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Seasonal hydrological and water quality performance of individual and in-series stormwater infrastructures as treatment trains in cold climate

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ABSTRACT

The performance of stormwater treatment trains and of their individual green infrastructures was evaluated near Montreal, Canada. Three treatment trains were studied: Train 1 – five bioretention cells in series with a wet retention pond; Train 2 – an infiltration trench in series with a dry detention pond; and Train 3 – Train 2 in series with a wet retention pond. A total of 47 rain events were monitored to quantity the hydrological performance, while water quality samples were taken during 24 rainfall events. During the summer, the bioretention cells led to a reduction in runoff volumes varying from 8 to 100%. Overall, the three studied treatment trains and all of the individual infrastructures, except for the dry pond, provided reductions in the mean concentrations of total suspended solids, chemical oxygen demand, total nitrogen and total phosphorous. Results also showed that the use of a train of stormwater infrastructures can be more effective to reach Quebec's legislated targets than single infrastructures, but only if the infrastructures are sequenced properly. Indeed, the addition of a dry basin at the end of Train 2 affected negatively the removal efficiency of the four studied contaminants.

Key words: bioretention cells, dry basin, infiltration trench, removal efficiency, total suspended solids, wet retention basin

HIGHLIGHTS

- Hydrological and water quality performance of single and in-series (train) stormwater control infrastructures was assessed.
- The use of a train can be more effective for removing contaminants if sequenced properly.
- Adding a dry basin at the end of a train affected negatively the removal efficiency of the four studied contaminants.
- The mean removal efficiency of total suspended solids was positive during the winter months.

INTRODUCTION

The increased imperviousness of ground surfaces in urban areas has two main impacts: water quantity impacts, such as increased runoff volume and peak flows, and water quality impacts such as the degradation of aquatic ecosystems (Hollis 1975). The load of contaminants transported by stormwater runoff depends on the percentage of impervious surfaces and the mass of pollutants (Müller *et al.* 2020). Stormwater management green infrastructure (GI) has been used more and more over time to minimize the hydrological and water quality impacts of urbanization. Through storage, infiltration and evapotranspiration, it is designed to decrease runoff volumes and peak flows, as well as to minimize water pollution from non-point sources. Some widely used GI treatment measures are wetlands, retention ponds, bioretention cells, permeable pavements, infiltration trenches, swales and sedimentation ponds (Tsihrintzis & Hamid 1997; Ahiablame *et al.* 2012; Jayasooriya & Ng 2014).

Implementing a number of GIs in a 'treatment train' has several advantages over implementing a single treatment including providing a more natural flow regime, which favors the biodiversity of habitats (Hatt *et al.* 2006; Bastien *et al.* 2009; Jayasooriya *et al.* 2016). As well, using a number of GIs that provide different types of treatment processes (e.g. settling and filtration) can reduce the risk of system failure when one treatment measure fails. Brown *et al.* (2012) compared the hydrological impact of a treatment train, comprising pervious concrete and a bioretention cell, to that of the bioretention cell alone. Results obtained indicate that the treatment train resulted in the treatment of an additional 10% of the annual runoff volume, the discharge of approximately one-half as much outflow volume and significantly lower peak outflow rates. Jia *et al.* (2015) studied the effectiveness of a treatment train, which included a number of GIs (grassed swales, buffer strip, bioretention cell, infiltration pits, etc.). It was noted that the bioretention cell reduced peak flow by 50–84% and runoff volume by 47–80%, while the grassed swales provided a 17–79% reduction in peak flows and a 9–74% reduction in runoff volume.

There is growing evidence in the literature that placing GIs in series can provide significant water quality benefits (Hathaway & Hunt 2010; Jia *et al.* 2015; Doan & Davis 2017; Winston *et al.* 2020; Irvine *et al.* 2021). The study by Jia *et al.* (2015) showed excellent load removal of ammonia (NH_3-N) (73%), total nitrogen (TN) (74%) and total phosphorous (TP) (95%) and some load removal of chemical oxygen demand (COD) (19%) and total suspended solids (TSS) (35%). The limited removal rate of TSS, in that case, was due to the release of sediments by the newly constructed bioretention cell, which was one of the first GIs in the sequence of the studied treatment train. The addition of an infiltration pit and of grassed swales downstream of the bioretention cell allowed to catch part of these released TSSs, showing the benefits of a treatment train in that case. Winston *et al.* (2020) investigated the water quality impacts of a treatment train consisting of permeable interlocking concrete pavement and underground stormwater harvesting. This sequence led to load removal rates of 99.5 and 59% for TSS and TN, respectively, during the study period (72 rainfall events during a 13-month period). Most of the sediment-bound pollutants were removed by the permeable pavement, demonstrating that it was an effective pre-treatment for the stormwater harvesting cistern. Doan & Davis (2017) analyzed a treatment train for runoff from an impervious parking lot, comprising a bioretention facility under-drained to a cistern to store treated stormwater for irrigation use, for a number of water quality contaminants (TSS, TP, TN and metals). Final concentrations of TP, TN, copper and zinc in the cistern were measured to be lower than those of tap water. The mean concentration removal rate of TSS for the system, comprising the bioretention and the cistern, varied from 78 to 99% for the 27 sampled rainfall events. Hathaway & Hunt (2010) monitored three GIs (wetlands) in series to examine the reduction in TSS, TP, TN and turbidity. At least 80% of the total concentration reduction for all pollutants occurred within the first wetland cell, indicating that GIs in a treatment train do not perform as well as the first when each GI relies on the same removal mechanisms. Irvine *et al.* (2021) studied the performance of a treatment train composed of a rain garden and two detention ponds, where the second pond received runoff from another area in addition to the effluent of the first pond. They found that the rain garden provided a 93% reduction in TSS and TP loads, although for only four monitored rainfall events, and that the mean turbidity level dropped by 56% between the inlet and outlet of the first pond during the 27-week study period, indicating that a portion of the TSS from the rain garden outlet were trapped in the pond. The addition of a detention pond downstream of the rain garden was thus beneficial in that case. Although a number of studies have looked at the hydrological and water quality impacts of treatment trains for urban stormwater management, very few have been carried out in northern climates. The objective of this study is to evaluate and compare the seasonal and overall hydrological and water quality performance of treatment trains and of single GIs (bioretention cells, a draining trench, a dry basin and a permanent retention basin), at a public market site outside of Montreal, Canada.

METHODS

Study site

A 2.4 ha public market in Longueuil, Quebec, south of Montreal, was designed to better manage rainwater. Rainfall on the site passes through one of two treatment trains, comprising a combination of grassed swales, a dry pond, a wet retention pond, infiltration trenches and bioretention cells (see Figure 1).

The treatment train for the front parking area (0.91 ha) is made up of five bioretention cells in series with a wet retention pond. The bioretention cells perform two functions: first, to slow down runoff flow through temporary storage and infiltration (thus contributing to flow volume reduction, peak flow delay and peak flow reduction) and second, to provide contaminant removal through biological and physical processes. The water is then conveyed to the retention pond which was designed to further promote the removal of contaminants via chemical, physical and biological processes, and to provide storage to alleviate flooding downstream.

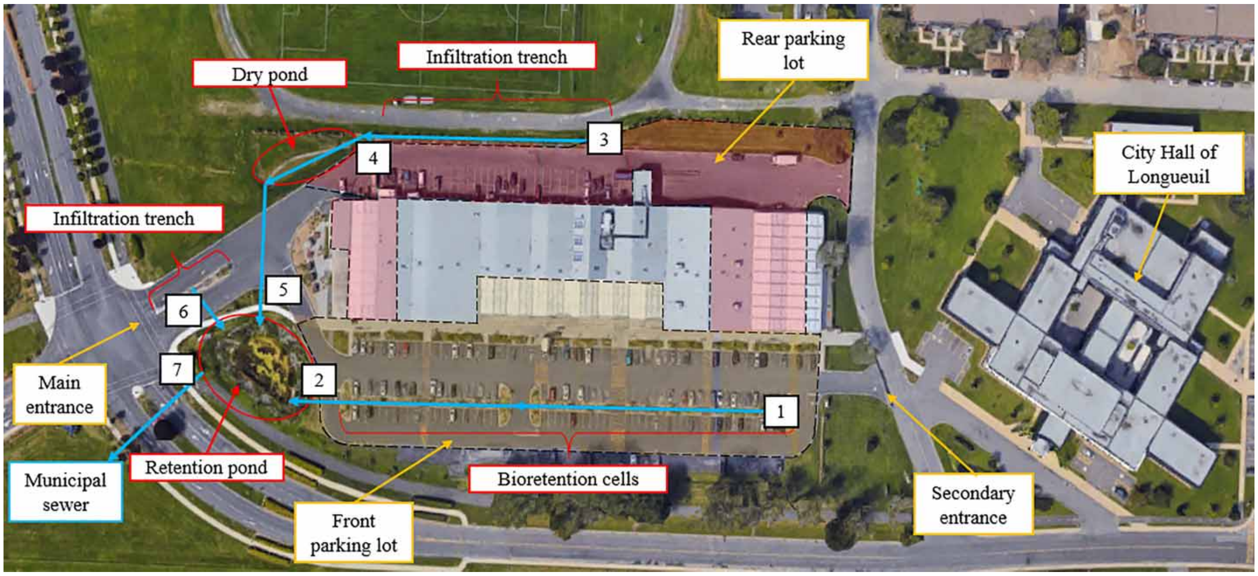

Figure 1 | Public market. Aerial view showing site characteristics (yellow arrows), installed GIs (red arrows), runoff flow direction (blue arrows). The seven water sampling sites are shown on the diagram as follows: (1) influent into bioretention cells, (2) effluent from bioretention cells, (3) influent into infiltration trench, (4) effluent from infiltration trench, (5) effluent from dry pond, (6) effluent from infiltration trench at the entrance of the parking lot and (7) effluent from wet retention pond. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.10.2166/wqrj.2021.026

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The five bioretention cells (2.6 m wide, 26–28 m long and 1.05 m deep) are connected by a 250-mm diameter underdrain pipe, which allows the collection of runoff resulting from a 50-year return period rainfall event (47.5 mm). The soil media used was developed especially for bioretention cells (https://www.savaria.ca/wp-content/uploads/2020/03/Substrat-Bioretention_Natureausol-Natureaufiltre-Sable_drain.pdf; in French). The retention pond was designed for a 100-year return period rainfall event (52.7 mm) to maintain a water depth of 1.2–2.0 m. To facilitate aerobic processes in order to avoid odor nuisance, a 12.5-mm diameter air intake pipe was installed at the bottom of the pond. The outlet is an inlet grate on a manhole located within the pond, which is connected to the municipal system.

The treatment train in the rear parking is made up of an infiltration trench, a dry pond and a wet retention pond. The infiltration trench acts to remove contaminants through physical processes such as adsorption while slowing down the flow of runoff. The dry basin also favors the slowing of runoff flow. Finally, the wet retention pond is added to these two GIs to promote sedimentation of contaminants. The wet retention pond thus receives the flow from the two treatment chains.

Sampling campaign

A sampling campaign took place at the market site from June 2016 to December 2018. During this campaign, the site was instrumented to measure rainfall and inflows to the wet retention pond. Additionally, water samples were obtained at various points in the system (Figure 1) in order to evaluate the contaminant removal efficiency of the individual GIs and the treatment trains. Runoff in the rear parking area was sampled only until August 2017, since construction work started at that time on the adjacent lot, modifying the site configuration and bringing high amounts of TSS.

Quantitative monitoring

A tipping bucket (0.2 mm) Texas Electronics TR-525USW rain gauge was installed on the roof of the market. The data recorded by this instrument was validated by comparing it to the data from Environment Canada's rain gauge at the St-Hubert airport. The Texas Electronics rain gauge did not record between April 12 and June 13, 2018. During this period, the rain data used were recorded by the City of Longueuil's rain gauge, located across the road from the market. These data were verified using data from the St-Hubert airport, as well. The rain gauges at the market and the City of Longueuil were approximately 200 m apart, while approximately 1,500 m separated these from the gauge at the airport. An ISCO 2150 Doppler area velocity flow logger was installed in the pipe connecting the bioretention cells and the wet retention pond (sampling site 2 in Figure 1). Additionally, a Thelmar gauging weir and a graduated container were used to measure inflow to the wet retention pond from the dry pond and from the infiltration trench manually for certain events.

Runoff inflows, such as those into the bioretention cells, which could not be measured, were estimated using the SWMM (Storm Water Management Model; Rossman 2015). The SWMM model was set up to estimate the runoff to the treatment trains. Impervious and pervious catchment areas and average slopes for each treatment train were measured and parametrized in terms of hydraulic connectivity, characteristic width, Manning's *n* for overland flow over impervious and pervious areas and depth of depression storage on impervious and pervious areas, values which were obtained from the design and monitoring experience of the consulting engineers and researchers for similar infrastructure in the same climate. Since a rain gauge was present on site and impervious areas were designed to drain to the treatment trains, uncertainty on runoff from impervious areas is low and simulated runoff flows and volumes can be used for calculating the hydraulic performance. Hydraulic performance was characterized by the retention efficiency of the GIs, percentage decrease in peak flow and flow delay.

Qualitative monitoring

The seven sampling points (as labeled in Figure 1) were selected to characterize the contaminant removal efficiency of the GIs. Site 1 corresponds to the water flowing over the parking lot and into the bioretention cells. The second site (Site 2) is at the outlet of the pipe draining the bioretention cells. Site 3 corresponds to the runoff at the entrance to the infiltration trench, while Site 4 corresponds to the outlet of the pipe draining this trench. Site 5 is the outlet of the pipe connecting the dry basin to the wet basin. The sixth site (Site 6) corresponds to the effluent from the infiltration trench located at the entrance to the front parking lot. Finally, Site 7 corresponds to the manhole connecting the permanent retention basin to the municipal sewer system.

Given that the market was very busy, manual sampling took place, as opposed to the installation of an autosampler, which could be vandalized or stolen. Sampling was dictated by the duration and intensity of the rain events and, thus, proportional to a volume of water over time. One-liter samples were collected over the period of precipitation, with intervals between samples determined depending on the intensity of the rain and with shorter sampling intervals at the beginning of events. These samples were combined and a final composite sample was taken for analyzing the concentrations of TSS, COD, TN and TP. The analytical methods are presented in Supplementary Material, Table SM-1, along with the detection limits.

The performance of the individual GIs and the treatment trains was calculated as follows:

$$Efficiency = \frac{\sum_{i=1}^{n} (Q_{in,i} * C_{in,i}) - (Q_{out} * C_{out})}{\sum_{i=1}^{n} (Q_{in,i} * C_{in,i})}$$

where n is the number of inflows to a GI (or treatment train), $Q_{in,i}$ is the flow from the ith inflow to the GI, Q_{out} is the outflow from the GI, $C_{in,i}$ is the contaminant concentration of the ith inflow to the GI and C_{out} is the contaminant concentration of the outflow from the GI.

RESULTS AND DISCUSSION

Characteristics of rainfall events

Table 1 shows the characteristics of the rain events when samples were collected. Details about these events are provided in Supplementary Material, Table SM-2. The characteristics of rain events used to quantify the hydraulic performance of bioretention cells are given in Table 2. Winter is defined as those months when the average air temperature is $<$10 °C, which translates to the months of October to April, inclusively. The 1981–2010 daily mean temperature and monthly rainfall and snowfall data from Environment Canada's St-Hubert airport meteorological station are presented in Supplementary Material, Table SM-3.

On average, a seasonal difference in the rainfall characteristics is observed: the average duration of events and the number of antecedent days without precipitation are longer in the winter than in the summer, while the amount of rain, the mean rainfall intensity and the maximal 5-min rainfall intensity are higher for summer events.

Hydraulic performance

Bioretention cells

Table 2 shows the percentages of runoff volume reduction achieved through the bioretention cells. Losses correspond to the portion of water that infiltrates the underlying soil, is removed through evapotranspiration or is stored in the soil. The water

Table 1 | Comparison of overall, summer and winter sampled rain events

	Duration of event h	Number of antecedent days without precipitation days	Amount of rain mm	Mean rainfall intensity mm/h	Maximal 5-min rainfall intensity mm/h
Overall (19 events)					
Mean	9:15	3.60	15.60	2.70	15.60
Minimum	1:05	0.30	1.70	0.30	3.80
Maximum	21:15	14.40	85.10	20.50	79.20
Summer (14 events)					
Mean	8:28	2.92	16.83	3.27	18.61
Minimum	1:05	0.30	1.70	0.30	3.80
Maximum	20:20	7.40	85.10	20.50	79.20
Winter (5 events)					
Mean	11:29	5.60	13.51	1.02	7.22
Minimum	6:30	0.70	6.50	0.40	4.80
Maximum	21:15	14.40	20.30	2.00	12.10

that might be present in the soil before the start of the event was not measured and thus not added to the volume generated by the rain. In the summer, this soil moisture is probably low, especially when the number of antecedent days without precipitation is longer than 48 h, but in the winter, it could be significant, leading to an underestimation of the volume of water entering the bioretention cells. For this reason, winter results for volume retention are not reported in Table 2. Results obtained, for the summer season only, show that bioretention cells alone reduce the volume of water reaching the retention basin (8–100%).

The bioretention cells also caused a reduction in peak flows. Reductions in peak flows between 82 and 100%, with an average of 95%, have been observed. Khan *et al.* (2012) reported similar results, with an average decrease in peak flows of 96% varying between 85 and 100%. DeBusk & Wynn (2011) also found an average reduction of 99%.

Finally, in this study, flow delays between 10 min and 3 h, with an average of 52 min, were observed. From June 2016 to August 2017, the flow delay was assessed visually and corresponds to the period when water runoff was first observed on the parking impervious surface and the beginning of the outflow from the bioretention cells. From November 2017 to December 2018, a comparison between the simulated peak runoff inflows and the measured peak outflows from the bioretention cells was used to quantify the flow delay. Results obtained are similar to the delay in peak flows (69 min) found in summer by Muthanna *et al.* (2008) in Norway. The cells are, therefore, effective in delaying and attenuating the flow.

Infiltration trench, dry pond and wet retention pond

The delay produced by the infiltration trench was obtained by comparing the time at which runoff entered the GI and the time when a flow was first observed at the outlet of the pipe connected to the dry basin. Delays between 30 and 45 min were observed. Delays for the combination of the infiltration trench and dry pond were found by comparing the start of the runoff in the infiltration trench to the time when water started to flow at the outlet of the dry basin. Delays between 40 and 50 min were observed. The basin, therefore, allows for an additional delay of at least 5 min.

Results indicate that the addition of the wet basin at the end of the treatment trains allows a total delay in flow rates that varies between 120 and 240 min following the generation of runoff. Since there are a number of inflows into the retention basin, it is difficult to separate the time of outflow for each treatment train. Compared to other infrastructures on the site, this basin contributes the most to delay of runoff flows.

Water quality performance

The 24 rain events listed in Supplementary Material, Table SM-2 were sampled to determine the effectiveness of the individual GIs and the treatment trains in removing contaminants from the runoff.

Table 2 | Hydraulic performance of bioretention cells

Rainfall event	Duration of event (hh:mm)	Number of antecedent days without precipitation (days)	Amount of rain (mm)	Mean rainfall intensity (mm/h)	Maximal 5-min rainfall intensity (mm/h)	Volume retention (%)	Peak flow reduction (%)	Flow delay (hh:mm)
10/13/2016[a]	5.3	4.7	7.1	1.3	9.6	85	96	–
10/16/2016[a]	7.1	4.8	9.1	1.0	15.6	62	96	–
05/25/2017	8.4	2.9	15.2	1.8	12.2	69	93	1:05
05/27/2017	8.8	3.0	9.4	1.1	6.1	77	98	0:55
06/05/2017	12.3	2.5	23.4	1.9	12.2	66	86	0:45
06/27/2017	1.1	1.5	23.9	20.5	79.2	60	91	0:10
07/17/2017[a]	2.3	0.3	1.7	0.7	10.8	100	100	–
07/24/2017[a]	20.3	2.7	8.0	0.6	3.8	54	95	0:55
08/18/2017	2.8	2.9	20.6	5.4	23.4	55	90	0:55
11/25/2017	8:25	3.0	5.2	1.2	4.8	–	82	3:30
12/05/2017	12:45	4.5	7.6	0.5	16.8	–	86	2:35
01/11/2018	21:15	0.7	19.6	0.9	7.2	–	–	2:21
02/19/2018	6:30	3.0	15.2	0.4	4.8	–	35	3:08
03/29/2018	10:35	14.4	13.0	1.1	4.8	–	17	0:25
04/04/2018	4:35	2.8	32.8	1.8	9.6	–	55	0:35
04/12/2018[a]	9:10	8.0	7.0	0.7	7.2	–	56	0:25
04/25/2018[a]	5 :15	7.5	29.3	0.9	6.0	–	25	1 :42
04/29/2018[a]	4:35	1.9	19.3	0.6	3.6	–	22	1:20
05/03/2018[a]	10:55	2.1	13.2	1.1	12.0	–	63	0:25
05/19/2018[a]	16:45	4.1	17.2	1.0	18.0	–	82	1:02
05/27/2018[a]	2:40	1.2	6.4	6.4	31.2	–	92	0:35
05/28/2018[a]	0:35	1.2	5.0	5.0	19.2	–	88	1:00
06/04/2018[a]	5:55	2.8	26.4	0.9	9.6	–	70	0:42
06/13/2018[a]	3:45	7.1	6.2	0.3	9.6	93	93	2:00
06/18/2018	18:45	3.7	41.0	2.1	76.8	41	94	0:10
06/23/2018	13:35	3.1	12.0	0.4	4.8	44	71	3:00
07/17/2018	9:40	2.9	18.8	1.7	36.0	80	95	0:30
07/25/2018	15:30	0.3	29.6	4.1	91.2	50	95	0:35
08/01/2018	3:25	4.1	11.2	2.8	48.0	55	96	0:40
08/17/2018	7:50	7.7	5.2	0.6	9.6	100	100	0:00
08/26/2018	6:50	3.8	10	1.3	38.4	98	99	0:20
08/28/2018	1:50	1.3	8.2	2.7	43.2	49	97	0:50
09/02/2018	11:35	1.3	30.2	3.0	48.0	29	95	0:22
09/03/2018	1:15	0.5	15.8	7.9	81.6	13	94	0:15
09/25/2018	4:20	3.6	8.4	1.7	9.6	44	79	1:02
10/02/2018	13:45	1.0	11.4	1.2	2.4	44	33	1:05
10/08/2018	15:10	1.6	26.00	2.6	38.4	26	89	0:37
10/10/2018	9:10	0.7	12.6	1.2	45.6	–	90	0:47
10/11/2018	10:05	0.8	12.4	1.1	12.0	–	76	0:43
10/15/2018	8:20	3.9	5	0.6	7.2	52	89	1:15
10/27/2018	22:10	3.4	17.6	0.9	7.2	8	70	0:35

(Continued)

Table 2 | Continued

Rainfall event	Duration of event (hh:mm)	Number of antecedent days without precipitation (days)	Amount of rain (mm)	Mean rainfall intensity (mm/h)	Maximal 5-min rainfall intensity (mm/h)	Volume retention (%)	Peak flow reduction (%)	Flow delay (hh:mm)
10/31/2018	9:30	1.8	8.8	0.8	4.8	–	36	0:40
11/01/2018	10:40	1.0	14.4	1.2	4.8	–	51	0:50
11/03/2018	6:05	1.1	13.4	1.91	9.6	–	57	0:35
11/05/2018	8:05	1.8	13.4	0.4	4.8	–	55	1:30
11/09/2018	13:10	2.9	23.2	1.65	4.8	–	31	0:55
11/25/2018	7:50	11.9	14.8	1.64	7.2	–	51	0:55

Winter data are shaded in gray.
[a]Data from the City of Longueuil.

Runoff

Results are summarized in Table 3, with concentrations suggested for a commercial area by MELCC (2014) for comparison. More detailed results are presented in Supplementary Material, Figure SM-1. Results indicate that the quality of runoff from the rear parking area is generally similar to the one suggested for a commercial area, with TSS and TP values being slightly higher. The front parking area had all contaminants measuring noticeably higher, except for TN which is similar to typical values. In general, the front parking area is the main parking lot for the market. Since movement is more frequent in this section of the market, the deposition of contaminants on the ground surface from automobiles is higher. These observations coincide with the findings of Davis & Birch (2011) who specify that TSS is correlated with road traffic. The high COD concentrations are an indication of the organic matter attached to the surface of the solids.

Results obtained for the public market are of the same order of magnitude as those found in the literature. For TSS, an average of 37 mg/L was found in Géhéniau *et al.* (2014), which is lower than the results of this study. This difference may be explained by the less frequent traffic at the store studied by Géhéniau *et al.* (2014), compared to the public market, which hosts different shops, as well as the number of parking spots which is at least double at the public market. It may also be a result of different sampling methods. In this study, each rain event was sampled individually to create composite samples for each of the sampled events. In Géhéniau *et al.* (2014), water was collected over a period of time, which may have covered more than one rain event, possibly causing a dilution effect. Concentrations for TN were only slightly lower in Géhéniau *et al.* (2014) (1.3 mg/L) than in this study (1.5 mg/L – rear parking; 1.6 mg/L – front parking); however, Géhéniau *et al.* (2014) found concentrations of TP (0.1 mg/L) that were significantly lower than those found at the front parking

Table 3 | Mean concentrations (±standard deviation) of stormwater pollutants in runoff: public market case study versus typical commercial area

Contaminant	Season	Rear parking	Front parking	Typical commercial area (from MELCC 2014)
TSS (mg/L)	Summer	55 ± 76	77 ± 70	n.a.
	Winter	29 ± 8	129 ± 106	n.a.
	Overall	48 ± 65	99 ± 88	43
COD (mg/L)	Summer	59 ± 41	102 ± 67	n.a.
	Winter	32 ± 11	62 ± 32	n.a.
	Overall	52 ± 32	84 ± 57	63
TP (mg/L)	Summer	0.30 ± 26	0.60 ± 0.46	n.a.
	Winter	0.20 ± 0.21	0.90 ± 0.38	n.a.
	Overall	0.27 ± 0.26	0.70 ± 0.44	0.2
TN (mg/L)	Summer	1.4 ± 0.7	1.6 ± 1.0	n.a.
	Winter	1.6 ± 0.5	1.6 ± 0.8	n.a.
	Overall	1.5 ± 0.5	1.6 ± 0.9	1.6

area of the market (0.7 mg/L). Having a large garden center outside the building, it is not surprising to see higher nutrient concentrations at the public market.

During the winter, although the snow falling on the market parking lot is not shoveled on the bioretention cells, most of the snow that falls directly on it remains there. This snow can contain pollutants and when the snow melts, it can percolate through the bioretention cells. The collection of treated meltwaters (without runoff water), from the outlet of the pipe that drains the bioretention cells, was carried out on April 4 and December 2, 2018. Following these analyses, it was found that the pollutant concentrations in this treated meltwater are very low (<10 mg/L) for TSS and close to the analytical detection limit for TN and TP (Supplementary Material, Table SM-1). Water from the melting of snow on bioretention cells does not significantly contribute contaminants to the effluent. However, this water does help leach out soluble contaminants stored in the soil.

Individual green infrastructures

The calculation of efficiency in terms of percentage decreases in concentrations follows the Quebec provincial regulation, which presents a target of 80% decrease in TSS concentration for 90% of events of annual precipitation (LegisQuebec 2021). Average individual retention efficiencies for the bioretention cells, wet retention pond, infiltration trench and dry pond are given in Figure 2.

Bioretention cells. Bioretention cells remove, on average, 84% of TSS from runoff (Figure 2(a)). This result is slightly higher than the removal rate of 75% found by Généniau *et al.* (2014) and 60% found by Hunt *et al.* (2008), but similar to that of the projects of Yu *et al.* (1999) and the MRC-Brome-Missisquoi (2015), having obtained an average removal of 86 and 87%, respectively, and lower than that obtained by Khan *et al.* (2012). The differences in the removal efficiencies between studies relate directly to the differences in influent concentrations. In Généniau *et al.* (2014), the influent concentration averaged 37 mg/L, compared to between 200 and 600 mg/L in the study by Khan *et al.* (2012). At the market in Longueuil, the influent values averaged 90 mg/L. Furthermore, the removal efficiency for TSS during the winter is higher than during the summer, which relates to the higher influent concentration in the winter (129 mg/L) compared to that in the summer period (51 mg/L).

An overall reduction (33%) in COD is observed. The range of values found varies between −142 and 83%. The rain event on the one sampling day (June 27, 2017) that resulted in a large release of COD (−142%) produced a large amount of precipitation (23.9 mm) over a short duration (1.05 h) after another event 1.5 days prior. As a result, the average retention for the summer months was much less than that in the winter. The bioretention cells, however, were relatively efficient overall for the removal of COD compared to those in the study by Généniau *et al.* (2014) where an average removal rate of −50% was obtained.

The bioretention cells show a slight overall release of TN (−5%) and only minor retention of TP (6%), with efficiencies during winter months significantly exceeding these values and significant releases seen in the summer months. Literature values indicate that bioretention cells tend to release TP with Généniau *et al.* (2014) reporting an average efficiency of −65% and MRC-Brome-Missisquoi (2015) showing an average release of 350%. Osman *et al.* (2019) indicate that the removal efficiency of different pollutants in bioretention cells is generally satisfactory, except for nitrogen in certain bioretention systems explaining that nitrogen has a complex biogeochemical cycle, resulting in a removal process that is typically slower than other pollutants.

The overall higher contaminant retention efficiency in the winter can be related back to the characteristics of the rainfall events. As indicated in Table 1, there is a seasonal difference in rainfall characteristics, with the winters having a longer duration, lower intensity rainfalls of smaller amounts on drier soils, while summers are characterized by shorter, more frequent, higher intensity events that produce larger amounts of precipitation. During the winter, the amount of water treated by the cells is significantly less and any water added to the cells will move more slowly through the GI, thereby allowing for more time for the removal of contaminants.

Wet retention pond. Results for the wet retention pond (Figure 2(b)) indicate relatively low overall removal efficiency for COD (8%), TN (28%) and TP (40%), and a release of TSS (−20%). These results are lower than those found in the literature. Clary *et al.* (2017) obtained a median TSS removal rate of 69%, and Tondera *et al.* (2018) found a 77% removal efficiency for TSS. These studies, however, have influent concentrations that are much higher than those found in this

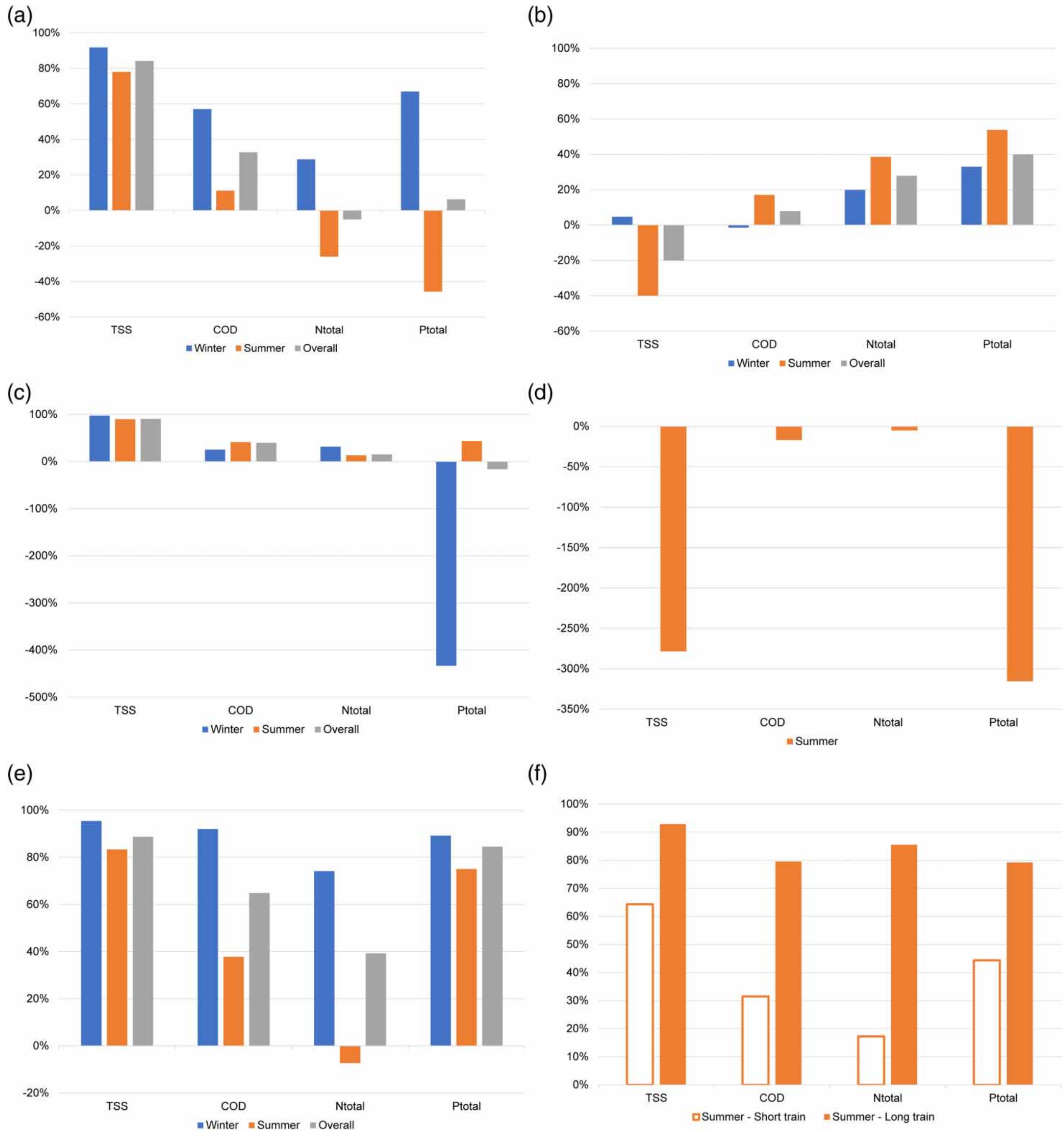

Figure 2 | Average concentration removal rate for (a) bioretention cells; (b) wet retention pond; (c) infiltration trench; (d) dry basin; (e) front parking treatment train and (f) rear parking treatment trains.

study. TSS retention is more efficient in the winter; however, retention of COD, TN and TP is shown to be more efficient in the summer (Figure 2(b)).

It should also be noted that the results in this study vary greatly over the sampling season. For instance, the minimum and maximum efficiencies calculated for TSS removal by the retention pond are −136 and 59%, respectively. The retention pond does have a positive effect on the removal of TN and TP. The Charles River Watershed Association (2008) in Massachusetts reported that retention ponds provided between 10 and 75% removal for TP and 10 and 50% removal for TN. These two pollutants being nutrients are necessary for the metabolic functioning of plants (Khiari 2016); therefore, their uptake reduces concentrations in the basin. The water entering this GI has already been treated by one or more GIs and, as a result, the inflow is less loaded with pollutants and close to the irreducible concentration, which is the concentration impossible to make smaller with conventional treatment processes (Schueler & Holland 2000).

Infiltration trench. Overall removal efficiency of the infiltration trench (Figure 2(c)) for TSS and COD is comparable to the bioretention cells with average efficiencies of 90 and 39%, respectively, for the infiltration trench compared to 84 and 33%, respectively, for the bioretention cells. Results obtained are comparable to those of the Toronto & Region Conservation (2015) where an average TSS removal efficiency of 98% was obtained from an infiltration trench in a parking lot in Ontario.

For TN and TP, the efficiencies overall are 15 and −16%, respectively. The infiltration trench appears to have little effect on the removal of TN, with an efficiency that is much lower than the 60% obtained by the Toronto & Region Conservation (2015). Results as shown in Figure 2(c), indicate that there is a large release of TP during the winter. It should be noted, however, that the winter values in this figure are based only on one sampling day. The overall efficiency for TP is greatly affected by this one value and would be 43% (rather than −16%) overall without including it. Even at 43% efficiency, this is still lower than the 93% found in the Toronto & Region Conservation (2015) study.

Dry pond. Unlike the infiltration trench and bioretention cells, the dry basin does not contribute to the removal of contaminants (Figure 2(d)). Dry ponds, in fact, do not provide water quality enhancements due to the bottom scour that occurs with each rain event (Alberta Government 2013). In this study, average releases of −279% (TSS), −17% (COD), −5% (TN) and −316% (TP) were calculated. These values are for samples taken in the summer of 2017 only. Sampling in the dry pond did not take place in the winter months and, in 2018 during the summer, an adjacent construction site was using the dry pond to discharge water with large amounts of sediment. Since water does not stay for long in the pond (about 5–10 min), there is little treatment of the water flowing through this GI. This water picks up contaminants (bottom scour) and flushes these out with each rain event.

Treatment trains

Front parking treatment train. The treatment train made up of bioretention cells and the wet retention basin allows an average overall removal of 89% of TSS (Figure 2(e)). Compared to the overall removal rate of the bioretention cells on their own (84%; Figure 2(a)), the addition of the retention basin adds little qualitative treatment for TSS. Seasonal efficiencies follow this trend as well. For COD retention, the overall efficiency for the treatment train is 65%, which is a marked improvement over the bioretention cells on their own (33%). The seasonal values also show that the addition of the pond significantly increases the efficiency of COD retention in both summer and winter. This trend is also evident for TN and TP, although there is still an indication of a release of TN, however minor, from this treatment train during the summer season.

The bioretention cells and the wet retention pond both use biological and physical contaminant removal processes relying mainly on filtration and adsorption for the bioretention cells and plant uptake and sedimentation for the pond. The results indicate that the use of two different types of GIs, resulting in stormwater being subjected to multiple processes for the removal of contaminants, is more effective than using just one GI type. In this case, TSS removal was mainly from the bioretention cells; however, COD, TN and TP were more effectively removed in the wet retention pond, likely through plant uptake.

As previously discussed, the bioretention cells were more efficient in the winter for the removal of all contaminants. The wet retention pond was found to be more efficient in the summer for all contaminants except for TSS. Overall, the treatment train is more efficient in the winter, compared to the summer, although gains of the treatment train, over just the bioretention cells, are significant in both seasons.

Rear parking treatment train. Results are given in Figure 2(f) for the short (infiltration trench and dry basin) and long (infiltration trench, dry basin and wet retention basin) treatment trains in the rear parking, for the summer only. For the short train, the infiltration trench (Figure 2(c)) contributes mainly to the removal of contaminants from the runoff, while the dry basin does not improve the quality of the water (Figure 2(f)). In fact, the addition of the dry basin reduces the treatment efficiency. When the wet retention basin is added to the treatment train (long train; Figure 2(f)), additional treatment takes place and compensates for the release of contaminants from the dry pond. During the sampling campaigns, only one winter rain event produced flow for the infiltration trench, and there was no flow to enable sampling in the dry pond. As a result, more study during winter events needs to be done before any conclusions on the seasonal efficiency of these treatment trains can be made.

CONCLUSIONS

The objective of this study was to evaluate and compare the seasonal and overall hydrological and water quality performance of bioretention cells, an infiltration trench, a dry basin and a wet retention basin, alone and in series. Three treatment trains were analyzed: (1) bioretention cells + wet retention basin; (2) infiltration trench + dry basin; and (3) infiltration trench + dry basin + wet retention basin. The study was carried out at a public market site outside of Montreal, Canada.

Results of this study show that the treatment trains installed at the site provide overall efficient contamination removal based on the provincial regulation target of 80% decrease in TSS concentration for 90% of events of annual precipitation. The treatment trains were well designed for hydraulic performance to ensure longer retention times of the runoff on the site, which allows for various treatment processes to remove contaminants (adsorption, infiltration, sedimentation, etc.). The front parking treatment train (bioretention cells + wet retention basin) performs well all year long and was shown to be more efficient for contaminant removal during the winter. This is particularly important for the removal of road sand used in the winter on the parking lot. The long rear parking treatment train, comprising the infiltration basin, dry pond and wet retention pond, is also efficient for the removal of contaminants. The short rear treatment train (infiltration trench + dry basin), however, is not as efficient and actually releases contaminants. This is due to the dry pond, installed between the infiltration trench and wet retention pond, which provides little flow retention and releases contaminants. Care should be taken when using a dry pond as an end-of-pipe GI, due to the possibility of contaminant release; however, it can be effective for erosion and flood control. The addition of the wet retention pond as the end-of-pipe GI allows for enhanced removal of TN and TP, due to the longer retention times that allows for increased plant uptake, prior to the release of water into the municipal system. In the rear parking treatment trains, the wet retention pond offsets the release of contaminants by the dry pond.

Overall, results indicate that the use of a train of GIs is more effective for removing the studied contaminants, compared to the use of just one GI. It is, however, important to sequence GIs to achieve the various goals of stormwater management (capture and slow, infiltrate and clean, store and convey). In this study, this has been effectively done in the front parking train (bioretention cells + wet retention basin) and in the long train in the rear parking lot (infiltration trench + dry basin + wet retention basin). This study is one of the few that have attempted to characterize stormwater treatment trains in cold climates. Results of this study indicate that the individual GIs have varying seasonal efficiencies for the studied contaminants that should be taken into consideration when designing treatment trains for cold weather conditions. More seasonal data on the hydraulic performance (in particular, snowmelt and soil moisture) and contaminant removal capacities of individual GIs and treatment trains are required before more definite conclusions can be made.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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