Long-Term Treatment Efficiency of a Constructed Stormwater Wetland: Preliminary Results

Ahmed Mohammed AL-RUBAEI[1*], Malin ENGSTRÖM[2], Maria VIKLANDER[1], Godecke-TOBIAS BLECKEN[1]

[1]*Urban Water, Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, 971 87 Luleå, Sweden*
[2]*Växjö Municipality, 351 12 Växjö, Sweden*
[*]*Corresponding author*
Email: ahmed@ltu.se

ABSTRACT
Constructed stormwater wetlands (CSWs) are commonly used in Sweden and worldwide because of their high efficiency in urban stormwater management. However, questions have been raised about the long-term performance of CSWs. This study investigated the performance of a 19-year-old constructed wetland, which was designed to treat the stormwater from a 320-ha catchment located in the city of Växjö, southern Sweden. The system has not been maintained since its construction in 1994. The results of the present study were compared with results obtained from a previous study conducted by Växjö Municipality in 1997. The results showed that the CSW significantly reduced peak flows by 72%. High concentration reductions were found for Cd, Cr, Cu, Zn, Pb, TSS and TP (90, 89, 91, 90, 96, 96 and 86%, respectively). TN concentrations were reduced by 61%. The results indicated that lack of maintenance had no effect on the performance of wetland system during this long period of operation (19 years). In contrast, especially the removal of Cu and nitrogen was enhanced compared to 1997, which may be due to maturing of the system. The results show that CSWs are resilient systems, which (provided that design is sufficient) can work efficiently for at least two decades.

KEYWORDS
Urban stormwater, constructed stormwater wetland, long-term function, suspended solids, nutrients, metals

INTRODUCTION
Urban stormwater runoff has been recognized as one of the main pollution sources causing degradation of the receiving water body's quality (US EPA, 2000). Urban stormwater runoff often contains high levels of pollutants; e.g. sediments, nutrients, heavy metals and hydrocarbons. Furthermore, large volumes of stormwater runoff are discharged into the receiving water which may cause (*inter alia*) flooding, high flows, and erosion (Walsh, 2000).
To address these concerns, e.g. the concept of water sensitive urban design (WSUD) has been implemented. Constructed stormwater wetlands (CSWs) are one technique within WSUD. CSWs have the ability to effectively remove pollutants from urban stormwater runoff and attenuate peak flows and discharge volumes (Martin, 1988; Scholes et al. 1998; Walker and Hurl, 2002; Li et al. 2010).
However, the long term function (exceeding 10 years) of CSWs has not been evaluated widely (Vymazal, 2011). Often maintenance of stormwater control measures is lacking; Chen, (2011) and Martin (1988) reported that accumulation of retained pollutants in CSW system without regular maintenance measures may affect the effectiveness of the system,

especially in case of receiving of high discharges of stormwater runoff. Furthermore, maintenance of vegetation is also plays an important role, not only in terms of water quality treatment, but also as a habitat value (Chen, 2011).
The objective of this study was to determine the removal efficiency of TSS, heavy metals and nutrients in the 19 years old *Bäckaslövs* CSW in Växjö, Sweden. To investigate the development of the long term performance of this CSW for metal removal, the results of this study were compared an existing data set collected at the same CSW during the first three years of operation after its construction in 1994 (Växjö Municipality, 1998). The results of this study exemplify whether a lack of maintenance affects the function of this system that has not been maintained since its construction in 1994.

MATERIALS AND METHODS

Site Description

Bäckaslövs CSW is located in the city of Växjö in southern Sweden. Växjö is surrounded by lakes being the receiving water bodies for stormwater discharges from the city. Severely impaired water quality in these lakes led to the widespread construction of different types of stormwater control measures in Växjö in the 1990s. Being one of these systems, *Bäckaslövs* CSW serves as the stormwater treatment facility for a 320 ha catchment including 130 ha residential area, 190 ha industrial /commercial area and several major roads. Before the construction of Bäckaslövs CSW, the stormwater had been discharged into the receiving lakes without treatment which consequently led to their degradation. The CSW system consists of an upstream sedimentation pond with a water surface of 1.8 ha and an average depth of 1.6 m followed by a 5 ha wetland with a meandering main stream channel (Figure 1).

Existing Study from 1997

After construction, in 1997 Växjö Municipality investigated the CSW's performance (Växjö Municipality, 1998). As a part of this project, flow-weighted water samples were collected at three monitoring stations (W1, W2 and W3; Figure 1) equipped with automatic samplers. W1 was located at the pond's inlet (i.e. collecting untreated influent samples), W2 at the passage between the pond's outlet and the wetland's inlet and W3 at the wetland's outlet (i.e. collecting the water being discharged to the receiving water body). In that study, water samples were taken during summer 1997 (14 June – 10 July).

Data Collection

In the present study, the same sampling stations (W1, W2, and W3; Figure 1) were used as in the previous study done by Växjö municipality. The stations have been equipped with automatic samplers (ISCO Avalanche Portable Refrigerated Samplers at W1 and W3 and ISCO 6712 Portable Sampler at W2). Mainstream ™ premier fixed AV flow meters were installed at W1 and W2 for measuring and recording water flow in the pipes, while MJK 713 flow meter was installed at W3. Rainfall depth and intensity were recorded using a rain gauge placed on site. Flow data from 10 storm events and water quality data from 40 events during 8 months (April – November 2013) are presented in this paper. The water quality samples were analysed for total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and heavy metals (Cd, Cr, Cu, Zn, Ni, and Pb) using inductively coupled plasma atomic emission spectrometry and mass spectrometry. The samples were delivered within 24 - 48 h to the laboratory; during that time they were placed in a cool bag with ice packs.

Figure 1. Study area of the CSW, showing the location of the monitoring stations (W1, W2, and W3).

Data Analysis

The stormwater quality data were statistically analysed for the 2013 monitoring results. The Kolmogorov-Smirnov and Shapiro-Wilk tests were used for normality. If data were normally or log-normally distributed, a paired t-test was used to compare between event mean concentrations (EMCs) from the three monitoring stations (1) Pond's inlet (W1) and its outlet (W2), (2) pond's inlet (W1) and wetland's outlet (W3). Otherwise, a nonparametric Wilcoxon signed rank test was used. The confidence level for all statistical tests was accepted at an α-level of 0.05.

For each storm event, pollutant removal efficiency of the CSW was calculated as:

Pollutant Removal Efficiency (%) = 100 x $[EMC_{in} – EMC_{out}] / EMC_{in}$

where EMC_{in} and EMC_{out} are the event mean concentrations of pollutants in the runoff samples at the inlet and outlet, respectively.

RESULTS AND DISCUSSION

Hydraulic Performance

The characteristics of the sampled storm events are summarized in Table 1 with runoff hydrographs shown in Figure 2. The total covered rainfall depth of these ten storms is 126.8 mm.

The flow measurements showed a significant reduction in peak flow for all storm events through the pond and wetland (Figure 2). The mean peak flow reduction for the ten storm events for the pond and wetland were 79 % and 72 % respectively (Table 1 and Figure 2). The results showed that the pond accounts for a substantial percentage of the total peak flow reduction; for some events even higher peak flows then after the pond were observed downstream the wetland. The difference in peak flow reductions between the ten storm events could be attributed to the differences in antecedent dry periods and/or rain intensity (Lenhart and Hunt, 2011). However the as yet rather small data set does not allow the verification of these hypotheses. Further events have to be monitored to enable generalization of the results.

A comparison of the present data with the previous study from 1997 reveals that the peak flow reduction is still in the same range (June 1997: 87%; peak flow at W1= 1500 l/s, W2= 250 l/s, and W3= 200 l/s). Given the clearly increased vegetation cover of the wetland today compared to the period directly after construction one could have expected a larger reduction. However, obviously still the main stream conveys the water relatively quickly through the wetland without increased flow reduction by increased vegetation.

Table 1. The characteristics of the sampled storm events for eight months period (April 2013 – November 2013). Water quality was analysed in detail for events 1, 2, 6 and 7

Event no.	Event date	Previous dry period (day)	Total rainfall (mm)	Peak rainfall intensity (mm/10 min)	Peak flow (l/s)			Peak flow reduction %	
					W1	W2	W3	Pond	Wetland
1*	09 May	12	10.6	3	1050	146	216	86	79
2*	14 May	2	3	0.4	479	65	88	86	82
3	21 May	1	18	1	1193	195	454	84	62
4	13 Jun	12	17.8	1.8	1027	322	223	69	78
5	16 Jun	1	12.6	3.2	2020	400	442	80	78
6*	08 Aug	7	14.8	3.8	1260	149	191	88	85
7*	01 Sep	1	24.2	3.8	1675	420	491	75	71
8	15 Sep	3	5.8	0.6	336	32	73	90	78
9	28 Oct	1	9	1	350	85	155	76	56
10	01 Nov	1	11	1.4	727	133	205	82	72
Average of the ten storm events					912	195	254	79	72

W1= Pond's inflow; W2= Pond's outflow; W3= Wetland's outflow

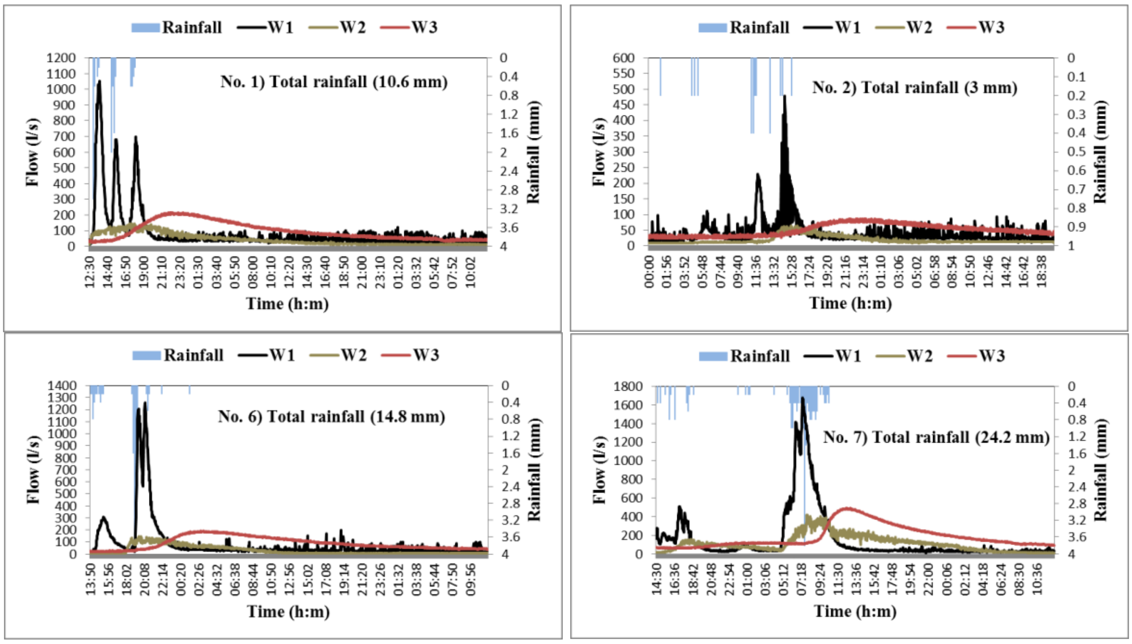

Figure 2. Hydrographs and rainfall hyetographs recorded during the monitored storm events.

Removal Efficiency of Pollutants

The mean EMCs of all constituents analyzed for the ten storm events are presented in Table 2. The statistical comparison of the inlet and outlet EMC of all pollutants is performed in Table 2. This comparison shows that these EMCs differ significantly from each other at a confidence level of 95% (paired t-test; p-value < 0.05).

The difference in EMCs between the pond's inlet W1 and outlet W2 and wetland's outlet W3, was significant with high removal efficiency for all pollutants (Table 2). The results for the ten storm events showed that the highest removal efficiencies were observed in the pond and wetland for TSS 95 – 96%, Pb 93 – 96%, Cu 85 – 91%, Cd 85 – 90%, Cr 79 – 89%, Zn 80 – 90%, and TP 83 – 86%. Table 2 also shows that the CSW has effectively reduced the EMC of Ni and TN by 55%, and 61%, respectively. As Table 2 shows, there is a clear trend of decreasing of the removal efficiency of Ni from 63% after the pond to 55% after the

wetland (i.e. at all 10 events a higher concentration of Ni leaves the wetland stream (W3= 2.76 µg/l) than the pond (W2= 2.26 µg/l)).
The results showed that outlet EMCs of pollutants may vary depending on inlet EMCs of pollutants which are in turn dependent on the stormwater characteristics (i.e. rainfall depth, peak rainfall intensity, peak flow rate, and previous dry period).
The results clearly showed that the pond accounts to a large extent for the reductions of pollutants. However, the wetland enhanced removal efficiencies especially for nitrogen and to a lesser extent also for the metals.

Table 2. Mean inlet and outlet EMCs of TSS, nutrients and metals ± standard deviation and the removal efficiency for the ten storm events, 2013

Constituent	W1	W2	RE%	p-value	W3	TRE%	p-value
Cd (µg/l)	0.2 ± 0.12	0.03 ± 0.01	85	0.002	0.02 ± 0.003	90	0.005
Cr (µg/l)	8.24 ± 6.7	1.74 ± 0.8	79	0.016	0.93 ± 0.28	89	0.007
Cu (µg/l)	36 ± 27.17	5.33 ± 1.89	85	0.007	3.29 ± 0.97	91	0.004
Ni (µg/l)	6.07 ± 3.9	2.26 ± 0.53	63	0.019	2.76 ± 0.56	55	0.031
Zn (µg/l)	289.5 ± 187.81	58.41 ± 35.09	80	0.001	28.15 ± 8.63	90	0.002
Pb (µg/l)	13.52 ± 12.93	0.95 ± 0.44	93	0.013	0.61 ± 0.23	96	0.012
TSS (mg/l)	169.15 ± 163.86	8.63 ± 2.14	95	0.000	6.79 ± 2.02	96	0.000
TP (mg/l)	0.26 ± 0.23	0.044 ± 0.01	83	0.000	0.036 ± 0.01	86	0.000
TN (mg/l)	2.05 ± 1.52	1 ± 0.4	51	0.039	0.79 ± 0.24	61	0.001

RE%= Pond’s removal efficiency; TRE%= Total removal efficiency

Event mean concentration (EMC) of suspended solids, nutrients and metals as well as the removal efficiency for four storm events are presented in Tables 3 and 4.
The storm events were characterized by different conditions (Table 1). The storm event 2 (May 14) had the lowest rainfall depth and intensity and was preceded by two dry days while the storm event 7 (Sep 01) had the highest rainfall depth and intensity, but was also preceded by a very short dry period (1 day). In contrast, the rather intense events 1 and 6 (May 09 and Aug 08) were preceded by a relatively long dry period (12 and 7 days, respectively). This is clearly evidenced by the substantial differences between inlet EMCs of all pollutants except for TN as shown in (Table 3). The significant difference of the pollutant concentrations can be attributed to the effect of the antecedent dry periods. It is evident that long antecedent dry periods had a greater effect on the influent pollutant concentrations than other stormwater characteristics (e.g. rainfall depth, peak rainfall intensity, and peak flow rate). These findings support Li et al. (2010) who reported that stormwater runoff becomes more polluted when a storm event is preceded by a long dry period, consequently, affect the wetland system.
Overall, despite its age and generally lacking maintenance, the wetland system removes pollutants efficiently from the stormwater. As can be seen from Table 3, the inlet EMC of all pollutants was much higher for storm event Aug 08 than May 14, except for TN. However, the removal efficiency of all pollutants for storm event Aug 08 was slightly higher than May 14, except for Ni, and TP where slightly decreased from 65 to 62%, and 91 to 84%, respectively. This result can be explained by the fact that event Aug 08 had longer dry periods (7 days) than May 14 (2 days), since this affects sedimentation mechanism by the pond. As Table 4 shows, the performance of the constructed wetland for pollutants removal was more efficient for storm event May 09 than Sep 01. The reductions in inlet EMCs of Cd, Cr, Cu, Zn, Pb, TSS, and TP were excellent (96 – 99%) during the storm event May 09, with 84% and 85% reduction of Ni and TN, respectively, but these pollutants decreased to 79, 78, 83, 90, 78, 84, and 45%, respectively, during the storm event Sep 01, with 0 and 8% reduction of Ni and TN, respectively. The results also show that Ni removal was not effective during the storm event Sep 01 where the inlet and outlet EMCs of Ni did not change (2.5

µg/l). Unlike, a difference trend was observed for TN removal, where the TN removal rates varied from negative removal (- 6%) to positive removal (8%). However, the low removal was clearly caused by the very low TN influent concentrations at this event; despite low removal the effluent concentrations from both the pond and the wetland were lower or in the same range as at the other events. Clearly, the wetland cannot further reduce a TN concentration of approximately 0.6 mg/l.

Table 3. Inlet and outlet EMCs of TSS, nutrients and metals and the removal efficiency for two storm events May 14 and Aug 08, 2013

Constituent	May-14					Aug-08				
	W1	W2	W3	RE%	TRE%	W1	W2	W3	RE%	TRE%
Cd (µg/l)	0.2	0.03	0.02	85	90	0.3	0.024	0.02	92	93
Cr (µg/l)	8.9	1.2	1.07	87	88	13	1.4	1.3	89	90
Cu (µg/l)	41	5.3	3.95	87	90	56	3.1	2.3	94	96
Ni (µg/l)	7.1	2.3	2.45	68	65	9.8	2.5	3.7	74	62
Zn (µg/l)	275	150	48.5	45	82	490	32	26	93	95
Pb (µg/l)	13.4	0.72	0.38	95	97	27	0.7	0.57	97	98
TSS (mg/l)	168.5	7.2	5.5	96	97	270	9.2	6.4	97	98
TP (mg/l)	0.29	0.05	0.02	82	91	0.36	0.042	0.059	88	84
TN (mg/l)	3.15	1.8	1.35	43	57	2.7	0.63	0.69	77	74

RE%= Pond's removal efficiency; TRE%= Total removal efficiency

Table 4. Inlet and outlet EMCs of TSS, nutrients and metals and the removal efficiency for two storm events May 09 and Sep 01, 2013

Constituent	May-09					Sep-01				
	W1	W2	W3	RE%	TRE%	W1	W2	W3	RE%	TRE%
Cd (µg/l)	0.46	0.023	0.02	95	96	0.091	0.02	0.02	79	79
Cr (µg/l)	23.97	0.84	0.81	96	97	3.4	1.3	0.75	62	78
Cu (µg/l)	99.17	4.17	2.68	96	97	16	5.8	2.7	64	83
Ni (µg/l)	15.18	1.6	2.37	89	84	2.5	2.2	2.5	12	0
Zn (µg/l)	703.33	25.4	21.83	96	97	180	36	18	80	90
Pb (µg/l)	41.67	0.95	0.43	98	99	5	0.86	1.1	83	78
TSS (mg/l)	555	8.4	6	98	99	46	5.3	7.5	88	84
TP (mg/l)	0.88	0.04	0.03	96	97	0.073	0.04	0.04	45	45
TN (mg/l)	5.5	1.14	0.81	80	85	0.66	0.7	0.61	-6	8

Comparison of the present study with the monitoring in 1997

15 storm events were monitored during the period of (14 June – 10 July 1997), 3 of which were analysed in detail by the municipality at the three monitoring stations (W1, W2, and W3). The samples were analysed for selected pollutants (Cd, Cr, Zn, Pb, TSS, TP, and TN). The characteristics of the three storm events are summarized in Table 5.

A comparison of the two monitoring periods shows that rainfall depths and dry periods were similar. A similar trend was observed for the period of (14 June – 10 July 1997) compared to the monitoring period of 2013, where the highest inlet EMCs of pollutants were measured for the storm event June 14 which was preceded by a 10 day dry period followed by the storm event July 1 (3 day dry period), indicating the effect of antecedent dry periods on the influent pollutant concentration (Table 6). A comparison of the Tables 2 and 7 reveals that the inlet EMCs of Cd, Zn, and Pb in 1997 were higher than in 2013, while EMCs of Cu, TSS, TP, and TN were lower. This is most likely due to the changes in the catchment area.

Table 5. The characteristics of the monitored storm events for period (14 June –10 July 1997)

Characteristics	14 June	21-22 June	1 July
Rainfall depth (mm)	4.8	22.4	13
Previous dry period (day)	10	1	3

Table 6. Inlet EMCs of pollutants for three storm event for period (14 June – 10 July 1997) (Växjö Municipality, 1998)

Constituent	14 June	21-22 June	1 July
Cd (µg/l)	10	0.2	0.2
Cu (µg/l)	60	22	33
Zn (µg/l)	470	174	151
Pb (µg/l)	58	17	31
TSS (mg/l)	426	51	145
TP (mg/l)	0.46	0.17	0.39
TN (mg/l)	2.5	1.1	2.7

The mean EMCs of pollutants at the three monitoring stations and the removal efficiency for the pond and wetland for the entire period (14 June – 10 July 1997) are presented in Table 7. Also in 1997 the pollutant concentrations were significantly reduced by the CSW system. The results also showed that the pond contributed to a large extent to the total pollutant removal.

Table 7. Mean inlet and outlet EMCs of TSS, nutrients and metals and the removal efficiency for 15 storms for the period (14 June – 10 July 1997) (Växjö Municipality, 1998)

Constituent	W1	W2	RE%	W3	TRE%
Cd (µg/l)	0.4	0.1	75	0.02	95
Cu (µg/l)	22	14	36	10	55
Zn (µg/l)	510	130	75	40	92
Pb (µg/l)	18	4	78	1	94
TSS (mg/l)	71	19	73	17	76
TP (mg/l)	0.19	0.09	53	0.06	68
TN (mg/l)	1.7	1.2	29	0.92	46

A comparison of the removal efficiencies for the two monitoring periods (1997 vs. 2013) shows that the performance of the wetland did not change significantly for removal of Cd, Zn, and Pb. However, the performance has increased significantly for Cu (55 vs. 91 %), TSS (76 vs. 96%), TP (68 vs. 86%), and TN (46 vs. 61%). This is likely due to a maturing of the wetland: increased plant growth enhances and develops the sedimentation and biological/microbial processes. Sedimentation removes most particulates; organic matters and the decomposed nutrients (TP and TN) are consumed by microorganisms and plants (Lee et al. 2009). Aerobic and anaerobic zones may have been created supporting nitrification and denitrification thus having increased the nitrogen removal (Kadlec, 2008).

One objective of this study was to evaluate if the lack of maintenance affected the performance of the wetland system. Although the wetland system has not been maintained since its construction in 1994, pollutant removal and peak flow reduction are still efficient. Thus, in this specific case a lack of maintenance had no effect on the performance of wetland system during this very long period of operation (19 years) illustrating that CSWs can be a suitable technology when maintenance resources are limited. However, this does not mean that maintenance and control can be neglected; as with many WSUD systems, CSWs susceptible to clogging by solids and sediment accumulation over time, consequently, a reduced efficiency (Marsalek et al. 2006).

CONCLUSIONS

The study has been carried out in combined pond-wetland system where 10 storm events were monitored during 8 months. The study aimed to evaluate the removal efficiency of urban pollutants (TSS, heavy metals and nutrients) through a CSW system after 19 years of operation without maintenance and to investigate the development of the long term performance of this CSW for metal removal.

The wetland system significantly reduced peak flows. Pollutant removal was very efficient; removal was found to be very high for Pb and TSS (96%). Also, Cd, Cr, Cu, Zn, and TP were removed efficiently (90, 89, 91, 90, and 86%, respectively). Ni and TN concentrations were reduced by 55% and 61%, respectively. Also, it was found that the performance of the wetland system is more influenced by antecedent dry periods and therewith related variability of influent concentrations. Comparing the two monitoring periods (1997 and 2013) reveals that the treatment performance of the wetland had not changed significantly for Cd, Zn, and Pb, while the performance has increased significantly for Cu (55 and 91%, respectively), TSS (76 and 96%, respectively), TP (68 and 86%, respectively), and TN (46 and 61%, respectively). Thus, the lacking maintenance had no negative effect on the performance of the wetland system during this long period of operation (19 years). It is rather likely that the maturing of the system caused the observed increased removal of nutrients.

ACKNOWLEDGEMENTS

The authors thank the staff at the Växjö municipality for their substantial help with sample collection and analysis. This project was conducted as part of the research cluster Dag & Nät. The financial support for this project by the Swedish Water and Wastewater Association is gratefully acknowledged.

REFERENCES

Chen, H. (2011). Surface-flow constructed treatment wetlands for pollutant removal: applications and perspectives. Wetlands, 31(4), 805-814.

Kadlec, R. H. (2008). "The effects of wetland vegetation and morphology on nitrogen processing." Ecological Engineering. 33(2), 126-141.

Lenhart, H. A. and Hunt, W. F. (2011). "Evaluating Four Storm-Water Performance Metrics with a North Carolina Coastal Plain Storm-Water Wetland." Journal of Environmental Engineering.137(2), 155-162.

Lee, C. G., Fletcher, T. D., & Sun, G. (2009). Nitrogen removal in constructed wetland systems. Eng. Life Sci., 9(1), 11-22.

Li, D. W., Zhang, W. S., Yin, W., & Lei, A. L. (2010). Combined Pond–Wetland Systems for Treatment of Urban Surface Runoff and Lake Water. Environmental Engineering Science, 27(12), 1027-1034.

Marsalek, J., Watt, W., & Anderson, B. (2006). Trace metal levels in sediments deposited in urban stormwater management facilities. Water Science & Technology, 53(2), 175-183.

Martin, E. H. (1988). Effectiveness of an urban runoff detention pond-wetlands system. Journal of Environmental Engineering, 114(4), 810-827.

Scholes, L., Shutes, R. B. E., Revitt, D. M., Forshaw, M., & Purchase, D. (1998). The treatment of metals in urban runoff by constructed wetlands. Science of the Total Environment, 214(1), 211-219.

US EPA. 2000. Water Quality Conditions in the United States: A Profile from the 1998 National Water Quality Inventory Report to Congress. Office of Water, Washington, DC.

Växjö Municipality, 1998. Bäckaslövs våtmark - Kontroll och uppföljning (Inspections and monitoring). Tekniska förvaltningen 1998-10-30 (In Swedish).

Vymazal, J. (2011). Long-term performance of constructed wetlands with horizontal sub-surface flow: Ten case studies from the Czech Republic. Ecological Engineering, 37(1), 54-63.

Walker, D. J., & Hurl, S. (2002). The reduction of heavy metals in a stormwater wetland. Ecological Engineering, 18(4), 407-414.

Walsh, C. J. (2000). "Urban impacts on the ecology of receiving waters: a framework for assessment, conservation and restoration." Hydrobiologia, 431(2), 107-114.