%, −14% and 85%; TN: 15%, −49% and 46%; TP: 33%, −55% and 87%). Compared to this, the Bäckaslöv CSW performed well. The removal percentages are in the upper range of the data reported by Carleton et al. (2001).

A comparison of the pollutant concentrations to the Swedish water quality guidelines for lakes and watercourses (Swedish EPA 2000) revealed that all total metal (except Cd) and nutrient concentrations in the influent were classified as "high" or "very high". After treatment by the CSW, the concentrations were "low" or "moderately high", indicating the 19-year-old system was capable of achieving its original goal. The development of the treatment performance over these 19 years has been described in detail by Al-Rubaei et al. (2016).

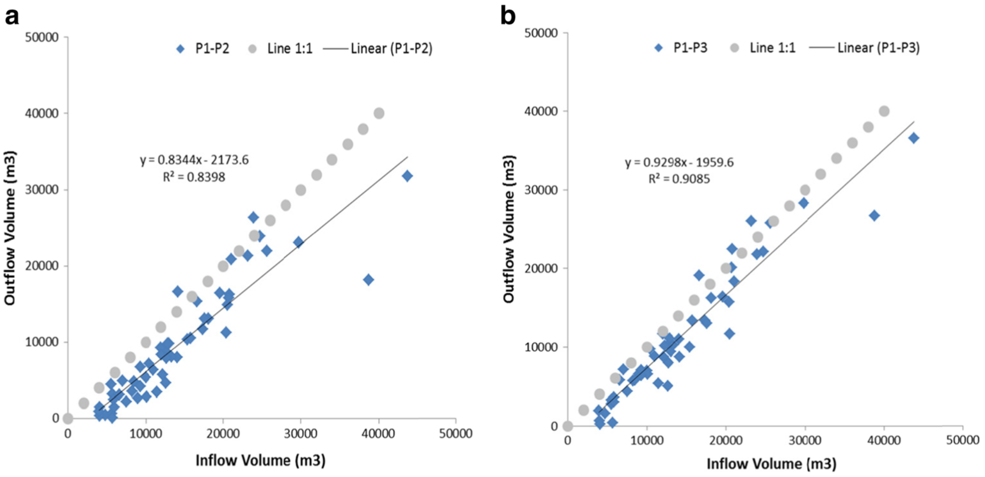

Fig. 2 Scatter plots showing: (**a**) the pond inflow volumes vs. outflow volumes (P1 – P2); (**b**) the pond inflow volumes vs. the wetland outflow volumes (P1 – P3)

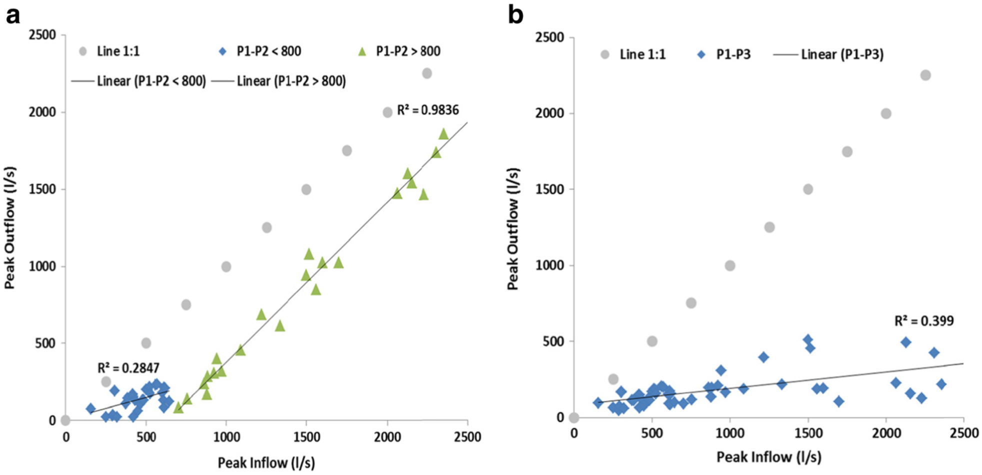

Fig. 3 Scatter plots showing: (**a**) the pond peak inflow vs. peak outflow (P1 – P2); (**b**) the pond peak inflow vs. the wetland peak outflow (P1 – P3)

Pond vs. Wetland Performance

Given that wetlands are better than ponds at capturing finer sediment with higher metal concentrations (Sansalone and Buchberger 1997) and promoting more bio/geochemical treatment processes, it was hypothesized that the wetland section would increase the overall metal treatment even more effectively than observed in the study. In the Bäckaslöv CSW, the pond alone removed a significant percentage of the metals, particularly those in particulate form (Table 4). The removal of dissolved metals in the pond was more variable, but still exceeded 50% (except for Ni; Table 4). However, the wetland enhanced the treatment of dissolved metals further, particularly for Cu, Pb, and Zn, underlining the importance of more advanced treatment processes for dissolved pollutants. Also, TP and TN removal was increased significantly in the wetland compared to the pond alone. $NO_3 + NO_2$-N removal was more than doubled after the wetland compared to the pond only. For some events, there were even slight increases in EMCs observed between the pond outlet (P2) and the wetland outlet (P3) for Pb, Ni, TN, and NH_4-N (which, however, did not reduce the overall performance significantly).

The pollutant removal by the pond only was relatively high compared to other pond studies (Marsalek et al. 2005). The fact that a large proportion of the pollutants were in particulate form facilitated their removal by sedimentation in the pond (Vanloon et al. 2000). Given that sedimentation is the main treatment process in ponds, their capacity to treat dissolved pollutants is usually low (Van Buren et al. 1997). Various studies report similar inflow and outflow concentrations of dissolved pollutants in stormwater ponds (Stanley 1996; Pettersson 1998). Thus, the observed removal of dissolved pollutants in the pond section was comparably high which indicates that the conditions in the pond are at least partly favourable for bio/geochemical treatment processes (Van Buren et al. 1997). The reasons may be that there are relatively large shallow sections along with well-established vegetation. The results validated the importance of using combined pond-wetland systems rather than using wetland systems separately when dissolved and/or nutrients (especially nitrogen) are

Table 3 Seasonal variations for mean flow volumes and peak flows reductions for the period of May 2013 – April 2014

Seasonal Analysis	Spring (*n* = 12)	Summer (*n* = 12)	Autumn (*n* = 14)	Winter (*n* = 15)	*P*-value (ANOVA)
Volume In (m^3)	13,626	13,698	13,027	15,614	
Volume Out (m^3)	10,229	9918	10,003	13,772	
Volume Reduction (%)	25	28	23	12	0.049
P-value (Paired t-test)	0.000	0.000	0.009	0.006	
Peak Flow In (l/s)	952	1473	735	610	
Peak Flow Out (l/s)	182	165	181	181	
Peak Flow Reduction (%)	81	89	75	70	0.000
P-value (Paired t-test)	0.000	0.000	0.000	0.000	
Mean Antecedent dry days	4.67	6.91	3.27	4.72	0.468
Mean Rainfall Depth (mm)	8.13	10.33	8.54	6.64	0.000
Mean Peak Rainfall Intensity (mm/10 min)	1.2	2.53	0.94	0.65	0.000

Table 4 Mean inlet and outlet pollutant Event Mean Concentrations (EMCs) and mean removal efficiencies (± standard deviation) for 13 storm events. * The removal percentage at P2 describes the removal by the pond only; ** the removal percentage at P3 describes the removal by the combined pond-wetland system

Pollutant		Concentrations			Removal (%)	
		Inlet (P1)	Pond outlet (P2)	Wetland outlet (P3)	Pond outlet (P2) *	Wetland outlet (P3) **
Cd (µg/l)	Particulate	0.14 ± 0.16	0.01 ± 0.01	0.00 ± 0.01	92 ± 14	94 ± 16
	Dissolved	0.08 ± 0.04	0.02 ± 0.00	0.02 ± 0.00	63 ± 21	64 ± 21
Cu (µg/l)	Particulate	29.67 ± 35.20	1.68 ± 1.45	1.08 ± 0.70	88 ± 11	91 ± 9
	Dissolved	11.66 ± 6.18	3.76 ± 1.34	2.76 ± 1.05	58 ± 32	69 ± 20
Pb (µg/l)	Particulate	12.85 ± 15.28	0.53 ± 0.46	0.34 ± 0.24	89 ± 14	83 ± 32
	Dissolved	1.95 ± 2.21	0.42 ± 0.21	0.27 ± 0.10	50 ± 43	64 ± 36
Ni (µg/l)	Particulate	4.56 ± 5.42	0.43 ± 0.39	0.5 ± 0.5	82 ± 12	67 ± 62
	Dissolved	2.32 ± 1.13	1.72 ± 0.40	2.07 ± 0.48	8 ± 50	- 5 ± 41
Zn (µg/l)	Particulate	170.12 ± 217.22	12.54 ± 9.43	7.31 ± 5.22	84 ± 18	92 ± 8
	Dissolved	149. 66 ± 74.69	44.13 ± 35.86	23.45 ± 10.76	64 ± 24	81 ± 12
TSS (mg/l)		187.41 ± 187.10	9.75 ± 4.08	7.03 ± 2.58	90 ± 7	91 ± 7
TP (mg/l)		0.32 ± 0.35	0.04 ± 0.01	0.03 ± 0.01	76 ± 13	80 ± 13
TN (mg/l)		2.14 ± 1.38	1.07 ± 0.41	0.88 ± 0.27	39 ± 25	45 ± 27
NH_4-N (mg/l)		0.46 ± 0.54	0.23 ± 0.15	0.18 ± 0.10	14 ± 62	12 ± 96
$NO_3 + NO_2$-N (mg/l)		0.63 ± 0.41	0.42 ± 0.30	0.27 ± 0.21	18 ± 64	45 ± 43

target pollutants (Li et al. 2010; Sharma et al. 2013; Choi et al. 2015). However, the results also underline that a well-designed, vegetated pond is capable of achieving high removal rates. When comparing the area of the pond and the wetland with their relative contribution to the overall treatment, especially of particulate pollutants, it becomes clear that the 1.8 ha pond is far more efficient than the 5 ha wetland. This is, however, specific to this particular system. A pond which would otherwise perform less efficiently would benefit even more from a downstream treatment wetland than the well-performing pond in Bäckaslöv. Further, this simple comparison neglects possible additional benefits of the wetland such as ecosystem services (these were not evaluated in this study).

Removal of TSS from the water column in treatment wetlands can be achieved primarily with sedimentation and filtration (Vymazal et al. 1998). Heavy metals are removed through a variety of processes including physical processes (sedimentation), biological processes (uptake by plants and microorganisms) and chemical processes (sorption, precipitation and co-precipitation, oxidation and hydrolysis, metal carbonates and sulphides etc.) (Zhang et al. 2012). Given that a significant proportion of the metals in the influent were present in particulate form and the remaining metals in the outflow were mainly dissolved, sedimentation is responsible for a significant proportion of the total metal removal in the CSW, especially in the pond section. The other aforementioned processes also take place since the dissolved metals are efficiently removed (except dissolved Ni).

Factors Affecting the Performance of the CSW for Pollutant Removal

Main Factors which Affect the Performance

For maintaining and understanding the function of CSWs, identifying the main factors which affect their performance is of great importance. The pollutant removal performance of the CSW varied widely due to the different conditions in the sampled storm events including season and air temperature, ADD, rainfall depth and intensity, and the duration of the storm events (Table 2). The PCA loading plot provides an overview of the variables that can affect the pollutant removal performance of the CSW (Fig. 5). The removals of particulate Cd, Cu, and Pb, particulate and dissolved Ni and Zn, and TSS, TP, TN and its compounds, season, ADD, and retention times are grouped together along the first component (PC1). Meanwhile, the dissolved fraction removals of Cd, Cu, Pb, and Zn, air temperature, and season are grouped together along the second component (PC2). The factor season is grouped with other factors along PC1 and PC2, suggesting that the performance of CSWs for pollutant removal was significantly influenced by the effect of seasons associated with the effect of ADDs. Short dry periods between the sampled events had a negative influence on pollutant removal. Also, the second principal component (PC2) indicates that the dissolved fraction removals of Cd, Cu, Pb, and Zn correlate positively with season, air temperature, and peak rainfall intensity.

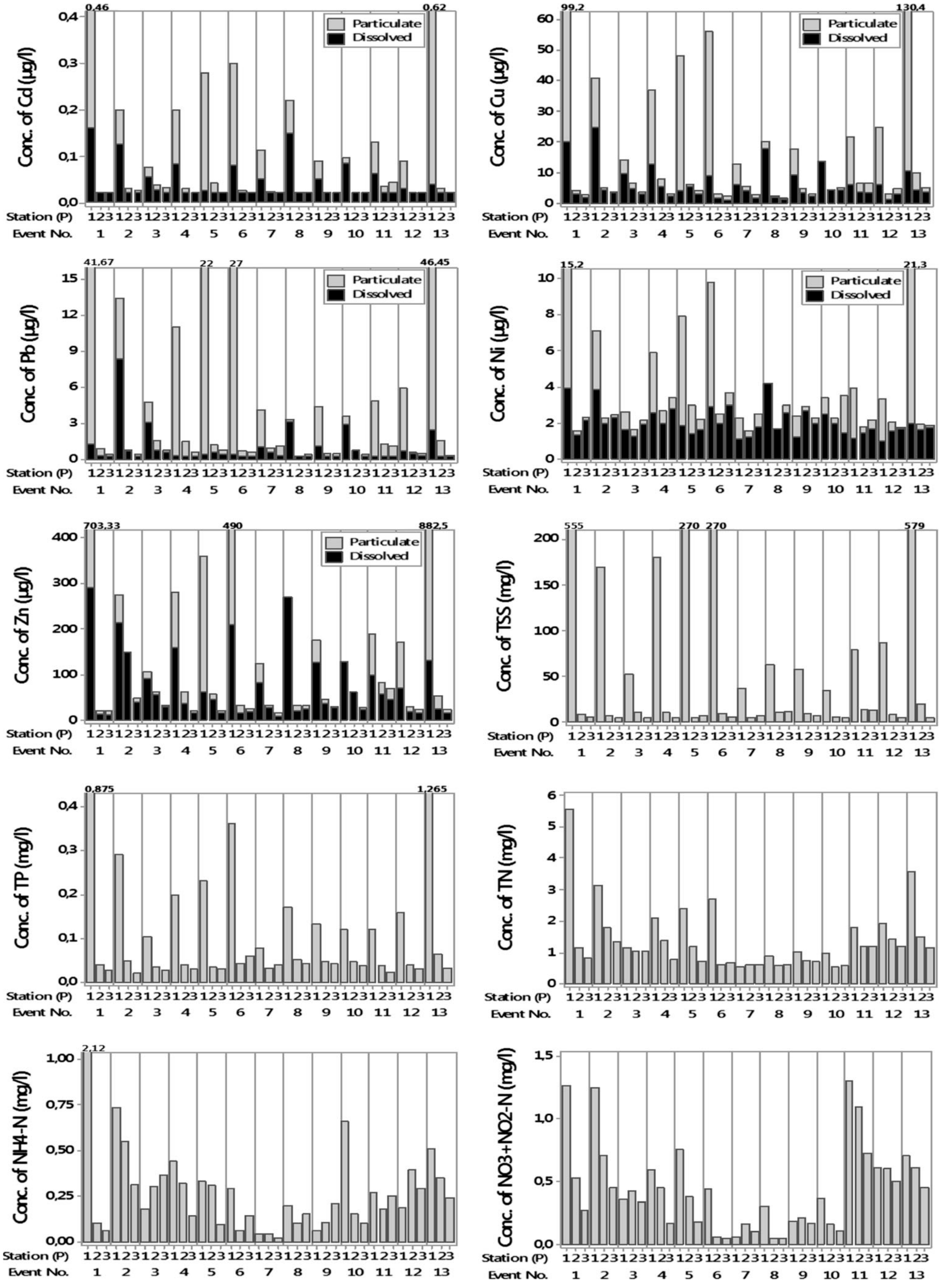

Fig. 4 Bar charts showing EMCs of selected pollutants (Cd, Cu, Pb, Ni, Zn, TSS, TP, TN, NH_4-N, and $NO_3 + NO_2$-N) at the three monitoring stations (P1, P2 and P3) for 13 storm events (**1:** 9 May 2013; **2:** 14 May; **3:** 21 May; **4:** 13 June; **5:** 16 June; **6:** 8 August; **7:** 1 Sep.; **8:** 15 Sep.; **9:** 28 Oct.; **10:** 31 Oct.; **11:** 14 Feb. 2014; **12:** 25 March; **13:** 8 April **2014**)

Rainfall intensity and depth are located opposite the other factors and parameters along PC1.

The PCA also shows that an increase in pollutant removal was largely correlated with an increase in TSS removal, except for the dissolved metals (Fig. 5). In addition, the TSS removal had a moderate impact on particulate Cd and NH_4-N, indicating that it is a good predictor of pollutant removal efficiency. The difference in TSS removal between the 13 storm events could be attributed to the high variability in the inlet TSS concentrations which are, themselves, most likely attributable to the effect of ADDs (Revitt et al. 1999; Karlsson et al. 2010) and/or rainfall intensity (Nie et al. 2008; Francey et al. 2010). However, the outlet TSS concentrations were relatively stable year-round.

Seasonal Performance of the CSW for Pollutant Removal

One hypothesis was that seasonal variations would affect the CSW pollutant removal performance (i.e. result in changes in the EMCs of particulate and dissolved pollutants). Possible reasons include (inter alia) less biological activity in winter, vegetation dormancy, temperature-dependent bio-chemical

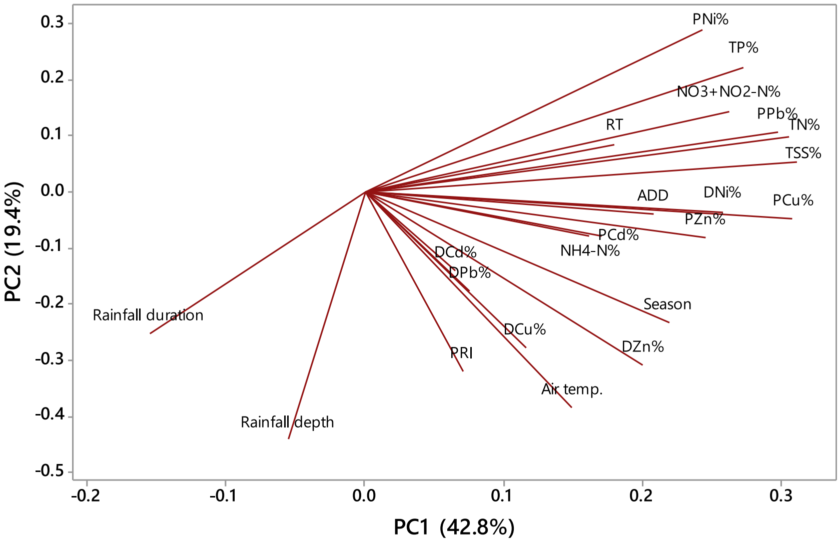

Fig. 5 Loading plot for principal components 1 and 2 obtained from a PCA of pollutant removals, season, air temperature, ADD, retention times (RT), rainfall depth and duration, and peak rainfall intensity (PRI); PC1 and PC2 explain 42.8% and 19.4% of the variance in the data, respectively

treatment processes, higher pollutant concentration and/or road salt in snowmelt/winter runoff (Kadlec and Reddy 2001; Weis and Weis 2004). Cold temperatures especially can affect the temperature-dependent nitrogen removal mechanisms (Bachand and Horne 1999). The daily mean air temperatures during the sampled events were 11 °C ± 3 °C, 15 °C ± 3 °C, 11 °C ± 3 °C and 1 °C ± 0.1 °C in spring, summer, autumn, and winter, respectively. The air temperatures were significantly lower (*p*-value =0.003) in winter than in the other seasons which did not differ significantly from each other. Chloride concentrations were not measured; however, a high conductivity of 615 μS cm^{-1} during event 11 (February 14) indicates that road salt was present in the stormwater at this time. All other events had lower conductivities (192μS cm^{-1} ± 12μS cm^{-1}). There were no seasonal differences in the inflow pollutant concentrations detected; the high variations in the inflow concentrations did not follow a seasonal pattern.

These facts may explain why no statistically significant variations of most pollutant removals and outflow concentrations between the seasons were detected (One-way ANOVA; *p*-value >0.05). Only for Pb, TSS and TP (*p*-value <0.05) were significantly lower removal percentages detected in autumn, most likely due to the relatively low inflow concentrations at these events (events 7–10 in Fig. 4) and thus low removal percentages, despite similar outflow concentrations compared to the other storm events.

Only the lower NH_4-N and $NO_3 + NO_2$-N outflow concentrations during summer/early autumn (Fig. 4) indicate more effective bio-geochemical treatment processes during the warmer seasons (Kadlec and Reddy 2001; Purchase et al. 2009). However, the TN outflow concentrations do not follow a seasonal pattern and are always around 1 mg/L. The summer of the sampling period was relatively cold (mean air temperature only 15 ± 3 °C). Possibly over a warmer summer, the wetland might perform better since many biochemical processes (e.g. nitrification and denitrification), whose rate is influenced by temperature, work best at 20–35 °C, depending on the environment, with minimum nitrification temperatures of between 2 and 5.5 °C (Stark 1996). Blecken et al. (2010) reported a clear temperature dependency of nitrogen removal processes in vertical-flow wetlands when comparing their performance in a temperature range between 2 and 20 °C.

Semadeni-Davies (2006) investigated the performance of the pond section of the Bäckaslöv CSW under winter conditions. The author reported that Pb, Zn and TSS removal efficiencies dropped from around 80% in summer to 42%, 48% and 49% in winter, respectively. Cd and Cu removal remained stable at around 75% and 49%, respectively. These removal rates are lower than those measured in this study for the pond (Table 4). Given the relatively few winter runoff events included in this study and the long time-span (and thus factors such as increased sediment accumulation and changing vegetation cover) between both studies, it is difficult to assess the reasons for these differences.

Heavy Metals in Sediments

The metal analyses of the collected sediment showed high metal concentrations in the sediment within the CSW (Fig. 6). However, a large spatial variation in the sediment's metal content between the sampling locations (see Fig. 1) was observed. No clear trend of increasing or decreasing concentrations along the system was detected. No statistically significant differences in the sediment's metal concentrations between the pond and the wetland were detected (*p*-value >0.05), with the exception of Pb (*p*-value =0.03). By far the lowest metal concentrations were detected at the most downstream sampling point.

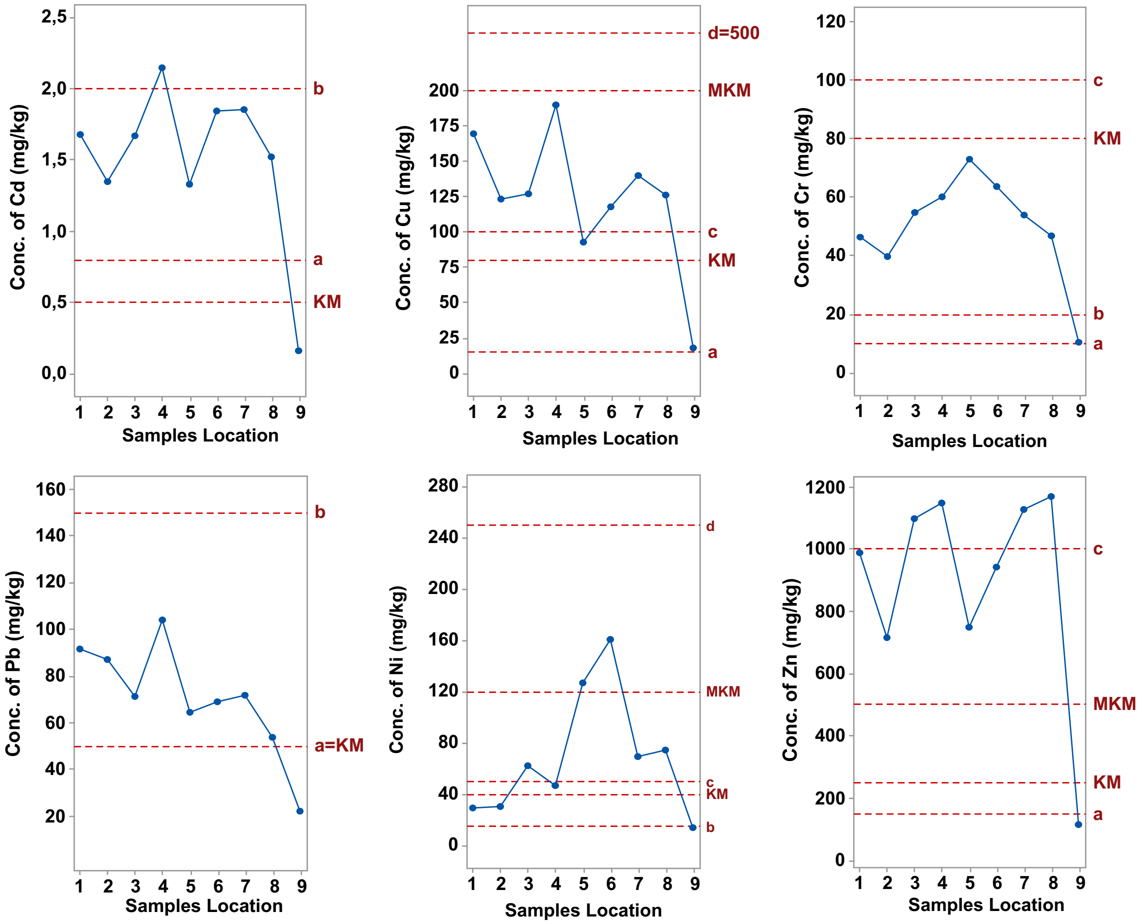

Fig. 6 Metal concentrations in sediments (measured in mg/kg dry weight) at nine locations in the CSW with reference lines given by the classifications defined in the Swedish EPA guidelines (Swedish EPA 2000: (**a**) Very low concentrations (**b**) low concentrations (**c**) moderately High concentrations (**d**) high concentrations (**e**) very high concentrations; and Swedish EPA 2009: (MKM) less sensitive land use and (KM) sensitive land use)

The measurements of sediment quality were assessed against Swedish guidelines for the protection and management of lakes and watercourses, guidelines which define five pollutant concentration classes (Fig. 6, Swedish EPA 2000). This assessment showed that Cu, Ni and Zn were classified as having high concentrations (d). All metal concentrations in the sediment were below the less sensitive land use threshold values as defined by Swedish EPA (2009) except for Ni and Zn which exceeded these values.

Although short-term and long-term exposure to high levels of heavy metals can cause serious human health effects, this study underlines the advantages of using pond-wetland systems in the retention of pollutants prior to discharge into receiving waters.

Summary and Conclusions

This study investigated a 6.8 ha, 19-year old combined pond-wetland system constructed to treat the stormwater runoff from a 320 ha urban catchment. Thirteen storm events were monitored over one year. In this investigation, the aim was to assess the hydraulic and treatment performance of this system after 19 years of operation, which is a long operational time compared to many other wetland studies. Also, this study highlighted the importance of using a sedimentation pond as a pre-treatment facility prior to discharge to the wetland. The main factors which affect the performance of this system were also identified; these included season and air temperature, ADD, rainfall depth and intensity, and the duration of the storm events.

This study has shown that the evaluated CSW was efficient in attenuating peak flows (41–95%), but attenuation of volumes varied greatly (−15–95%), depending on the event characteristics and the filling of pond storage. Pollutant concentrations in the influent to the wetland were highly variable. The pond-wetland system could efficiently remove an average of 91%, 80%, 94%, 91%, 83% and 92% of TSS, TP, particulate Cd, Cu, Pb, and Zn respectively, whereas the removal of particulate and dissolved Ni was highly variable with an average of 67% ± 62% and −5% ± 41%, respectively. However, the dissolved removal performance of the wetland system was less efficient and more variable, treating 64%, 69% and 64% of dissolved Cd, Cu, and Pb respectively, whereas mean concentrations of dissolved Zn were efficiently reduced by 81%. In addition, the treatment of TN, NH_4-N and NO_3 + NO_2-N was highly variable with an average of 45% ± 27%, 12% ± 96%, and 45% ± 43%, respectively, being removed. Principal component analysis (PCA) showed that pollutant removal efficiency was significantly influenced by some factors including ADDs, seasonal variations, air temperature, retention times, rainfall depth and duration, and peak rainfall intensity.

Overall, the pond accounted for a substantial reduction of the pollutant concentrations. Nevertheless, the wetland significantly improved both the treatment performance and the peak flow reduction still further. Thus, stormwater managers should consider implementing combined pond/wetland systems especially when dissolved pollutants and/or nitrogen are targeted.

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