Pollutant removal efficiency of a retrofitted stormwater detention pond

Jason Faber Carpenter, Bertrand Vallet, Geneviève Pelletier, Paul Lessard and Peter A. Vanrolleghem

ABSTRACT

The objectives of this study were to characterize the stormwater runoff for a residential catchment, evaluate the present detention pond removal efficiency for different pollutants, and evaluate how its efficiency can be increased by controlling the pond stormwater retention time. The analysed pollutants were total suspended solids (TSS), total metals and ammonia. Runoff pollutant concentrations were generally found to agree with literature for the small residential catchment. The design of the original pond was such that low retention times of most analysed pollutants occurred, causing a lower than expected removal efficiency when compared to similar types of ponds. The retrofitting of the pond consisted of adding a sluice gate at the outlet in order to retain stormwater for longer periods of time. The retrofit allowed drastic improvement of the removal efficiency for TSS, NH3-N and zinc, from 39 to 90%, 10 to 84%, and 20 to 42%, respectively.

Key words | integrated urban wastewater system, separate sewers, stormwater best management practice (BMP), stormwater control measures, urban pollutants

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INTRODUCTION

In order to reduce urban stormwater runoff impacts, governments in North America and Europe have adopted legislation or practices to either remove up to 80% of the total suspended solids (TSS) present in urban stormwater (Maryland Department of the Environment (MDE) 2000; Ontario Ministry of Environment (OMOE) 2003; New York State Department of Environmental Conservation 2010; Ministère du Developpement Durable de l'Environnement et des Parcs (MDDEP) 2011) or satisfy emission limits of pollutant loads discharged over a certain time (Engelhard & Rauch 2008). In many urban areas, these legislations led to implementation of different types of best management practices (BMPs), including low-impact development, pollutant source reduction, and structural BMPs, to reduce stormwater runoff pollutant loads.

According to reference design manuals (OMOE 2003; MDDEP 2011), some structural BMPs, such as detention or retention ponds, can provide effective removal of pollutants transported by urban runoff (Scholes *et al.* 2008). According to the United States Environment Protection Agency (EPA 2002), detention and retention ponds offer an average removal efficiency of respectively 49 and 80% for TSS, 20 and 52% for total phosphorus, and −3 and 64% for dissolved phosphorus. Expected performance can also be found in an international stormwater BMP database pollutant category summary (Geosyntec and Wright Water Engineers 2012).

The main processes by which pollutant load is reduced are sedimentation, flotation, infiltration, adsorption, biological uptake, biological conversion and pollutant degradation (EPA 1999; MDDEP 2011). As these processes take time, the retention time in stormwater ponds is the main factor affecting removal efficiency, especially for suspended solids (Shammaa *et al.* 2002). Indeed, in view of the wide distribution of densities of suspended solids transported by runoff and particle sizes ranging from less than 20 μm to more

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than 4,000 μm, the settling velocity varies between 0.01 m/h to over 20 m/h (OMOE 2003). It can therefore take from minutes to days for particles to settle across the water column in a wet pond after a rain event. Since many pollutants, such as heavy metals, nutrients or microorganisms, are adsorbed on particles, removal of particulates through sedimentation can further increase removal of these associated pollutants (EPA 1999).

In Quebec City, many new urban areas were equipped with detention or retention ponds in order to manage runoff. The objective was essentially to control flooding and not improve water quality, which explains the implementation of a large number of detention, as opposed to retention, ponds. Retrofitting these detention ponds in order to improve their efficiency regarding pollutant removal must therefore focus on increasing the water retention time. Different retrofit techniques can be found in Marsalek *et al.* (1992) and Shammaa *et al.* (2002). They include the modification of the outlet diameter or structure (Guo *et al.* 2000), the implementation of baffles inside the pond (Matthews *et al.* 1997), and the control of the outlet with a gate for batch treatment (Middleton & Barrett 2008). These modifications showed improved removal efficiency for TSS as well as other pollutants present in stormwater compared to earlier studies of non-retrofitted detention or retention ponds. Guo *et al.* (2000), on the other hand, found that the removal efficiency was not conclusively correlated to retention time, but rather to inlet concentration. Retrofits of ponds were most beneficial for total phosphorus. Matthews *et al.* (1997) were able to increase TSS removal by 28% by introducing baffles inside a stormwater pond to increase detention time. Middleton & Barrett (2008) reached TSS removal efficiencies of 91% with their batch-type stormwater detention pond, as well as 52% for total phosphorus and 69% for total lead.

The rivEAU research project aimed at creating real-time control strategies for an outlet gate for stormwater quality management through the use of meteorological forecasts and hydrological, hydraulic, and water quality models (Muschalla *et al.* 2009). These models will be used to choose the best real-time controls to increase retention times in stormwater ponds and improve quality of the water discharged into urban rivers. The specific aims of this paper were to: (1) characterize the urban runoff for a residential catchment in Quebec City; (2) evaluate the removal efficiency of a stormwater detention pond for different pollutant types; and (3) evaluate the effect of adding an outlet control and the resulting retention time increase on the removal efficiency of the stormwater pond. This information forms the basis for the water quality modelling used for the elaboration of the aforementioned control strategies (Gaborit *et al.* 2013).

METHODOLOGY

The stormwater detention pond selected for the sampling campaign is located in a new suburban neighbourhood 15 km north of downtown Quebec City. It collects the runoff of a 15.1-ha area mostly consisting of residential single-family homes. The stormwater sewer system is a dual drainage system. The minor stormwater sewer (pipes) was designed based on a synthetic 1-h rain event and a 2-year return period. The major sewer system (roads) and the stormwater basin were designed based on a synthetic 1-h rain event and a 100-year return period (Genivar 2005). The pond has an elliptical shape (Figure 1) and a storage volume of 4,300 m^3, a surface area of 3,400 m^2 and a maximum water depth of 1.71 m.

The inlet and outlet were concrete pipes with diameters of 0.90 and 0.45 m, respectively. The pond was equipped with a 6-m^2 span sedimentation basin at the inlet, almost

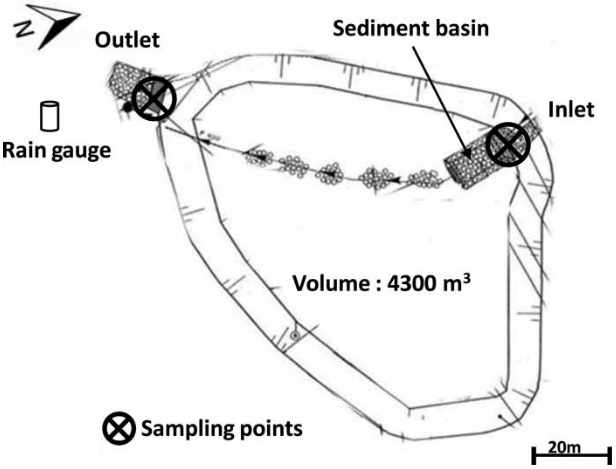

Figure 1 | Stormwater detention pond plan (GENIVAR 2005) and location of rain gauge and sampling points.

completely filled by sediments. A 30-m long and originally 0.2-m deep channel linked the inlet to the outlet. As for the sedimentation basin, accumulation of sediments since its construction reduced the channel depth by 0.1 m at the time of the study. The slope of the pond was about 0.017 m/m. The outflow was discharged in the storm sewer collector reaching the Saint-Charles River, 300 m downstream.

The methodology used during the sampling campaign was based on the *Urban Stormwater BMP Performance Monitoring* manual (EPA 2002). The Environment Canada radar located at Villeroy was used to monitor upcoming rainfall events, to make a rough estimate of their duration and the ensuing runoff period. During all rainfall events, time – or flow – composite samples were taken at the detention pond inlet and outlet. Grab samples were taken as well and kept in 1-L polypropylene bottles. Composite samples were created by combining 1-L samples in a 20-L polyethylene bucket. The number of 1-L samples used to create the composite sample varied from one event to the next. The rough rain event duration estimate was used to establish the time interval at which the 1-L samples were taken in order to ensure that the samples were representative of the entire runoff period. On-site observations of the rain intensity and runoff flow were used to adapt the previously determined time intervals between samples. Water height at the outlet and sample temperature were recorded for each sample. Finally, dry weather concentrations were obtained from the average of four samples taken at the inlet for TSS, two samples for NH_3-N, and one sample for heavy metals.

Rain intensity over the watershed was monitored using a CSI TB4 tipping bucket rain gauge coupled with a HOBO datalogger installed near the outlet of the pond. Flow was measured inside the inlet and outlet pipes using Sigma 950 flowmeters with area/velocity sensors. Flow measurements proved to be unreliable at the inlet due to high turbulence inside the steep inlet pipe, often leading to zero values for important flows. Inflows and outflows were therefore obtained using recorded rainfall data and a calibrated Storm Water Management Model (SWMM) hydraulic model of the catchment (Vallet 2011). The model was calibrated using the outflow measurements from three independent rainfall events and validated using three more events. The fit between simulated and measured outflow was very good for calibration (Figure 2(a)) and acceptable for validation (Figure 2(b)). The Nash-Sutcliffe coefficients are respectively 0.97 and 0.95. Details on the calibration can be found in Gaborit *et al.* (2013).

The original outlet structure consisted of a 0.45-m concrete pipe (Figure 3(a)) with an IPEX flow regulator limiting the outflow to 350 L/s (23 L/s ha). The detention pond was retrofitted by installing a wooden box around the outlet structure, fitted with a guillotine-type door (Figures 3(b) and 3(c)). It allowed complete closure of the detention pond outlet or reduction of its outflow in order to increase this retention time to hours or days depending on meteorological predictions. The box was 1.1-m high and 0.61 m below the 1.71-m pond overflow weir to prevent overflow of the detention pond in case of unpredicted intense summer storms. The top of the box was left open with an area larger than the original outlet pipe surface to act as an emergency weir.

Sample analyses were either done at the Environmental Laboratory of the Civil and Water Engineering Department at Université Laval or at Quebec City East Wastewater Treatment Plant Laboratory. Heavy metals (iron and manganese) were analysed using the standard method (American Public Health Agency (APHA) *et al.* 1998), while ammonia

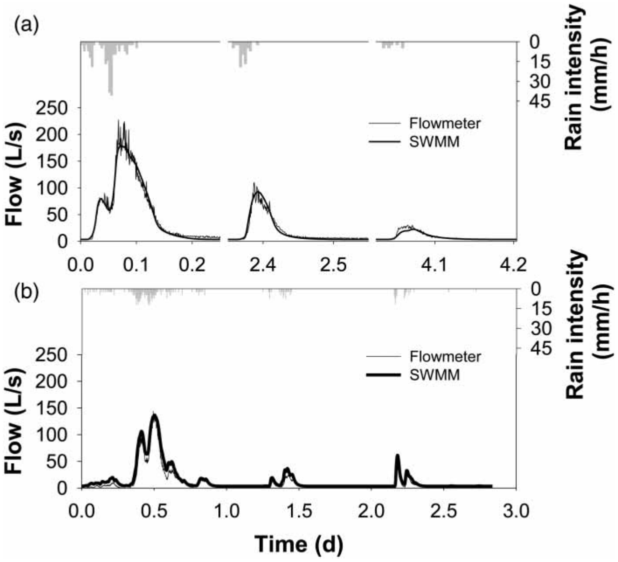

Figure 2 | Calibration (a) and validation (b) of simulated (SWMM) flow rates against measured outflows for three consecutive rainfall events.

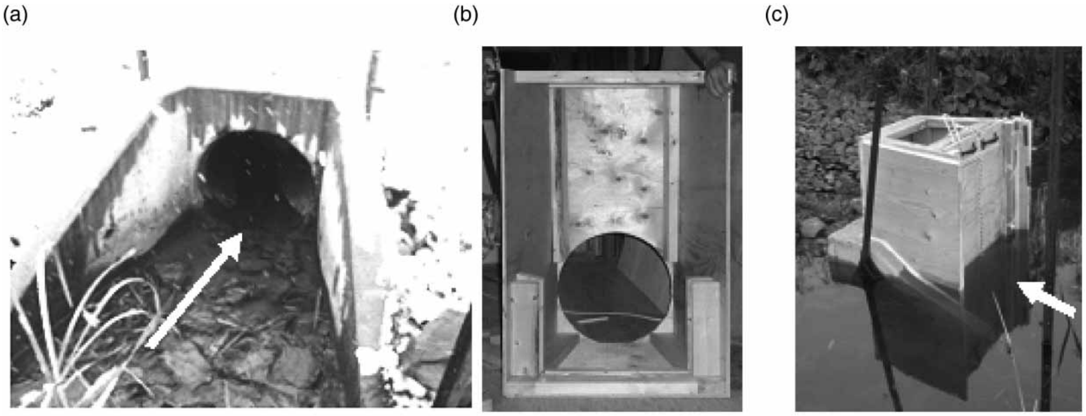

Figure 3 | (a) Original outlet structure; (b) outlet control structure (without front gate); (c) new outlet structure (in operation).

was analysed using a Hach kit (HACH 2007). Copper was also analysed but no significant results were found to be presented in this study. TSS, heavy metal, and ammonia loads were computed using flow values obtained through the SWMM model as well as concentrations obtained from grab samples taken during rain events, as presented in Equation (1)

$$\text{Load} = \sum_{i=0,j=1}^{i=f,j=n} q_i \cdot \left(C_{i-1} + \frac{C_{j+1} - C_j}{t_{j+1} - t_j} (t_i - t_{i-1}) \right) \cdot (t_i - t_{i-1}) \quad (1)$$

where q_i is the flow rate at time t_i; C_{i-1}, the concentration at time t_{i-1}; C_j and C_{j+1}, the concentrations of samples taken at time t_j and t_{j+1}, respectively; f is the final point of an event; and n, the number of samples taken during the event.

The removal efficiency was calculated as presented in Equation (2)

$$\text{Efficiency} = \frac{(\text{Load}_i - \text{Load}_o)}{\text{Load}_i} \cdot 100 \quad (2)$$

where Load_i is the pollutant mass entering in the pond and Load_o, the pollutant mass exiting the pond.

Runoff event mean concentrations (EMCs) for TSS (EMC_{TSS}) were calculated by dividing the total load in the pond inflow by the total inflow volume computed with the SWMM calibrated model. This technique was also used to calculate outflow pollutant loads. When rain data were not available for computing the volume of water, EMC_{TSS} was assumed to be the concentration of the composite sample. Data for heavy metals were available at a lower frequency than for TSS; EMCs were then calculated based on the composite sample analyses.

RESULTS AND DISCUSSION

Sampled events

Fifteen rain events were sampled during the summers of 2008, 2009 and 2010. In the text, summer refers to the time period between the end of the snow melting period, characterized by street cleaning to remove sand and gravel accumulated during winter for road de-icing, and the first freezing event. This period, usually occurring between May and October in Quebec City, was chosen to avoid unusual behaviour of sampled particles. Many different types of events were sampled (Table 1): from short and intense summer storms (e.g. maximum intensity of 100.8 mm/h, 1.9 h) to long showers (e.g. average intensity of 2.2 mm/h, 14.7 h). Dry weather periods were calculated using the method described by Powell *et al.* (2007) and ranged from 0.1 to 6.2 days, with an average of 2.6 days between events. Runoff volumes were obtained through the hydraulic model of the catchment. No sampled event created sufficient runoff to reach the capacity of the detention pond storage volume; the average volume was 543 m^3, 13% of

Table 1 | Summary of sampled event characteristics and runoff volumes

		Rain intensity			Dry weather period preceding		
Date	Total rainfall mm	5-min Max mm/h	Average mm/h	Rainfall duration h	Rain event d	Runoff volume m^3	EMC_{TSS} mg/L
06/08/2008	16.2	100.8	8.4	1.9	2.0	N/A	175[a]
18/08/2008	37.6	91.2	12.2	3.1	3.5	1,751	337
14/05/2009	13.2	12.0	5.1	2.6	4.6	N/A	679[a]
25/06/2009	5.2	19.2	4.4	1.2	6.2	301	560
07/07/2009	1.6	2.4	1.1	1.5	0.5	108	75
11/07/2009	28.0	55.2	3.0	9.5	3.8	239	105
13/07/2009	1.4	5.4	2.8	1.6	0.6	26	40
18/07/2009	32.0	36.0	2.2	14.7	1.2	1,544	91
27/07/2009	1.6	7.2	2.1	0.8	0.8	56	27
02/08/2009	16.4	24.0	4.8	3.4	3.9	747	30
21/08/2009	3.8	9.6	3.6	0.7	0.1	270	63
21/08/2009	4.8	9.6	4.8	1.0	0.5	192	53
18/09/2009	9.4	24.0	2.7	3.5	4.7	440	71
22/09/2009	3.6	6.0	1.4	2.5	4.0	158	29
09/07/2010	24.0	81.6	9	2.3	2.6	1,226	337

N/A (not available): rain gauge data unusable in hydraulic model for runoff flow rates.

[a] Value given by composite sample analyses because of the non-availability of rain gauge data.

the pond capacity. The largest event, on 18th August 2009, filled the detention pond to 37% of its 4,300 m^3 capacity. Events of 13th and 27th July 2009, were short summer storms (1.6 and 0.8 h, respectively), creating low runoff volumes (26 and 56 m^3), but with rainfall intense enough (maximum intensity of 5.4 and 7.2 mm/h) to wash off accumulated particles on the catchment.

All events from 2008 to 2nd August 2009 were sampled on the original stormwater detention pond, while following rain events were sampled after the retrofit. A dry-weather flow averaging 2 to 5 L/s constantly entered the pond during both summers of the sampling campaign. Since no coliforms were detected in the dry-weather water samples taken during the summer, and concentrations of ammonia, TSS and heavy metals were very low (Table 2), the dry-weather flow was concluded to be due to a stream at the northern end of the catchment and not to cross-connections with the wastewater system.

Characterization of runoff

Runoff pollutant concentrations found during the sampling campaign are presented in Table 2. Concentrations for

Table 2 | Characterization of stormwater runoff for summers 2008, 2009 and 2010 (EMC)

Parameter	# Sampled events	Average conc. (mg/L)	Median (mg/L)	Range (mg/L)	NSQD[a] (median value) (mg/L)	Dry-weather average conc. (mg/L)
TSS	13	140	71	27–560	49	7
Total Zn	9	0.05	0.04	0.02–0.15	0.073	0.01
Total Mn	9	0.14	0.11	0.06–0.4	n/a	0.26
NH_3-N	8	0.25	0.15	0.066–0.63	0.32	0.07

[a] NSQD – National Stormwater Quality Database.

total zinc and total NH_3-N are similar to the median values found by the National Stormwater Quality Database (NSQD) (Pitt *et al.* 2004) for residential catchments. Manganese was not measured in the NSQD and has been rarely studied for stormwater quality purposes, but the element is included in Environment Canada National Pollutant Release Inventory. A preliminary sample of the runoff on the selected catchment showed manganese to be in greater concentrations than zinc, copper and lead combined. It was then decided to include manganese as a parameter for this study.

EMC_{TSS} varied between 27 and 679 mg/L (Table 1) depending on flow conditions. Two events had higher TSS concentrations than the others. Firstly, the 14th May 2009 event presented a high concentration due to the wash-off of accumulated sand used during winter for road de-icing. Secondly, prior to the 25th June 2009 event, construction work was being done on one-tenth of the catchment, releasing a lot of sand, dirt and oil on the streets of the catchment. Construction on the catchment was finished a few days before 25th June 2009 and was therefore not a factor for the rest of the sampling campaign. Due to these two events, the average measured TSS concentration of 140 mg/L was much larger than the 49 mg/L found in the NSQD (Table 2). However, the median of 71 mg/L of TSS was closer to this value. The concentrations of other pollutants were in the same range as the NSQD values. The highest pollutant concentrations were recorded during the 25th June 2009 event and are also attributed to construction in the catchment.

TSS and pollutant loads were found to vary widely during the rain events. Peak loads sometimes occurred at the beginning of the rain event, not necessarily during peak flow, identifying a first flush behaviour common for small catchments (Lee *et al.* 2002). Figure 4 presents a comparison between peak flow, TSS concentration and TSS load for the 2nd August 2009 event. For this particular event, peak rain intensity (24 mm/h) and peak flow (200 L/s) were observed 95 and 103 min, respectively, after the beginning of the rain event. The peak TSS concentration of 87 mg/L was reached 30 min into the rainfall event. However, the peak load of 412 g TSS per minute (Figure 4) occurred 60 min into the rain event, at the first runoff peak. The first concentration peak therefore had little effect on the peak TSS load in the runoff, because of the very low flows at the beginning of the event.

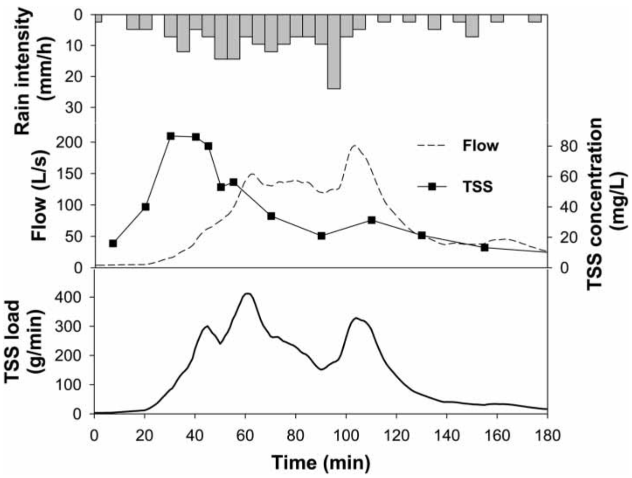

Figure 4 | Rainfall intensity, runoff flow rate and TSS concentration for the 2nd August 2009 event.

Stormwater pond removal efficiency without outlet control

The average pollutant concentrations at the outlet of the detention pond (Table 3) were in the same order of magnitude as the values reported in the international stormwater BMP database pollutant category summary for detention ponds (Geosyntec and Wright Water Engineers 2012). Metals and ammonia concentrations were very low. The average removal efficiency of TSS (Table 4) was 39%, which is lower than the 72% efficiency found by Stanley (1996) for a similar pond and similar average inlet TSS concentrations. Zinc and NH_3-N removals were also well below removal efficiencies for a detention pond (Stanley 1996). Manganese even showed negative removal efficiencies for most of the events, indicating a release of the contaminant

Table 3 | Outlet pollutant EMCs for open outlet

	# Sampled events	Average conc. (mg/L)	Median (mg/L)	Range (mg/L)
TSS	8	75	35	17 to 196
Total Zn	5	0.04	0.03	0.02 to 0.07
Total Mn	5	0.17	0.12	0.07 to 0.35
NH_3-N	3	0.19	0.06	0.06 to 0.44

Table 4 | Average pollutant mass entering and exiting the stormwater pond and removal efficiency for open outlet events

		Average mass		Removal efficiency	
	# Events	In (g)	Out (g)	Average (g), %	Range (g), %
TSS	8	189,120	98,269	39	1 to 67
Total Zn	9	18.0	17.7	22	0 to 53
Total Mn	9	48.2	60.7	−9	−33 to 13
NH_3-N	7	101.1	79.2	16	7 to 30

from the pond. These poor removal efficiencies could be due to the channel which quickly exited the low flow, highly concentrated runoff at the beginning of a rain event.

Figure 5 shows the typical behaviour observed for open outlet events. It presents the flow and TSS loads at the stormwater pond inlet and outlet for the 2nd August 2009, rain event. The flow at the pond outlet is nearly as high as at the inlet, which would translate into a low TSS removal efficiency. Indeed, the removal efficiency for this particular event was 39% for TSS for a total runoff volume of 862 m^3.

Removal efficiencies for heavy metals (zinc and manganese) were harder to evaluate since concentrations were very low. The 25th June 2009 event was the one with the highest concentrations of the entire sampling campaign. Removal efficiencies for this event were 13 and 53% for manganese and zinc, respectively. This variability is probably due to the fact that different heavy metals are adsorbed on different particle sizes (Tuccillo 2006).

Effect of outlet control

From 21st August 2009 onwards, five rain events were sampled with the retrofitted detention pond. Runoff from both rain events of 21st August (330 m^3 in the morning; 305 m^3 at night) were sampled at the inlet of the detention pond and stored inside the pond for 36 hours starting from the beginning of the first event. Then the pond outlet was opened to about one third of its capacity and the pond emptied itself in approximately 90 min. The second sampling campaign performed with the retrofitted pond took place between 18th and 23rd September 2009. Two rain events were captured during this period, on 18th September (563 m^3) and 22nd (247 m^3) and water was released on the 23rd, 102 hours after the initial closure of the pond. The last sampling campaign took place between 9th and 13th July 2010. Only one rain event was captured but runoff volume was much higher than in the two first sampling campaigns (1,225 m^3). The water was released after 97 hours of storage without perturbation (rain event entering). For all these events, the pond retention time was driven by the weather forecast. The decision of opening the outlet was a compromise between maximizing the retention time and avoiding the potential negative effects (resuspension of particles or pond overflow) caused by the collection of the following event runoff.

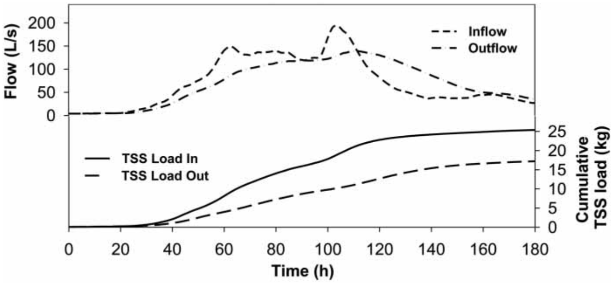

Figure 5 | Flow rates and cumulative TSS loads in stormwater pond for the 2nd August 2009 event.

Table 5 shows the mass of pollutants entering and exiting the pond for the three sampling campaigns. With approximately 4 days of retention time without rain, the third campaign showed better removal efficiency than the first two campaigns, 98% instead of 84 and 87%, for a much higher mass of TSS entering the pond (413 kg of TSS compared to 39 and 60 kg). The difference can thus be explained in two ways: (i) with increased influent concentration, more load is entering, and thus the better the efficiency will be when similar outflow concentrations are obtained; and (ii) the longer the time that is offered for particle settling the better the efficiency will be as well. Indeed,

Table 5 | Inlet and outlet pollutant mass with retrofitted pond

Campaign	Date		Inlet mass	Outlet mass	% reduction
1	08/21/09–08/22/09	TSS (g)	38,946	6,234	84
		Zn (g)	25.4	17.4	32
		NH_3-N (g)	65.1	14.5	78
2	09/18/09–09/23/09	TSS (g)	59,807	8,055	87
		Zn (g)	38	14.1	63
		NH_3-N (g)	163.5	7.8	95
3	07/08/10–07/13/10	TSS (g)	413,277	10,186	98
		Zn (g)	–	–	–
		NH_3-N (g)	568.4	97.3	93

the third campaign offered 4 days for settling but it mainly collected the runoff for only one event, unlike the first two which collected two subsequent events, which may possibly have led to resuspension of sediments in between the two events. Middleton & Barrett (2008) were able to reach an average TSS removal of 91% with their batch-type stormwater detention pond, with a retention time of 12 hours. This difference could be partly explained by the off-line nature of the detention pond studied by Middleton and Barrett. That type of structure collects the overflow of the sewer only at high flows. Neither the small flows nor the finest particles are thus captured in such a system. The settling velocities of the captured particles are thus higher than in the present study, leading to better removal efficiencies.

The average TSS removal of 90% is better than the 80% required in many states and provinces as removal efficiency of structures treating runoff pollutants (MDE 2000; OMOE 2003). For the two first campaigns with closed outlet where zinc was analysed, removal of zinc reached 32 and 63%. It is not a big improvement but it is higher than the average removal efficiency for the events with open outlet (Table 4). Zinc removal of 62% was reported by Middleton & Barrett (2008) for comparable inflow concentrations. Removal of NH_3-N was 78, 95 and 93%.

Figure 6 shows the water height at the pond outlet during the first sampling campaign with the retrofitted pond, as well as runoff flows and TSS loads at the inlet for the first two rain events, and at the outlet once it was opened to empty the pond. The TSS load released in the receiving water body during the emptying of the pond was obviously lower than the load entering the pond even if the releasing flow was higher, leading to a reduced impact on the urban river ecosystem. The outflow rate could easily be reduced to lessen its erosion potential at the discharge point.

Comparing the removal efficiencies of the retrofitted pond to the original one, the retrofitted pond is on average 2.3, 2 and 8 times more efficient than the original detention pond for removal of TSS, zinc and NH_3-N, respectively, whereas manganese removal is 20 times worse (Table 6). The latter could be due to the release of manganese present in the sediments accumulated in the pond. For TSS, removal efficiencies after retrofit are not only higher but are also less variable, showing that the closed outlet permitted a better control on the quality of the water discharged to the receiving water body. It is difficult to directly compare the effect of open or closed outlets because each event is different and the number of retention days has a strong effect on efficiency. However, the last sampling campaign with the retrofitted pond (9th July 2010) can be compared to the 18th June 2008 event with the original pond. Both events are single events, with comparable antecedent dry weather period, rain intensity and EMC_{TSS} (Table 1). For these two specific events, TSS removal efficiency was 47% with open outlet, which is the third best performance observed, and 98% with the retrofitted outlet configuration. This result confirms the conclusion of the overall improvement of retrofitting on the TSS load released to the river.

Figure 7 illustrates that all measured outlet TSS concentrations were much lower when the closed outlet was

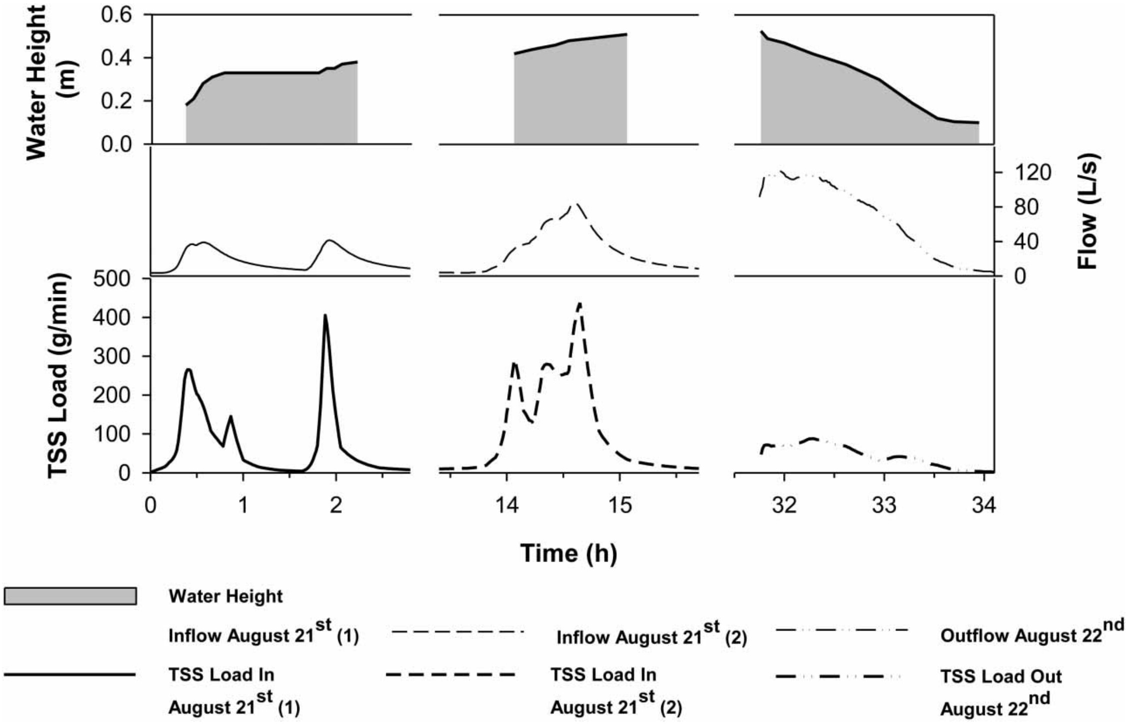

Figure 6 | Water height, runoff flow rates and TSS loads in and out of the retrofitted stormwater pond between 21st and 22nd August 2009.

Table 6 | Effect of retrofit on detention pond removal efficiency by mass

	Before retrofit			**After retrofit**		
	# Sampled events	**Average, %**	**Range, %**	**# Sampled events**	**Average, %**	**Range, %**
TSS	8	39	1 to 67	5	90	84 to 98
Total Zn	9	20	0 to 53	4	42	25 to 58
Total Mn	8	−21	−33 to 13	4	−429	−118 to −739
NH_3-N	7	10	7 to 30	4	84	74 to 94

re-opened than when the outlet was kept opened. For clarity, only events with concentrations below 200 mg/L are presented, which excludes the first four events of Table 1 because they were affected by the construction works in the catchment, as previously explained. In addition to the three closed outlet campaigns presented in Table 5, three more campaigns (3rd June, 21st July and 16th August 2010) are presented in Figure 7. Problems with the inlet sampling during these campaigns prevented their inclusion in mass and removal efficiency calculations.

TSS concentrations were low during the first hours of emptying when re-opening the closed outlet. At the end of the emptying period, when the flow was decreasing, TSS concentrations were increasing but without exceeding 40 mg/L. This increase was due to resuspension of sediments, as the water height decreased and the local velocity increased. The load released in the receiving water body remained low, however, due to efficient removal and low flows. At the end of the emptying period, a permanent pool could be kept in the pond to decrease sediment resuspension, leading to even better removal efficiencies.

The implementation of such a solution could be achieved by the use of an automatic sluice gate and water level sensor. It would then be very important to design a

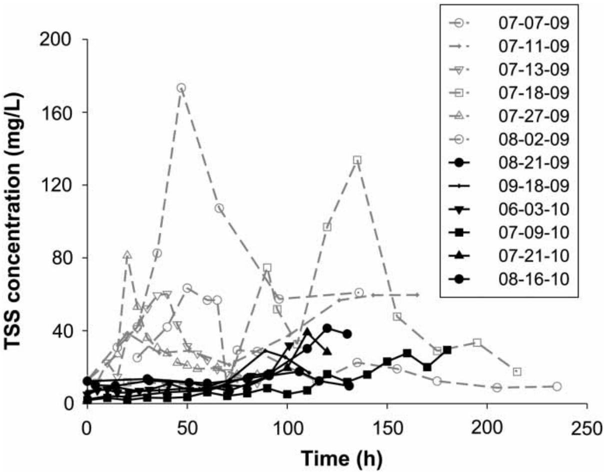

Figure 7 | Outlet TSS concentration for six rainfall events for the open outlet sampling campaign (grey) and six for the closed outlet sampling campaign (black).

set of rules for the control of the outlet sluice gate to ensure optimal benefits regarding the river water quality and the safety of the population (and infrastructures) in their surroundings. These rules should optimize the retention time of the water in the pond to maximize particle settling and take into account weather forecast to have enough time to empty the pond and avoid flooding. First results along this line are reported in Gaborit *et al.* (2013).

CONCLUSION

The present study showed that urban stormwater runoff in Quebec City contained similar concentrations of pollutants as previously reported in Canada and the USA. This study also found that the original detention pond showed removal efficiencies of 39% for TSS, 10% for ammonia, 20% for zinc and −21% for manganese. These relatively poor removal efficiencies are partly due to short-circuiting of the pond through the channel connecting the inlet to the outlet, allowing the first flush to exit the pond with low retention time and thus low removal efficiency.

Retrofitting of the pond to catch and keep runoff for an extended time improved significantly the removal efficiencies for TSS, NH_3-N and zinc, reaching 90, 84 and 42% respectively. Manganese presented negative removal efficiencies probably due to its release from the pond sediments during water retention. Control of the retention time of stormwater ponds is therefore a good means to reduce pollutant loads reaching urban receiving waters, thereby increasing water quality in urban rivers and streams. Of course flexibility must be maintained to fully open the sluice gate in case of an important upcoming rain event.

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