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 infrastructure 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 quantify 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 to remove those four contaminants, but only if the infrastructures are sequenced properly. Indeed, the addition of a dry basin at the end of Train 2 reduced the removal efficiency of the four studied contaminants.

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

HIGHLIGHTS

- Hydrologic 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 reduced 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). A load of contaminants transported by stormwater runoff depends on the percentage of impervious surface 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 hydrologic 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 basins, 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 hydrologic 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) (93%) 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 observed during a 13-month period). Most of the sediment-bound pollutants were removed by the permeable pavement structure, demonstrating that it was an effective pretreatment 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 of 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 detention pond downstream of the rain garden was thus beneficial in that case. Although a number of studies have looked at the hydrologic 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 hydrologic 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 promote the slowing of 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.
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 the 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 the rain gauge at the St-Hubert airport (installed by Environment Canada). It is noted that 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 gauge for the City of Longueuil, 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 at the site, were estimated using the SWMM (Storm Water Management Model; Rossman 2015). The SWMM model was set up to estimate the runoff to the three treatment trains. Impervious and pervious catchment areas and average percent slopes for each treatment train were measured and parametrized in terms of hydraulic connectivity, characteristic width, Manning’s $n$ for overland flow over the impervious and pervious areas and depth of depression storage on the impervious and pervious areas, values of 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 the impervious areas were designed to drain to the treatment trains, the 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, the percentage decrease in peak flow and the flow delay over time.

Qualitative monitoring

The seven sampling points (as labeled in Figure 1) were selected to characterize the water quality 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 city’s 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, therefore, 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 Table SM-1, along with the detection limits.

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

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

where $n$ is the number of inflows to a GI (or treatment train), $Q_{in,i}$ is the flow from the $i$th inflow to the GI, $Q_{out}$ is the outflow from the GI, $C_{in,i}$ is the contaminant concentration of the $i$th 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 Table SM-2. The characteristics of the rain events that were 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 $<10 \, ^{\circ}C$, 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 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
that might be present in the soil before the start of the event was not measured and thus not added to the volumes 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 that it is 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 volumes 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 bioretention cells was carried out to quantify the flow delay. The 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 rate of flow while spreading it over time.

Infiltration trench, dry pond and wet retention pond

The delay time 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. Delay times between 30 and 45 min were observed. The delay times 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 to the outlet of the dry basin. Delay times between 40 and 50 min were observed. The basin, therefore, allows for an additional delay time 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 the delay of runoff flows.

Water quality performance

The 24 rain events listed in Supplementary Table S-1 were sampled to determine the effectiveness of the individual GIs and the treatment trains in removing contaminants from the runoff.

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

|                      | Duration of event h | Number of antecedent days without precipitation | 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                                |
Table 2 | Hydraulic performance of bioretention cells

| Rainfall event | Duration of event (hh:mm) | Number of antecedent days without precipitation | 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) |
|----------------|---------------------------|-----------------------------------------------|--------------------|-------------------------------|----------------------------------------|---------------------|------------------------|---------------------|
| 10/13/2016a    | 5.3                       | 4.7                                           | 7.1                | 1.3                           | 9.6                                    | 85                  | 96                     | –                   |
| 10/16/2016a    | 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                |
| 07/17/2017a    | 2.3                       | 0.3                                           | 1.7                | 0.7                           | 10.8                                   | 100                 | 100                    | –                   |
| 07/24/2017a    | 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     | 4.5                       | 0.7                                           | 19.6               | 0.9                           | 7.2                                    | –                   | –                      | 2:21                |
| 02/19/2017     | 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                |
| 04/12/2018a    | 9:10                      | 8.0                                           | 7.0                | 0.7                           | 7.2                                    | –                   | 56                     | 0:25                |
| 04/25/2018a    | 5:15                      | 7.5                                           | 29.3               | 0.9                           | 6.0                                    | –                   | 25                     | 1:42                |
| 04/29/2018a    | 4:35                      | 1.9                                           | 19.3               | 0.6                           | 3.6                                    | –                   | 22                     | 1:20                |
| 05/03/2018a    | 10:55                     | 2.1                                           | 13.2               | 1.1                           | 12.0                                   | –                   | 63                     | 0:25                |
| 05/19/2018a    | 16:45                     | 4.1                                           | 17.2               | 1.0                           | 18.0                                   | –                   | 82                     | 1:02                |
| 05/27/2018a    | 2:40                      | 1.2                                           | 6.4                | 6.4                           | 31.2                                   | –                   | 92                     | 0:35                |
| 05/28/2018a    | 0.35                      | 1.2                                           | 5.0                | 5.0                           | 19.2                                   | –                   | 88                     | 1:00                |
| 06/04/2018a    | 5:55                      | 2.8                                           | 26.4               | 0.9                           | 9.6                                    | –                   | 70                     | 0:42                |
| 06/13/2018a    | 5:45                      | 7.1                                           | 6.2                | 0.3                           | 9.6                                    | –                   | 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                           | 45.2                                   | 49                  | 97                     | 0:50                |
| 09/02/2018     | 11:35                     | 1.5                                           | 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.)
Runoff

Results are summarized in Table 3, with concentrations suggested for a commercial area by MELCC (2014). More detailed results are presented in Supplementary 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 P-values being slightly higher. The front parking area had all contaminants measuring noticeably higher, except for N which equaled the suggested value. 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.

The 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 N were only slightly lower in Géhéniau et al. (2014) (1.5 mg/L – rear parking; 1.6 mg/L – front parking); however, Géhéniau et al. (2014) found concentrations of P (0.1 mg/L) that were significantly lower than those found at the front parking area of the

### 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     | 15:10                     | 2.9                                                   | 23.2               | 1.65                          | 4.8                                    | –                   | 51                       | 0:55             |
| 11/25/2018     | 7:50                      | 11.9                                                  | 14.8               | 1.64                          | 7.2                                    | –                   | 51                       | 0:55             |

Winter data are shaded in gray.

aData from the City of Longueuil.

### 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                                       |
| P (mg/L)    | Summer | 0.30 ± 0.26  | 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                                      |
| N (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                                      |
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 stored 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 Table SM-1). It can be concluded that the 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 Géhéniau 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 concentration between the studies. In Géhéniau et al. (2014), the influent concentration averages 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 average 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 (53%) in COD is observed. The range of values found for this project 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 Géhéniau et al. (2014) where an average removal rate of −50% was obtained.

The bioretention cells in this study show a slight overall release of TN (−5%) and only minor efficiency in the 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 P with Géhéniau et al. (2014) reporting an average efficiency of −65% and the 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. They go on to explain 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 dryer soils, while summers are characterized by shorter, more frequent, higher intensity events that produce larger amounts of precipitation. This means that 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 the
current 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 current 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 nitrogen and phosphorus. The Charles River Watershed Association (2008) in Massachusetts also maintains that retention ponds provide between 10 and 75% removal for P and 10 and 50% removal for N. 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

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.
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.** The overall removal efficiency of the infiltration trench (Figure 2(c)), for TSS and COD, is comparable to that of the bioretention cells with average efficiencies of 90 and 59%, respectively, for the infiltration trench compared to 84 and 33%, respectively, for the bioretention cells. The 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 in this study appears to have little effect on the removal of nitrogen, with an efficiency that is much lower than that 60% obtained by the Toronto & Region Conservation (2015). The results, as shown in Figure 2(c), indicate that there is a very large release of P during the winter. It should be noted, however, that the winter values for this graph 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, a large construction site was using the dry pond to discharge water, which included a large amount of sediment. Since water does not stay for long in the pond (about 5–10 min flow retention), there is little treatment of the water flowing through the 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 N, however minor, from the 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 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, during this study, 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 in 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 hydrologic and water quality performance of bioretention cells, a draining trench, a dry basin and a permanent retention basin, alone and in series. Three treatment trains were analyzed: (1) bioretention cells + 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 act on the contaminants (adsorption, infiltration, sedimentation, etc.). The front parking treatment train (bioretention cells + 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, the dry pond and the wet retention pond, is also efficient for the removal of contaminants. The short rear treatment train (infiltration trench + dry basin), however, is not efficient and actually releases contaminants. This is due to the dry pond, installed between the infiltration basin and the 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 and can be used for these purposes. The addition of the wet retention pond as the end-of-pipe GI allows for enhanced removal of TN and TP, due to the long retention time of the water 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, the 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 which makes it important to take this into consideration when designing treatment trains for cold weather conditions. More seasonal data on the hydraulic performance (in particular, snowmelt and soil moisture effects) 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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