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Sediment Assessment of Stormwater Retention Ponds within the Urban Environment of Calgary, Canada

Krista Westerbeek-Vopicka*

Strategic Planning and Policy, The City of Calgary, P.O. Box 2100, Station M, LOC #433 T2P 2M5, Calgary, AB, Canada

The treatment of urban stormwater by retention ponds is known to be effective for water quality improvement as well as storm flow management and, in the past two decades, has become widely implemented. However, limited research has been conducted on the quality of sediment deposited in ponds. Therefore this study focuses on contaminant concentrations within the sediment from stormwater ponds built in Calgary, Canada. Electrical conductivity and the sodium adsorption ratio consistently exceeded the Canadian Council of Ministers of the Environment (CCME) agricultural soil quality guidelines, indicating a city-wide salt contamination issue. F3 hydrocarbon fractions, cadmium, chromium, copper, lead, selenium, and zinc were also identified as parameters of concern. In particular, the 61 Avenue SE duck pond displayed the greatest diversity and severity of contaminants due to the industrial catchment area. Removal and disposal options were limited due to the characteristics of the sediment. The examination of the solids content illustrated that all retention ponds will require the sediment to be dewatered prior to disposal. Disposal options were subsequently restricted to landfill disposal due to salt, metal, and/or hydrocarbon parameters exceeding CCME soil guidelines. One exception was the Deerfoot Trail and Highway 22X pond which could be directly disposed of in areas designated as commercial and industrial land use.

***Key words*: disposal, heavy metals, hydrocarbons, retention pond, contaminants, sediment**

Introduction

Water quality is increasingly being researched due to growing water usage throughout Canada. Moreover, the distribution of Canada's water and population are creating pressures on water quality and quantity. Approximately 60% of Canada's useable freshwater drains towards the north, while 90% of Canada's population resides in the south (Environment Canada 1987). Although Canada generally has sufficient water to supply population demand, the distribution of people and fresh water creates localized pressures on water quantity and quality, especially in the lower populated portion of Canada. This is particularly important for urban centres as they have a significant impact on watersheds, predominately due to the effect of development increasing the amount of impervious groundcover which subsequently increases stormwater runoff (U.S. EPA 1993a; The City of Calgary 2000). Specifically, in southern Alberta, the Bow River sub basin managed under the South Saskatchewan River basin has a population density of 1 to 150 people/km^2. However, this then exceeds 1,000 people/km^2 within The City of Calgary limits (BRBC 2005). The dramatic increase in population density amplifies the percentage of impervious groundcover which in turn increases stormwater runoff. This consequently impacts the receiving watershed which is utilized by numerous downstream communities, reemphasizing the need for upstream management.

Urban runoff generally contains contaminants which include sediment, nutrients, metals, and hydrocarbons (U.S. EPA 1993a; The City of Calgary 2000). These contaminants are particularly important as they can cause severe impacts to a watershed. To address stormwater runoff, The City of Calgary has implemented the use of retention ponds for all new developments since they are known to be effective for water quality improvement and storm flow management (U.S. EPA 1993a; The City of Calgary 2000). Retention ponds have several mechanisms to remove contaminants. In particular, sediment is removed due to the deceleration of stormwater as it enters the retention pond, allowing the sediment to settle out of the water column by way of gravity (Kadlec and Knight 1996). Removal of sediment is important because it causes adverse affects to fish activity, and impairs spawning areas and benthic habitats (BRBC 2005). Nutrient removal focuses specifically on phosphorus and nitrogen since they drive eutrophication in receiving waters (U.S. EPA 1993a; Kadlec and Knight 1996). The uptake and release of nitrogen and phosphorus within a retention pond is dependent on water chemistry, sediment characteristics, and vegetation (Levine and Willard 1990). However, the primary method of removal from the water column is sedimentation with associated particulates (Kadlec and Knight 1996). Metals present in stormwater drainage systems typically include copper, chromium, cadmium, nickel, lead, iron, manganese, and zinc but may include other metals depending on activities present within the catchment area (U.S. EPA 1993a). Metals are important as they are persistent pollutants which can bioaccumulate in soil or plants and are most likely to influence sediment toxicity as they quickly concentrate (Mungur et al. 1995; Kadlec and Knight 1996; Heal 1999). Retention ponds are capable of removing metal pollutants through three

* Corresponding author: krista.vopicka@calgary.ca

mechanisms. These include binding to soils, sediments, particulates, and soluble organics or precipitation as insoluble salts, or uptake by plants and bacteria (Kadlec and Knight 1996). Hydrocarbons are important due to the long half lives of the compounds and have been known to persist in water and soil matrices (Thurston 1999; Dabrowski et al. 2002). Runoff typically introduces these either as water-dissolved or particulate-associated when they enter the stormwater management system. Removal of hydrocarbons is achieved through several processes including volatilization, photochemical oxidation, sedimentation, sorption, and biological degradation (including fermentation, aerobic and anaerobic respiration) (Kadlec and Knight 1996). However due to the highly hydrophobic nature of hydrocarbons, sedimentation with associated particulate matter dominates as the main factor which removes hydrocarbons from the water column (Thurston 1999; Dabrowski et al. 2002; Braskerud and Haarstad 2003).

These internal removal processes illustrate two important points. Firstly, the primary removal mechanism of contaminants is sedimentation with associated particulates. Secondly, retention ponds continually accumulate sediment. It is also known that excessive sediment accumulation within retention ponds can lead to a reduction in water quality. This is due to the loss in storage volume, decreased velocity attenuation, and decreased sedimentation capabilities (Revitt et al. 1999). Therefore, to properly maintain treatment efficiencies of retention ponds, regular dredging is required (GIC Inc. 1999). Extensive research has been directed to the removal efficiency of retention ponds and the subsequent water quality leaving the stormwater system. However, limited research has been directed towards the sediment, the fate of the contaminants sequestered by the system, or the concentration of these contaminants within the retention ponds.

With the introduction of retention ponds being utilized as treatment systems within the stormwater network, applicable legislation was examined. Alberta Environment has adopted the federally issued Canadian Council of Ministers of the Environment (CCME) guidelines (CCME 1999) to supplement provincial legislation. Sediment within constructed wetlands cannot be regulated by criteria intended for natural wetland sediment. CCME sediment guidelines are intended to maintain biodiversity and organism abundance. Retention ponds are not designed to be pristine systems, replace removed wetlands, or be maintained as ecosystems. Instead, they are intended for the removal of sediment and to improve water quality. The accumulation of sediment however must be periodically dredged to maintain pond efficiency (Kadlec and Knight 1996; The City of Calgary 2000), and be disposed of offsite. With the required ex situ disposal of sediment and the lack of applicable sediment-specific criteria, any sediment removed from the retention ponds will hereafter be classified as a soil and subsequently regulated under CCME soil guidelines.

The primary objective of this paper was to provide a base of knowledge on the contaminant concentrations within the sediment in a variety of ponds receiving stormwater from differing residential, commercial, industrial, and highway land uses. Secondly, sediment removal and disposal options were evaluated.

Selection of the Study Sites

Stormwater retention ponds have been utilized by The City of Calgary since 1979 when Calgary constructed its first wet pond at 68 Street and 17 Avenue SE to moderate stormwater event volumes reaching the river systems. By 1988, retention ponds were designed as part of the storm drainage systems with a storage capacity to accommodate a 1-in-100-year rainfall event (The City of Calgary 2006a). During this time it was also recognized that retention ponds demonstrate beneficial water quality improvements as they are efficient at pollutant removal, capable of addressing multiple contaminants, are sustainable, require relatively low maintenance, have a high aesthetic appeal, and are cost effective (Mitsch and Gosselink 1993; Kadlec and Knight 1996; Magmedov et al. 1996; Griffin and Upton 1999; Lin et al. 2002). This has led to all new residential subdivisions requiring the installation of retention ponds to treat the stormwater prior to its discharge into the rivers.

Site Selection Criteria

The retention ponds chosen as sampling sites for this study were selected from Calgary wet ponds and wetlands which have been receiving stormwater for an extensive period of time and subsequently have developed a distinct sediment layer. The intention was to encompass retention ponds that were reaching their water treatment capabilities and would require dredging shortly to maintain treatment efficiency. Furthermore, sites were chosen to represent a variety of dominant land uses present within the catchment area, and represent degrees of ongoing development within Calgary. Based on these criteria, the following five stormwater facilities were selected:

Deerfoot Trail and Highway 22X pond (Reid Crowther & Partners Ltd. 2000) has been in operation since 2001 to treat runoff from a 64 ha area collecting solely highway runoff. Pond design specifics consist of a surface area of 7,950 m^2, a permanent water level (PWL) of 1,031.5 m, and a pond bottom elevation of 1,029.0 m.

68 Street SE retention lake became operational in 1979 and accommodates runoff from an exceptionally large catchment area of approximately 2,925 ha (The City of Calgary 2006b). The land use and approximate percentage present within the catchment area are residential (70%), parkland (10%), commercial (15%), and light industrial (5%). Pond design specifics available include the pond surface area of 20.0 ha, a pond bottom elevation of 1,047.6 m, and a PWL of 1,049.9 m.

Edgemont wetland has been in operation since 1996 (IMC Consulting Group Inc. 1995), servicing a designated drainage area of 114.2 ha. Land use consists of approximately 90% residential and 10% parkland. Edgemont wetland was designed with a PWL elevation of 1,175.5 m, a pond bottom elevation of 1,173.5 m, and total surface area of 17,768 m^2.

Harvest Lake construction was completed in 1988 and has been in operation for 20 years. It was designed to treat a drainage area of 390 ha (The City of Calgary 2006b). Land use consists of approximately 90% residential and 10% parkland. Pond specifics include a surface area of 44,587 m^2, a PWL of 1,066.0 m, and a set pond bottom elevation of 1,062.7 m.

61 Avenue SE duck pond became operational in 1985 and was designed to treat stormwater originating from a 28 ha catchment area consisting of solely industrial land use (Westhoff Engineering Resources Inc. 1998). However, due to growth of Calgary, the pond currently receives runoff from 1,375 ha. Pond design specifics encompass a surface area of 5,477 m^2, a pond bottom elevation of 1,032.0 m, and a PWL of 1,034.0 m.

Material and Methods

Sampling Events

All samples were collected from February 24 to 26, 2004 during the winter freeze. Sediment samples were collected in midwinter, which allowed the samples to be more accurately obtained and mapped. Additionally, winter collection avoided disturbance of the sediments that might occur if ponds were accessed by boat (paddle or poling action) and avoided drifting that would occur when utilizing a boat. Discrete grab samples were collected at even intervals from the inlet to the outlet of the pond, following the main flow path which was determined from the facility design plans. Grab samples were collected using an Eckman dredge, and appropriately preserved and kept on ice.

Methods

All of the parameters were analyzed using standard methods. Total solids, fixed solids, and volatile solids were measured using Method 2540G from *Standard Methods* (APHA et al. 1998). Particle size distribution was determined using the Mastersizer 2000 (Malvern Instruments 1998) which was equipped with a Hydro G sample dispersion unit. Heavy metal analysis was conducted by MAXXAM Analytics laboratory in Calgary, Alta. The metals were digested using the EPA Method 3050B (U.S. EPA 1996a), and the samples were subsequently analyzed for the elements of interest using the appropriate inductively coupled plasma atomic emission spectroscopy (ICP-AES) and inductively coupled plasma mass spectrometry (ICP-MS) instrumentation. Total Kjeldahl nitrogen (TKN) was analyzed by MAXXAM Analytics laboratory in Calgary, Alta. TKN was digested following the EPA Method 351.2 (U.S. EPA 1993b) and subsequently analyzed using a spectrophotometer. Total phosphorus (TP) was analyzed by MAXXAM Analytics laboratory following EPA Method 351.2 (U.S. EPA 1993b). Collection, preservation, and storage of samples were the same as that for TKN. Samples were analyzed for F2 and F3 hydrocarbon fractions following procedures outlined in the *Canada-Wide Standard for Petroleum Hydrocarbons in Soil – Tier 1* document (CCME 2001). Samples were cleaned in situ with silica gel and analyzed on the gas chromatograph using a DB1 column. Electrical conductivity, pH, and chloride were analyzed for all samples using field probes. Determination of free liquids for all samples was completed by obtaining a composite sample of all the sample points from each retention pond and completing the EPA Method 9095A (U.S. EPA 1996b) paint filter liquids test.

Results

Solids

The total solids concentration by mass of each pond was found to have an average of 44.10, 30.34, 44.40, 41.83, and 38.48% for the Deerfoot Trail and Highway 22X pond, 68 Street SE retention lake, Edgemont wetland, Harvest Lake, and 61 Avenue SE duck pond, respectively. The highest average volatile solids concentration by mass was determined to be 4.5% for the 61 Avenue SE duck pond.

Particle Size Distribution

Deerfoot Trail and Highway 22X pond, 68 Street SE retention lake, Harvest Lake, and 61 Avenue SE duck pond (Fig. 1 A, B, D, E) all displayed a high proportion of sand at the inlet, while the Edgemont wetland displayed a consistent distribution of particle fractions throughout (Fig. 1C).

Metals

The main summary of the analyzed chemical constituents with their respective guidelines are displayed in Table 1. Chromium, copper, and lead mean concentrations exceeded CCME guidelines in the 61 Avenue SE duck pond, while cadmium and zinc mean concentrations exceed guidelines in both the 61 Avenue SE duck pond and the 68 Street SE retention lake. Furthermore, selenium concentrations exceeded guidelines in Harvest Lake and the 68 Street SE retention lake. An analysis of variance test and Tukey's test were utilized to identify differences

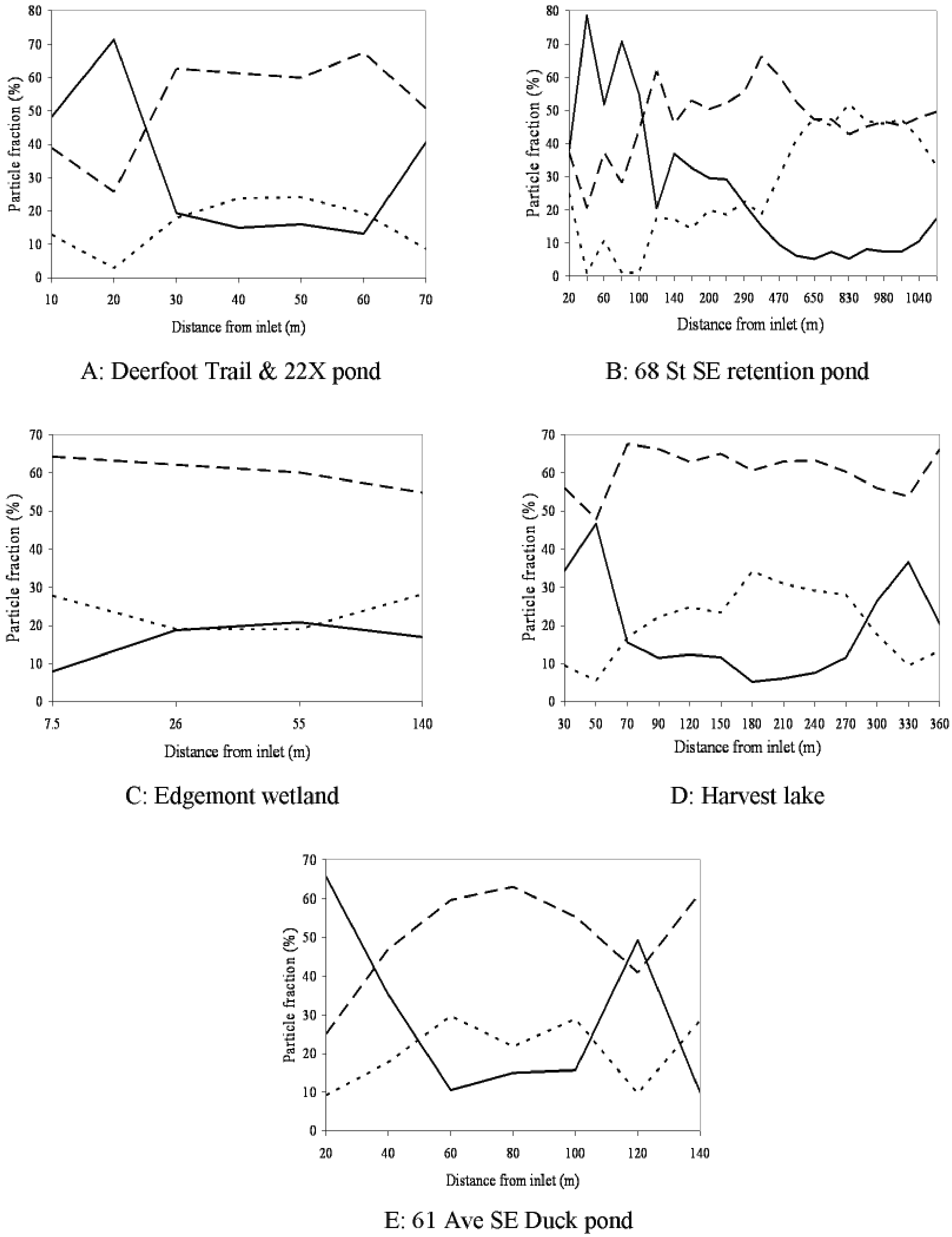

Fig. 1. Particle fraction (%) of each fraction for sand (>50 microns), silt (50 to 2 microns) and clay (<2 microns). sand (—); silt (- -); clay (...)

TABLE 1. Total chemical concentrations for compounds with soil quality guidelines per sampling location[a,b]

		Concentration (mg/kg)										
		As	*Ba*	*Cd*	*Cr*	*Cu*	*Pb*	*Ni*	*Se*	*Tl*	*V*	*Zn*
CCME Guidelines	Agricultural	12	750	1.4	64	63	70	50	1	1	130	200
	Industrial	12	2,000	22	87	91	600	50	3.9	1	130	360
Deerfoot Trail & Hwy 22X	In	4	226	0.5	13	12	10	14	0	0.1	17	58
	Mid	6	250	0.8	21	22	14	31	0	0.3	29	118
	Out	4	204	0.6	15	15	10	18	0	0.2	22	80
68 St SE retention lake	In	6	231	1.4	38	48	**78***	27	**2***	0.2	26	**347***
	Mid	6	275	**1.5***	25	44	60	27	**3***	0.2	29	**307***
	Out	8	279	1.3	28	37	47	26	**3***	0.2	32	**240***
Edgemont wetland	In	7	330	0.9	26	28	17	32	1	0.2	32	151
	Mid	7	318	0.8	25	27	19	31	1	0.2	30	150
	Out	7	297	1.7	31	33	25	33	0	0.2	30	**233***
Harvest Lake	In	4	339	1	20	18	12	24	**3***	0.2	22	102
	Mid	4	282	0.8	23	27	18	29	**11***	0.2	22	155
	Out	9	312	0.6	20	22	16	23	**4***	0.2	26	114
61 Ave SE duck pond	In	4	195	**20***	**72***	44	**78***	20	1	0.2	20	**504***
	Mid	6	360	**64***	**192***	**74***	**106***	36	1	0.3	34	**1,220***
	Out	6	375	**64***	**352***	**89***	**104***	38	1	0.7	34	**1,110***

[a] As, arsenic; Ba, barium; Cd, cadmium; Cr, chromium; Cu, copper; Pb, lead; Ni, nickel; Se, selenium; Tl, thallium; V, vanadium; Zn, zinc.
[b] Bolded values with an asterisk (*) indicate mean values that exceed fine-grained CCME agricultural and industrial soil criteria (CCME 1999).

between ponds. Cadmium ($F_{0.05,4,13}$ = 14.11), chromium ($F_{0.05,4,13}$ = 6.65), copper ($F_{0.05,4,13}$ = 13.17), lead ($F_{0.05,4,13}$ = 45.82), and zinc ($F_{0.05,4,13}$ = 15.67) concentrations were determined to be significantly higher in the 61 Avenue SE duck pond compared with the remainder of the sites. Additionally, cadmium ($F_{0.05,4,13}$ = 14.11), zinc ($F_{0.05,4,13}$ = 15.67), and selenium ($F_{0.05,4,13}$ = 5.12) concentrations were determined to be significantly higher in the 68 Street SE retention lake, while only selenium concentrations were significantly greater in Harvest Lake ($F_{0.05,4,13}$ = 5.12) when compared with the remainder of the sites.

Nutrients

With respect to nutrients, nitrogen and phosphorus were examined. Specifically, TKN and TP were measured (Table 2).

TABLE 2. Total Kjeldahl nitrogen and total phosphorus mean concentrations of dredge samples per sampling location

Sample	*TKN (mg/kg)*	*TP (mg/kg)*
Deerfoot Trail & Hwy 22X	1,680.14	1,134.60
68 Street SE retention lake	3,332.27	1,185.81
Edgemont wetland	1,717.50	1,346.24
Harvest Lake	1,756.62	739.84
61 Ave SE duck pond	1,661.43	1,648.63

Hydrocarbons

Hydrocarbon analysis of the F2 fraction (Fig. 2) displays no significant difference between ponds ($F_{0.05,4,10}$ = 1.60). For all sites, the average concentration and ranges are well below the CCME agricultural soil F2 hydrocarbon fraction guideline of 900 mg/kg (Fig. 2).

With respect to the F3 fraction (Fig. 3), the hydrocarbon content of the 68 Street SE retention lake and the 61 Avenue SE duck pond were significantly higher than the remaining ponds ($F_{0.05,4,10}$ = 11.64). Figure 3 also illustrates that both the 68 Street SE retention lake and the 61 Avenue SE duck pond exceeded the allowable CCME agricultural soil F3 hydrocarbon fraction guideline of 800 mg/kg. Additionally, none of the sample points in any pond exceeded the industrial soil guideline of 2,500 mg/kg. However, it is important to note that the 68 Street SE retention lake and the 61 Avenue SE duck pond do approach the guideline.

Additional Sediment Parameters

With respect to the average pH values, all retention ponds were within the CCME soil quality guideline range of 6 to 8. The average pH of each pond was found to be 7.9 for the Deerfoot Trail and Highway 22X pond, 7.5 for the 68 Street SE retention lake, the Edgemont wetland, and Harvest Lake, and 7.4 for the 61 Avenue SE duck pond.

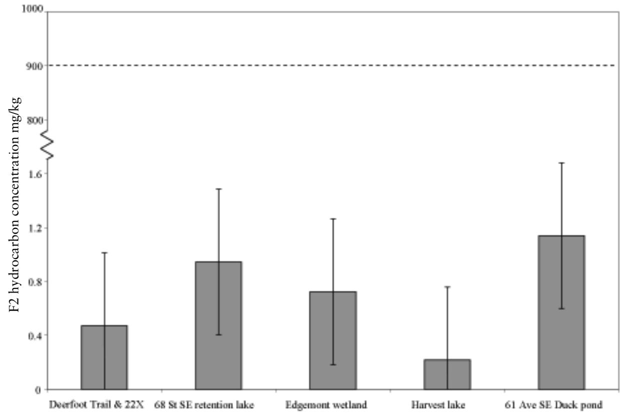

Fig. 2. F2 CCME hydrocarbon fraction concentrations of dredge samples per sampling site including CCME agricultural soil (dashed line) quality guidelines.

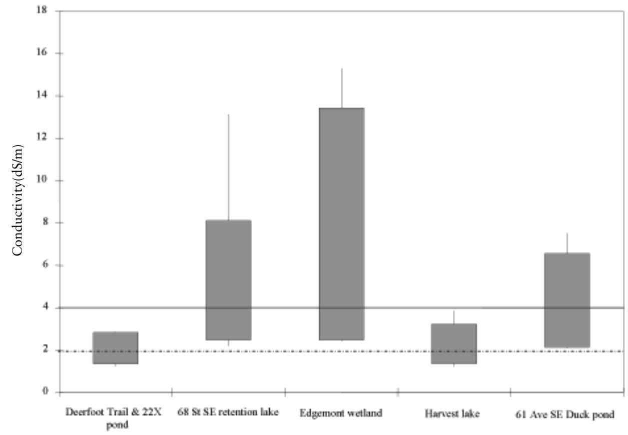

Fig. 4. Conductivity of dredge samples including CCME agricultural soil (dashed line) and industrial soil (solid line) quality guidelines.

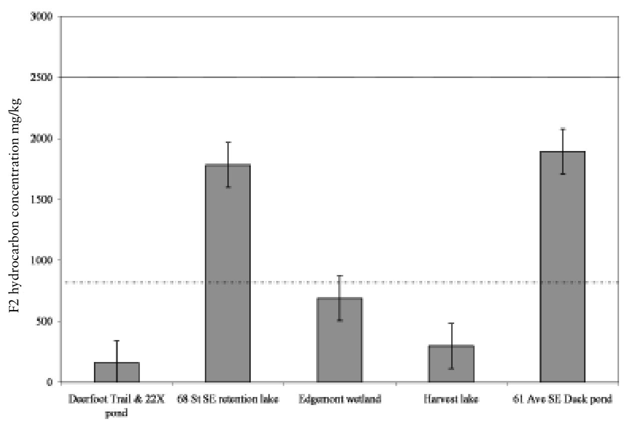

Fig. 3. F3 CCME hydrocarbon fraction concentrations of dredge samples per sampling site including CCME agricultural soil (dashed line) and industrial soil (solid line) quality guidelines.

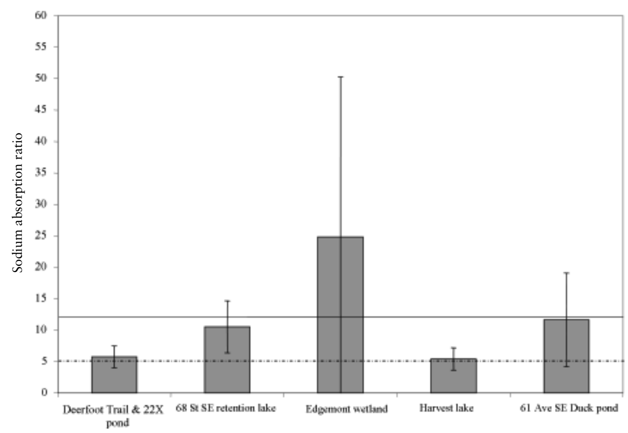

Fig. 5. Sodium absorption ratio of dredge samples including CCME agricultural soil (dashed line) and industrial soil (solid line) quality guidelines.

The electrical conductivity (EC) varied significantly between sites ($F_{0.05,4,48}$ = 6.11), with measurements in the Edgemont wetland and 68 Street SE retention lake being significantly greater compared with those from the remaining sites. Additionally, all of the site averages exceeded agricultural soil guidelines, but only Edgemont wetland and 68 Street SE retention lake exceeded the industrial soil guideline (Fig. 4).

The average sodium adsorption ratio (SAR) of every retention pond exceeded the soil quality guideline of 5.0 for agricultural soil (Fig. 5). However, only Edgemont wetland exceeded the CCME industrial soil criteria of 12.0 (Fig. 5).

Paint Filter Test

Landfill criteria, regulated by Alberta Environment (1995), requires that any material disposed of within a landfill cannot have any free liquids present. To determine the presence of free liquids, a paint filter test was conducted utilizing EPA Method 9095A (U.S. EPA 1996b). Subsequently, results indicated that all sites contained free liquids.

Discussion

The primary objective was to determine the presence and concentration of contaminants in order to understand the extent of contamination of accumulated sediment within the retention ponds. Consequently, each parameter was evaluated against the CCME agricultural soil guideline, which was used as the baseline for comparison. This provided the most stringent guidelines and therefore is a suitable guideline to define between contaminated and noncontaminated soils. Additionally, parameter concentrations were evaluated against literature.

The parameters that exceeded the CCME soil guidelines in all ponds were EC and the SAR. This indicates that all of the retention ponds within The City of Calgary have salinity and sodicity contamination regardless of the catchment area differences. The major ions identified as contributors to the high EC were found to be chloride, sodium, calcium, and magnesium. The SAR also exceeded guidelines due to the larger proportion of sodium compared with calcium and magnesium. Examination of background soils present within the catchment areas illustrated limited areas of high saline soils, limited to 2.5% of the surrounding Calgary area (Kwiatkowski et al. 1996). This suggests that the increases in EC and the SAR are due to anthropogenic sources. This is important as The City of Calgary uses mainly sodium chloride, and to a lesser extent calcium chloride, for deicing roads (The City of Calgary 2006c), which potentially is the source for this widespread contamination. However, the presence of solonetzic soils within the Calgary area and the potential for natural salt leaching from the catchment areas cannot be discounted as a contributor to the high EC and SAR results (Wyatt et al. 1960; Macmillan 1987). The consistently exceeded guidelines also illustrates that salt is the primary contaminant of concern for this study area.

The remaining parameters varied between retention ponds, illustrating localized influences due to specific catchment area contribution differences. It was observed that of all the metals evaluated within this study, only cadmium, chromium, copper, lead, selenium, and zinc accumulated sufficiently to exceed the CCME agriculture guidelines in one or more ponds. Mean cadmium and zinc concentrations exceeded the CCME agricultural soil quality guidelines by 1.1 to 35 times for cadmium and 1.4 to 4.7 times for zinc in the 68 Street SE retention lake and the 61 Avenue SE duck pond, respectively. Chromium, copper, and lead exceeded guidelines by 3.2, 1.1, and 1.4 times, respectively, for the 61 Avenue SE duck pond. Additionally, selenium exceeded guidelines 3 and 6 times for the 68 Street SE retention lake and Harvest Lake, respectively. Literature reports of background soil levels (mg/kg) within Alberta are known to be 0.16, 0.01, 20, 12, and 74 for cadmium, chromium, copper, lead, and zinc, respectively (Knight and Klassen 2005). This indicates that anthropogenic sources are contributing to the contaminant loading of the sediment. Cadmium, chromium, copper, lead, and zinc concentrations were subsequently compared with other studies including Yousef et al. (1994a, 1994b); Kadlec and Knight (1996); Marsalek and Marsalek (1997); Heal (1999); Marsalek et al. (1999); Mallin et al. (2002); Vymazal and Krasa (2003); and Kamalakkannan et al. (2004). The metal concentrations in sediments from other urban retention pond studies have found concentrations (mg/kg) to range between 0.051 to 53.0 (cadmium), 0.97 to 128.0 (chromium), 0.45 to 1,441 (copper), 1.5 to 1,047 (lead), and 1.0 to 779 (zinc). These studies encompass diverse urban environments including residential, parkland, commercial, highway, and light industrial uses, similar to the diversity in urban land uses examined within this study. These concentrations illustrate two important points. Firstly, all of the retention ponds within this study had comparable concentrations to those observed in other urban retention pond sediments, with the exception of the 61 Avenue SE duck pond. Secondly, the ranges found in the literature emphasize the severity of the contamination observed within the 61 Avenue SE duck pond. This is especially true for cadmium, chromium, and zinc with respective average concentrations (mg/kg) of 49, 205, and 945, illustrating that sediment from this catchment area, dominated by industrial use, is severely contaminated compared with urban retention ponds within other studies.

TKN and TP concentrations are not regulated by the CCME soil quality guidelines. Literature reports levels of nitrogen-n in soil from Calgary's urban perimeter to be an average of 3,859 mg/kg for an A horizon, and 1,245 mg/kg for a B horizon (Macmillan 1987). Consequently, all nitrogen concentrations within the retention ponds are similar to the natural soil levels since average TKN concentrations within the ponds were found to range between these natural concentrations. Other studies have observed nitrogen concentrations between 108 to 464 mg/kg, and phosphorus concentrations between 9.6 to 164 mg/kg (Yousef et al. 1994a; Lazaridou-Dimitriadou et al. 2004) which are lower than 1,661 to 3,332 mg/kg and 740 to 1,649 mg/kg for nitrogen and phosphorus concentrations observed within this study. This illustrates that the nutrient contribution retained within the retention pond sediment is low within this and other studies. This provides minimal benefit when considering disposal options.

Hydrocarbons were anticipated to be present in urban areas due to fuel storage and automotive wear and maintenance (Allcock et al. 1991). The two most prominent hydrocarbon fractions found were the F2 (C_{10} to C_{16}) and F3 (C_{16} to C_{34}) fractions. F3 hydrocarbon anthropogenic sources are related to the handling, transport, storage, and disposal of heavy end fuel, oil, and grease products within urbanized areas (Allcock et al. 1991; Heal 1999). Meanwhile, F2 hydrocarbon can originate from the subsequent handling, transport, storage, and disposal of lighter end fuels. It was found that the F2 fraction was consistently well below the CCME agricultural soil guidelines, while F3 hydrocarbons were present in concentrations which exceeded guidelines for the 68 Street SE retention lake and 61 Avenue SE duck pond. This could be because the light end hydrocarbons are very mobile, are easily volatilized, and have a high microbial degradation potential (Allcock et al. 1991; Heal 1999; CCME 2001). Conversely, heavy end hydrocarbons such as oil and grease persist longer in the environment, have a stronger association to particulate matter, and cannot be easily degraded (Allcock et al. 1991; Heal 1999). Subsequently, this allows the F3 hydrocarbons to readily associate with the settling particulate matter and persist longer within the sediment. With respect to the industrial sector, oils and greases are more prevalently used than in residential areas, and subsequently have an increased potential of entering the stormwater system (Allcock et al. 1991; Heal 1999).

To examine the internal dynamics, correlations were conducted between the contaminant parameters and sediment parameters. Multiple correlations were completed using Pearson correlation with a significant correlation indicated by a correlation coefficient greater than $r = 0.8$. It was anticipated that once material enters the system, there would be a close association between contaminants and clay particles (Horowitz 1991). Within each pond, only a few contaminants displayed a close affinity to clay particles, but this relationship was consistent for neither the contaminant nor the retention pond. One exception was the 61 Avenue SE duck pond, which illustrated a high positive association with the majority of the metal constituents as well as the F3 hydrocarbon fraction to clay/silt particles, and a negative correlation with sand. Phosphorus measured in the 61 Avenue SE duck pond also illustrated this trend, which has been observed in other industrial site studies investigated by Verstraeten and Poesen (2002). Collectively for metal, hydrocarbon, and nutrient correlations, associations of contaminants to small particulates are stronger at high parameter concentrations. This positive relationship with silt and clay is reiterated in the retention ponds with observed high concentrations of selenium, namely Harvest Lake and the F3 hydrocarbon fractions present in the 68 Street SE retention lake. The associations are due to the charges of each particle, wherein clay particles have a higher negative charge in relation to surface area than sand with respect to bulk sediment volume. Consequently, at higher concentrations of contaminants, a proportionally greater amount adheres to the highly charged clay particles (Horowitz 1991; Scholes et al. 1998).

The distribution of particle sizes combined with the association of contaminants to smaller particles illustrates an advantageous phenomenon, particularly within retention ponds that have high contamination levels. Since sand typically accumulates at the inlet, this particulate fraction forms the bulk of the sediment present at the inlet. Sand also has the lowest association to contaminants. This trend can be utilized to facilitate sediment disposal wherein the less contaminated inlet portion of retention ponds can be dredged and handled separately. This could be beneficial as the subsequent disposal options may be more cost effective. This should be considered once the appropriate disposal option has been defined.

Disposal

With insight into the properties of sediment, the removal and disposal options can be investigated. Considerations of each option will depend on the physical and chemical properties of the sediment as well as monetary considerations, regulatory viability, and public acceptance (Mitsch and Gosselink 1993; Kadlec and Knight 1996; Magmedov et al. 1996; Griffin and Upton 1999; Lin et al. 2002). To complete the disposal of sediment, it will be necessary to consider removal options and possible treatment requirements.

With such a broad spectrum of contaminants present in differing quantities, a system must be introduced that can treat the various pollutants but remain economical, especially since public funds are being utilized (The City of Calgary 2000). Typical treatment processes such as chemical additions or elaborate processing facilities were not considered since these processes are costly and maintenance intensive.

Sediment volumes were determined to assess the amount of sediment in the retention ponds requiring disposal. Sediment volumes were derived from the surface areas, and sediment depth was taken along the main flow path. With respect to disposal, the approximate sediment volumes (m^3) were 2,000, 5,000, 15,000, 28,000, and 172,000 for 61 Avenue SE duck pond, Deerfoot Trail and Highway 22X pond, Edgemont wetland, Harvest Lake, and 68 Street SE retention lake, respectively. The large volumes reiterate that a cost-effective disposal method is required to maintain economic viability.

Removal of sediment was subsequently considered. The limiting factor with respect to sediment removal is the solids content. Generally, sediment behaves as either a solid, semisolid, or liquid depending upon the solids content. These limits are defined as 30% solids for the liquid limit (which is the transition point between liquid and semi solid) and 69% solids for the plastic limit (which is the transition point between semi solids and solids). The average percent solids for the retention ponds ranged between 30 to 44% by mass with the exception of the 68 Street SE retention lake, which approached the liquid limit of clay. Therefore, it is recommended that the sediment be dredged mechanically for all of the ponds.

Subsequently, the possible sediment disposal methods were examined. Three disposal options were identified; these included direct disposal, land application, and landfill. Direct disposal of the sediment was evaluated initially since direct disposal of material was deemed to be the most economical disposal method. As already illustrated by the contamination evaluation, all of the pond sediments exceed salt, hydrocarbon, and/or metal parameters for agricultural land use. Examination of different land use criteria were then completed to determine if sediment material could be accepted as fill material in specific applications within the city. Comparison with the respective criteria for all retention ponds illustrated that the retention pond sediment exceeded residential guidelines for one or more parameters. Moreover, one or more commercial guidelines were exceeded, with the exception of the Deerfoot Trail and Highway 22X pond. Industrial guidelines were finally examined as this provided the best opportunity for disposal. This is due to the less restrictive criteria and a high demand for clean fill material within the city. Particularly, it is the demand for daily cover with respect to landfill operations that would utilize a significant amount of material. However, Deerfoot Trail and Highway 22X pond remained the only pond that could be used as fill material for this application. It has been identified that direct disposal of material as a soil cannot be achieved for the remaining retention ponds, and alternate disposal options require investigation. Due to the volume of sediment anticipated, the alternative options are restricted either by cost or land use.

Land application of the material could potentially be viable, and in many cases, land application is less expensive than other disposal methods (U.S. EPA 2005). Land application is the planned and controlled application of a qualified waste into the soil surface and therefore applications must be made directly to and approved by the governing body. As defined within the *Wastewater and Storm Drainage Regulation* (Alberta Environment 1993), sediment taken from a storm drainage system is defined as sludge, which can be land applied but must be disposed of in accordance with the *Guidelines for the Application of Municipal Wastewater Sludges* (Alberta Environment 1996). To allow the application of the material to soils, a maximum cumulative addition of specific metals must not be exceeded, a minimum nutrient-to-metal ratio must be met, and a net benefit must be illustrated. This is to ensure that the nutrient benefits are not outweighed by the cost of utilizing the soil's capacity to sequester heavy metals. The criteria are therefore designed to discriminate against waste that has high metal concentrations and low nutrient levels (Alberta Environment 1996). Subsequently, the nutrient and metal concentrations that were found within each pond were compared with the criteria.

Within this study, the waste was initially examined to ensure that the metal concentrations did not exceed the maximum allowable application rate. Upon examining each site, the metal concentrations did not alter the application rate and, subsequently, the spread rate remained at 10 tonnes per hectare. The only exception however was 61 Avenue SE duck pond which required a spread rate of 7 tonnes per hectare due to the cadmium levels. Secondly, since application rates are plausible, the next requirement that must be met is the nutrient-to-metal ratio. Upon examination of the retention ponds, all the ponds exceeded the required ratio with one or more metal, with the exception of the 68 Street SE retention lake. The final requirement is that the application of the sludge to soils will result in a net benefit for the soil, defined by nutrients, organic content, and saturation parameters. The water availability in the local area is moderate and, therefore, benefits from saturated sediment would be minimal. Examination of the contamination content compared with nutrient and organic content illustrated that any net benefit achieved in the application of retention pond sediment would also be minimal. Therefore it was deemed that this disposal method was not acceptable as it did not provide sufficient net benefit to the land (The City of Calgary 2005).

The final disposal option available is the disposal of material into a landfill site. Disposal into a landfill should only be considered once other disposal options are exhausted. This is typically the most expensive disposal option since material must be transferred to the landfill site, possibly dewatered to achieve a high solids content, and has large tipping fees ($42 per tonne devoid of free liquids) associated with the waste. Landfills however can accept a broad array of waste products.

Disposal restrictions include waste that: has no free liquids, does not contain any restricted waste, contains concentrations less than the regulated limits, does not contain a substance that ignites or propagates combustion, and has a pH less than 12.5 (Alberta Environment 1995). Comparison of sediment from each pond indicated that the sediment met landfill disposal options; however, all the sediment samples failed the standard paint filter test, illustrating the presence of free liquids. Therefore all ponds could potentially be disposed of directly into a landfill site, if dewatered.

Conclusions

- All the retention ponds within the study were deemed to be contaminated since they exceeded criteria for one or more of the following parameters: salt, cadmium, chromium, copper, lead, selenium, zinc, and/or the F3 fraction hydrocarbons.
- A strong positive relationship was found between heavy metals, F3 fraction hydrocarbons, and phosphorus when correlated to finer particulates. However, this was only observed at higher contamination concentrations.
- Sediment from all retention ponds must be placed in a landfill with the exception of sediment from the Deerfoot Trail and Highway 22X pond, which could be directly disposed of in areas designated as commercial and industrial.
- The 61 Avenue SE duck pond was the most contaminated retention pond studied and displayed the greatest diversity and severity of contaminants compared with CCME agricultural soil guidelines. Therefore, the 61 Avenue SE duck pond receives a significantly higher contamination load originating from anthropogenic sources dominated by industrial land use.

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