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BOTTOM SEDIMENT CHARACTERISTICS IN STORMWATER PONDS AND WETLANDS IN CALGARY, ALBERTA

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Abstract: This paper presents the characteristics of metals and nutrients concentrations in bottom sediment from two wet ponds and two wetlands in Calgary, Alberta. Sediment cores were sampled at four to six locations along the flow path in each facility. In total, twenty-six core samples were taken from the four facilities. Each core was processed in the lab and sediment samples were extracted from different deposited layers. Seventy sediment samples were extracted from the cores and were analyzed for nutrients and metals concentrations. In general, pollutants concentrations of Fe and Zn are higher in the wet ponds than in the wetlands, but Mg, K, Ca, S and TN are higher in the wetlands than in the wet ponds. The values of Mn and P were fairly similar between the wet ponds and wetlands. Also, it was observed that in general, the pollutants concentrations decreased along the flow path and with depth of the sediment.

1 INTRODUCTION

Runoff from urban catchments often contains significant amounts of pollutants (e.g., sediments, metals and nutrients). The sources of these pollutants are numerous and their release into the environment is governed by several complex mechanisms (Davis et al., 2001). The sources of some metals are directly related to human activities such as: lead (Pb), copper (Cu), Sodium (Na) and zinc (Zn) from road activities; potassium (K) and manganese (Mn) from farming and fertilizing activities; and aluminum (Al) and iron (Fe) from construction activities (Nelson and Booth, 2002; Frost et al. 2015). High concentrations of metals would prevent the reuse of the dredged sediment as a residential fill material. Nutrients such as phosphorus (P) and nitrogen (N) naturally exist in water bodies, but their concentrations can significantly increase due to runoff from pasture and croplands, atmospheric deposition, and seepage from sewage systems (US EPA, 2000). High concentrations of nutrients in the bottom sediments may have a significant impact on the water quality and may result in eutrophication. Therefore, there is a need to understand the loading, deposition, and cycling of the pollutants in urban stormwater facilities (Song et al. 2017).

In urban areas, stormwater facilities (e.g. wet ponds and wetlands), if properly designed, can improve water quality by removing pollutants such as suspended sediments, heavy metals and particulate nutrients (Muthukrishnan, 2010). The most dominant pollutant removal mechanism in these facilities is attributed to the settlement of suspended particles on the pond bottom (Marsalek and Marsalek, 1997). Once deposited, water quality is further modified through a complex set of physical, chemical and biological processes between the bottom sediment and the overlaying water (Reddy and DeLaune, 2008). These processes are significantly affected by the pond's morphological characteristics such as surface area, shape, depth, volume and substrate composition. The Alberta stormwater management guidelines (AENV, 2001) require that stormwater facilities to be designed to remove a minimum of 85% of sediment with a particle size of 75 μm or greater. The environmental quality guidelines for Alberta surface waters (AEP, 2018) includes a set of sediment quality guidelines which were adopted from the Canadian sediment quality guidelines (CCME, 2002) and the Ontario guidelines for the protection and management of aquatic sediment (MOE, 2008). The CCME (2002) provides contamination values (mostly for organic matters and pesticides in freshwater sediment) for the probable effects level (PEL) which is the concentration above which adverse biological effects frequently occur. The MOE (2008) defines two levels of sediment contamination by metals and nutrients: lowest effect level (LEL) and severe effect level (SEL). Unless continuous field monitoring is conducted (which is economically unfeasible to perform on each facility), it is a challenge for municipalities and stormwater professionals to assess the performance of stormwater facilities against these guidelines. This is because the overall operation of these facilities largely depends on complex interactions between several factors such as: the hydrological conditions, catchment land use, pond design parameters and maintenance practices. Therefore, there is a need to conduct comprehensive studies to evaluate the integrated effect of these factors on the performance of these systems.

Knowledge of the deposited sediment characteristics is needed for assessing the efficiency and improving our understanding of the complex processes governing the performance of these facilities. In this study the characteristics of bottom sediments from two wet ponds (~3 m deep) and two stormwater wetlands (~1 m deep) in the City of Calgary, Alberta, have been investigated. This is part of a comprehensive research study aiming at quantifying the sediment and nutrient loadings to ponds/wetlands and to investigate the processes that govern their transport, deposition and cycling within the ponds/wetlands. The results from this study will be used to develop improved design and operation guidelines for stormwater facilities. Although, sediment samples were analyzed for physical properties (i.e., particles size, bulk density and water content), metals (i.e., manganese Mn, iron Fe, zinc Zn, sodium Na, magnesium Mg, potassium K, calcium Ca), and nutrients (i.e., phosphorus P, sulfur S, total nitrogen TN) concentrations, for brevity, only the results for selected metals and nutrients are presented in this paper. Differences between the sediments' characteristics in the wet ponds and wetlands were examined. Also, the horizontal and vertical variability of each parameter were analyzed and observed trends highlighted.

2 METHODS

2.1 Study Sites

Two wet ponds: Auburn Bay (AB) and Cranston (CR) in the southeast corner of Calgary and two stormwater wetlands: Royal Oak (RO) and Rocky Ridge (RR) in the northwest corner of Calgary, were selected for this study. An aerial view of these facilities is presented in Figure 1. AB and CR (both built between 2006 and 2007) were excavated during the development of these subdivisions, but RO and RR (built in 2000 and 1995, respectively) were existing depression/wetlands that were adapted for stormwater use. More detailed information on the catchments characteristics of each pond/wetland is available in Ahmed et al. (2019). AB and CR are serving residential catchment areas of 200 and 120 ha, and their surface area at normal water level (NWL) is 32,000 and 22,000 m^2, respectively. The average normal water depth within these two wet ponds is ~3.0 m and both ponds have a sedimentation forebay separated from the rest of the pond by a constructed berm (Figure 1). The distance along the flow path (from the furthest inlet to the outlet) is 300 and 280 m for AB and CR, respectively. AB has one inlet and CR has two inlets. All inlets are located in the sedimentation forebay. RO and RR have catchment areas that are similar in size, ~14 ha, and their surface areas at NWL are 5,500 and 11,800 m^2, respectively (Figure 1). The average normal water depth within these two wetlands is about 0.8 m. The distance along the flow path is 130 and 90 m for RO and RR, respectively. RO has two inlets. Inlet 2 discharges into a sedimentation forebay within the main water body (referred to as the eastern basin) where the water depth is ~1.5 m. Downstream of the forebay, the depth decreases to ~0.9 m; water then flows through a heavily vegetated narrow channel where the water depth decreases to ~0.3 m at NWL and then discharges into a smaller slightly deeper (~0.5 m) basin (referred to as western basin) near the outlet. Inlet 1 discharges into the western basin but the volume of flow entering via this inlet is minimal. RR does not have a sedimentation forebay but has a sediment vault (settling basin) with an overflow weir and bypass pipe upstream of the pond. The normal water depth of ~0.8 m is fairly uniform across the pond. For all four study sites, the catchment areas have a residential land use with the percent imperviousness ranging from 50% to 60%.

2.2 Sediment Sampling and Processing

In September 2018, sediment core samples were collected at all four facilities using a 5 cm diameter and 50 cm long Wildco ® hand corer equipped with a 4.5 m long extension handle. Cores were collected from an inflatable boat or by wading whenever the water depth was less than 0.8 m. The corer was pushed vertically into the bottom sediments until the sediment was stiff enough to prevent the corer from penetrating it further or the deposited sediment depth was greater than the corer length (i.e. 50 cm). For AB and CR, when possible, parts of the native clay fill were sampled in the bottom of the cores. For RO and RR, there was no clay fill as these are natural wetlands adapted for stormwater use. Upon their removal from the water, the sediment cores were labeled and stored in a cooler.

The cores were sampled at five to six locations along the primary flow path in each pond/wetland. In general, 3 to 4 cores were collected near the inlet and within the sedimentation bay, one core half way along the primary flow path, and another core near the outlet. Additional cores were also taken away from the primary flow path to investigate the distribution of pollutants within the water body. In each pond, one field duplicate core sample was collected within 5 meters of the original sampling location and labeled with the letter "T" (with the exception of core CR-1T which was ~30 m downstream of CR-1). The locations and labels of these cores in each pond/wetland are shown in Figure 1. In total, twenty-six cores were collected (seven in AB and CR, and six in RO and RR) from the four facilities and the core depths ranged from 4 to 50 cm. Each core was processed in the University of Alberta Hydraulics laboratory and between 1 and 4 sediment samples were extracted from each core at different depths based on a visual inspection of the strata in each core. Accordingly, between 16 and 20 samples were extracted from each facility. An image of a collected sediment core is shown in Figure 2. In total, seventy (70) sediment samples were extracted from all cores and sent to the Natural Resources Analytical Laboratory at the University of Alberta for the determination of the particle size distribution, nutrients and metals concentrations, and moisture content.

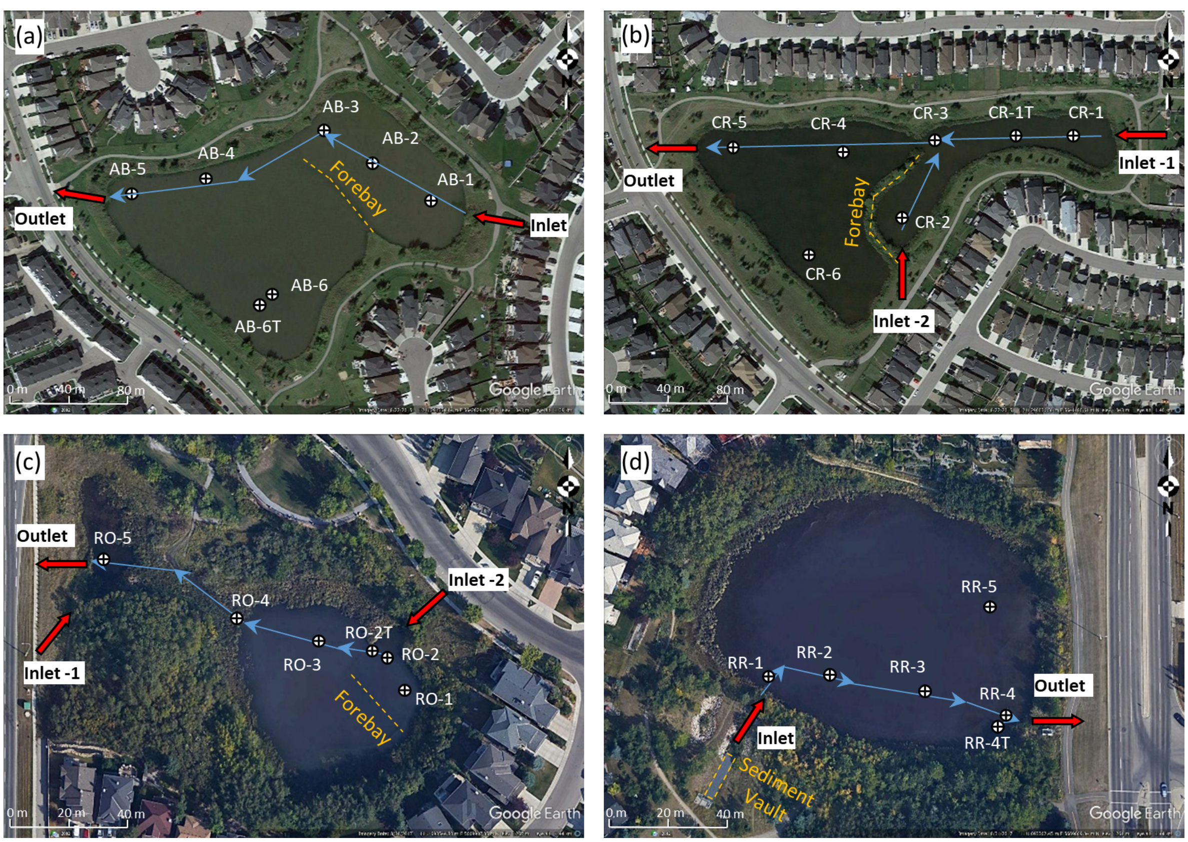

Figure 1: Aerial view of the study ponds: (a) Auburn Bay, (b) Cranston, (c) Royal Oak, and (d) Rocky Ridge [Image source: Google Earth © 2018 Google]. The symbol ⊕ indicates core location, blue arrow indicates the flow path, and the red arrow indicates the locations of inlets/outlets.

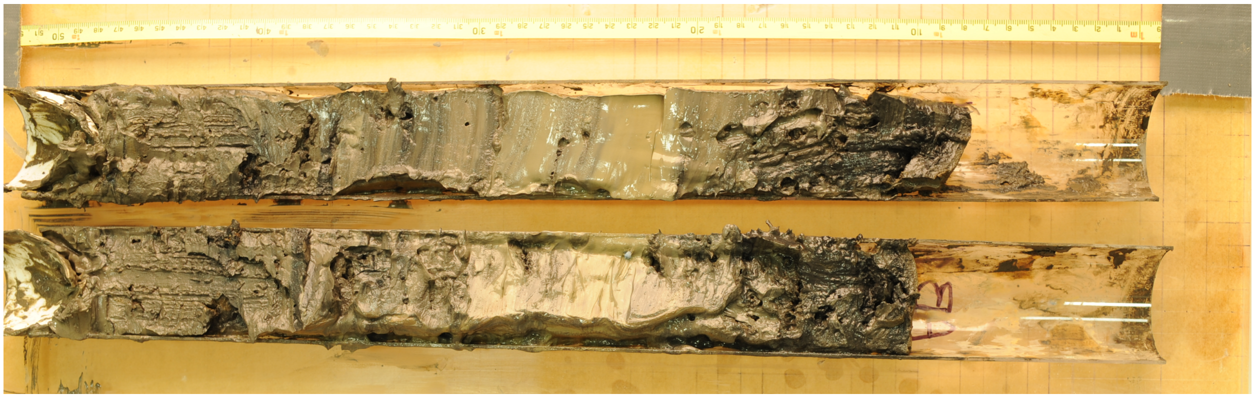

Figure 2: A photo of a sediment core from sampling location AB-1 showing the different sediment layers. The core was split in half and laid horizontally on a ruler table. The core top is on the right, and the bottom on the left with the ruler on the top in cm. Note: for this core location, four sediment samples were extracted for analysis.

3 RESULTS

3.1 General Observations and Overall Statistics

In general, the sediment deposition was concentrated near the inlets and within the forebay, and decreased significantly downstream of the forebay and away from the primary flow path. Near the inlets, sediment was much softer and showed no resistance to the hand corer, as opposed to the cores near the outlets and off the flow path where the sediments were much stiffer and relatively hard to penetrate. Core depths were 35, 25 and 50 cm near the inlets, and 10, 10 and 15 cm downstream of the forebays at AB, CR and RO, respectively. At RR the sediment depths were more uniform and averaged ~20 cm ± 5 cm at all locations. This is likely because the sedimentation vault removes most of the sediment from the inflow before it enters the wetland.

The overall average and standard deviation of the parameters measured from the sediment samples extracted from each facility are summarized in Table 1. These statistics are based on the overall number of samples extracted from all the cores taken from each facility (Table 1). Out of the measured parameters in this study, AEP (2018) guidelines provides contamination levels only for Mn (LEL = 460 µg/g) and Zn (PEL = 315 µg/g) but no guidelines are provided for nutrients or other metals. On the other hand, the MOE (2008) guidelines provide contamination levels (LEL and SEL) for more parameters measured in this study: Mn (460 and 1100 µg/g), Fe (2 and 4 %), Zn (120 and 820 µg/g), P (600 and 2000 µg/g) and TN (550 and 4800 µg/g). Although the MOE (2008) guidelines are not governing in Alberta, but these were used here for discussion purposes and for comparison with other reported values in the literature (e.g. Marsalek and Marsalek, 1997). First, the "average + standard deviation" (to provide a statistically significant higher bound) for these parameters within each facility were compared against the AEP (2018) and/or the MOE (2008) guidelines. The Mn concentration levels fell below the LEL at all facilities. The Zn, Fe and P concentrations were below PEL (for Zn) and between LEL and SEL at most of the facilities (except at RR, Zn and Fe concentrations were on average below the LEL). The TN concentrations were between the LEL and SEL for the two wet ponds (AB and CR), and above the SEL for the two wetlands (RO and RR).

In order to examine the overall variability between the ponds and the wetlands, the coefficient of variation (COV), was calculated between the pond-averaged (i.e., depth and location averaged) concentrations for each parameter (Table 1). The COV ranged from 4% for P to 62% for Na. In order to quantify the levels of variability between the facilities, the parameters were grouped based on the overall value of the COV as follows: COV ≤ 10% is considered invariable, 10% < COV < 25% is considered moderately variable, and COV ≥ 25 % is considered significantly variable. On average, Mn and P had a COV ≤ 10% and did not exhibit any trend between the different facilities types. The concentrations of Fe, Zn, Mg, and K, were moderately variable having 10% < COV < 25%. It is apparent from Table 1 that on average, Fe and Zn are higher in the wet ponds than in the wetlands, but Mg and K are higher in the wetlands than in the wet ponds. The concentrations of Na, Ca, S and TN had COV ≥ 25 % making them significantly variable. There was no apparent trend in the Na concentrations, but the average concentrations of Ca, S and TN were 1.6, 1.8 and 3.0 times higher in the wetlands than in the wet ponds, respectively.

Table 1: Summary of overall statistics (average ± standard deviation) for sediment metals and nutrients concentrations for each stormwater facilities in this study. The COV is calculated using the average value from each facility. Parameters highlighted in grey were included in AEP (2018) and/or MOE (2008).

Pond / Wetland		AB	CR	RO	RR	COV (%)
# of Sediment Samples		17	16	20	17	
Metals	Mn (µg/g)	323 ± 61	365 ± 23	307 ± 71	391 ± 26	10
	Fe (%)	2.09 ± 0.13	1.77 ± 0.24	1.72 ± 0.5	1.55 ± 0.17	11
	Zn (µg/g)	132 ± 34	150 ± 45	120 ± 38	93 ± 16	17
	Na (µg/g)	923 ± 458	643 ± 66	1829 ± 1368	293 ± 29	62
	Mg (%)	0.93 ± 0.18	1.23 ± 0.18	1.19 ± 0.22	1.25 ± 0.09	11
	K (%)	0.25 ± 0.02	0.23 ± 0.04	0.32 ± 0.08	0.31 ± 0.05	14
	Ca (%)	3.2 ± 1.09	4.42 ± 0.34	6.19 ± 1.1	5.94 ± 0.31	25
Nutrients	P (µg/g)	675 ± 44	746 ± 77	729 ± 108	726 ± 12	4
	S (%)	0.21 ± 0.07	0.17 ± 0.05	0.34 ± 0.08	0.34 ± 0.03	29
	TN (µg/g)	1539 ± 349	1534 ± 311	4542 ± 3275	4772 ± 735	50

3.2 Horizontal Variability

The horizontal variability of each parameter along the primary flow path was also assessed within each facility. For this purpose, all the parameters' concentrations were depth-averaged within each core, and the depth-averaged values were normalized using the overall mean value within the pond. The results for this analysis are presented in Figures 3 to 6 for the four facilities. In these figures, when a ratio is > 1, it indicates the concentration at this location is higher than the average, and vice versa. At the AB wet pond, the cores were distributed along the flow path from the inlet (AB-1) to the outlet (AB-5). AB-6 and AB-6T were off the flow path (see Figure 1a). As shown in Figure 3, most of the parameters follow the same trend, that is, the concentration is higher near the inlet and within the forebay (i.e., a ratio between 1 and 2), but decrease below the average downstream of the forebay and off the flow path (i.e., a ratio between 0.5 and 1). This trend is most significant in the concentrations of Na as it started with a concentration of ~1800 µg/g (ratio of ~2) near the inlet (AB-1), and decreased gradually until it reached a value of ~500 µg/g (ratio of ~0.5) near the outlet. One exception is the concentrations of S and TN that were slightly below the average at the inlet (AB-1) and stayed above the average even downstream of the forebay (AB-4). The two samples taken off the flow path (AB-6 and AB-6T) were fairly similar in the ratio of most parameters' concentrations.

For the CR wet pond, the cores were distributed along the primary flow path from the inlet (CR-1 and CR-2) to the outlet (CR-5). CR-6 was off the flow path (see Figure 1b). As shown in Figure 4, generally the concentrations near the inlets (CR-1 and CR-2) were slightly below the average (ratios between 0.8 and 1), and then increased above the average within the forebay at CR-1T with ratios between 1 and 1.7. This is most evident in the concentrations of Zn and S (ratio of ~ 1.7) that reached concentrations of 256 µg/g and 0.29%, respectively. The concentrations then started to decrease from the outlet of the forebay (CR-3) until the pond outlet (CR-5) and off the flow path (CR-6). The only exception is the concentration of Fe and K which were slightly higher than the average near the outlet and off the flow path with a ratio of 1.2 at CR-6.

At the RO wetland, the cores were distributed along the flow path from the inlet (RO-2) to the outlet (RO-5). RO-1 was off the flow path but within the sedimentation forebay (see Figure 1c). As shown in Figure 5, in general the concentrations were higher than the average near the inlet and decreased below the average along the flow path and near the outlet. This is highlighted in the concentrations of Na that reached a maximum of 4240 µg/g (ratio of 2.3) at RO-2T, and decreased to 355 µg/g (ratio of 0.2) at RO-4. The exception to this trend is for the concentrations of S and TN that were below the average near the inlet, and increased above the average at the outlet. Near inlet-2, TN had a concentration of ~1500 µg/g (ratio of 0.3) and at the outlet, this concentration increased to 10250 µg/g (ratio of 2.3).

At the RR wetland, the cores were distributed along the flow path from the inlet (RR-1) to the outlet (RR-4T). RR-5 was off the flow path (see Figure 1d). As shown in Figure 6, the concentrations of most parameters were consistently closer to the average with slightly higher concentrations near the inlet (ratios between 1 and 1.4) and slightly lower concentrations (ratios between 0.8 and 1) near the outlet. One exception to this trend is the concentration of TN which were ~ 3460 µg/g (ratio of ~0.7) near the inlet (RR-1) and increased to 5800 µg/g (ratio of ~1.2) near the outlet (RR-4).

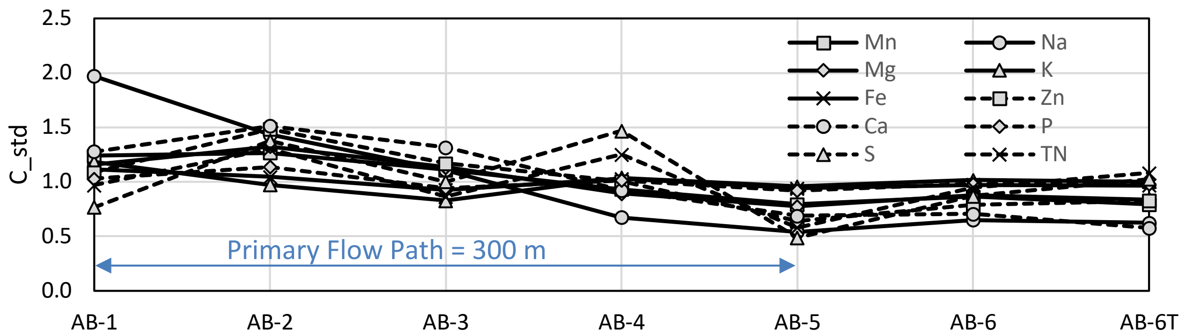

Figure 3: Standardized (over the mean) depth-averaged concentrations (C_std) for the analysis parameters at the different core locations at AB. The number of samples n used for the depth averaging were 5, 3, 2, 2, 1, 2, and 2 for AB-1, AB-2, AB-3, AB-4, AB-5, AB-6 and AB-6T, respectively.

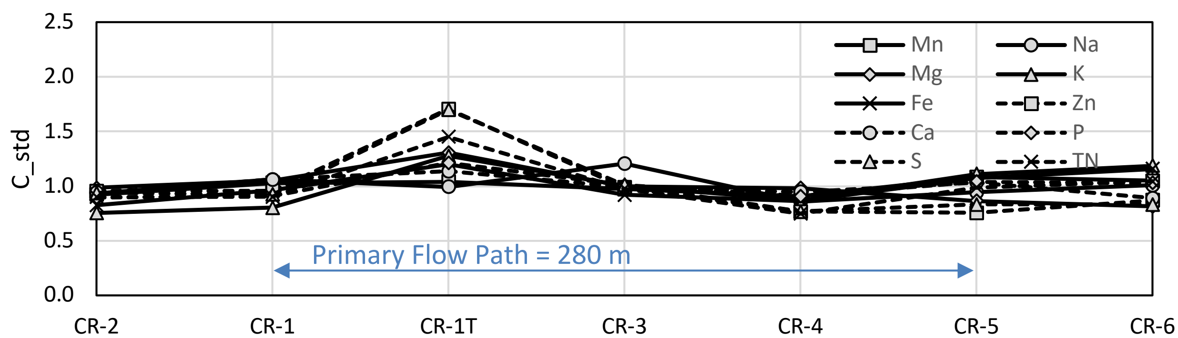

Figure 4: Standardized (over the mean) depth-averaged concentrations (C_std) for the analysis parameters at the different core locations at CR. The number of samples n used for the depth averaging were 3, 1, 2, 3, 2, 3, and 2 for CR-1, CR-1T, CR-2, CR-3, CR-4, CR-5, and CR-6, respectively.

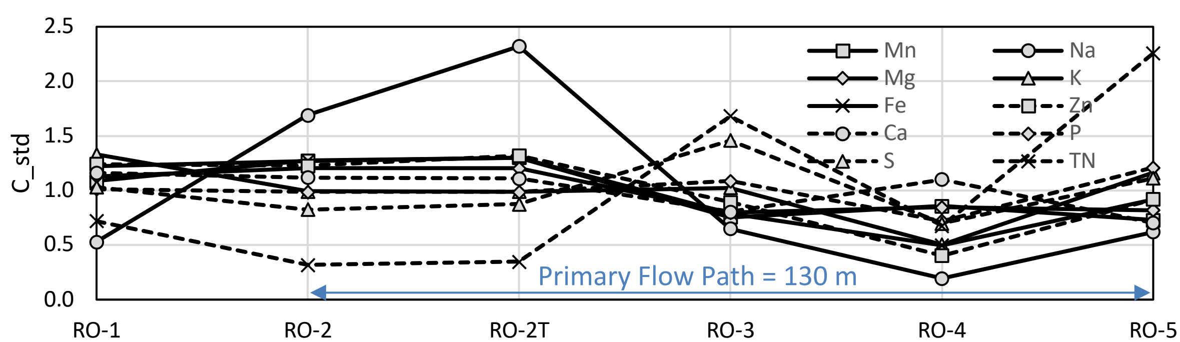

Figure 5: Standardized (over the mean) depth-averaged concentrations (C_std) for the analysis parameters at the different core locations at RO. The number of samples n used for the depth averaging were 4, 4, 5, 2, 2, and 3 for RO-1, RO-2, RO-2T, RO-3, RO-4, and RO-5, respectively.

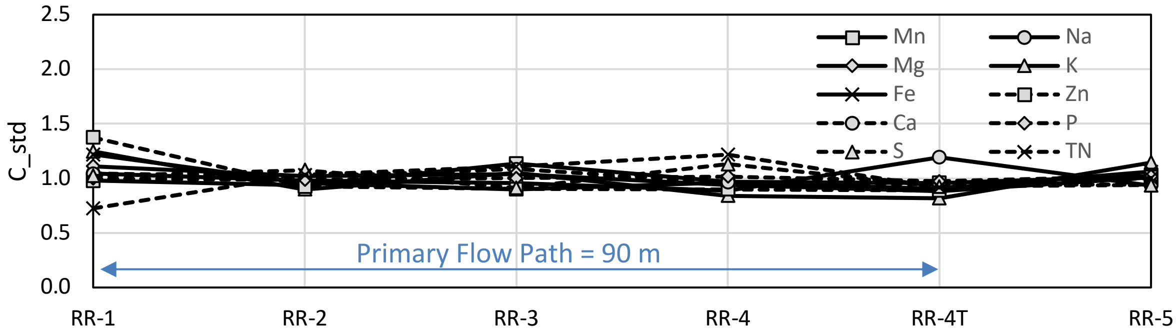

Figure 6: Standardized (over the mean) depth-averaged concentrations (C_std) for the analysis parameters at the different core locations at RR. The number of samples n used for the depth averaging were 3, 3, 3, 2, 2, and 4 for RR-1, RR-2, RR-3, RR-4, RR-4T, and RR-5, respectively.

3.3 Vertical Variability

It was of interest to investigate the variation of the concentrations with the depth of the samples. Since in most cases the concentrations varied along the flow path and most of the stormwater deposited sediment was concentrated near the inlets; therefore, only the cores sampled near the inlets were used in the analysis (i.e., the cores: AB-1, CR-1, RO-2, and RR-1). To quantify the level of variation with depth, the horizontally-averaged concentrations were normalized with their mean concentration value, similar to the analysis used to quantify the horizontal variation. Since the maximum core depths were different between the facilities, the sample depths were non-dimensionalized using the maximum sample depth between the cores taken from each facility. In this way, it was possible to compare the variation with depth between the different facilities. The results from this analysis are shown in Figure 7. To quantify the variation with depth, a linear regression line was fitted to each set of data at each facility. The goodness of the linear fit was assessed using the coefficient of determination R^2, and the level of variation of the concentration from the average was quantified using the COV. The variation with depth was considered significant when $R^2 > 0.5$ and the COV > 25% in at least two facilities. The results of this analysis are summarized in Table 2. Based on these criteria, only the Zn, Na, S and TN parameters varied significantly with depth, and therefore, only results for these four parameters are discussed below.

The concentrations of Zn at CR-1, RO-2 and RR-1 all decreased with depth with linear regression slopes of -0.7, -0.5 and -1.0, and R^2 of 0.99, 0.58, and 0.86, respectively, which is considered a strong correlation. At AB-1, R^2 was ~ 0, indicating that there was no trend observed at this pond. For Na, the concentrations also decreased with depth at CR-1 and RO-2 with slopes of -0.7 and -0.8, and R^2 of 0.71 and 0.83, respectively. At AB-1 and RR-1, R^2 was ~0.13 indicating there was no trend in the variation with depth. For S, the concentration decreased with depth at all four facilities with slopes of -0.3, -0.8, -0.3, and -0.6 and R^2 of 0.12, 0.99, 0.59, and 0.65 at AB-1, CR-1, RO-2, and RR-1, respectively. In general, the concentrations of TN decreased with depth. The correlation was strongest at CR-1 and RO-2 with linear regression slopes of -0.7 and -0.6, and R^2 of 0.93 and 0.74, respectively. Concentrations at CR-1 showed the strongest correlation with depth with R^2 between 0.50 and 0.99 and at AB-1 the correlation with depth was weakest with R^2 ~ between 0.00 and 0.59.

4 DISCUSSIONS AND CONCLUSIONS

This paper presented metal and nutrient concentrations in bottom sediment from two wet ponds and two wetlands in Calgary, Alberta. In general, pollutant concentration levels are different between the wet ponds and the wetlands. The concentrations of Fe and Zn are higher in the wet ponds than in the wetlands, but Mg, K, Ca, S and TN are higher in the wetlands than in the wet ponds. The values of Mn and P were fairly consistent between the wet ponds and the wetlands. The concentrations of Na were significantly variable between facilities but there was no apparent trend between the wet ponds and the wetlands. These observations indicate that the type of facility, age, construction method, and catchment characteristics such as the catchment size, slope, and percent imperviousness may impact pollutant concentration levels.

Table 2: Summary of statistics for the linear regression and the COV for the vertical variability of the horizontally-averaged pollutants concentrations. Negative slopes indicate concentrations decrease with depth and vice versa. Cells highlighted in red indicating R^2 >0.50 or COV >25%.

Core	Parameter	Mn	Fe	Zn	Na	Mg	K	Ca	P	S	TN
AB-1	Slope	2.8	0.8	-0.5	-1.0	-0.7	-3.7	0.0	-0.1	-0.3	-0.3
	R^2	0.59	0.08	0.04	0.13	0.02	0.49	0.00	0.00	0.12	0.03
	COV	10	12	15	13	7	7	10	10	37	20
CR-1	Slope	-2.0	-1.3	-0.7	-0.7	-2.4	-1.1	-2.7	-1.8	-0.8	-0.7
	R^2	0.50	0.78	0.99	0.71	0.94	0.74	0.99	0.96	0.99	0.93
	COV	10	20	42	36	12	22	11	15	35	38
RO-2	Slope	-4.8	0.3	-0.5	-0.8	-2.1	-0.9	-1.7	-3.5	-0.3	-0.6
	R^2	0.24	0.00	0.58	0.83	0.54	0.58	0.45	0.86	0.59	0.74
	COV	3	4	51	37	12	29	14	9	83	52
RR-1	Slope	2.1	-2.7	-1.0	1.6	-15.4	4.1	7.7	2.4	-0.6	0.2
	R^2	0.87	1.00	0.86	0.13	0.45	0.96	0.30	0.30	0.65	0.05
	COV	14	15	29	9	10	18	8	5	32	27

Based on the AEP (2018) and the MOE (2008) guidelines, the sediment pollutant concentrations in all facilities were below the PEL and SEL for all parameters except for the TN concentrations that were above the SEL in the wetlands. High TN concentrations in the wetlands maybe have been naturally present in the substrate as a consequence of the area being surrounded by cattle at one time (since RO and RR were existing wetlands adopted for stormwater use). Similar “high” concentrations were reported in a wetland in Kingston, ON (Marsalek and Marsalek, 1997). It is important to note that AEP (2018) mentioned that “due caution should be exercised when applying these guidelines due to the relatively limited geographic area and datasets they were derived from”. The factors controlling the exchange (release and deposition) of these nutrients between the sediment and the overlaying water needs to be further investigated (Hou et al., 2013). This will be the focus of future research that includes the application of a three-dimensional hydrodynamic and water quality model to these wet ponds and wetlands.

Most of the concentrations were higher near the inlets and within the sedimentation forebays, and decreased along the flow path towards the outlets. This indicates that the sedimentation forebays are functioning as intended and removing some of the pollutants via deposition. A few exceptions to this trend were observed, especially in the concentrations of TN and S where their concentrations increased along the flow path. This trend was also observed for Zn and P in Ontario stormwater ponds by Marsalek and Marsalek (1997) and Song et al. (2017), respectively. For the pollutants that were considered significantly varying with depth, it was observed that in general, the concentrations were decreasing with depth. This implies that the particle-bound pollutants release as the sediment ages and concentrate mostly near the surface. This trend was also reported by Frost et al. (2015) for the metals examined in 17 ponds in southern Ontario.

The results from this study will be integrated with the analysis of water samples from the inlets/outlets as well as from different locations along the ponds/wetlands. The objective is to further understand the complex interaction between the sediment and the overlaying water and to better estimate the removal efficiency of the facilities.

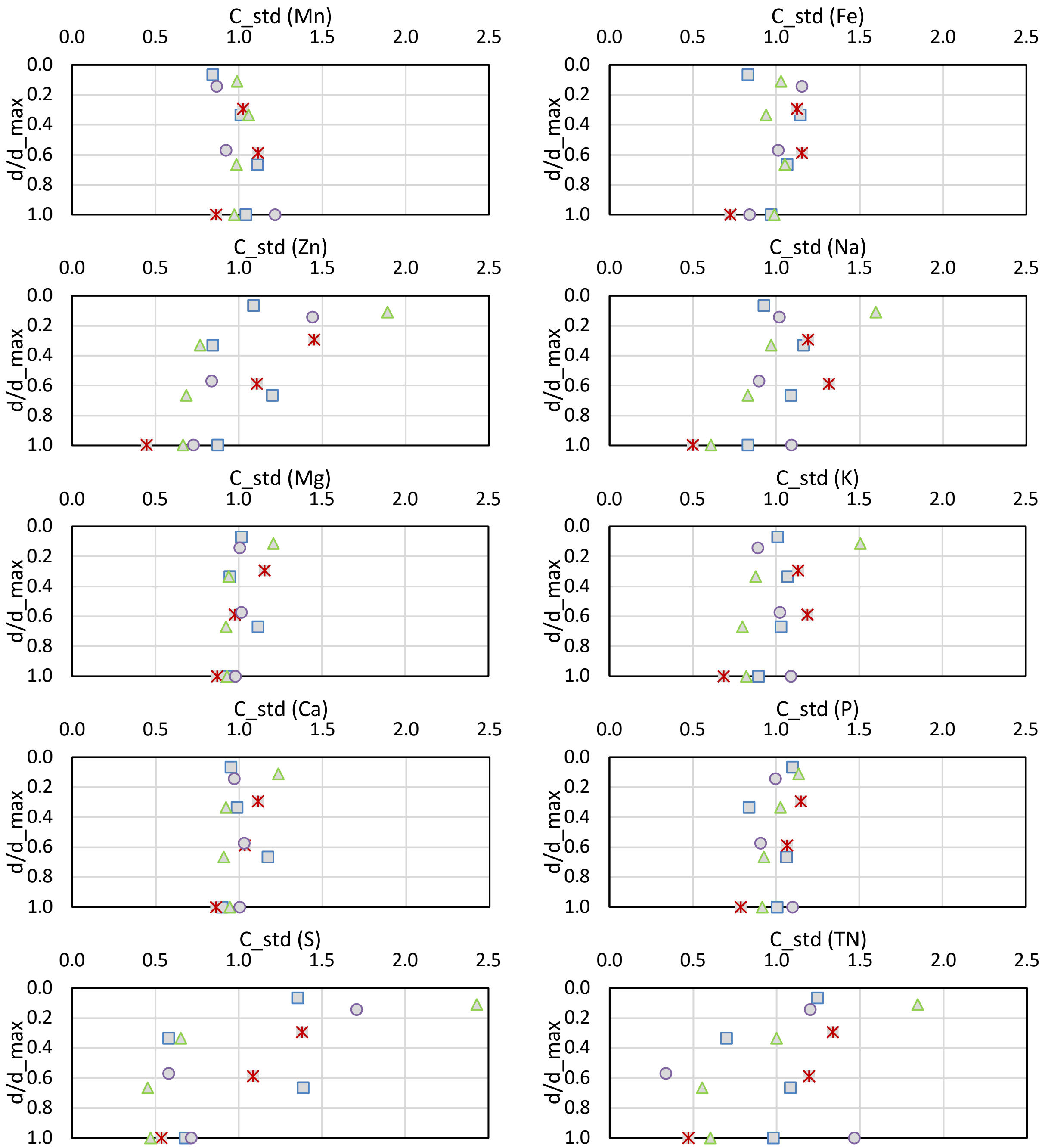

Figure 7: Standardized parameters' concentrations C_std (over the mean) versus the non-dimensional depth (depth d over the maximum depth d_max) for the four study facilities. AB-1 is shown in ■, CR-1 shown in ∗, RO-2 shown in ▲, and RR-1 shown in ●.

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REFERENCES

Ahmed, S., Ghobrial, T.R., Zhang, W. et al. 2019. Field monitoring of physical processes in stormwater wet ponds and wetlands in Calgary Alberta, in *Proceedings of the 2019 CSCE 26th Hydrotechnical Speciality Conference*, Laval, QC

Alberta Environment (AENV). 2001. *Municipal Policies and Procedures Manual*. Municipal Program Development Branch, Environmental Sciences Division, Edmonton, AB, Canada. ISBN: 0-7785-1696-2.

Alberta Environment and Parks (AEP). 2018. *Environmental Quality Guidelines for Alberta Surface Waters. Alberta Environmental Protection,* Edmonton, Alberta, Canada, 58 pp.

Canadian Council of Ministers of the Environment (CCME). 2002. *Canadian Sediment Quality Guidelines for the Protection of Aquatic Life: Summary tables.* In: Canadian Environmental Quality Guidelines (1999) CCME, Winnipeg, MB, Canada.

Davis, A. P., Shokouhian, M. and Ni, S. 2001. Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources. *Chemosphere*, **44**(5): 997-1009.

Frost P.C., Song K., Buttle J.M. et al. 2015. Urban biogeochemistry of trace elements: what can the sediments of stormwater ponds tell us? *Urban Ecosyst*, **18**:763–775. doi:10.1007/s11252-014-0428-2

Hou, D., He, J., Lü, C., Sun, Y., Zhang, F., and Otgonbayar, K. 2013. Effects of environmental factors on nutrients release at sediment-water interface and assessment of trophic status for a typical shallow lake, northwest China. *The Scientific World Journal*, 2013, 716342. doi:10.1155/2013/716342

Marsalek, J. and Marsalek, P.M. 1997. Characteristics of sediments from a stormwater management pond. *Wat. Sci. Tech.,* Volume 36(8–9): 117-122

Ministry of Environment (MOE). 2008. *Guidelines for Identifying, Assessing and Managing Contaminated Sediments in Ontario*. Available at: https://www.ontario.ca/document/guidelines-identifying-assessing-and-managing-contaminated-sediments-ontario

Muthukrishnan, S. 2010. Treatment of Heavy Metals in Stormwater Runoff Using Wet Pond and Wetland Mesocosms. Proceedings of the Annual International Conference on Soils, Sediments, Water and Energy: Vol. 11, Article 9. Available at: http://scholarworks.umass.edu/soilsproceedings/vol11/iss1/9

Nelson E.J. and Booth D.B. 2002. Sediment sources in an urbanizing, mixed land-use watershed. *J Hydrol*, **264**:51–68

Reddy, K.R. and DeLaune, R.D. 2008. *Biogeochemistry of Wetlands: Science and Applications.* 1st ed., CRC Press, Boca Raton, FL, USA.

Song K., Winters C., Xenopoulos M.A., Marsalek J. and Frost P.C. 2017. Phosphorus cycling in urban aquatic ecosystems: connecting biological processes and water chemistry to sediment P fractions in urban stormwater management ponds. *Biogeochemistry*, **132**:203–212.

US EPA. 2000. *Water Quality Conditions in the United States: A Profile from the 1998 National Water Quality Inventory Report to Congress.* Office of Water. Washington, DC. EPA841-F-00-006.