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**ASSESSMENT OF OPERATION OF
THE TOWN OF RICHMOND HILL'S
SNOW STORAGE FACILITY (RHSSF):
INTERIM REPORT**

**K. Exall, J. Marsalek, Q. Rochfort,
L. Grapentine, S. Kydd, and J. Nemeth**

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Interim report**

K. Exall¹, J. Marsalek¹, Q. Rochfort¹, L. Grapentine¹, S. Kydd¹, and J. Nemeth²

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Citation	<p><i>(Publication title, names of authors, publisher, journal, date of publication)</i></p> <p>Assessment of Operation of the Town of Richmond Hill's Snow Storage Facility (RHSSF): Interim report</p> <p>K. Exall¹, J. Marsalek¹, Q. Rochfort¹, L. Grapentine¹, S. Kydd¹, and J. Nemeth²</p> <p>NWRI Technical Note</p> <p>December 2008</p>
Plain language summary	<p><i>(Focus on key messages using plain language. Explain what's new. Be brief.)</i></p> <p>The snow pile stored at the Richmond Hill Snow Storage Facility (RHSSF) was monitored from January to April 2007. This system consists of a paved snow storage/melting pad, an oil and grit separator (OGS) and a stormwater pond, leading to a drainage ditch which discharges to a tributary of the Rouge River. The study objectives were: (1) to monitor the release of snowmelt and common urban stormwater / snowmelt pollutants from the snow pile stored at the RHSSF over the course of a snowmelt season (January-April 2007), (2) evaluate the sediment quality in the receiving (treatment) pond, and (3) evaluate the ecotoxicological status of the receiving pond and the downstream drainage ditch. To document the operation of the RHSSF, eight types of field data were collected: (a) on-site meteorological data, (b) snow pile data, (c) snowmelt and rainfall runoff flow rates, (d) water quality of snowmelt and runoff leaving the storage site, (e) water and sediment quality in the meltwater management system (OGS, stormwater pond and the downstream drainage ditch draining into the Rouge River), (f) toxicity of sediment in the stormwater pond and the drainage ditch, (g) chemical uptake by macrophytes in the stormwater pond, and (h) benthic community characteristics in the receiving pond and the drainage ditch. The findings of the first season of the study (winter 2006/2007) are presented in this report.</p>
Key findings or abstract	<p><i>(Key messages [one or two paragraphs] supported with facts)</i></p> <p>In total, about 7,200 m³ of water passed through the facility. Of this amount, about 2/3 were contributed by dumped snow and the remaining third by direct precipitation over the storage and surrounding area. Continuous monitoring of runoff indicated that although chloride concentrations in runoff from the storage pavement averaged 2500 mg/L over the entire melt period, chloride exhibited preferential elution (early release) from the snowpack and was not well retained by the system. The bulk of the solids remained with the snowpack until the end of the melt period, along with most of the metals.</p> <p>Sediment samples taken from the OGS, the stormwater pond and the drainage ditch showed that metal and PAH concentrations decreased along the length of the pond and were below the CCME sediment quality guidelines by the outlet of the pond. Wetland plant (macrophyte) samples collected from the stormwater pond were tested for copper, lead and zinc.</p>

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	<p>Concentrations were highest in the root tissue, then the shoot tissue. As was seen in the sediment samples, metal concentrations in root tissues generally decreased along the length of the pond.</p> <p>The benthic community total abundance and taxon richness showed a similar pattern to the chemical analyses: the benthic community is most sparse at the pond site closest to the inflow, most dense and taxon-rich at mid-pond, intermediate near the pond outflow, and further decreased in the drainage ditch. Acute toxicity of sediment was generally absent, major chronic (sublethal) toxicity was observed in 2 of 18 cases, and minor chronic toxicity in 5 of 18. Only the sample from the OGS showed substantial toxicity potentially attributable to sediment contaminants.</p> <p>Overall, the system appears to function well with respect to the MOE Guidelines for Snow Disposal and Deicing Operations in Ontario and the TAC Syntheses of Best Practice 8.0 Snow storage and disposal.</p>
<p>Policy and service delivery implications</p>	<p><i>(Provide a description of the key findings [a few lines] relevant to EC's policy or service delivery communities, as appropriate.)</i></p> <p>The study results will eventually serve for developing guidance on designing snow disposal sites and for identifying best management practices for reducing road salt output into the environment in response to the concerns expressed in the road salts assessment under the Canadian Environmental Protection Act, CEPA.</p>
<p>Key words</p>	<p><i>(Identify a handful of key words so this form can be part of a searchable index.)</i></p> <p>Snowmelt, snow dump, runoff, chloride, road salt</p>
<p>EC staff contact</p>	<p><i>(Name, e-mail, and phone number – usually the lead EC author)</i></p> <p>Kirsten Exall, kirsten.exall@ec.gc.ca, 905-319-7204</p>
<p>Approved by</p>	<p>John Lawrence, Director, Aquatic Ecosystem Management Research Division E-mail J.Lawrence@ec.gc.ca Tel 905-336-4566</p> <p>9 January, 2009</p>
<p>Citation</p>	<p><i>(Titre de la publication, noms des auteurs, périodique ou revue, date de publication)</i></p> <p>Évaluation de l'exploitation de l'installation d'entreposage de la neige de</p>

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Résumé en texte en clair

la ville de Richmond Hill (IENRH). Rapport d'étape.

K. Exall¹, J. Marsalek¹, Q. Rochfort¹, L. Grapentine¹, S. Kydd¹, et J. Nemeth²

Note technique de l'INRE

Décembre 2008

(Ciblez les messages principaux en texte en clair. Expliquez les nouveaux développements. Soyez concis.)

Le tas de neige entreposé à l'installation d'entreposage de la neige de Richmond Hill (IENRH) a fait l'objet d'un programme de surveillance de janvier à avril 2007. L'installation comprend une plate-forme pavée servant à entreposer la neige ou à la faire fondre, un dessableur-déshuileur (DD) et un bassin de retenue des eaux pluviales menant à un fossé de drainage qui se jette dans un tributaire de la rivière Rouge. Les objectifs de l'étude étaient les suivants : 1) surveiller le rejet des eaux de fonte et les polluants communs des eaux pluviales et des eaux de fonte urbaines provenant du tas de neige entreposé à l'IENRH durant une saison de fonte (janvier à avril 2007); 2) évaluer la qualité des sédiments dans le bassin récepteur (bassin de traitement); 3) évaluer l'état écotoxicologique du bassin récepteur et du fossé de drainage situé en aval. Pour obtenir des données sur l'exploitation de l'IENRH, huit types de données de terrain ont été recueillies : a) données météorologiques sur place; b) données sur le tas de neige; c) débits du ruissellement des eaux de fonte et de pluie; d) qualité de l'eau des eaux de fonte et des eaux de ruissellement à la sortie du site d'entreposage de la neige; e) qualité de l'eau et des sédiments dans le système de gestion des eaux de fonte (DD, bassin de retenue des eaux pluviales et fossé de drainage situé en aval se jetant dans la rivière Rouge); f) toxicité des sédiments dans le bassin de retenue des eaux pluviales et dans le fossé de drainage; g) absorption des produits chimiques par les macrophytes dans le bassin de retenue des eaux pluviales; h) caractéristiques des communautés benthiques dans le bassin récepteur et le fossé de drainage. Les résultats de la première saison de l'étude (hiver 2006-2007) sont présentés dans le présent rapport.

Principales constatations ou résumé

(Messages clés [un ou deux paragraphes] avec faits à l'appui)

En tout, quelque 7 200 m³ d'eau passent par l'installation. Environ les deux tiers de cette quantité proviennent de la neige déchargée et l'autre tiers des précipitations qui sont tombées sur l'installation d'entreposage de la neige et la zone environnante. La surveillance continue du ruissellement indique que même si les concentrations moyennes de chlorures dans les eaux de ruissellement provenant du pavage de l'installation d'entreposage sont de 2 500 mg/L pour la période de fonte complète, il y a élution préférentielle des chlorures (rejet rapide) présents dans la neige accumulée, et ces chlorures ne sont pas bien retenus par le système. La grande partie des solides, ainsi que la plupart des métaux demeurent avec la neige accumulée jusqu'à la fin de la période de fonte.

Dans les échantillons de sédiments prélevés dans le DD, le bassin de retenue des eaux pluviales et le fossé de drainage, les concentrations de

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	<p>métaux et de HAP diminuent en fonction de la longueur du bassin et, à la sortie du bassin, sont inférieures aux recommandations pour la qualité des sédiments du CCME. Des analyses de cuivre, de plomb et de zinc ont été effectuées dans des échantillons de plantes (macrophytes) de milieux humides recueillis dans le bassin de retenue des eaux pluviales. Les concentrations de métaux sont plus élevées dans les tissus des racines que dans les tissus des pousses. Comme c'est le cas pour les échantillons de sédiments, les concentrations de métaux dans les tissus des racines diminuent généralement en fonction de la longueur du bassin.</p> <p>Le profil de l'abondance totale des communautés benthiques et de la richesse taxinomique est semblable à celui des analyses chimiques : dans le bassin de retenue des eaux pluviales, les communautés benthiques sont plus éparses à proximité de l'entrée, plus denses et d'une plus grande richesse taxinomique au milieu du bassin, intermédiaires près de la sortie; leur abondance diminue encore dans le fossé de drainage. On constate l'absence générale de toxicité aiguë des sédiments, une importante toxicité chronique (sublétale) dans 2 des 18 cas et une faible toxicité chronique dans 5 des 18 cas. Seul l'échantillon provenant du DD affiche une toxicité substantielle, qui est peut-être attribuable aux contaminants présents dans les sédiments.</p> <p>Dans l'ensemble, le système semble bien fonctionner en ce qui concerne les lignes directrices en matière d'enlèvement de la neige et d'opérations de dégivrage en Ontario du MEO et la synthèse des meilleures pratiques – 8.0 Entreposage et élimination de la neige de l'ATC.</p>
Répercussions sur les politiques et la prestation de services	<p><i>(Donnez une description des principales constatations [quelques lignes] qui sont pertinentes aux communautés d'EC responsables des politiques et de la prestation de services, le cas échéant.)</i></p> <p>Les résultats de l'étude serviront éventuellement à l'élaboration de directives sur la conception des lieux d'élimination de la neige et à l'établissement de meilleures pratiques de gestion pour réduire les rejets de sels de voirie dans l'environnement, compte tenu des préoccupations exprimées dans l'évaluation des sels de voirie réalisée en vertu de la Loi canadienne sur la protection de l'environnement (LCPE).</p>
Mots clés	<p><i>(Déterminez un ensemble de mots-clés pour que ce formulaire puisse faire partie d'un index de recherche central.)</i></p> <p>Eaux de fonte de la neige, déchargement de la neige, ruissellement, chlorures, sels de voirie</p>
Personne-ressource du personnel d'EC	<p><i>(Nom, courriel et numéro de téléphone – habituellement l'auteur principal d'EC)</i></p> <p>Kirsten Exall, kirsten.exall@ec.gc.ca, 905-319-7204</p>
Approuvé par	<p><i>John Lawrence, Director,</i></p> <p><i>Aquatic Ecosystem Management Research Division</i></p>

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9 Janvier, 2009

Abstract

The Town of Richmond Hill and the National Water Research Institute, Water Science and Technology Directorate, Environment Canada, formed a partnership to investigate the Richmond Hill Snow Storage Facility (RHSSF) operation with respect to snowmelt flows, fluxes of chemicals contained in snowmelt, and direct effects on the receiving water comprising a stormwater pond and a downstream ditch. To document the operation of the RHSSF, eight types of field data were collected: (a) on-site meteorological data, (b) snow pile data, (c) snowmelt and rainfall runoff flow rates, (d) water quality of snowmelt and runoff leaving the storage site, (e) water and sediment quality in the meltwater management system (OGS, stormwater pond and the downstream drainage ditch draining into the Rouge River), (f) toxicity of sediment in the stormwater pond and the drainage ditch, (g) chemical uptake by macrophytes in the stormwater pond, and (h) benthic community characteristics in the receiving pond and the drainage ditch. The findings of the first season of the study (winter 2006/2007) are presented in this report. The study results will eventually serve for developing guidance on designing snow disposal sites and for identifying best management practices for reducing road salt output into the environment in response to the concerns expressed in the road salts assessment under the Canadian Environmental Protection Act, CEPA.

Résumé

La Ville de Richmond Hill et l'Institut national de recherche sur l'eau, Direction de la science et de la technologie de l'eau à Environnement Canada, ont constitué un partenariat afin de faire enquête sur l'opération de Richmond Hill Snow Storage Facility (RHSSF) en ce qui concerne les flux de fonte de la neige, les flux de substances chimiques contenues dans l'eau de fonte de la neige et les effets directs sur les plans d'eau récepteurs composés d'un bassin d'eau de tempête et d'un fossé en aval. Pour documenter l'opération du RHSSF, huit types de données de terrain ont été recueillies : a) les données météorologiques sur les lieux; b) les données sur la pile de neige; c) les taux de débit du ruissellement de la fonte des neiges et de la pluie; d) la qualité de l'eau de la fonte de la neige et du ruissellement quittant le site de stockage; e) la qualité de l'eau et des sédiments dans le système de gestion de l'eau de fonte (OGS, bassin d'eau de tempête et fossé de drainage en aval drainant dans la rivière Rouge); f) la toxicité des sédiments du bassin d'eau de tempête et du fossé de drainage; g) la reprise de substances chimiques par les macrophytes dans le bassin d'eau de tempête et h) les caractéristiques de la communauté benthique dans le bassin récepteur et le fossé de drainage. Les résultats de la première saison d'étude (hiver 2006/2007) sont présentés dans le présent rapport. Les résultats de l'étude serviront éventuellement à l'élaboration de conseils sur la conception de nouveaux sites de dépôt de la neige et pour identifier les pratiques exemplaires de gestion pour réduire la quantité de sel routier rejeté dans l'environnement en réponse aux préoccupations exprimées dans l'évaluation des sels de route en vertu de la *Loi canadienne sur la protection de l'environnement*, LCPE.

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1. Introduction

1.1 Background

In cold climates, winter road safety requires proper maintenance including snow plowing and eventual removal of snow from urban streets, roads and parking lots. This “used snow” may be contaminated with numerous pollutants originating from airborne fallout, vehicular deposition of petroleum products and corroded metals, application of de-icing and anti-skid agents, roadway deterioration, and litter. Over the years, the practice of used snow disposal has evolved from indiscriminate snow dumping (sometimes even into open water bodies) to storage and meltwater management at properly designed snow disposal sites. Such a site was built by the Town of Richmond Hill in 2003 and is currently used for disposal of used snow collected in the town. Recognizing that meltwater leaving the site may exert environmental affects on receiving waters, the Town of Richmond Hill and the National Water Research Institute, Water Science and Technology Directorate, Environment Canada, formed a partnership to investigate the Richmond Hill Snow Storage Facility (RHSSF) operation with respect to snowmelt flows, fluxes of chemicals contained in snowmelt, and direct effects on the receiving water comprising a stormwater pond and a downstream ditch (length = 0.5 km) draining into the Rouge River. The findings of the first season of the study (winter 2006/2007) are presented in this report, and besides providing a preliminary assessment of the facility, they also served to improve the study experimental design for the second study year, the winter of 2007/2008. Eventually, the study results will serve for optimizing operation of the RHSSF, developing guidance on designing snow disposal sites and for identifying best management practices for reducing road salt output into the environment in response to the concerns expressed in the road salts assessment under the Canadian Environmental Protection Act, CEPA (Environment Canada and Health Canada, 2001).

1.2 Study scope and objectives

The study objectives were: (1) to monitor the release of snowmelt and common urban stormwater / snowmelt pollutants from the snow pile stored at the RHSSF over the course of a snowmelt season (January-April 2007), (2) evaluate the sediment quality in the receiving (treatment) pond, and (3) evaluate the ecotoxicological status of the receiving pond and the downstream drainage ditch using the sediment quality triad approach comprising assessments of sediment chemistry, benthic toxicity, and impacts on benthic communities.

2. Urban snow and snowmelt quality – literature survey

The literature survey covers five issues: (a) pollutant accumulation in urban snow, (b) pollutant removal with used snow, (c) pollutant releases from urban snow, (d) snowmelt and winter runoff quality, and (e) environmental effects of snowmelt and winter runoff. To summarize briefly, urban snow accumulates pollutants from various sources generated at rates which exceed those in other seasons. Urban snow is considered too polluted for direct disposal into receiving waters, and therefore is transported to specially designed snow storage and disposal sites. During melting at snow storage sites, snow releases meltwater and soluble chemicals or chemicals attached to fine particulates. Coarser particles, debris and litter remain on the site surface and need to be removed at the end of the season. While there is a fair amount of literature on snowpack melting and

release of pollutants, the situation at snow storage sites is rather different, due to the large amount of processing of urban snow during its removal and transport to the dump site. Thus, the available guidance for snow dump site design is relatively limited and further research is needed.

2.1 Pollutant accumulation in urban snow

In cold weather, pollutants, including chemicals and total suspended solids (TSS), and various materials (debris, litter) accumulate in urban snow and eventually are transported to roadside snow piles. Sources of such pollutants include airborne fallout, roadway and roadside deposits, de-icing and anti-skid agents, and litter. Accumulation of pollutants in the snowpack over the cold weather season is a dynamic process, comprising pollutant influx with deposition and precipitation, and release during intermittent melts, or rainfall/runoff events (Viklander, 1997).

Falling snowflakes scavenge both particulate and aerosol pollutants (Colbeck, 1981) from local as well as remote sources (Schöndorf and Herrmann, 1987; Viklander, 1997). In fact, a substantial portion of the toxic materials in runoff/snowmelt can be attributed to atmospheric sources, originating from fossil-fuel combustion, refuse incineration, chemical processing, metal plating, manufacturing, and fertiliser/pesticide application (Horkeby and Malmquist, 1977; Malmquist, 1978). A number of studies (Horkeby and Malmquist, 1977; Schrimpf *et al.*, 1979; Boom and Marsalek 1988; Sakai *et al.*, 1988; Daub *et al.*, 1994) have shown regional patterns in the deposition of polycyclic aromatic hydrocarbons (PAHs) and heavy metals that were related to urban and industrial activities, with both PAH and TSS concentrations being much higher in melt runoff than in rain runoff. On a smaller scale, Viklander (1997) noted that pollutant burden in snow increased towards the city centre.

Road surface or road shoulder snow is typically polluted by vehicular deposition of petroleum products/additives and corroded metals, direct applications of salt and anti-skid materials (Marsalek, 2003), and roadway surface deterioration (Malmquist, 1978; Oberts, 1986; Amrhein *et al.*, 1992; Viklander, 1997; Novotny *et al.*, 1999; Glenn and Sansalone, 2002). The magnitude of such pollution increases with traffic density (Viklander, 1997) and is typically restricted to narrow bands (10 m) along roadsides (Novotny *et al.*, 1999).

In winter road maintenance in Canada, about 5 million tonnes of road salt (mostly sodium chloride, NaCl) was applied during the winter of 1997/98 (Environment Canada and Health Canada 2001). Concerns about the environmental effects of such road salt applications were expressed by Environment Canada and Health Canada in their assessment under the CEPA. Following the assessment submission, a task force was established to study best management practices for reducing salt usage in winter road maintenance. The task force will report on possible salt usage and impacts reductions due to the use of best management practices in salt applications. Road salts contain additional chemicals of concern, including anti-caking agents, such as sodium or ferric ferrocyanides (~0.01% by dry weight). While such ferrocyanides are not toxic, they can transform into toxic free cyanide (HCN) when exposed to light (Novotny *et al.*, 1999). Granato (1996) found that the composition of road salt varied in terms of major and trace constituents from year to year, but that major constituents of deicing chemicals (e.g., chloride, sodium, sulphate, calcium, magnesium and bromide) in highway runoff may account for a

substantial annual chemical load. The contributions of trace road salt constituents to runoff were not found to be large, but can still be important (Granato, 1996).

Alternative de-icers, such as calcium chloride (CaCl_2), magnesium chloride (MgCl_2), and calcium magnesium acetate (CMA), may offer some advantages compared to sodium chloride (e.g., lower eutectic or effective temperatures, less corrosive, or less toxic), but they are more expensive, particularly in the case of CMA. Anti-caking chemicals can be eliminated by applying road salts as brine, which requires pre-application before the snowfall. Particulates added as anti-skid agents (salt: abrasive ratios from 1:2-1:50) add large solids loads to snowmelt, and source sands used to control skidding may contain relatively high levels of phosphorus and several metals (Oberts, 1986).

Secondary sources of pollution in urban snow include abrasion of roadway surfaces and urban litter; both sources are poorly documented (Oberts *et al.*, 2000). Repeated applications of salt, numerous freeze-thaw cycles, the grinding of plows on asphalt and concrete surfaces, and the use of studded tires (where permitted) during a winter season take a physical toll on pavements. Urban litter consists of a myriad of different materials, including animal faeces, vegetation and discarded food and beverage containers.

2.2 Pollutant removal with used snow

Used snow is removed from urban areas for operational reasons, but this practice has environmental implications – it offers a management option for used snow, allowing the selection of the location where pollutants will end up after melting. Thus, it is possible to develop strategies for control of pollutants contained in used snow (Sharma *et al.* 1991). Snow disposal strategies include leaving snow in the place where it fell, transporting it a short distance to a local snow storage site, or transporting it over a longer distance to a central snow storage and disposal site. At local and centralized snow disposal sites, the dissolved substances leave the snow deposit with the melt water (Westerström 1995; Viklander 1997) and sediments remain on the surface of the dump, particularly the coarser particles with adsorbed pollutants.

Snow storage site sediments are allowed to accumulate over a long time, and are thus subject to slow leaching, or they are removed from the site surface and transported to another storage site, or re-used as fill material. The mobility of heavy metals in snow dump sediments depends on such factors as the type of soil, humus content, water quality and geochemical environment. At low pH, the soil capacity to retain metal ions decreases and adsorbed ions may be released. High salt concentrations also decrease the adsorption of heavy metals. Milne and Dickman (1977) showed that the lead concentrations in sediments at a snow deposit area in Ottawa were more than an order of magnitude greater than those in non-contaminated sediments. Scott and Wylie (1980) showed that some sodium and chloride were leached from the snow dump soil during the summer months, but much of the salt and most of the lead tended to accumulate from year to year. Note that leaded gasoline was prohibited in Canada under CEPA in 1990 and lead concentrations detected in stormwater have decreased since it was phased out (Marsalek *et al.* 1997), so concentrations in used snow and snowmelt could also be expected to be substantially lower.

2.3 Pollutant releases from urban snow

Two types of pollutant releases from urban snow can be distinguished: (a) snowpack releases (i.e., in-situ), and (b) releases from snow piles (i.e., from mechanically processed snow, by plowing and/or loading and dumping). Snowpack melting processes encompass elution and melt water infiltration and runoff. Repeated snowpack freezing and thawing cycles result in snow and ice metamorphism, and preferential early elution of soluble pollutants (Colbeck, 1981). This may result in a "first" or "acid" flush of early season meltwater carrying harmful contaminants (Oberts *et al.*, 2000). High salt levels in the urban snowpack may shift the speciation of metals into the soluble phase. Solids and associated hydrophobic substances, such as PAHs, stay in the snowpack until the last 5-10% of meltwater leaves the snowpack (Schöndorf and Herrmann, 1987). Medium and coarse particles usually remain behind after the snowpack is fully depleted (Viklander, 1997). This type of elution has been confirmed by a number of researchers mostly for relatively undisturbed snowpacks, in rural or suburban areas.

Early elution for soluble ions in meltwater was reported by Droste and Johnston (1993) at snow dumps and by Westerström (1995) from an urban field lysimeter. Schöndorf and Herrmann (1987) noted that in rain-on-snow events, fine-grained particulates were washed through the pack and flushed out metals and adsorbed organic pollutants. Viklander and Malmquist (1993) and Schöndorf and Herrmann (1987) reported that 90% of the particulate-associated (hydrophobic) PAHs in a snow column were eluted in the last 10% of the melt. Viklander (1999) also examined snow samples melted in the laboratory and found that dissolved substances left snow with meltwater early during the melt, but 90-99% of particulate-bound chemicals stayed in the sediment residual observed after the snow melted. Novotny *et al.* (1999) reported that 60-90% of snowpack solids remained on the street or in roadside gutters; quick maintenance can remove this material before the first spring rainfall washes it off the streets into sewer inlets, catch basins, storm sewers, and eventually stormwater management facilities, or receiving waters (Sharma *et al.*, 1991). Timely interception of street sediment by sweeping or other sediment control measures (e.g., oil & grit separators) reduces sediment accumulations in sewers or stormwater management facilities, and contributes to lower maintenance costs arising from less frequent needs to remove sediment from catch basins, stormwater ponds and wetlands, and other drainage facilities.

Snow deposited in piles along roads, or at dump sites, has been extensively processed during plowing, loading on trucks and dumping, and with respect to release of pollutants may behave differently from in-situ snowpacks. This was the finding of Westerlund (2007) who studied pollutant releases from a roadside snow pile (a windrow) and noted a fairly uniform release of H^+ , TSS and particulate metals.

Roadway snow is quickly removed during road maintenance by rapid melt caused by salt applications, plowing over the roadway curb/edge, or removal to snow dumps. Oberts (1982) observed that total phosphorus (TP) and total lead (TPb) concentrations in small melts in January and February accounted for very little (0.4-5%) of the annual TP and TPb loads, whereas the end-of-winter melt accounted for about 8-20% of the TP and TPb annual loads (Oberts, 1982). Sansalone and Buchberger (1996) compared selected inorganics and TSS concentrations in snowmelt and rainfall runoff, and noted that total element and solids concentrations were higher in snow washoff. While metal elements in rainfall runoff were predominantly dissolved, they were bound to particulates in snow washoff. Similarly, Glenn and Sansalone (2002) found Pb, Zn, Cu, and Cd

concentrations at four urban highway sites ranging from 1 to 10 mg/L, with >90% of the mass of the metals being particulate bound.

Pollution from snow dumpsites has been extensively studied, with the reported levels of Cl (2-2500 mg/L), Pb (0.02-50 mg/L – high values were obtained before Pb was phased out), Fe (7-102 mg/L), TP (2.4-19.6 mg/L), BOD (8.2-57 mg/L), TS (256-10500 mg/L), and TSS (1570-4000 mg/L) (Van Loon, 1972; LaBarre *et al.*, 1973; Oliver *et al.*, 1974; Pierstorff and Bishop, 1980; Scott and Wylie, 1980; Droste and Johnston, 1993; Exall *et al.*, 2006).

2.4 Snowmelt and winter runoff quality

Meltwater moves along paved and soil surfaces that have accumulated debris for an entire winter; this can result in some buffering of the meltwater. Because the initial stages of melt are generally slow, the first, highly soluble-laden runoff can exert a concentration "shock", but not a high pollution load (Oberts *et al.*, 2000). The major water mass of the snowpack and the latter portion of the melt add both high concentrations and high loads because of wash-off of paved and saturated soil surfaces, and the movement of particulates out of the pack. This process may be affected by rainfall occurring during the melt, which dilutes soluble pollutants and promotes the movement of particulates through the pack (Couillard, 1982; Schöndorf and Herrmann, 1987), and increases flows engaged in wash-off processes. An extreme water quality impact is experienced during the end-of-the-season event when rain falls on a deep, saturated pack that has undergone repeated freeze-thaw cycles. This leads to a sudden release of soluble pollutants from the wetted front, combined with a flushing of soluble and particulate pollutants caused by the rainfall. The intensity of the resulting rainfall/melt wash-off may be higher than that associated with a summer rainfall because of the low infiltration capacity of the soil and the added volume of water coming from the melting snowpack.

Urban snowmelt, winter runoff and stormwater quality data are listed in Table 1 for selected Minnesota sites (Oberts *et al.*, 2000), WERF urban snowmelt studies (Novotny *et al.*, 1999), and the Nationwide Urban Runoff Program (NURP) median and 90% sites (U.S. EPA, 1983). Comparison of snowmelt and NURP median site stormwater data indicates that mean concentrations of TKN, COD and TP in snowmelt exceed those in stormwater.

Table 1. Summary of snowmelt and runoff water quality data (from Oberts *et al.*, 2000; Novotny *et al.*, 1999; U.S. EPA, 1983).

Source of data	TSS	COD	TP	Concentration (mg/L)			Cl	TPb
				TKN	NO ₃			
Minnesota sites – snowmelt	14-311	52-319	0.33-1.01	1.48-2.06	0.45-2.06		37-4920	0.002-0.405
Median of Minn. Sites	82	111	0.74	3.20	0.85		152	0.072
WERF sites - snowmelt	8-259	15-167	0.10-1.08	0.3-4.3	0.61-1.19		194-6242	0.02-0.057
NURP - runoff (median)	100	65	0.33	1.50	0.68	---		0.144
NURP - runoff (90%)	300	140	0.70	3.30	1.75	---		0.350

2.5 Environmental effects of snowmelt and winter runoff

Urban snowmelt adversely impacts on soils, plants and biota. De-icing salts in snowmelt change the structure and fertility of exposed soils through cation replacement (Na^+ for Ca^{2+} and Mg^{2+}) and leaching out of metals (Cr, Pb, Ni, Fe, Cd and Cu; Amrhein *et al.*, 1992; Backström *et al.* 2004). Such processes generally lead to destruction of the soil structure and to lowered soil fertility. Salt laden snowmelt also impacts on roadside vegetation, though some halophytic plants may be resistant to such impacts. Isabelle *et al.* (1987) found after one month of exposing wetland plant seeds to various mixes of meltwater that germination and the growth of seedlings was adversely affected by metals and oil/grease, with community biomass and productivity notably impacted.

Salt runoff impacts on receiving waters, particularly small lakes and ponds, by contributing to their densimetric stratification, which impedes vertical mixing (Judd, 1970; Novotny *et al.*, 1999). Marsalek (1997) observed both thermal and chemical stratification in an on-stream urban stormwater management pond. The chemical stratification dominated, but was destroyed during spring runoff, when chlorides were largely washed out of the pond. Similar stratification may form in stormwater oil and grit separators (Henry *et al.*, 1999).

The acidic early melt carries with it many dissolved contaminants that may be at levels harmful to aquatic life; this is reinforced by high levels of salt (Environment Canada and Health Canada, 2001). While acute toxic effects of chloride on aquatic organisms are usually observed at relatively elevated concentrations (e.g., the 4-day median lethal concentration (LC_{50}) for *Ceriodaphnia dubia* is 1400 mg/L), chronic toxicity occurs at lower concentrations. Toxic effects on aquatic biota are associated with exposures to chloride concentrations as low as 870 mg/L for median lethal effects on fathead minnow embryos. The No-Observed-Effect Concentration (NOEC) for the 33-day early life stage test for survival of fathead minnow was 252 mg chloride/L. It was estimated that 5% of aquatic species would be affected (LC_{50}) at chloride concentrations of about 210 mg/L, and 10% of species would be affected at chloride concentrations of about 240 mg/L. Changes in populations or community structure can occur at lower concentrations; shifts in algae populations in lakes were associated with concentrations of 12–235 mg/L (Environment Canada and Health Canada, 2001). At high concentrations, chloride has the ability to change the speciation of metals in soils alongside roads or in sediments settled in receiving waters, enhancing the occurrence of the dissolved and more toxic forms of certain metals (Novotny *et al.*, 1999).

The acidic early-melt waters leaving the snowpack can be toxic enough to stress or kill aquatic life in receiving streams or lakes (Johannessen and Henricksen, 1978; Novotny *et al.*, 1999). Potentially toxic levels of metals and organic pollutants in urban snowmelt and rainfall runoff have been documented by many researchers (e.g., see Horkeby and Malmquist, 1977; Couillard, 1982; Schöndorf and Herrmann, 1987). Novotny *et al.* (1999) found cyanides in roadside snow in concentrations ranging from 3 to 270 $\mu\text{g/L}$. Snowmelt releases of cyanides from roadside snow could exceed the U.S. EPA aquatic life protection criteria in fresh waters, which specify free cyanide levels (HCN) of 22 $\mu\text{g/L}$ for acute toxicity, and 5 $\mu\text{g/L}$ for chronic toxicity.

Recognising that chemical protocols do not reflect well contaminant speciation and bioavailability, White and Rasmussen (1995) tested the potential effects of urban snowmelt in the Montreal area by evaluation of genotoxicity using the SOS Chromotest. There was a positive correlation between genotoxicity detection and the ambient levels of suspended particulates. It was speculated that fuel combustion byproducts were the main cause of genotoxicity. Marsalek *et al.* (1999) studied toxicity of urban stormwater from various sources and noted that winter highway runoff was the most toxic. Among the 28 events sampled, severe toxicity (defined by the observation of 50% *Daphnia magna* mortality at sample dilutions of $\leq 75\%$ of the original concentration) was detected only in eight snowmelt events (Fig. 1).

A synthesis of physico-chemical data of used snow and their environmental impacts was produced for the Montreal area (Delisle *et al.*, 1997). For this purpose, they applied the potential ecotoxic effects probe (PEEP), a novel index used to assess and compare the toxic potential of industrial effluents. The authors concluded that used snow had a low toxicity. Thompson *et al.* (1987) simulated the effect of initial and "leached" acidic meltwater on soil bacteria and found that bacteria in the soil A horizon were adversely affected, but the infiltrating melt actually released nutrients and fostered growth in the B and C horizons.

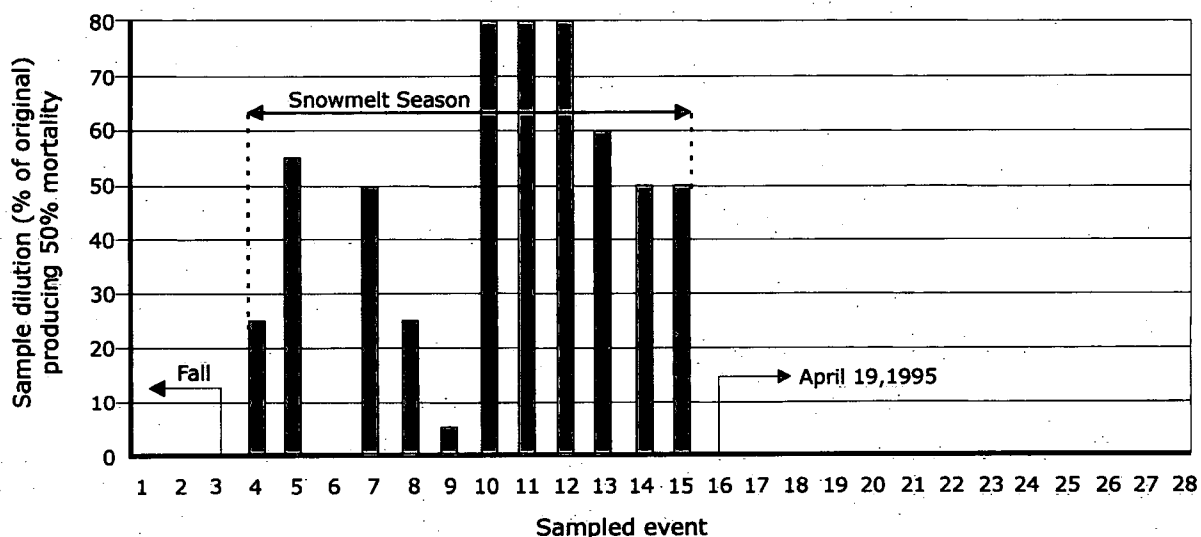


Fig. 1: Seasonal acute toxicity of highway runoff, based on 48-h *Daphnia magna* bioassay (after Marsalek, 2003)

Williams *et al.* (2000) reported chloride contamination of groundwater springs ranging from <2 to >1200 mg/L, resulting from winter application of road de-icing salts in a major metropolitan area in Canada. A biological index of contamination was developed to reflect the response of macroinvertebrates living in the springs to increasing salinity, and the absence of the amphipod *Gammarus pseudolimnaeus* was suggested as an indication of moderate to high contamination. Similarly, poor water quality in surface water bodies receiving urban snowmelt led to a loss of biodiversity measured by the benthic community structure (Crowther and Hynes, 1977). Adverse effects were not seen in an Ontario study of the impact of snowmelt on clams by Servos *et al.* (1987). Finally, Hagen and Langeland (1973) found that lake fish and invertebrates can

experience increased mortality and reproductive difficulties because of the inflow of lower density, acidic meltwater entering the biotic zone and displacing cleaner water.

3. Study Site: Town of Richmond Hill Snow Storage Facility (RHSSF)

The RHSSF is located on the grounds of the Richmond Green Sports Centre. The total runoff contributing area of 4.36 ha includes a baseball diamond with a surrounding landscaped area (1.72 ha) and a paved area of 1.62 ha, which serves as a parking lot and, in its northwest section, as a snow storage area. Runoff/snowmelt from this contributing area enters a meltwater management treatment train comprising an oil and grit separator, and a 0.14-ha stormwater pond (normal-water-level surface area of the pond) with a small sediment forebay. When the surrounding landscaped area (0.20 ha) sloping towards the pond is included, the overall pond catchment is 0.34 ha (as shown in Fig. 2).

When stored snow from the snow storage area of the parking lot melts, or during rainfall, meltwater and runoff follow the impervious area surface slope (more or less in the north-south direction) towards two twin sewer inlets with catch basins (CBs) located at low points on the pavement. The south-east CB drains into a 0.45-m pipe (28 m long) connected to an oil and grit separator (OGS); the north-west CB drains into a 0.3-m storm sewer pipe (5.5 m long), which joins a 0.45-m storm sewer pipe, at a right angle, immediately upstream of the OGS (see Fig. 2). The paved area substrate is drained by five perforated subdrains; two are connected to the north-west CB, and three to the south-east CB. The lower part of the parking lot is fitted with a concrete barrier curb preventing water from leaving the site without any treatment. Between both twin inlets there is a 2-m wide depression in the curb crown (a broad-crested overflow weir), followed by a rip-rap spillway draining into the stormwater pond, providing a flow bypass during high snowmelt flows or when the inlets would become blocked.

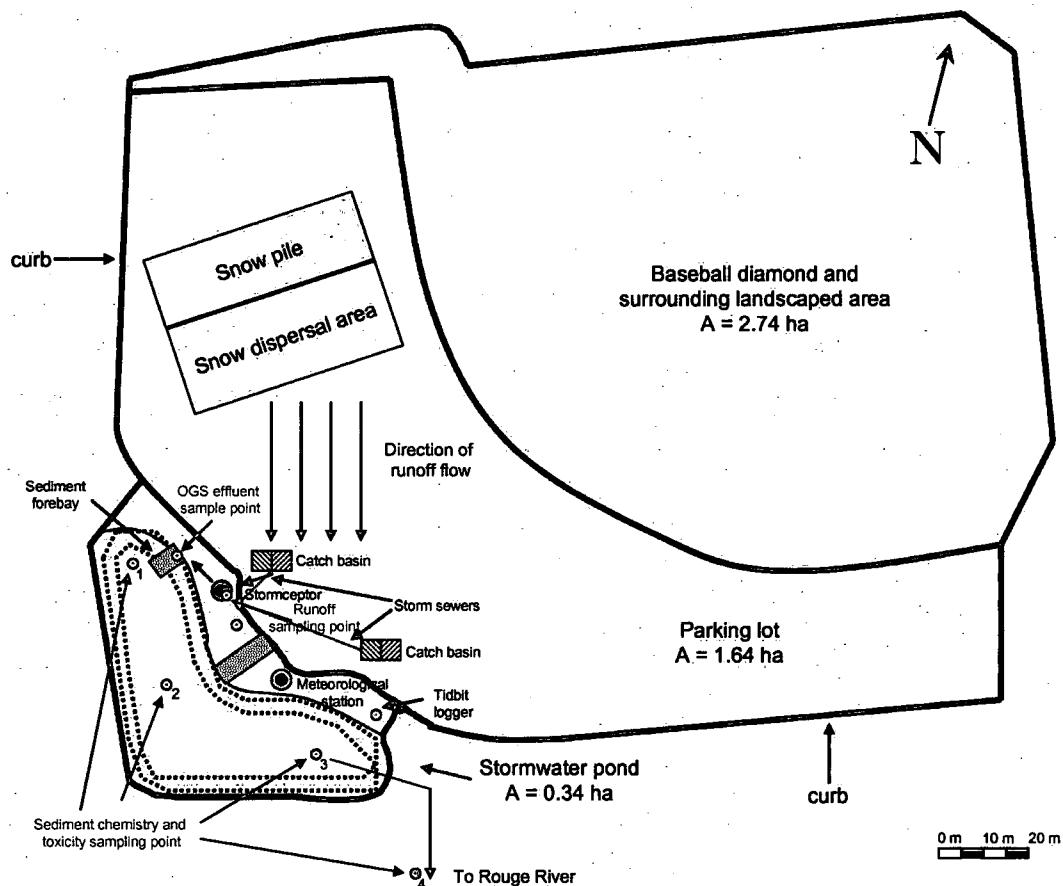


Fig. 2: Richmond Hill Snow Storage Facility

The 0.45-m storm sewer conveys flow to an oil and grit separator (model Stormceptor STC 4000). Following the removal of coarse sediment and free oil in the separator, water flows through a 600-mm pipe (10.2 m long) into a small outlet structure draining into a sediment forebay via a 4-m long rip-rap channel. The water surface area of the sediment forebay is approximately 225 m² (at normal water level). The sediment forebay, serving for further settling of sediments, is separated from the rest of the pond by a rock berm which becomes partially submerged during high water periods. The pond surface area is 0.14 ha (with the forebay) and the normal water depth is 1.5 m (referenced to the original pond bottom elevation). The main pond is shaped like a letter L, with the overall flow path length of about 80 m. The pond outlet is formed by a submerged inversely sloping pipe, with the inlet opening located 0.5 m above the pond bottom. Typical retention time was estimated at 24 hours. Treated water leaving the pond travels an additional 400 m in a southerly direction, through a concrete pipe, which discharges into a drainage ditch running parallel to Elgin Mills Rd. It continues for another 75 m before it discharges into a tributary of the Rouge River.

The implemented treatment system, comprising a combination of individual stormwater management practices, complies with Procedure B-4-1, Guidelines for Snow Disposal and Deicing Operations in Ontario (MOE, 1975), on land disposal, by providing opportunities for collecting and properly disposing of refuse after the thaw, reducing particulate solid inputs into a

watercourse, enhancing reduction of other contaminants (attached to solids), balancing (averaging) soluble salt inputs into the receiving waters, and reducing or eliminating oxygen demand loadings. The site design also follows the principal recommendations of the Transportation Association of Canada (TAC) best management practice 8.0 Snow Storage and Disposal relating to efficient site operation, proper base construction, drainage and meltwater management, and site security and environmental controls (TAC, 2003).

4. Methods

To document the operation of RHSSF, eight types of field data were collected: (a) on-site meteorological data, (b) snow pile data, (c) snowmelt and rainfall runoff flow rates, (d) water quality of snowmelt and runoff leaving the storage site, (e) water and sediment quality in the meltwater management system (OGS, stormwater pond and the downstream drainage ditch,) (f) toxicity of sediment in the stormwater pond and the drainage ditch, (g) chemical uptake by macrophytes (large aquatic plants) in the stormwater pond, and (h) benthic (bottom-dwelling) community characteristics in the receiving pond and the drainage ditch.

4.1 Meteorological data

Meteorological data were collected using a meteorological station (Fig. 3; Lat 43-53-59 N, Long 79-24-29 W), which measured the following parameters at 3 m above the ground: air temperature, barometric pressure, relative humidity, solar radiation, infrared radiation, and wind speed and direction (see Table 2 for the sensor specifications). Air temperature, barometric pressure, and relative humidity were read every 2 minutes, with 10-minute averages written to the datalogger. Solar radiation (285 - 2800 nm) and infrared radiation (3.5 – 50 μm) were read every 5 seconds and averaged to the logger every 10 minutes. Wind speed and direction were read by the anemometer every 5 seconds and averaged and logged every 10 minutes.



Fig. 3: Meteorological station

Table 2. Meteorological sensor specifications.

Parameter	Range	Resolution	Accuracy
Temperature	-53 to +48 °C	0.1 °C	Typically ± 0.2 °C, ± 0.4 °C worst case
Relative Humidity	0 to 100 %	0.1 %	± 2 % RH, 0 to 90 %; ± 3 % RH, 90 to 100 %
Barometric Pressure	60 to 110 kPa	0.01 kPa	± 0.05 kPa at -50 to +60 °C
Solar Radiation	0 to 2,800 W/m ²	9 μ V/W/m ²	± 0.5 %
Infrared Radiation	0 to 700 W/m ²	4 μ V/W/m ²	± 1.0 %
Wind Speed	0 to 100 m/s	0.001 m/s	± 0.3 m/s or 1 % of reading
Wind Direction	0 to 360 degrees	0.1 degrees	± 3 degrees

The onboard data canister was replaced monthly and the data downloaded and verified back at the laboratory. Complete data records were obtained for the period from Jan. 1 to Apr. 20, 2007. Additional precipitation and temperature data were available from the meteorological station at the Buttonville airport, 3.5 km to the southeast of the RH Snow Storage Facility.

Two additional air temperature instruments, TidbiT Temperature Loggers (Fig. 4), fitted with Stevenson screens, were deployed on-site, about 65-85 m south of the snow pile (Fig. 1). These instruments read air temperatures with an accuracy of ± 0.4 °C and best resolution of 0.3°C (at 10°C); readings were recorded as 10-minute averages. The loggers were positioned 3 m above the ground, remained in place for the entire season, and data were downloaded back at the laboratory.

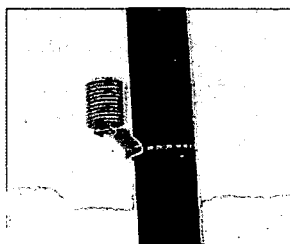


Fig. 4: TidbiT logger, with a Stevenson screen, mounted on light standard

4.2 Snow pile data and flow monitoring

Snow pile. Starting in late January 2007, snow pile data were collected during weekly site visits. The main parameters monitored included: (a) estimates of volume of deposited snow, and (b) snow quality. The disposed snow volume was estimated from the number of truckloads brought to the facility and recorded by the Town's staff. Each oversized tandem dump truck was assumed to carry a snow load of 15 m^3 . A summary of such data is presented in Table 3. These data were supplemented by photographs of the snow pile documenting the pile shape and size.

Table 3. Records of snow transport to the RHSSF

Date	Quantity (Loads; each load = 15 m^3 of snow)	Total Volume (m^3)
17-Jan-07	15	225
18-Jan-07	20	300
25-Jan-07	10	150
25-Jan-07	17	255
26-Jan-07	12	180
26-Jan-07	14	210
30-Jan-07	16	240
31-Jan-07	27	405
1-Feb-07	25	375
2-Feb-07	18	270
7-Feb-07	115	1725
12-Feb-07	6	90
12-Feb-07	8	120
16-Feb-07	74	1110
16-Feb-07	8	120
19-Feb-07	24	360
20-Feb-07	137	2055
8-Mar-07	117	1755
9-Mar-07	20	300
Total	683	10245

Snow sampling was initially accomplished by collecting snow cores (using an acrylic corer, $D = 76 \text{ mm}$) from the pile, targeting the recently deposited snow around the pile perimeter, and combining five to seven cores into a single composite sample. The samples were combined in a polyethylene bag, melted in the laboratory at room temperature, and typically yielded 12 L of

water for analysis. The first two such samples were collected in January and mid-February 2007. As of February 26th, the accumulated snow pile had solidified to the point where coring was no longer possible, and a pickaxe was used instead to scrape away the surface crust and extract enough snow to yield approximately 12 L of meltwater for chemical analyses. The last sampling was done on Apr. 4, 2007, when the pile was almost completely melted, leaving only some accumulated debris on site. The meltwater samples were analyzed for chloride, total metals, total organic carbon, polycyclic aromatic hydrocarbons, total petroleum hydrocarbons, cyanide, and solids; the specific constituents are listed in Table 4 and the corresponding analytical methods are listed in the Appendix. The snow pile data were used for a general verification of hydraulic and chemical loads leaving the snow storage site. Because snow piles are not uniform in nature, the data collected represent approximate characteristics of the stored snow and no specific claims concerning the accuracy of such data can be made. A summary of snow pile and runoff data collection events is presented in Table 5.

Table 4. Chemical analyses of runoff and snow samples: constituents analyzed

	Class of Water Quality Constituents		
	Total & Dissolved Metals	Inorganics	Organics
Constituents	Ca, Cd, Cr, Cu, Fe, Mn, Na, Ni, Pb, Zn	Chloride, Total & Free Cyanide, Total Suspended Solids (TSS), Total Solids (TS)	PAHs (naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, debenzo(a,h)anthracene, benzo(g,h,i)perylene) Total Petroleum Hydrocarbons (TPH) Total Organic Carbon (TOC)

Table 5. Snow pile and runoff sample collection dates.

Date	Samples Collected		OGS Effluent	Maximum Air Temp (°C)	Visible Runoff	Notes
	Recently Deposited Snow	Runoff				
30-Jan-07	X	X		-7.7		Parking lot covered in snow
20-Feb-07	X	X		4.0		Parking lot covered in snow
26-Feb-07	X	X		-1.7		Parking lot covered in snow, snow core collected with pickaxe
13-Mar-07	X	X		15.1	X	Parking lot partially covered in slush, snow core collected with pickaxe
14-Mar-07		X	X	13.4	X	Parking lot partially covered in slush, light rain
22-Mar-07	X	X	X	14.2	X	Parking lot bare, light rain, snow core collected with pickaxe
27-Mar-07	X	X	X	17.4	X	Parking lot bare, snow core collected with pickaxe, 6 mm rain previous day
4-Apr-07	X	X	X	7.9	X	Parking lot bare, snow core collected with pickaxe, rain, 11.6 mm rain previous day
12-Apr-07		X	X	6.6	X	Parking lot bare, rain, 4.0 mm rain previous day, snow pile gone
7-May-07		X				YSI removed from OGS
10-May-07						YSI Profiles done in OGS and pond, samples collected at both locations

Flow monitoring. A Sigma 920 Area/Velocity flow meter was installed in the 450 mm concrete storm sewer, 0.5 m upstream of the OGS (Fig. 5), and used to monitor the flow discharged into the oil and grit separator. The flow meter records water level by a pressure transducer, calculates the flow cross-sectional area for a given pipe geometry, measures the average flow velocity along an acoustic beam using the Doppler Effect, and calculates the flow rate as the flow area times the average flow velocity. Both sensors, for measuring the flow depth and velocity, are combined in one probe, which is secured on the pipe invert with an expandable metal band. Water depths, velocities, and flow rates are logged every 10 minutes, and the data were downloaded approximately every two weeks. The flow meter was operated continuously during the monitoring period from Jan. 17 to May 16, 2007.



Fig. 5: Installation of the Sigma Area/Velocity Sensor

During the initial installation, it was assumed that the flow profile at the point of discharge measurement was well developed and the cross-section immediately upstream of the pipe entrance into the OGS chamber would serve as an acceptable measurement location. Further investigations of flow conditions at this location in a scale model (scale 1:2) revealed that the above assumption was correct for low to intermediate discharges, but flow became highly agitated at higher discharges. Under such circumstances, the assumed flow profile would introduce significant uncertainties into measurements of high discharges, mostly because of deviations of the actual flow conditions at the point of measurement from those representing uniform pipe flows. As seen in Fig. 5, the main flow from the snow disposal area is conveyed by a lateral sewer ($D = 0.3$ m) joining the main pipe ($D = 0.45$ m) just a short distance (0.5 m) upstream of the flow measurement point. The lateral flow impacts on the opposite wall of the main pipe and contributes to a non-uniform flow distribution in the main pipe, even at the point of measurement, particularly for higher discharges. Scale model observations were used to develop a flow rating curve for the flow measurement cross-section (Fig. 6), and this curve was used in conjunction with the Sigma meter read depths of flow to estimate discharges at this cross-section. The resulting flow measurement accuracy, which reflects random errors in the flow rating curve ($\pm 5\%$) and in the depth sensor reading (± 3 mm), was estimated at $\pm 22\%$ (or ± 0.0003 m³/s) for low flows (0.001 m³/s) and $\pm 6\%$ (or ± 0.0006 m³/s) at intermediate flows of about 0.018 m³/s. This range of flows covers probably more than 95% of all flows in terms of duration, with higher peak flows occurring relatively infrequently and for short durations. Recognizing the nature of the study, and the random nature of measurement errors (they tend to balance out in flow volume calculations), the above flow measurement errors were deemed fully acceptable.

At a discharge of 0.0175 m³/s, the flow remains about constant in spite of rising head (from 0.13 to 0.16 m), when a vortex is being formed downstream of the measuring cross-section by the Stormceptor inlet drop pipe. For even greater depths (> 0.16 m), flow rate starts to rise again and the corresponding rating curve can be described by a third degree polynomial listed in Fig. 6. In this region, the main source of uncertainty is the rating curve and the flow measurement error was

estimated at $\pm 15\%$. Above 0.18 m, it was found that the second order equation developed for flows at levels below 0.13 m applies quite well again.

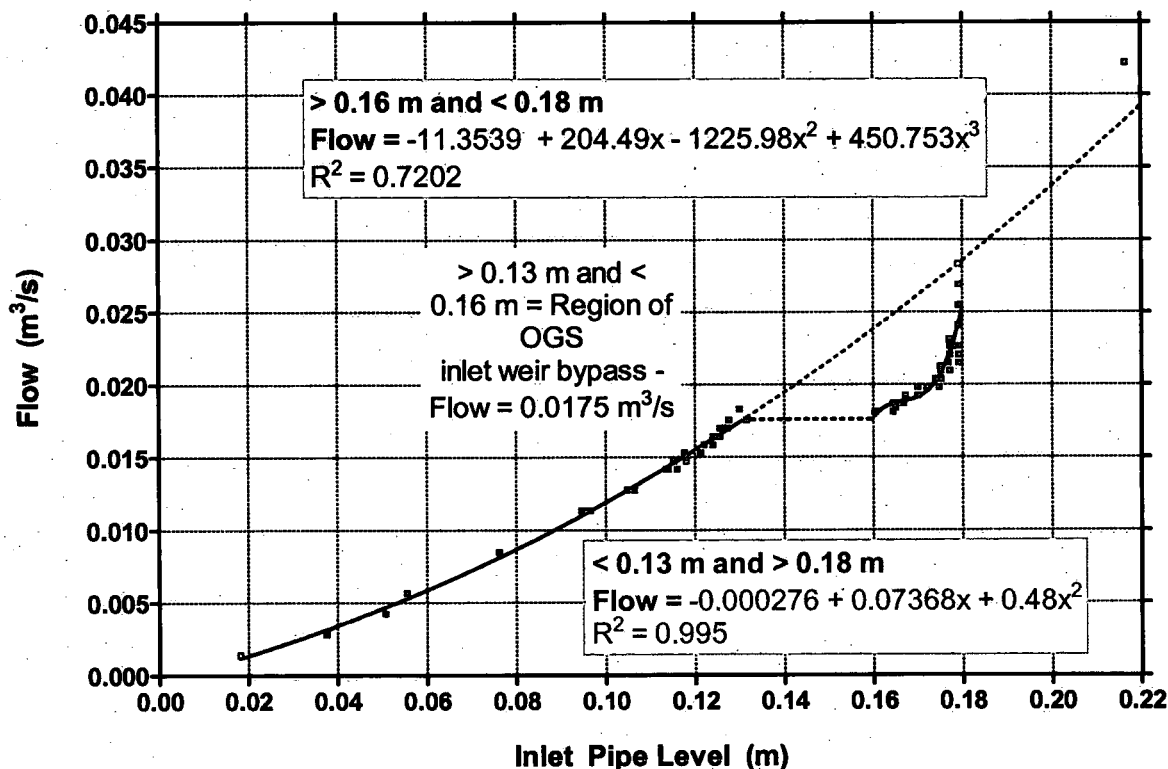


Fig. 6: Calibration curve of flow vs. depth in inlet pipe using OGS model

4.3 Snowmelt and runoff quality

Snowmelt and runoff quality were measured in two ways: (a) continuous monitoring of several basic parameters by a data probe, and (b) by grab sampling during site visits and subsequent sample analysis in the laboratory.

The YSI Datasonde (Model YSI 6600) was used to monitor selected properties of snowmelt from the snow pile and runoff from the entire contributing area. For this purpose, the probe was suspended in the inlet drop pipe of the oil and grit separator, with the sensors submerged 0.3 m below the water surface in the separator (Fig. 7). The probe was used to measure (rapid pulse) dissolved oxygen, conductivity, temperature, pH, depth, turbidity (optical), and chloride. Ranges, resolutions and accuracies of individual sensors are presented in Table 6. Data averages were written to the onboard memory every 5 minutes. The YSI Datasonde recorded data continuously from Jan. 17 to Aug. 27, 2007, when it was removed from the OGS for calibration and servicing.



Fig. 7: YSI Datasonde 6600 in the OGS down-pipe inlet

Table 6. YSI 6600 Datasonde Sensor Specifications

Parameter	Range	Resolution	Accuracy
Rapid-Pulse Dissolved Oxygen	0 – 50 mg/L	0.01 mg/L	0-20 mg/L: ± 0.1 mg/L, or 1% of reading, whichever is greater
Conductivity 6560 Sensor	0 -100 mS/cm	0.001 to 0.1 mS/cm, range dependent	$\pm 0.5\%$ of reading + 0.001 mS/cm,
Temperature 6560 Sensor	-5 to +50 °C	0.01°C	$\pm 0.15^\circ\text{C}$
pH 6561 Sensor	0 to 14 units	0.01 unit	± 0.2 unit
Depth	0 to 9.1 m	0.001 m	± 0.02 m
Turbidity 6136 Sensor	0 -1,000 NTU	0.1 NTU	$\pm 2\%$ of reading or 0.3 NTU, whichever is greater
Chloride	0 to 1,000 mg/L	0.001 to 1 mg/L, range dependent	$\pm 15\%$ of reading or 5 mg/L, whichever is greater

Additional water quality data were obtained by collecting grab samples at two sites during routine site visits. The first site was at the OGS inlet, the second one was 10.2 m downstream of the OGS where the effluent discharges into the outlet structure. Runoff sampling started on Jan. 30, 2007 (i.e., about two weeks after the first snow was deposited at RHSSF) and continued until May 7, 2007. It was noted that from Jan. 30 until mid-March, most of the sampled water was groundwater baseflow from sub-drains beneath the paved area. From mid-March, rising temperatures and several rain events caused the snow pile to melt at an accelerated rate, increasing the inflow to the OGS. The samples collected at the OGS inlet in March represented snowmelt from the stored snow pile, as well as groundwater from the whole site. At this time, sampling was being performed at the OGS outlet as well. Water samples were collected at both locations until Apr. 12, 2007, when the snow pile was completely melted. Altogether, seven snow samples, 10 OGS inflow samples, and five OGS outflow samples were collected and analyzed by the Analytical Laboratory of AEMRD, WSTD, Environment Canada (a CAEAL accredited laboratory) for the constituents listed in Table 4 (chloride, selected total and dissolved metals, total organic carbon, polycyclic aromatic hydrocarbons, total petroleum hydrocarbons, cyanide, and total suspended solids (TSS)).

4.4 Water and sediment quality in the meltwater management facility (OGS and the stormwater pond/drainage ditch system)

In the OGS, water quality was measured by sampling and, on three occasions, by in-situ readings of water quality by the YSI Datasonde, which was gently lowered into the outlet riser pipe and readings were taken every 4 s as it descended to the bottom of the OGS. After this vertical profile of water quality in the OGS was completed, the Datasonde was slowly removed and water samples were collected every 0.5 m of depth with a peristaltic pump, over the total depth of the OGS, 3 m. The Datasonde provided readings of the seven parameters listed in Table 6, the water samples collected by the pump were analyzed for the constituents listed in Table 4. Furthermore, sediments from the OGS bottom were collected by Ponar and the Ekman dredge; the list of constituents analyzed is in Table 7.

Table 7. Chemical analyses of sediment and macrophyte samples

	Class of Constituent		
	Acid Extractable (Total) Metals	16 U.S. EPA Priority PAHs	Nutrients
Constituents	Ca, Cd, Cr, Cu, Fe, Mn, Na, Ni, Pb, Zn	naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene, benzo(g,h,i)perylene	Total Organic Carbon (TOC), Total Kjeldahl Nitrogen (TKN), Total Phosphorus (TP)

Water and sediment samples were collected at four sampling points in the stormwater pond: (a) the stilling basin below the outlet riser pipe from the OGS; (b) at the upstream end of the pond (i.e., in the sediment forebay, site 1 in Fig. 1); (c) at 0.35 of the main pond streamline length (measured from the upstream end, site 2 in Fig. 1); (d) at 0.85 of the main streamline length; and (e) in the drainage ditch along Elgin Mills Road, about 30 m downstream of the pond (site 4 in Fig. 1). Samples were collected during routine site visits and analyzed by the AEMRD laboratory for the constituents listed in Tables 4 (water) and 7 (sediments); analytical procedures are described in the Appendix. Additional data on water quality in the pond (Sites 1-3) were collected by the YSI probe positioned at two depths (at the surface and 0.3 m above the sediment/water interface), and temperature and conductivity were collected by a data probe installed by the Town of Richmond Hill's staff in the pond outlet chamber. The probe (AquiStar® CT2X Submersible Smart Sensor – Conductivity and Temperature probe, range from

10 $\mu\text{S}/\text{cm}$ to 100,000 $\mu\text{S}/\text{cm}$, resolution 0.1 $\mu\text{S}/\text{cm}$, and accuracy: $\pm 0.5 \%$) recorded water temperature and conductivity, with accuracies comparable to those listed in Table 5 for the YSI probe.

Sediment quality (chemistry) was measured in sediment surveys conducted three times in 2007, on 10 May, 27 June and 1 November. For this purpose, sediment samples were collected by a 63.5 mm corer pressed into the substrate, with a one-way valve permitting trapped air to escape from the tube. The core was removed from the sediment bed and capped while under water. Core samples were placed into cold storage in the laboratory, freeze dried, split into three sub-samples, and analyzed for particle sizes and sediment chemistry. Sizes were determined by the Sedigraph method (Duncan and LaHaie, 1979), determination of the chemical constituents listed in Table 6 was done by the analytical methods described in the Appendix.

4.5 Chemical uptake by macrophytes in the treatment pond

Recognizing that emergent macrophytes in the treatment pond will be exposed to elevated concentrations of heavy metals and other chemicals present in snowmelt, surveys of heavy metals in macrophytes were conducted. Towards this end, macrophytes in 1 m quadrats at Sites 1-3, and along the shoreline, close to each of these sampling sites, were collected, washed, air-dried and then weighed to determine wet biomass weight. Five representative sub-samples from each site were selected for further analyses and divided into roots and shoots. Roots were first washed with a nitric acid solution ($\text{pH} < 2$) to remove root plaque and then rinsed with deionized water. The root rinse water was analysed for total metals in water, using the same parameters as Table 6. The roots and shoots were placed in a drying oven at 50°C for 7 days, ground with a plant tissue grinder and then analyzed for the following acid extractable (total) metals: Ca, Cd, Cr, Cu, Fe, Mn, Na, Ni, Pb, Zn. Using information from the root rinse water indicates the parameters which are complexed on the root tissue, rather than those actually taken up into the plant tissues. These levels then serve to indicate the level of sediment contamination for each constituent.

4.6 Benthic community assessment and sediment toxicity

Additional sediment samples were collected at 4 sites (RHSD 1 through 4) in October 2006 and June 2007 for enumeration and identification of the benthic invertebrate species, and determination of the overall benthic community structure. To collect these samples, small core tubes (63.5 mm diameter), with a one-way valve attached (permitting air to be exhausted from the tube), were pressed into the substrate. The core was removed from the sediment and capped while underwater. The core was later extruded and the top 10 cm slice was placed in a jar and preserved with formalin solution. After 4 days, the formalin solution was exchanged for an ethanol solution and the samples were submitted to an external laboratory for macroinvertebrate identification and enumeration.

Taxonomic counts (classifications) for each sample were assessed by several statistics:

- Total abundance (= sum of individuals from all taxa in the sample);
- Taxon richness (S = number of taxa in the sample); and

- Evenness ($E = \left(\sum_{i=1}^S p_i \log p_i \right) / \log S$, where p_i = proportion of individuals of taxon i in the sample).

Sediment samples for toxicity tests were collected at 5 sites (in the OGS, and at 4 pond/ditch sites described above) in 2006 and 2007 using an Ekman dredge or a petite Ponar grab. The OGS was sampled using the Ekman sediment sampler, which utilizes spring-loaded jaws released by a trigger weight. The narrow opening and concrete bottom made it difficult to use the petite Ponar grab reliably. The device was lowered on a rope and a weight was then dropped to trigger the release of the jaws. Sediment was subsampled in a glass dish on the surface. The remaining sites in the pond were sampled using a petite Ponar grab. This device is good for sampling the top 5 - 10 cm sediment layer. At Site 1 the sampler waded into the forebay and released the device. Sediment was placed in a food-grade polyethylene bag and sampling was repeated until 2 L of sediment was accumulated. This same technique was used at the pond outlet site (Site 4) where the discharge entered the drainage ditch running along Elgin Mills Road. As Sites 2 and 3 were located in deeper waters, the petite Ponar grab was deployed by lowering it over the side of a small aluminium boat.

Sediment toxicity was measured in the laboratory using two benthic sediment bioassays developed at the National Water Research Institute in Burlington. Sediment samples were stored in the dark at 4 °C until used in toxicity tests. Each sediment sample was sieved through a 250- μ m mesh sieve to remove indigenous macrofauna (Reynoldson et al., 1994). Two litres of culture water were used for each 500-mL sediment sample to obtain 3 lab replicates per sample for testing. The sieved sediment was allowed to settle for a minimum of 24 hours, after which the water was decanted and used as the overlying water in the experiment. Water chemistry conditions (pH, dissolved oxygen, temperature and conductivity) were measured and recorded for each replicate test beaker both at the beginning and end of each test. Average total ammonia concentration was also determined for each sediment sample by taking a composite water sample from each replicate beaker at the start of the test and at test completion. Five replicates of a laboratory control sediment from Long Point, Lake Erie, were tested with each set of OGS and pond samples. Due to excess ammonia or algal growth, toxicity tests for some samples were delayed or repeated. Therefore, several samples of control sediment were tested. All test beakers were aerated for 7 days prior to and over the course of the test, and water loss due to evaporation was replaced with de-ionised water. Tests were run at $23 \pm 1^\circ\text{C}$ in environmental chambers. A photoperiod of 16 h-light, with a light intensity of 500-1000 lux, and 8 h-dark, was maintained throughout the tests.

Acute and chronic toxicity endpoints were determined using two species of benthic invertebrates; an amphipod (*Hyalella azteca*) in a 28-day survival and growth test, and a mayfly (*Hexagenia* spp.) in a 21-day survival and growth test. Detailed test methods for these species are given in Reynoldson et al. (1998); a brief summary follows below.

In the *Hyalella azteca* 28-day survival and growth test, each 250-mL test beaker received 50 mL of test sediment and 175 mL of overlying water. Two to 10-day old amphipods were randomly added to replicate beakers until 15 organisms were in each chamber. Each chamber was fed 8 mg Nutrafin® fish flakes twice weekly on non-consecutive days. On day 28, the contents of each

beaker were rinsed through a 250- μ m mesh sieve. Surviving amphipods were counted and dried for 24 hours at 60 °C, and dry weights recorded. Growth over the duration of the test was measured as final dry weight because initial weights were considered negligible.

In the *Hexagenia* spp. 21-day survival and growth test, each 1-L test chamber received 125 mL of test sediment and 650 mL of overlying water. Ten pre-weighed (5 - 8 mg wet weight) mayflies were randomly added to replicate jars. Each test jar was fed 50 mg of a prepared diet (Cerophyll, Nutrafin®, brewers yeast) once weekly. On day 21, the contents of each jar were sieved through a 500- μ m sieve. Surviving mayflies were counted then dried for 24 hours at 60°C, and dry weights recorded. Initial wet weights were converted to dry weights with the following conversion:

$$\text{Initial dry weight} = (\text{Initial wet weight} + 1.15)/7.35$$

Growth was determined by subtracting the initial dry weight from the final dry weight.

5. Results and Discussion

5.1 Meteorological data

The temperature recorded at the RHSSF between January 17 and April 19, 2007 is shown in Fig. 8. A short period of warm temperatures in mid-March resulted in a small melt, and by the end of March, temperatures were consistently above zero. Positive degree days are calculated from the start of the snowmelt period (taken here as March 14, 2007) by summing the temperatures on days when temperatures were above zero. The degree-day index indicates the intensity of snowmelt; 1 °C day may contribute to the melting of up to 11 mm of snow (Semadeni-Davies, 1999). The idea of using the degree-day method or other conceptual models to describe the snowmelt process at the study site was abandoned, because such methods had been developed for relatively undisturbed, uniform, shallow snowpacks and were not applicable to irregular, large piles of snow, mixed with salt and sediment, at the study facility.

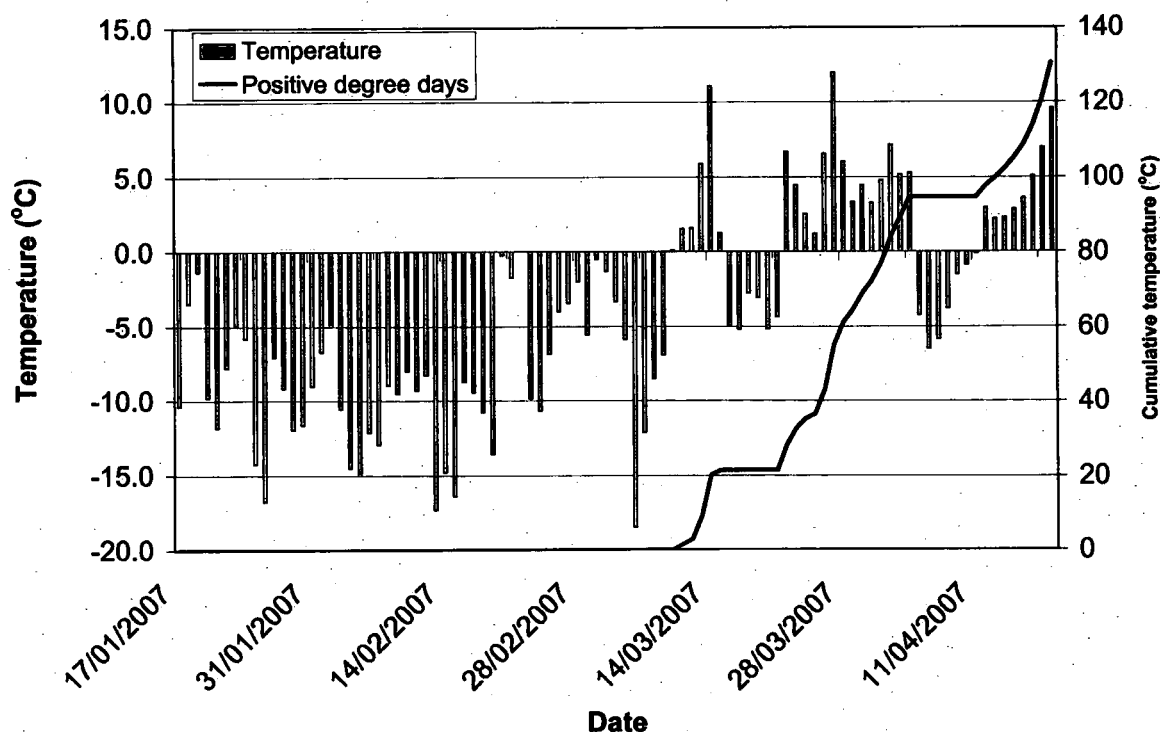


Fig. 8: Daily mean temperatures, measured at the Richmond Hill Snow Storage Facility

Precipitation records from the Buttonville airport (3.5 km southeast of the site) are shown in Fig. 9. Through January and February, most precipitation fell as snow; through March and April, precipitation was mixed, with some rain and some snow.

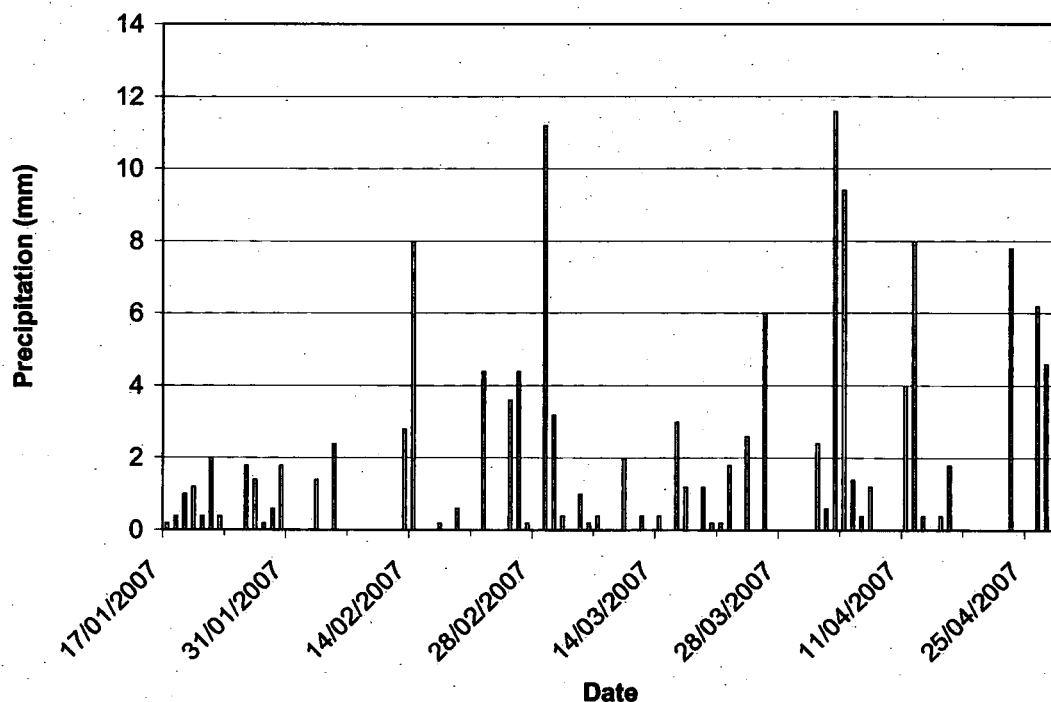


Fig. 9: Daily precipitation, measured at Buttonville airport meteorological station

Table 8 lists the monthly averages for temperature and precipitation, along with data on typical values from the Canadian Climate Normals 1971-2000 Database for the Richmond Hill station (Environment Canada, 2004). In general, the snowmelt period in 2007 was slightly colder than normal, but precipitation amounts were lower than typical values.

Table 8: Monthly average values for temperature and precipitation at Richmond Hill

Parameter	January*	February	March	April*
Temperature - 2007 RHSSF (°C)	-9.0 (-3.7 ^a)	-9.0	-0.5	1.9 (5.8 ^a)
Temperature - Richmond Hill 1971-2000 normal values (°C)	-6.7	-5.6	-0.5	6.5
Precipitation - 2007 Buttonville airport (mm)	11.4 (56.6 ^a)	28.0	35.4	60.4
Precipitation - Richmond Hill 1971-2000 normal values (mm)	63.6	53.9	66.1	70.9

* Note that RHSSF averages are for the period of study and reflect only part of the month in January (17-31) and April (1-28).

^a Buttonville airport meteorological station data for entire month

5.2 Snow pile data and flow monitoring

The first step of the analysis was to estimate the water balance of the RHSSF. This balance can be described by the hydrologic equation as

$$Q_{in} - Q_{out} = \Delta S$$

where Q_{in} is water input to the facility, Q_{out} is water output, and ΔS is change in storage. This equation can be integrated over the snow accumulation/melting period, and at the end of the period (water storage $S = 0$), it states that V_{in} equals V_{out} , where V is volume of water obtained by integration of $Q(t)$ over time.

Overall input of water to the facility comes from two sources: snow that is trucked in and dumped at the facility, and precipitation falling on the facility and surrounding lands, and draining through the system.

For estimating the water equivalent of the snow dumped at the facility, the number of standard truckloads was known and snow density was estimated from the samples collected from snow piles at the site. The water equivalent of snow dumped (in m^3) was calculated as follows:

$$V_{sd \text{ weq}} (\text{snow dumped}) = V_{sd} \cdot \rho_{\text{snow}}$$

Where V_{sd} = snow volume dumped, in m^3 , and ρ_{snow} = estimated density of snow. For estimating snow density, snow samples were collected (see Section 4.2), melted in the laboratory, and yielded an estimate ρ_{snow} (m^3 water / m^3 snow) = 0.65. This is a rather high value, which reflects additional processing of the sample during truck unloading (possible compaction), consolidation (ripening and freezing) during storage on the ground, and water input due to precipitation. These changes in the snow pile over time are why eventually the collection of snow pile samples required the use of a pickaxe, rather than a corer. Under such circumstances, the literature data on snow piles should provide a better estimate of ρ_{snow} for the dumped snow. Semadeni-Davies (1999) published data on snow density piles in various parts of the city, including residential suburbs, industrial areas, and downtown areas, ranging from 0.25 to 0.7. For estimating the dumped snow water equivalent, an average of these values was adopted (0.475).

The precipitation contribution to water inflow to the facility was estimated from highly uncertain data. Using the Buttonville precipitation data, two contributing areas were considered: (a) the paved storage area (1.64 ha), and (b) the baseball and landscaped areas (1.72 ha) potentially contributing runoff draining onto the paved area. The literature data on conversion of winter precipitation into runoff do not exist; the so-called runoff coefficients serve for estimating peak flows generated by high-intensity rainfall with return periods of 2-10 years (WEF and ASCE, 1992). Under such circumstances, conversion of precipitation into runoff from the storage area was estimated using two conversion coefficients: $C_1 = 0.9$ for the paved area, and $C_2 = 0.5$ (an average of the maximum and minimum values attainable by C) for the pervious areas. The water equivalent of the measured precipitation (in m^3) was calculated as follows:

$$V_p \text{ weq} = P \cdot (C_1 A_1 + C_2 A_2) = P \cdot 23400$$

Where P = precipitation measured at the Buttonville airport meteorological station, in m

C_1 = precipitation / runoff conversion coefficient for the parking area = 0.9

A_1 = parking / paved area = 16400 m²

C_2 = precipitation / runoff conversion coefficient for the baseball and landscaped area = 0.5

A_2 = baseball and landscaped area = 17200 m²

Total input to the system, V_{in} , is equal to the sum of the two volumes, $V_{sd\ weq}$ (snow dumped) + $V_{p\ weq}$ (precip), as shown in Fig. 10.

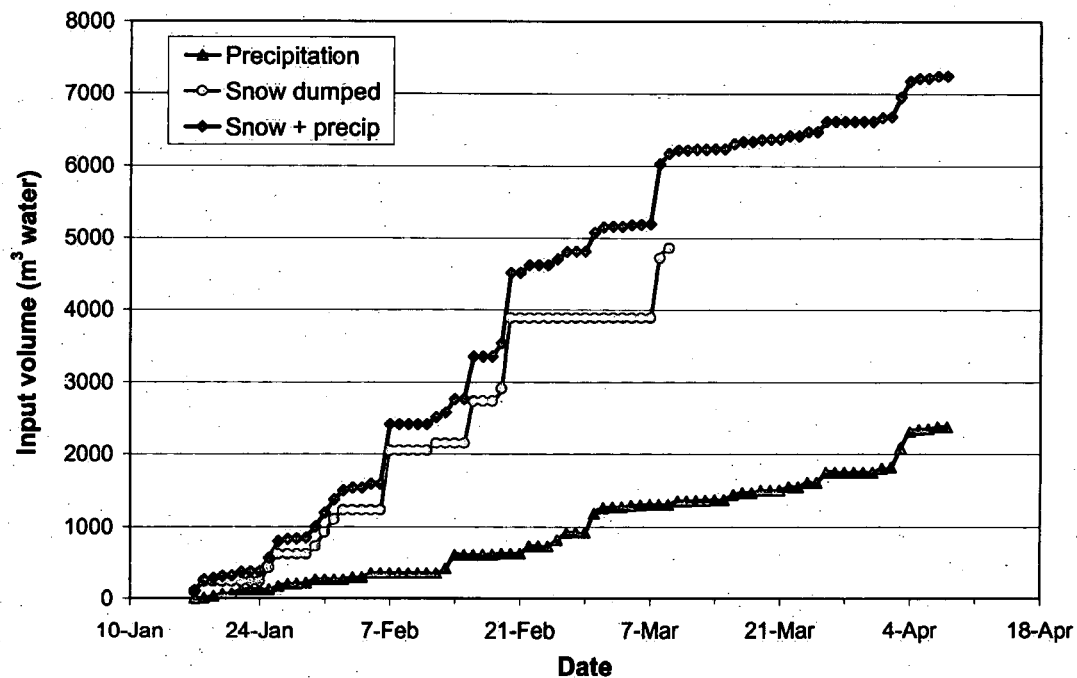


Fig. 10: Cumulative inputs to the RHSSF

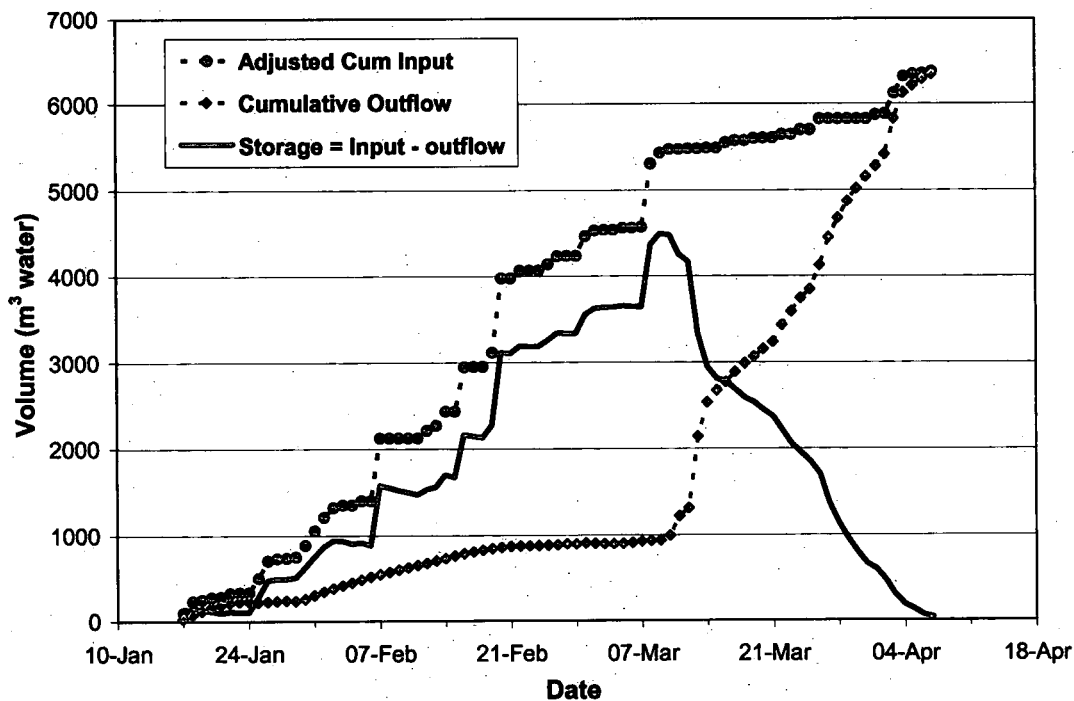


Fig. 11: Water storage at the RHSSF.

Outputs from the site were in the form of the measured snowmelt / runoff outflow, containing uncertainties discussed in Section 4.2, as well as water lost to sublimation or evaporation, or blowing snow (i.e., from the baseball and landscaped area). Such losses have been studied extensively for natural catchment snowpacks (Fassnacht, 2007), but no information exists for urban snow. Consequently, the latter two losses were neglected.

Water storage at the facility (Fig. 11) was equal to the difference between inputs and outputs from the site. Note that the cumulative input was adjusted by a factor of 0.88 in order to properly reflect the water balance observed at the site. This calibration factor takes into account such uncertainties as the volume and density of dumped snow, precipitation depth, runoff contributions to the paved area, losses due to sublimation, evaporation and snow drifting, and flow measurement errors. Early in the season, the site exhibited net storage of water in the form of the snowpack. As temperatures increased in March, discharge increased. As can be seen in Table 5, section 4.2, the snowpack was entirely depleted between April 4 and 12; at this point, storage = 0.

5.3 Snowmelt and runoff quality

Continuous monitoring of runoff. Continuous monitoring of chloride was performed with the YSI Datasonde, placed in the drop pipe of the OGS. As can be seen in Fig. 12, release of chloride began early in the season, although the bulk of the chloride was released during the large melt as temperatures increased and water was released from the snowpack. Over the course of the season, the total flux of chloride was estimated (by multiplying YSI measured chloride concentrations by

the measured flow rate) at over 16 tonnes of chloride. This estimate contains two sources of uncertainties, those in YSI measurements of chloride and those in flow measurement.

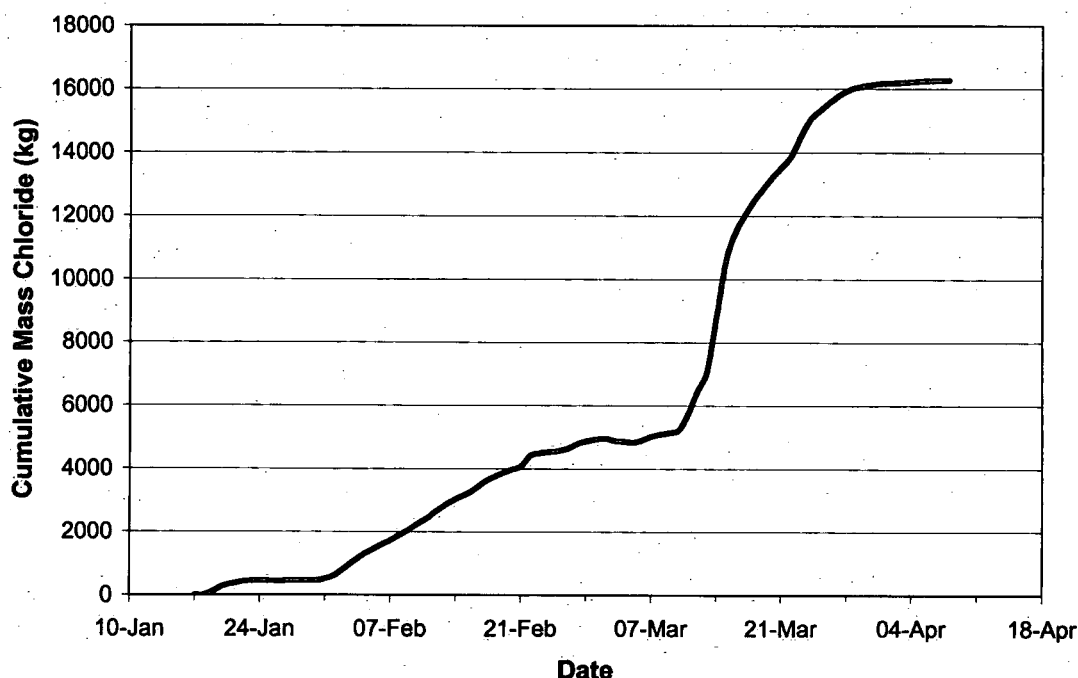


Fig. 12: Cumulative chloride flux at the RHSSF.

The average chloride concentration in runoff over the entire melt season can be estimated as follows:

$$\begin{aligned}
 C_{Cl, ave} &= 16\,276 \text{ kg Cl}^- / 6376 \text{ m}^3 \text{ water} \\
 &= 2553 \text{ kg Cl}^- / \text{m}^3 \\
 &= 2553 \text{ mg Cl}^- / \text{L}
 \end{aligned}$$

An average application rate of 70 kg per lane km of 50/50 salt/sand mix results in a salt application rate of 35 kg per lane km (Town of Richmond Hill, 2005). With 1200 lane km of paved roads to maintain, an event in which every road surface in the Town was salted could result in a total application of 42 000 kg salt, or nearly 25 500 kg of chloride. Even if one assumes that salt was only applied at that rate on the ten dates on which snow was dumped at the SSF, over 250 tonnes of chloride was applied to Richmond Hill roads in the winter of 2007. The 16 tonnes of chloride collected in used snow and transported to the snow storage facility is thus only a small portion (6%) of the total chloride applied to the roads in winter. Pinard *et al.* (1989) similarly found that only 2% of the salt spread on city streets was present in meltwater from snow disposal sites, with most of the salt likely released to the environment from the roadway or roadside.

As shown in Fig. 13, the release of chloride can be related to the release of water from the snowpack by plotting the percentage of chloride released (cumulative release of chloride divided by total mass of chloride released during snowmelt) as a function of the percentage of water released (Westerlund, 2007). In the case of uniform release of a pollutant, the percent load of the pollutant would equal the percent release of water, or follow a 45° line in the graph below. Since

the chloride plot lies above this line, chloride exhibits preferential elution or advanced release, as is typical for a soluble chemical (Droste and Johnston, 1993; Westerström, 1995; Westerlund 2007).

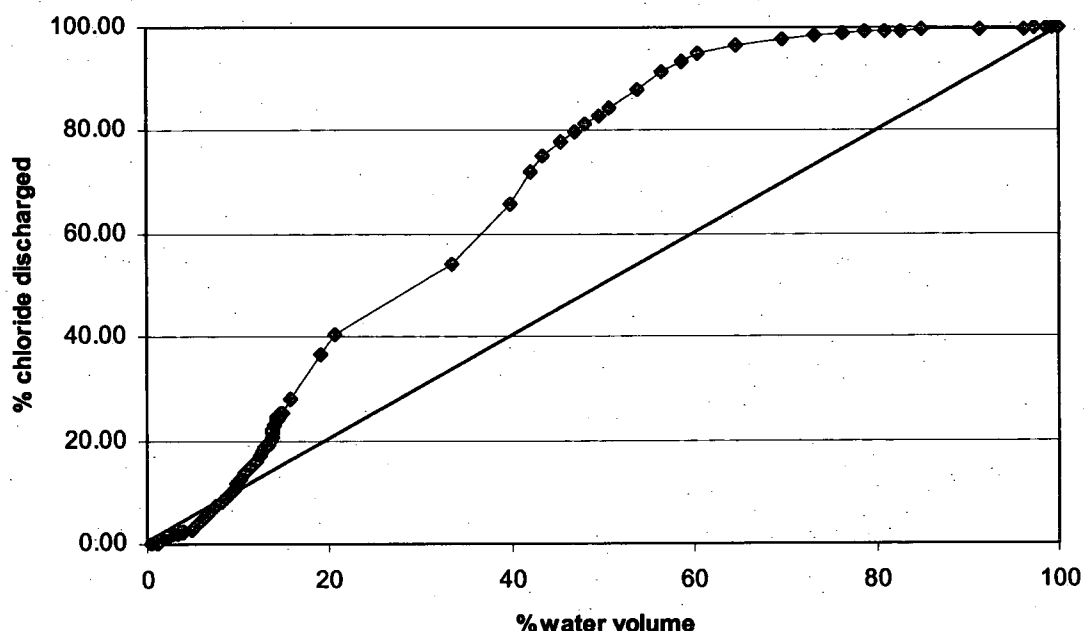


Fig. 13: Preferential elution of chloride.

The same treatment was applied to pH data from the YSI, as can be seen in Fig. 14. In spite of its solubility, H^+ did not exhibit a strong preferential elution pattern; its release was nearly uniform throughout the snowmelt period. Although studies of undisturbed rural snowpacks have shown an acidic first flush, a lack of preferential elution of H^+ from an urban snowpack was also observed by Westerlund (2007). The high concentration of solids in an urban snowpack may serve to buffer the snowmelt.

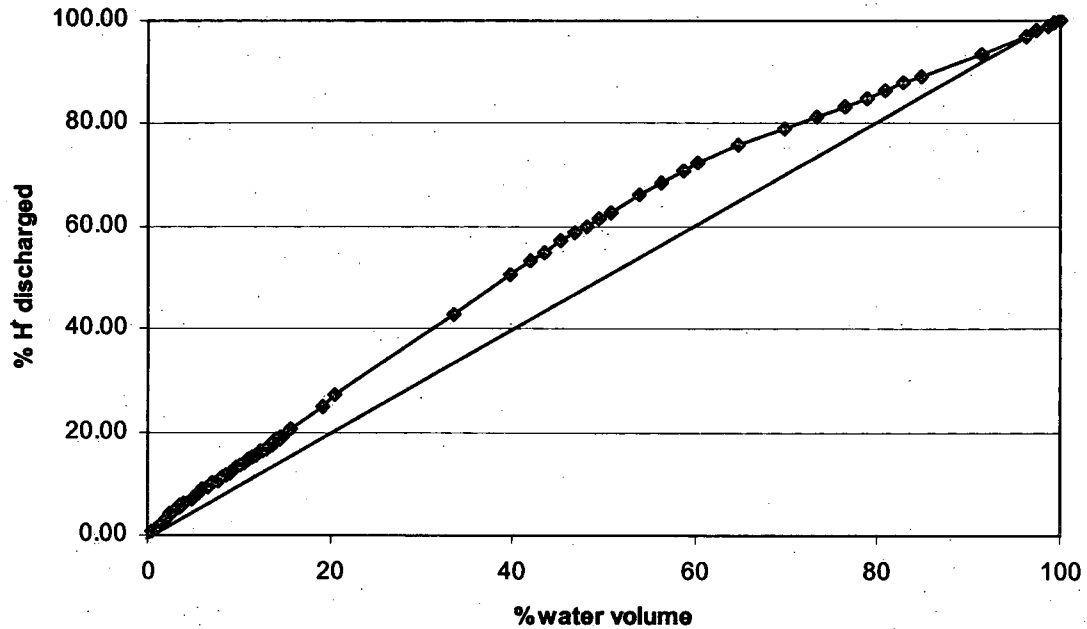


Fig. 14: Elution of H^+ .

Unfortunately, the data from the turbidity sensor on the YSI was unreliable (with unusually high values reported) for the first month, so total turbidity/solids could not be calculated for the 2007 snowmelt season based on continuous monitoring. Typically, one might expect delayed release of solids from the snowpack (curve falling below the 45° line), although Westerlund (2007) found a fairly uniform release of TSS in snowmelt from an urban snowpack in Lulea, Sweden.

Runoff grab samples. Grab samples were collected every two weeks during the melt period, and during large melt events. The results from analyses of the grab samples (Fig. 15) showed very high concentrations of chloride in the early samples, although the volume of water flowing was low (and total flux of chloride was thus low, as shown in Fig. 12). Although it does not account for the majority of the mass of chloride, this high concentration 'first flush' has the potential for high toxicity. As the flow of water increased at the end of March, the concentration of chloride decreased. Conversely, solids exhibited low concentrations in early, low volume samples, and were washed out of the snowpack during later season, higher volume flows.

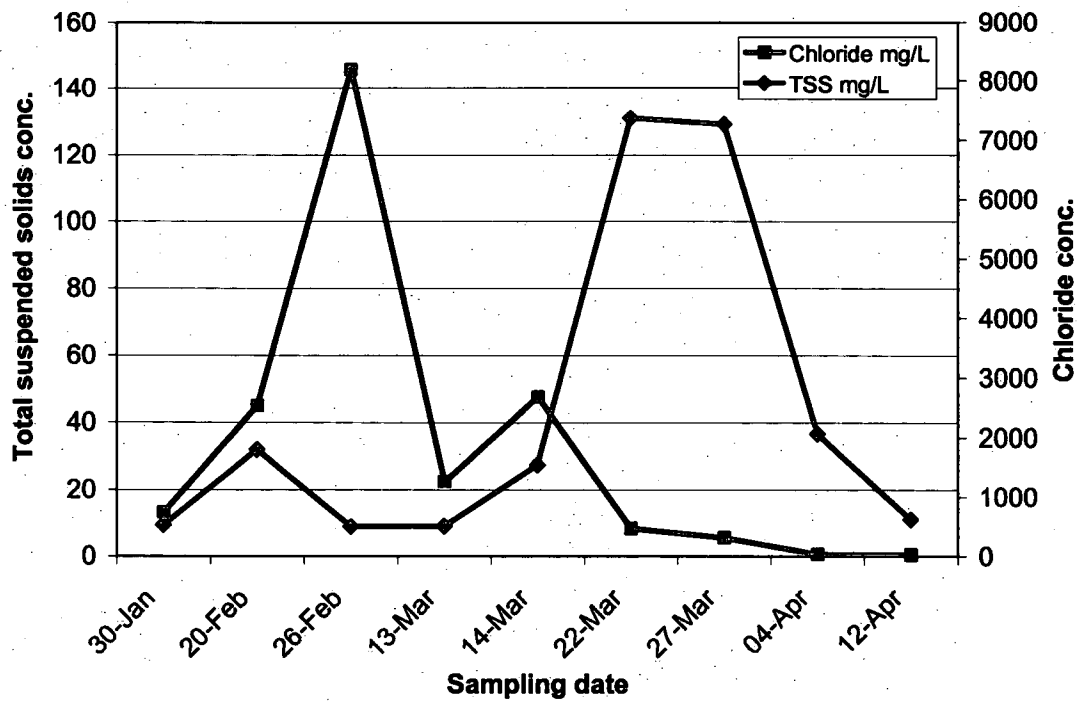


Fig. 15: Concentrations of chloride and TSS in grab samples of snowmelt runoff

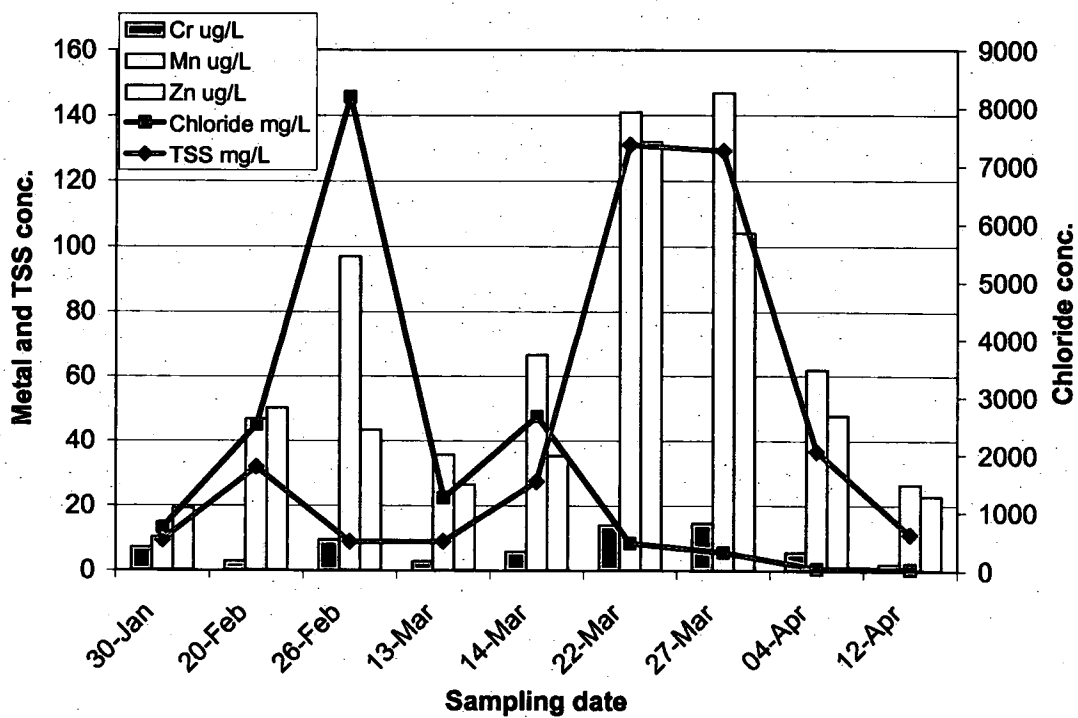


Fig. 16: Concentrations of selected total metals, chloride and TSS in grab samples of snowmelt runoff

The highest metal concentrations corresponded to the peak in TSS concentrations (Fig. 16). The bulk of the metals are thus released with TSS, at the end of the melt season under high volume flows. However, there is also an earlier peak observed for a number of metals that corresponds with the chloride peak. As discussed in section 2.3, salt shifts the speciation of metals to the (potentially more toxic) dissolved form, resulting in some early release of the metals, as well. The high salt concentrations in the samples created a challenge for analysis of metals, and many samples required dilution before analysis. It should be noted that dilution could have affected the detection of some metals or the accuracy of the reported concentrations for metals present at concentrations near the MDL.

The pattern for TOC (not shown) was similar to that of chloride, with a concentration peak on February 23 followed by a gradual tailing off, although the decrease was far more gradual than for chloride. The higher concentration of TOC (presumably in the form of dissolved organic carbon) may also have contributed to the advanced release of metals early in the season through formation of mobile metal-organic complexes.

Total and free cyanide were measured in the grab samples. The highest total cyanide concentrations were detected on March 22 (0.024 mg/L) and March 27 (0.0298 mg/L); these corresponded to the samples with the highest TSS concentrations. The CCME guideline for the protection of aquatic life for free cyanide is 0.005 mg/L (CCME, 2007). Unfortunately, the MDL for the cyanide method was 0.02 mg/L, so while a number of samples displayed total cyanide concentrations near this level, the concentrations could not be accurately measured.

Sixteen PAHs were monitored in eleven samples of OGS influent and five of OGS effluent. Concentrations of anthracene, benz(a)anthracene, benzo(a)pyrene, fluoroanthene, naphthalene, phenanthrene and pyrene were above the CCME guidelines in the influent sample collected on January 30, 2007. All other samples displayed PAH concentrations below the MDLs for the method used by the lab, although many of these MDLs were unfortunately above the CCME guidelines. One would typically expect to observe the highest PAH concentrations in samples corresponding to the highest TSS concentrations, but the low concentrations of PAHs made quantification difficult. No conclusions can therefore be drawn about the behaviour of PAHs over the course of the 2007 snowmelt. Similarly, the levels of total petroleum hydrocarbons (TPH) were below the MDL of 0.5 µg/mL in all the grab samples of OGS influent and effluent.

Snow pile samples. Grab samples were collected from the snow pile to obtain general information about pollutant stocks in the stored snow. Since snow piles are not uniform in composition (e.g., a thick black crust will form at the top of the pile, but may differ in depth and nature from north to south face), the data collected represent approximate characteristics of the stored snow. The addition of new dumped snow after each snowfall event also contributed additional solids, salt and other pollutants through the season. It should be noted that the exact composition of the sand-salt mixture applied to roads in the Town of Richmond Hill during a snowfall event varies with specific temperature and snowfall conditions (even varying within the Town or during an event), in line with the objective of the Salt Management Plan to minimize the amount of salt entering the environment (Town of Richmond Hill, 2005). As noted in the Methods section, the first two snow pile samples were collected as cores, but due to the hardness of the frozen pack, the remaining samples were collected by scraping away the dark crust and

then using a pickaxe to chip a sample off the pile. Results for snow pile concentrations of chloride, TSS and selected metals can be seen in Fig. 17.

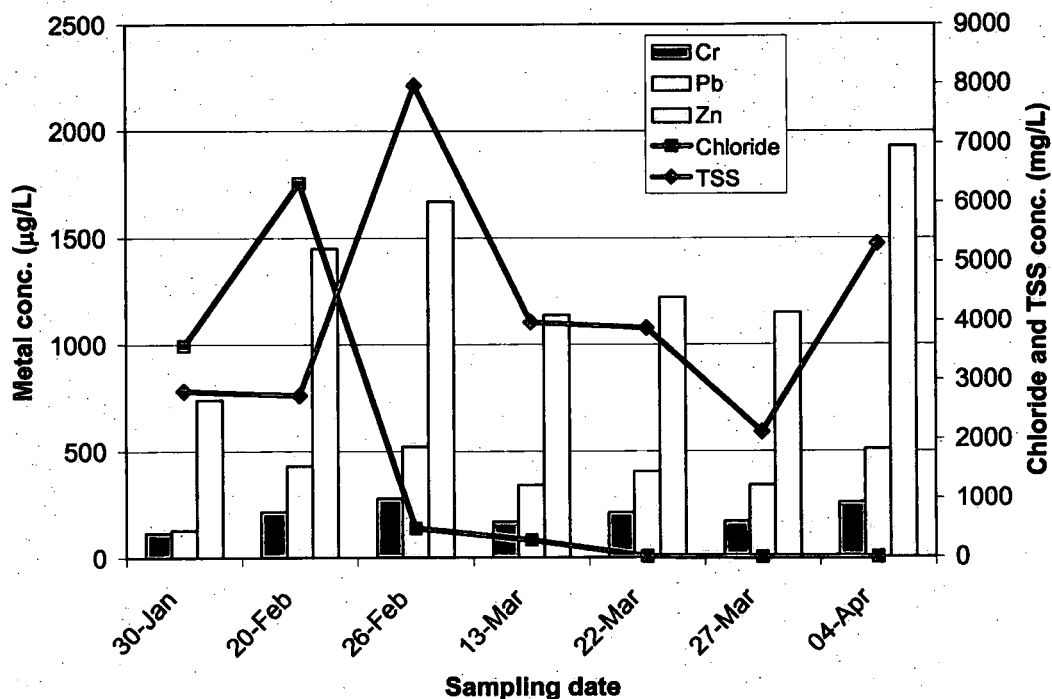


Fig. 17: Concentrations of selected total metals, chloride and TSS in snow pile samples

Chloride stocks were quickly depleted from the bulk of the pack, although some chloride may still have been associated with the base of the pile in the form of a meltwater front. Note that chloride concentrations in March 13 and 14 runoff samples (Figs. 15-16) were considerably higher than snow pile concentrations measured on March 13, indicating a preferential release of chloride from the bulk of the pack, as discussed earlier.

Concentrations of TSS and associated metals (Fig. 17) followed a different pattern. At the beginning of the season, concentrations of TSS and metals increased as solids accumulated in the pack. As the season progressed, solids were washed out of the bulk of the pack at the same time as new snow (with associated solids) was trucked in, so concentrations stayed relatively constant or decreased somewhat. Concentrations of PAHs (Fig. 18) decreased after the first sampling date, but then held fairly steady until the end of the season. Snowpack samples were collected from the centre of the pack, after removing the crust, so it cannot be determined from the data obtained if solids, metals and PAHs remained associated with the pack in the form of the crust or an accumulation at the base of the snow pile. By the end of the season, the volume of the snow pile was quite small and the relative concentration of solids and associated contaminants was relatively high. It is of interest to note that the snow pile samples in general contain metals at 10-30 times higher concentrations than snowmelt samples (i.e., Fig. 17 vs. 16), indicating the potential for further contaminant release. Whether the solids were mobilized with the meltwater or remained at the snow disposal site would depend on the rate of melting and the energy of the meltwater flow (i.e., intense rain-on-snow events can increase the volume and energy of the meltwater, causing more solids to be washed from the snowpack).

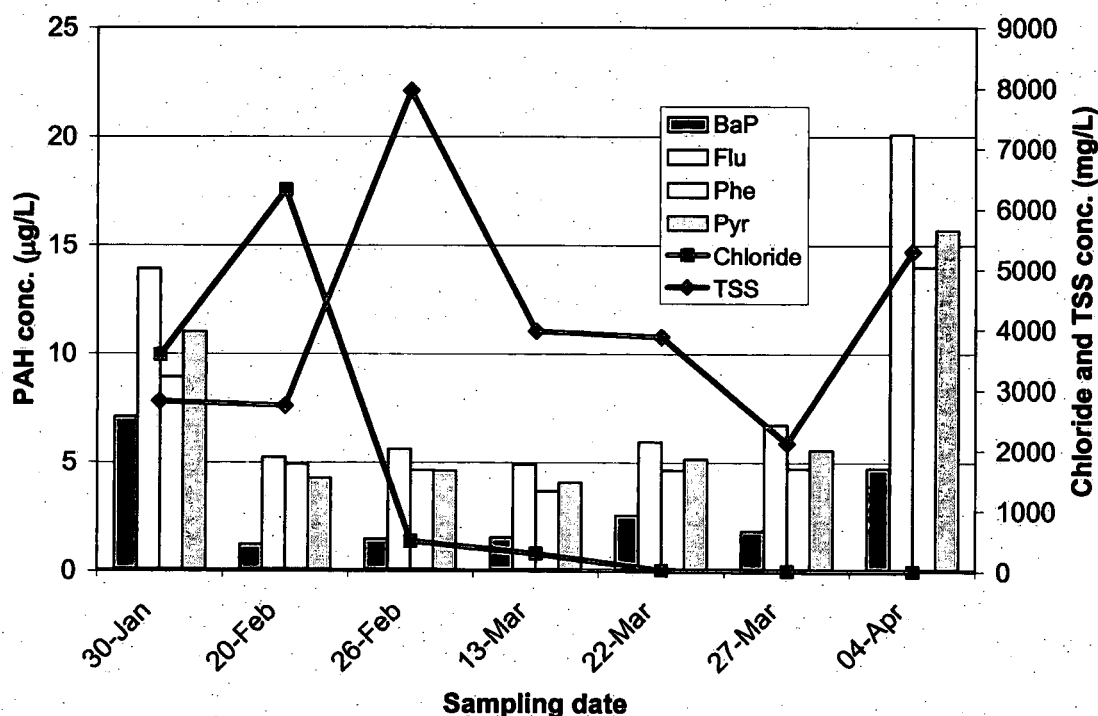


Fig. 18: Concentrations of selected PAHs, chloride and TSS in snow pile samples

5.4 Water and sediment quality in the meltwater management facility

Water quality. Water quality in the OGS was measured by slowly lowering the YSI Datasonde through the separator. As can be seen in Fig. 19, profiles of chloride showed chemostratification (formation of a denser, salt-laden layer) in the OGS on May 10, with a sharp increase in concentration near the bottom of the separator. The concentration of chloride ranged from 35 to 268 mg/L. On June 19, the opposite trend was observed, with the highest Cl⁻ concentration (only 40.5 mg/L) occurring at the top of the chamber. Because the gradient of chloride concentrations is low, its densimetric effects could be compensated by thermal stratification; alternatively, sampling or instrument error could be the cause of the unusual result. A follow-up assessment was performed on June 26, which confirmed the chemostratification trend seen on May 10, with a Cl⁻ concentration range of 22 to 159 mg/L. Similar patterns were observed for total dissolved solids (TDS). The pH increased slightly from top to bottom of the OGS on all three days, but was always between 7.2 and 8.3. Surprisingly, turbidity did not show a clear trend with depth in the OGS.

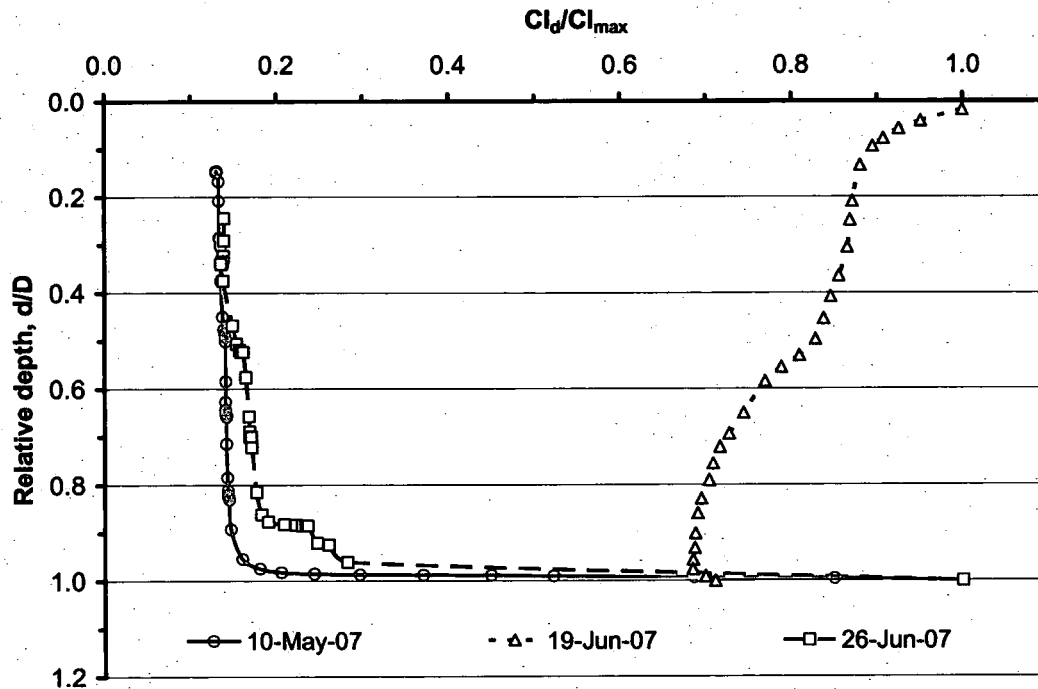


Fig. 19: Profiles of OGS chloride concentrations

Chloride profiles measured in the pond at RHSD1, -2, and -3 on May 10, 2007 (Fig. 20), indicated that only site RHSD1 was quite highly stratified, ranging from 31 mg/L Cl^- at the top to over 1500 mg/L near the pond bottom. Sites RHSD2 and -3 showed only a slight increase in chloride concentration with depth, with smaller ranges and much lower concentrations than RHSD1. Chloride profiles measured in June (not shown) did not show the extremely high chloride concentrations measured in May. Only RHSD2 showed some stratification in June, but with a Cl^- range of only 47 to 65 mg/L, this is probably insignificant and within the realm of measurement errors. From these results, it appears that the bulk of the stored chloride was washed out of the pond between May 10 and June 26, 2007.

Conductivity measurements made by the Town of Richmond Hill at the outlet of the stormwater pond (Fig. 21) indicate that the highest concentrations of salt actually passed through the pond in March. Conductivity levels fell from a high of about 12000 $\mu\text{S}/\text{cm}$ at the beginning of March to around 700 $\mu\text{S}/\text{cm}$ by mid-April, falling again slightly to approximately 450 $\mu\text{S}/\text{cm}$ by the end of May. This agrees with measurements of chloride in meltwater entering the pond (Figs. 12 and 15), as the highest chloride concentrations were seen in samples at the end of February and beginning of March. This indicates that relatively little chloride was stored in the pond over an extended period of time.

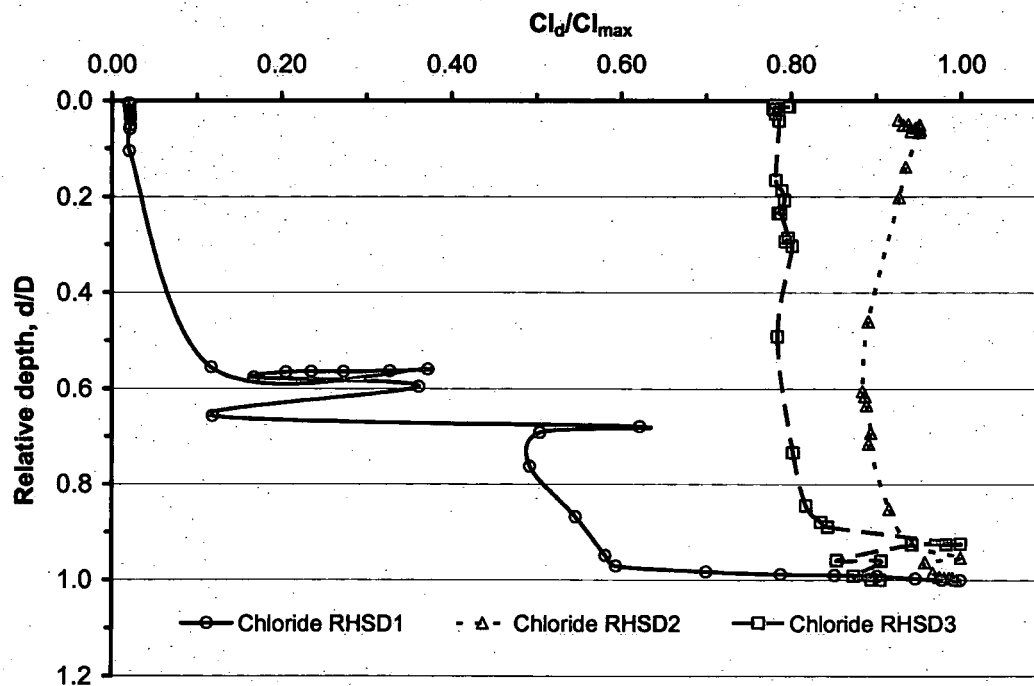


Fig. 20: Stormwater pond chloride profiles, May 10, 2007

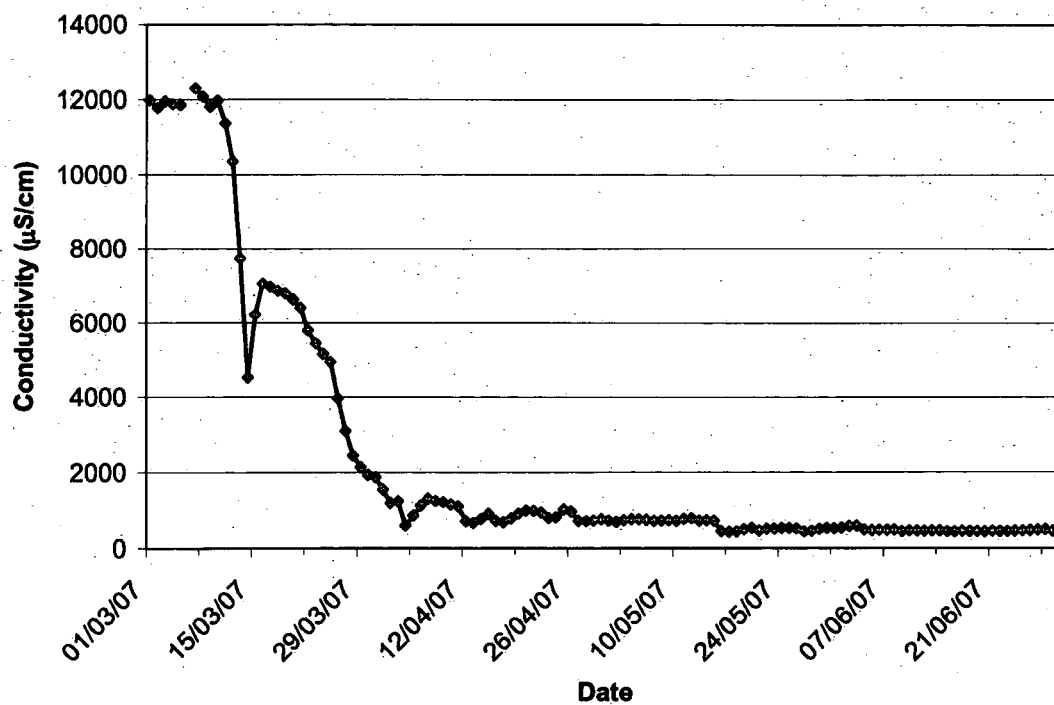


Fig. 21: Daily average conductivity at the stormwater pond outlet measured by Richmond Hill

Table 9: Total metal concentrations in the water phase of the OGS, stormwater pond and drainage ditch in May and June 2007.

Sample site	Parameter	May 10, 2007	Copper	Iron	Lead	Zinc
	Units	Cadmium	µg/L	µg/L	µg/L	µg/L
	MDL	0.22	0.5	2.21	0.64	9.65
	CCME guideline *	0.065	4	300	7	30
RH OGS Depth (m)	0.5	2.87	19.5	938	2.51	34.9
	1	2.85	18.8	783	0.783	27.8
	1.5	2.88	17.7	753	0.925	26.7
	2	2.93	18.3	720	nd	25.3
	2.5	2.86	18.4	740	1.23	26.2
	3	2.89	17.7	713	1.79	27.2
RHSD1	Surface	2.99	19.2	583	1.32	31.9
	Middle	2.90	20.2	651	2.08	34.1
	Bottom	2.96	18.6	660	2.42	30.8
RHSD2	Surface	2.82	15.1	116	nd	nd
	Middle	2.93	16.0	240	nd	12.0
	Bottom	2.85	16.3	310	nd	13.5
RHSD3	Surface	2.89	14.7	58.7	nd	nd
	Middle	2.86	14.9	51.5	nd	9.32
	Bottom	2.90	15.4	81.0	nd	4.33
RHSD4		-	-	-	-	-

Sample site	Parameter	June 27, 2007	Copper	Iron	Lead	Zinc
		Cadmium	µg/L	µg/L	µg/L	µg/L
RH OGS Depth (m)	0.5	0.402	nd	11.6	3.24	nd
	1	0.404	1.45	12.6	2.78	excl.
	1.5	0.356	2.50	40.0	6.13	16.0
	2	nd	0.626	57.1	4.31	nd
	2.5	0.383	1.50	137	3.19	nd
	3	0.348	nd	3190	4.06	nd
RHSD1	Surface	0.353	1.01	106	4.2	10.4
	Middle	-	-	-	-	-
	Bottom	0.343	0.899	271	4.61	nd
RHSD2	Surface	0.298	1.07	128	3.92	nd
	Middle	0.244	1.83	146	4.66	nd
	Bottom	nd	0.966	172	3.37	nd
RHSD3	Surface	nd	1.21	131	4.41	nd
	Middle	nd	0.903	149	3.94	nd
	Bottom	0.244	1.71	101	5.00	nd
RHSD4		0.535	0.651	210	4.23	nd

* guidelines assuming hardness = 219 mg/L (based on median Ca and Mg measured in 2008); nd = not detected or concentration below the MDL; excl. = data excluded as an outlier

Metal concentrations in the water phase of the OGS, stormwater pond and drainage ditch are shown in Table 9. Copper, iron, lead and zinc concentrations decreased along the pond in May; this trend was not evident in June. Surprisingly, the lead levels in the OGS and pond were noticeably higher in June than they were in May (although still below the CCME guidelines for very hard water), while the reverse was true for the other metals. There was presumably a source of lead present at the site in the spring and summer of 2007 that did not contribute as much during the snowmelt season.

In May, cadmium and copper concentrations greatly exceeded the CCME Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME, 2007) in all samples, while iron and zinc displayed exceedances only in the OGS and at RHSD1. Except for cadmium, most metal concentrations were below the CCME guidelines in samples taken in June.

Cadmium, copper and zinc levels remained relatively constant with depth at each location, while iron concentrations clearly increased with depth. As most (92%) of the iron was in particulate form, its concentration increased down the water column. The percentage of each of the other metals in dissolved form in the May samples was 89%, 93%, and 47% for cadmium, copper, and zinc, respectively.

Sediment quality. Sediment samples were collected from locations near the inlet (RHSD1), centre (RHSD2) and outlet (RHSD3) of the stormwater pond on May 10, June 27 and August 23, 2007. Sediment samples were also collected from the OGS on May 10, from the drainage ditch (RHSD4) on June 27, and from near shore samples corresponding to each of the original three pond sites on August 23. See Fig. 2 for more detailed sampling locations. Particle size analysis was conducted on the sediments, but the results were extremely variable and difficult to interpret. Particle size analysis will also be conducted on sediments collected in 2008; discussion of results for both years will be contained in the final report.

The concentrations of copper, lead and zinc in the sediments are shown in Fig. 22, 23 and 24, respectively. While sediment samples from the OGS contained metal concentrations above the CCME Interim Sediment Quality Guidelines (ISQG) for the Protection of Aquatic Life (2002), concentrations decreased along the length of pond. By the outlet (RHSD3), levels were below guideline values. Although lead and zinc concentrations were well below the ISQG in the drainage ditch (RHSD4), the level of copper well exceeded the ISQG of 35.7 µg/g. This anomaly may be due to historical contamination, other sources of copper upstream of the pond, or sample contamination. The reason cannot be ascertained with only one sample, but this will be explored further in 2008.

Concentrations of PAHs (Figs. 25-27) followed the same general pattern as the metal concentrations, with levels falling below ISQG values by RHSD3. Phenanthrene displayed unusually low concentrations in sediment samples taken on June 27, although other analytes displayed levels closer to those observed on the other dates. It is likely that the unusually low levels of phenanthrene are due to a sampling or analytical error, rather than real phenomena. As seen with copper, the levels of fluoranthrene and pyrene exceeded the ISQG in the drainage ditch, although levels were lower in the pond near the outlet.

In general, samples taken near the shore had lower levels of metals and PAHs, although the differences in near shore and centre samples at RHSD3 were small.

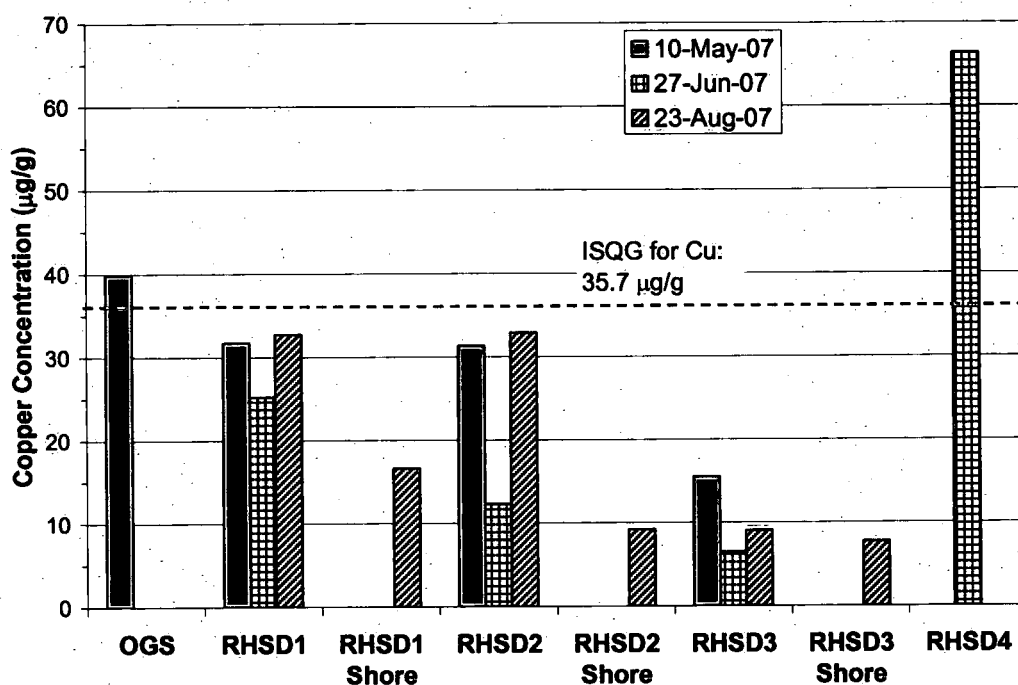


Fig. 22: Copper concentrations in OGS, stormwater pond (RHSD1-3) and drainage ditch (RHSD4) sediments

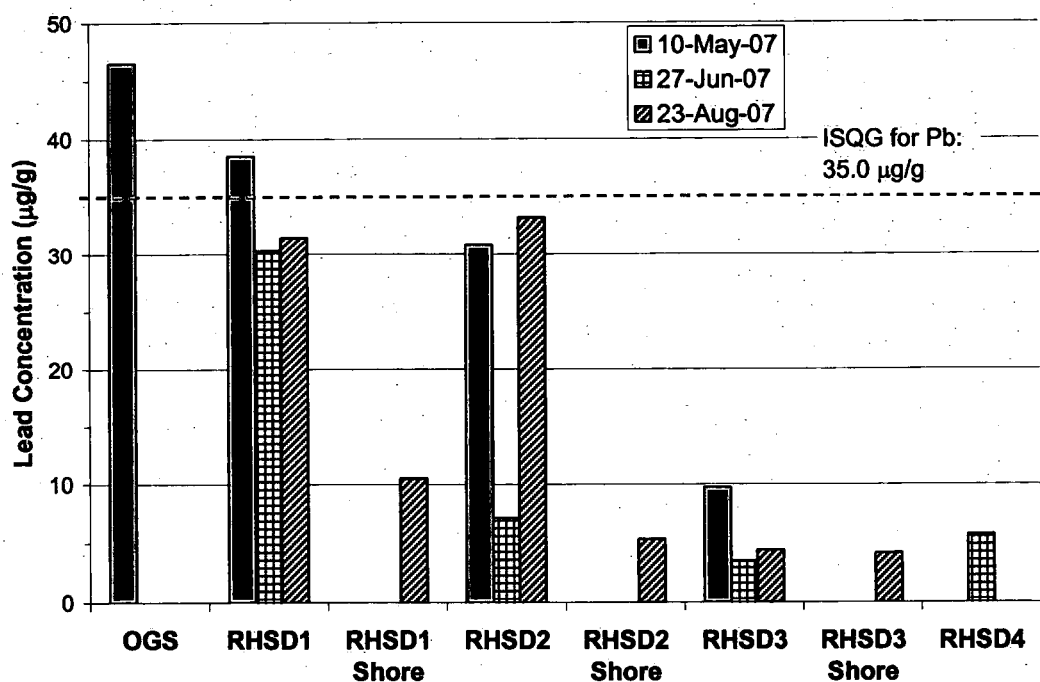


Fig. 23: Lead concentrations in OGS, stormwater pond and drainage ditch sediments

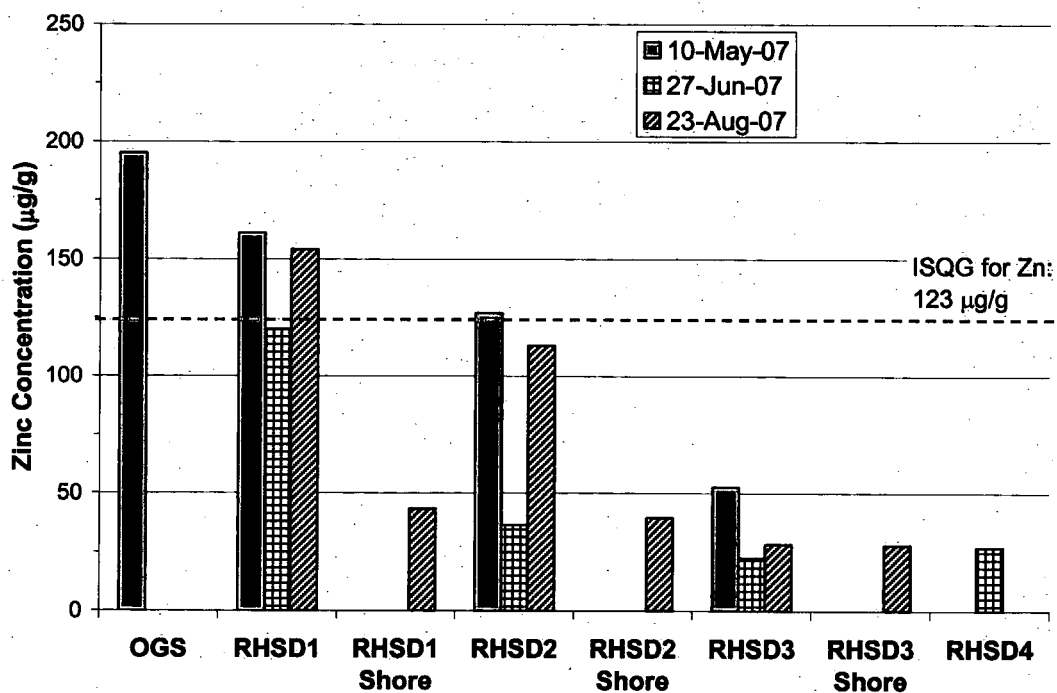


Fig. 24: Zinc concentrations in OGS, stormwater pond and drainage ditch sediments

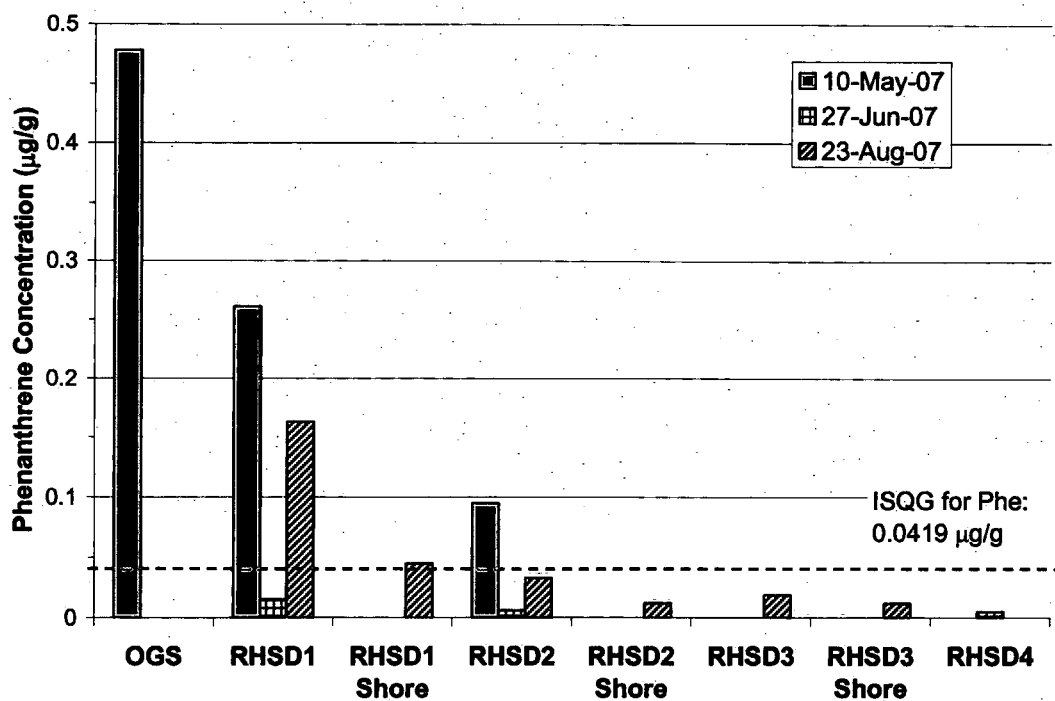


Fig. 25: Phenanthrene concentrations in OGS, stormwater pond and drainage ditch sediments

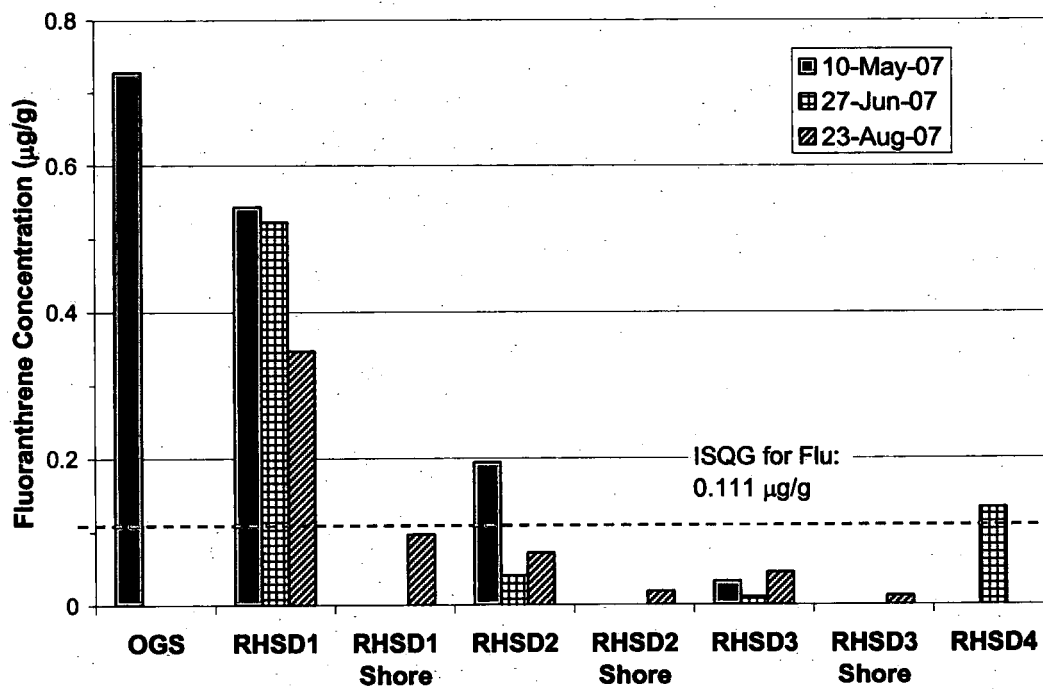


Fig. 26: Fluoranthrene concentrations in OGS, stormwater pond and drainage ditch sediments

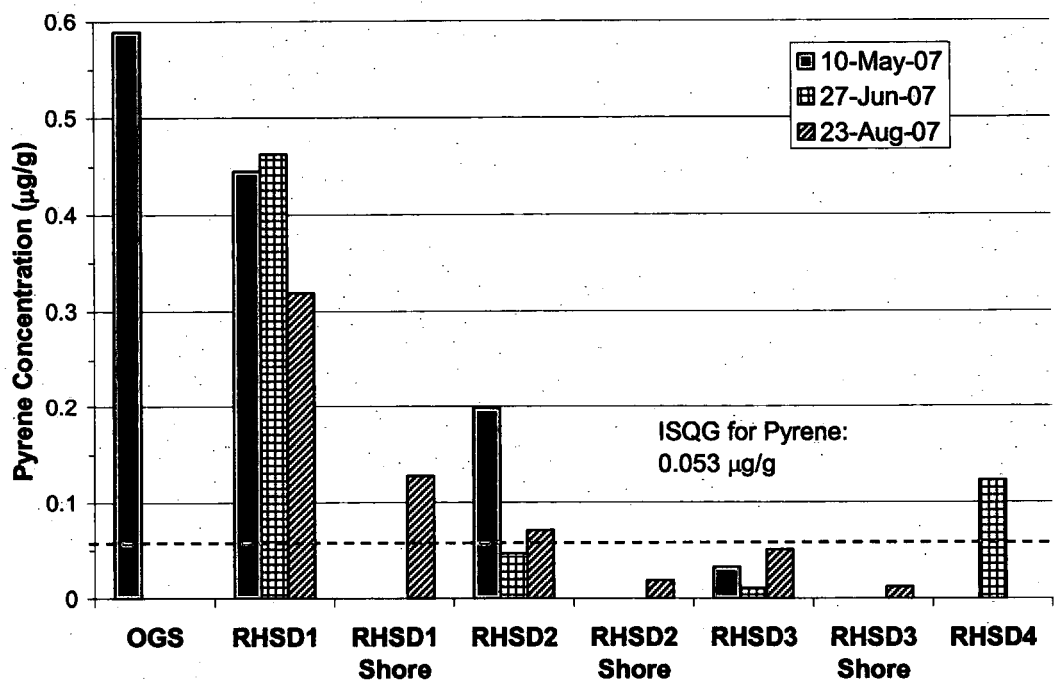


Fig. 27: Pyrene concentrations in OGS, stormwater pond and drainage ditch sediments

5.5 Chemical uptake by macrophytes in the treatment pond

Figs. 28, 29, and 30 display the concentrations of copper, lead and zinc, respectively, in the large aquatic plants (macrophytes) and sediment collected from the stormwater pond on August 23, 2007. Note that metal concentrations in the root plaque were very small ($<1 \mu\text{g/g}$) and did not display in the graphs. Concentrations of copper, lead and zinc in root and shoot tissues were highest at RHSD1 and generally decreased along the length of the pond.

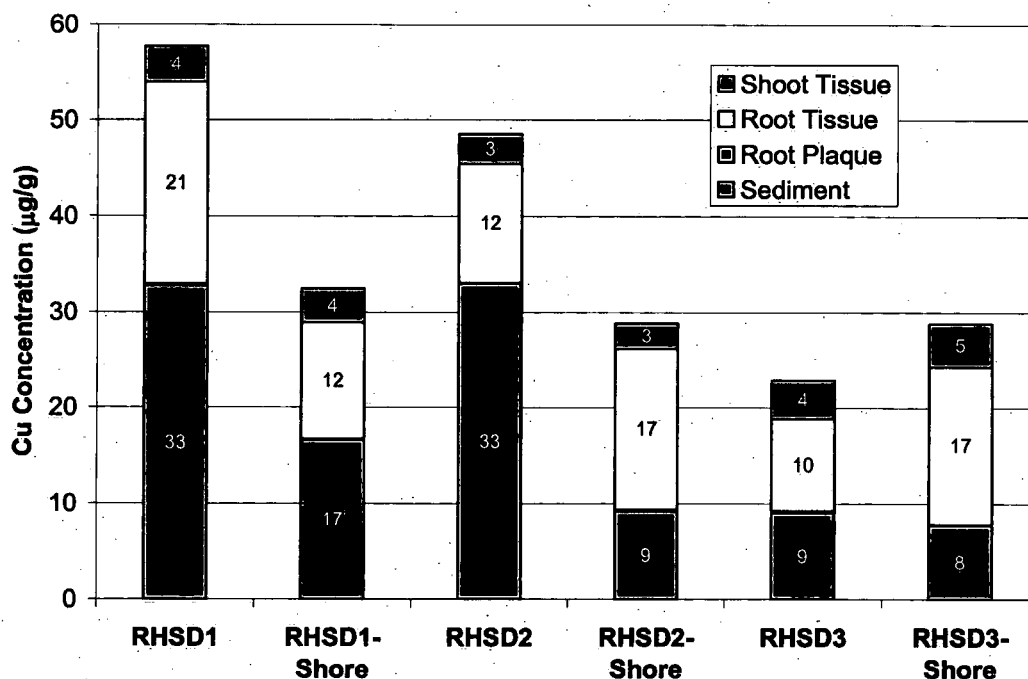


Fig. 28: Copper concentrations in macrophytes and sediments

Concentrations of all three metals in shoot tissues were considerably lower than in root tissues. Root tissue concentrations of copper, lead and zinc were lower than levels in the sediment at RHSD1 and -2, but higher than levels in the sediment at RHSD3 and most shore samples. In fact, concentrations of lead and zinc in root tissues were roughly 2-3 times as high as in sediment at RHSD3 (both centre and shore samples). It is not unusual for root metal concentrations to be elevated relative to sediment metal concentrations (Cardwell *et al.*, 2002); this bioconcentration effect forms the basis of phytoremediation.

Interestingly, near-shore root tissue samples at RHSD2 and -3 contained higher levels of the metals than those from the centre of the pond, although sediment chemistry displayed the opposite trend. The dominant macrophyte species observed both in the centre and near-shore areas of the pond was *Typha latifolia*, with a higher density of plants near-shore. Increased efficiency of metal uptake near the shore may be due to localized differences in sediment geochemistry (i.e., salinity, redox potential, pH, nutrient concentrations, etc.), which in turn influence metal bioavailability (Mayer *et al.* 2002; Jackson, 1998). Alternatively, it is possible that the near-shore plants may be older than those located in the centre of the pond (assuming plantings were done near the edge of the pond and the plants naturally spread through the pond over time); the older, near-shore plants may therefore have been exposed to sediment metals for a

longer period of time. The 2008 final study report will include an evaluation of the metal burden in the pond vegetation.

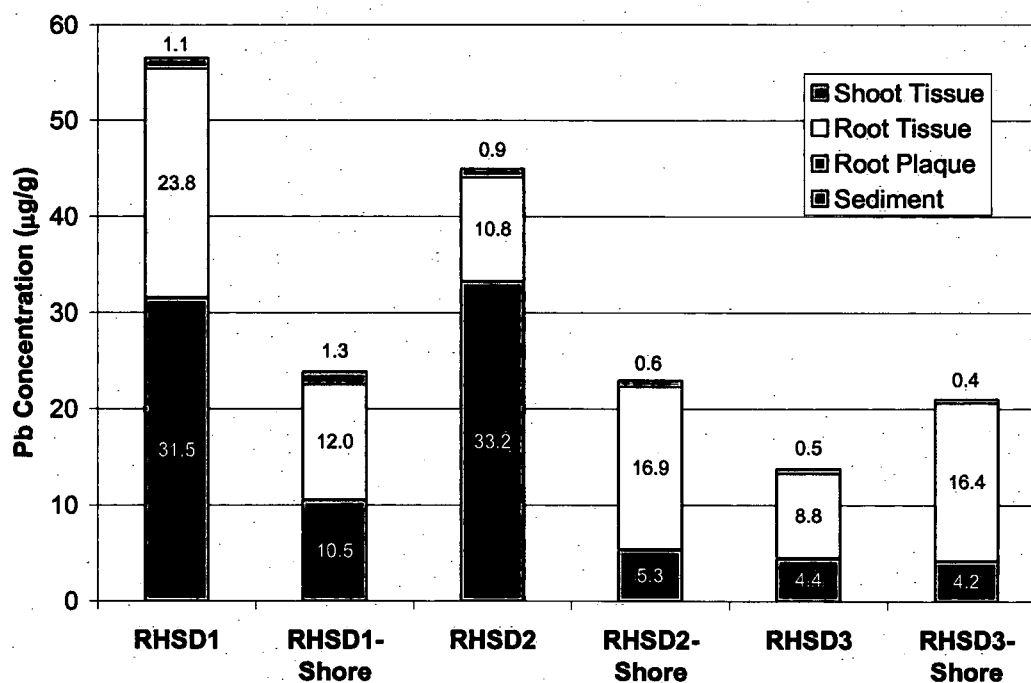


Fig. 29: Lead concentrations in macrophytes and sediments

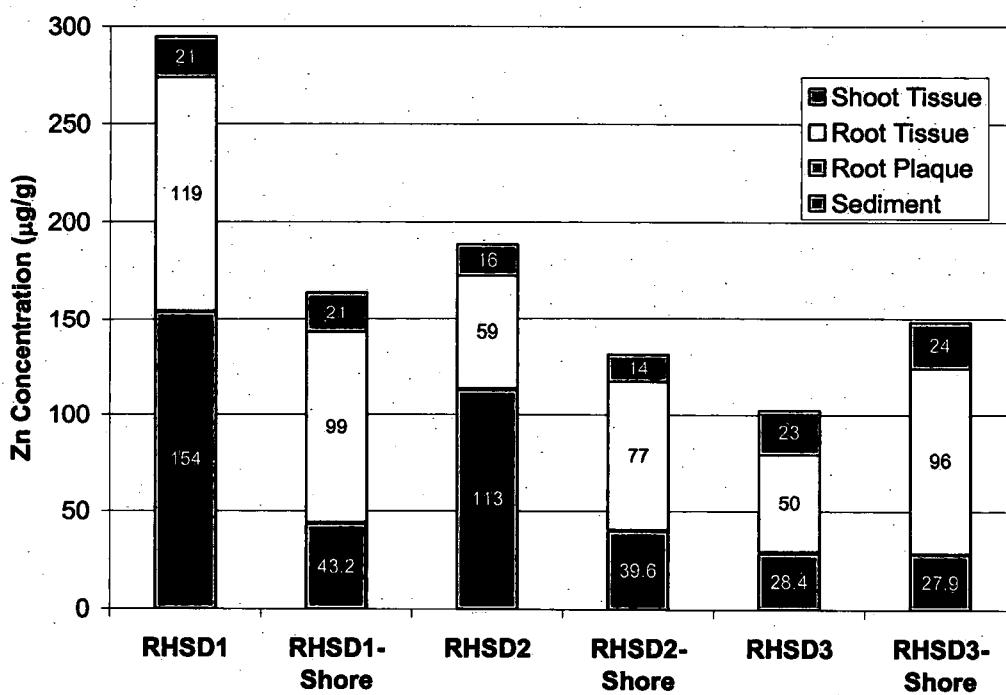


Fig. 30: Zinc concentrations in macrophytes and sediments

5.6 Benthic community assessment and sediment toxicity

Benthic Community. There were 60 benthic macroinvertebrate taxa (identified to lowest practical level, mainly species) in total found in sediment cores collected from the pond (RHSD1, RHSD2, RHSD3) and the drainage ditch (RHSD4) sites; 30 taxa were present in samples from early autumn 2006 and 49 taxa were present in samples from early summer 2007. Figure 31 shows the variation among samples in total abundance, taxon richness and evenness. The strongest pattern appears to be for total abundance and taxon richness in 2007: the benthic community is most sparse at the pond site closest to the inflow (RHSD1), most dense and taxon-rich at mid-pond site RHSD2, intermediate at site RHSD3 near the pond outflow, and further decreased in the drainage ditch. A similar but weaker pattern is shown for total abundance in the 2006 samples. Evenness (Fig. 31C), which is a measure of taxonomic diversity adjusted for the total number of taxa, is high for all samples and shows little variation among sites and years, except for a comparatively low value for the 2006 sample from RHSD2 (due to a preponderance of ceratopogonid fly larvae). The statistical significance of these differences is difficult to determine.

In terms of taxonomic composition, most of the samples were dominated by dipterans (flies) and oligochaete worms (Fig. 32), as is typical of stormwater-exposed ponds and streams in southern Ontario (Grapentine et al. 2004, 2008) and other aquatic habitats in urban areas (Walsh et al. 2005). Amphipods, ephemeropterans, plecopterans and trichopterans, which are generally sensitive to pollution, were virtually absent from the communities except for a baetid mayfly species in the 2007 sample from RHSD2.

Benthic communities from small habitats such as the RHSSF pond and drainage ditch are probably better compared to communities in groundwater springs, such as those studied by Williams et al. (2000), rather than larger ponds and streams. Williams et al. sampled 16 springs in the Greater Toronto Area exposed to various amounts of runoff contaminated from winter road de-icing salt. Chloride levels ranged from <2 to ~1200 mg/L. The number of taxa in each spring ranged from 5 to 11, with a mean of 8. Although these numbers are not directly comparable to the present study, because Williams et al. did not identify several taxa to species and included some nonmacroinvertebrate taxa, they do indicate that the 2007 samples from the RHSSF pond that had 24 and 32 taxa may not be impoverished.

A possible explanation for the sparse benthic community at site RHSD1, especially for June 2006, is the occurrence of high chloride conditions near the pond bottom during part of the spring (see Section 5.4). If this occurs annually, it could result in periodic mortality of invertebrates at the site. Comparatively high contaminant concentrations at RHSD1 (Fig. 22-27) could also be a factor impacting the benthic community, but together with the chloride conditions, would have to be further investigated.

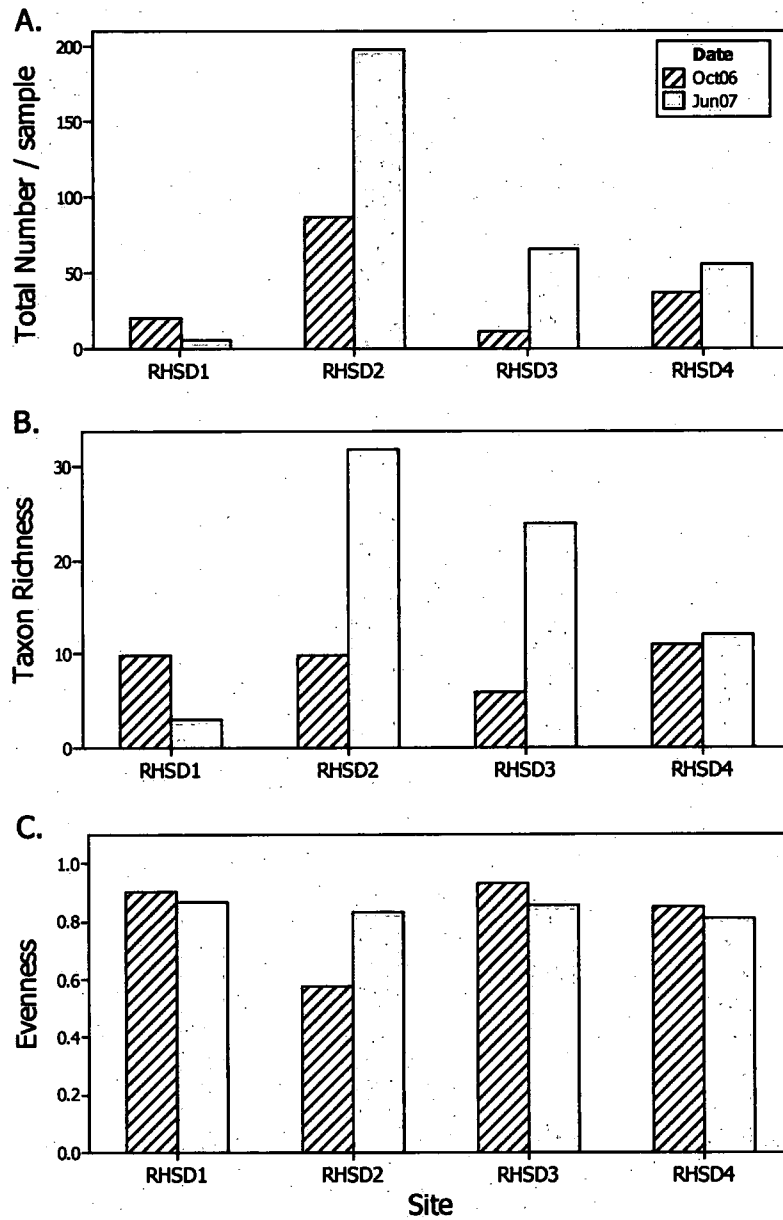


Fig. 31: Total abundance, taxon (genus/species) richness and evenness in benthic community samples from stormwater pond (RHSD1-3) and drainage ditch (RHSD4) sediment cores

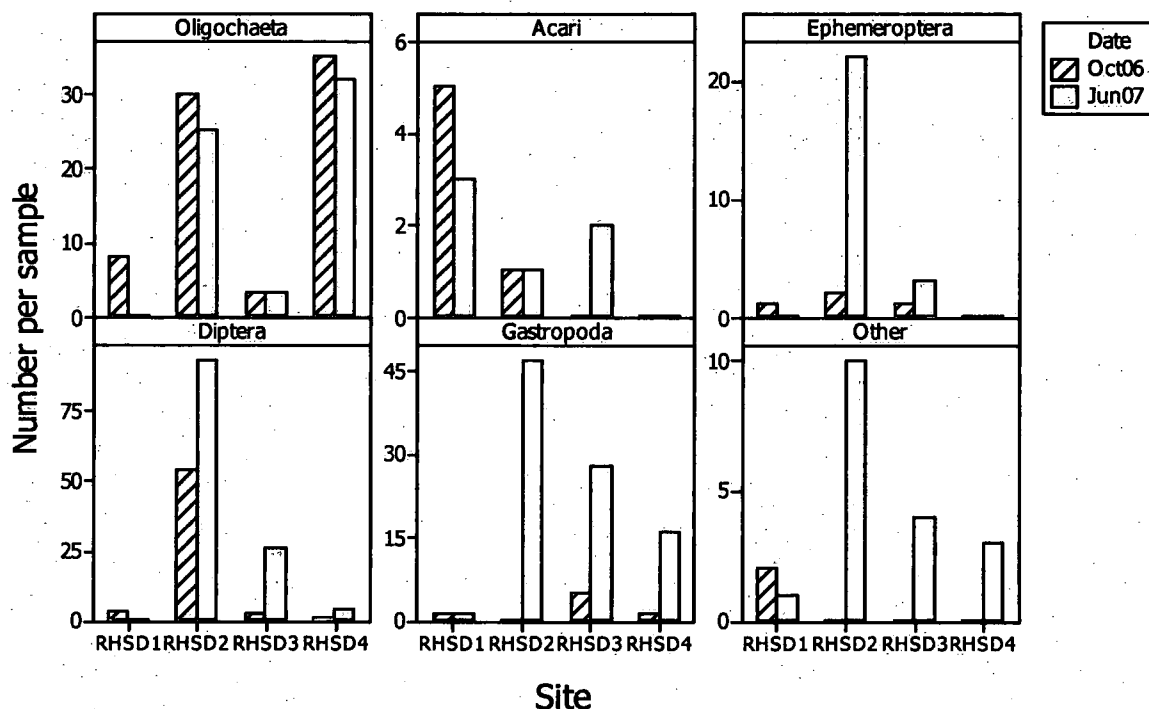


Fig. 32: Abundance of major benthic taxa in stormwater pond and drainage ditch sediment cores

Sediment Toxicity. The toxicity of sediment from the OGS, pond and drainage ditch was measured by both acute (survival) and chronic (growth) endpoints in laboratory tests. Survival of *Hexagenia* and *Hyalella* was close to 100% for nearly all samples (Fig. 33). Mean values were 93-100% for all samples from 2006, and 91-100% for all samples from 2007, except those from RHOGS and RHSD2, for which survival was 73% (*Hexagenia*) and 64% (*Hyalella*), respectively. The RHOGS and RHSD2 (2007) responses were also the only ones significantly lower than survival in control sediment ($P < 0.05$ based on Tukey simultaneous pairwise comparison). Based on the range of sediment toxicity observed for a large number of nearshore reference sites in the Great Lakes, the RHOGS and RHSD2 (2007) samples are classed as “potentially toxic” (Reynoldson and Day 1998).

Growth in the test sediments (Fig. 34) differed more frequently from control responses compared to survival. In 2006, growth was significantly lower in RHSD2 (*Hexagenia* and *Hyalella*) and RHSD4 (*Hexagenia*) samples, and higher in the RHSD3 (*Hexagenia*) sample compared to control sediment. In 2007, growth was depressed relative to the control response in the RHOGS (*Hexagenia* and *Hyalella*), RHSD3 (*Hyalella*) and RHSD4 (*Hexagenia*) sediment, but not in the RHSD2 sample. The RHSD2 sample from 2007 resulted in *higher* growth of *Hexagenia*, as did the RHSD3 sample. Differences in growth between years and species were marked. Among the 5 sites sampled at the RHSSF, the only fully consistent responses were for samples from RHSD1, which were the same as those for control sediment for both years and both species, and RHOGS, which were lower than control for both species for 2007 (no sample was obtained in 2006). Partial consistency was observed for samples from RHSD2 (lower than control for both species

for 2006), RHSD3 (higher than control for *Hexagenia* in 2006 and 2007), and RHSD4 (lower than control for *Hexagenia* in 2006 and 2007).

The reduction in growth relative to growth in control sediment was severe only for *Hexagenia* in the RHSD4 (2006) sample (mean = 4% of Control 1) and *Hexagenia* in the RHOGS sample (mean = 6% of Control 2). Mean growth of *Hexagenia* and *Hyaella* in the other samples that were significantly lower than control sediment ranged from 49 to 70% of control growth.

Among the potential causes of the sediment toxicity observed are contaminants in sediments, and particle size distribution. (Dissolved and suspended constituents in porewater, such as dissolved Na or Cl, would have been largely removed during sediment sieving.) Concentrations of metals and PAHs in sediment (Fig. 22-27) generally decreased in the direction from pond inlet (site RHOGS) to the pond outlet (RHSD3) and drainage ditch (RHSD4), except for Cu, which was highest in a sample from RHSD4. Although the RHOGS sample appears the most toxic overall (Fig. 32, 33), the pattern of toxicity among the other sites does not match the contaminant trend. Therefore, metal and PAH concentrations are not likely important in their overall impacts. This is not unexpected given that the highest concentrations of contaminants exceed the ISQG, but not the CCME Threshold Effect Level, above which toxicity is predicted to be likely. Poor growth of *Hexagenia* in the RHSD4 sediment from both 2006 and 2007 could be due to high proportions of sand, which were observed in the sample. *Hexagenia*, which inhabit burrows built within sediment, prefer substrates dominated by silt- and clay-sized particles and typically show low growth in toxicity tests with sandy sediment.

In summary, acute toxicity of sediment was absent, except possibly for samples from sites RHOGS and RHSD2, major chronic (sublethal) toxicity was observed in 2 of 18 cases, and minor chronic toxicity in 5 of 18. Only the sample from the RHOGS showed substantial toxicity potentially attributable to sediment contaminants, although this is not directly environmentally significant (as the pond samples are), since sediments can be removed from the OGS and properly disposed of.

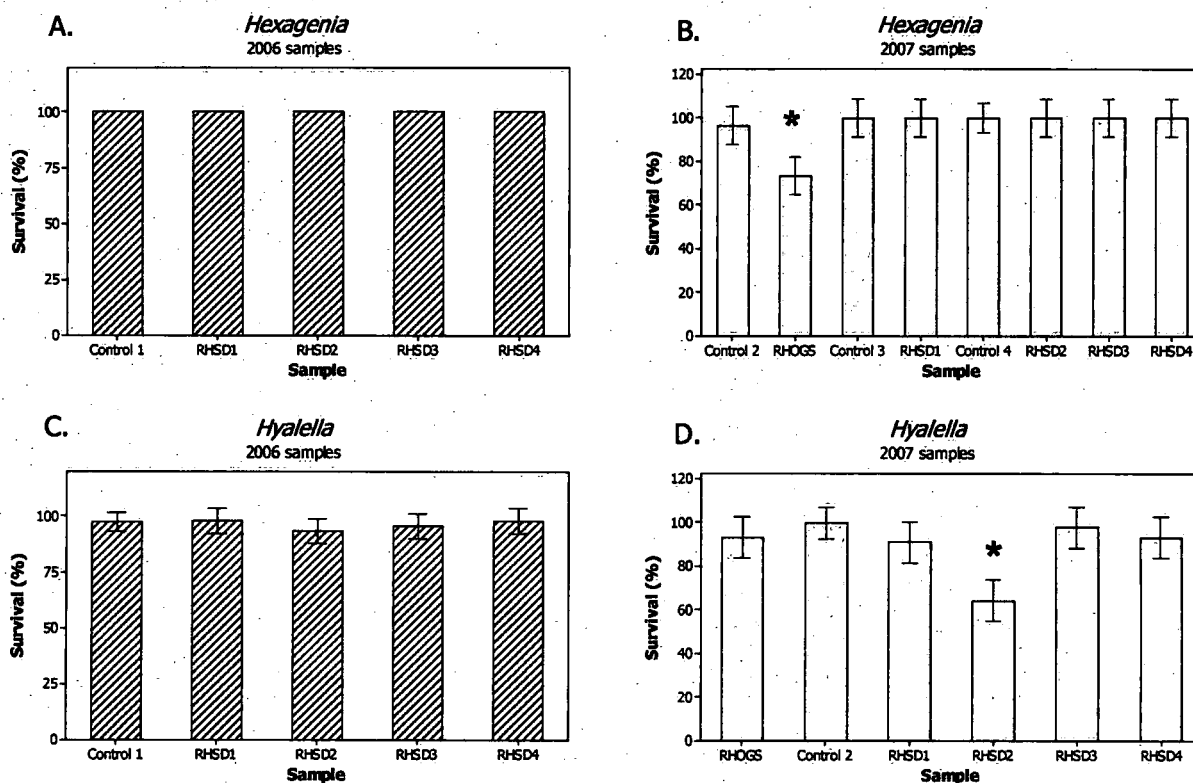


Fig. 33: *Hexagenia* spp. and *Hyalella azteca* survival (mean of replicates with 95% confidence interval based on pooled error across groups) in laboratory control, OGS and pond sediments. Asterisk indicates survival is significantly different from appropriate control sediment (95% Tukey simultaneous pairwise comparison).

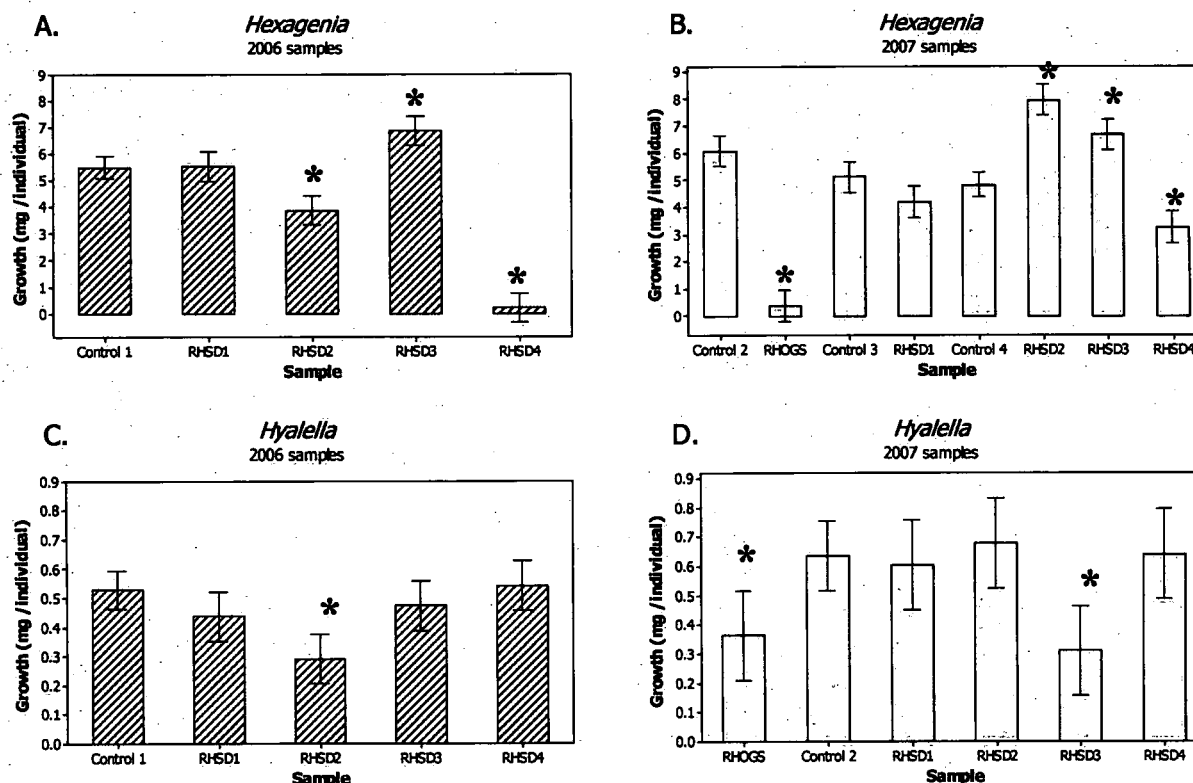


Fig. 34: *Hexagenia* spp. and *Hyalella azteca* growth (mean of replicates with 95% confidence interval based on pooled error across groups) in laboratory control, OGS and pond sediments. Asterisk indicates survival is significantly different from appropriate control sediment (95% Tukey simultaneous pairwise comparison).

6. Municipal Engineering Perspective

The Richmond Hill Snow Storage Facility received the 2007 Ontario Public Works Association Technical Innovation Award as a project representing a leading, innovative technology in urban snow disposal. As such, the facility is of great interest to other municipalities or their designers working on similar projects. To facilitate technology transfer, the main features and performance of the facility are overviewed in this section, from a municipal engineering perspective.

Site selection. The selection of the snow storage facility (SSF) site is critical for keeping the operating costs low and minimizing adverse impacts on the surrounding area. Research conducted in Sweden and Canada (Montreal) indicates the need to compromise between two major considerations: (a) proximity to the area from which snow is hauled (to minimize transportation costs and the associated carbon footprint), and (b) to locate the facility away from built up areas and thereby avoid the nuisance caused by heavy truck traffic and night operation. Both these conditions are met at the SSF site, which is located about 7 km from the business section of Richmond Hill on the grounds of the Richmond Green Sports Centre, a fair distance

from residential areas. The site has also another advantage, outside of the snow storage season, the storage pad is used for recreational activities and parking. Similarly, the vegetated treatment pond is a part of the natural landscape in this area and contributes to its recreational and aesthetic values.

Snow storage structure. The melting pad is formed by asphalt pavement, which is boarded along the down-slope perimeter by a concrete curb. The pad and curb are sloping towards two twinned sewer inlets draining the pad area. This arrangement ensures good drainage of the pad and full containment of snowmelt and its transport into the treatment train facility. The pavement prevents meltwater entry into the local groundwater aquifer and thereby prevents the groundwater pollution. To avoid problems with interflow underneath the pavement (e.g., uplift), the pad base is drained by five perforated sub-drains draining into the snowmelt conveyance system. During 2007, the site received about 700 truck loads, or about $10,500 \text{ m}^3$, of snow. With the depth of stored snow of about 3 m, the storage area could hold more than $40,000 \text{ m}^3$ of snow. Thus, for recent snowfalls (note that the 2007 snowfall was lower than the long-term average) and snow removal practices, there is a fair spare capacity at the facility. The forthcoming 2008 data will firm up the storage requirement data.

Climate change scenarios relevant to the study area predict increased precipitation (10-15%, in winter months) and higher air temperatures (5°C). It is unlikely that these changes would increase demands on snow storage – there would be more snow melting in situ, reducing removal and storage requirements, snow would be melting faster at the SSF, and potentially water losses due to sublimation or evaporation during storage would also increase.

The 2007 data indicated that there was snow present at the facility for almost 90 days; i.e., from the start of bringing snow in (mid January) to the end of snowmelt. The last snow melted away in about mid April 2007, and this did not delay preparation of the site for recreational season. Snowmelting at the site is accelerated by low albedo of the deposited snow; the snow pile surface seems covered by a thin layer of dark particulates (atmospheric deposition and soils collected during snow ploughing and removal). On the other hand, snow pile melting and refreezing during extended cold spells slows down snowmelt (referred to as ‘negative’ internal energy in the snowpack).

Snowmelt treatment train. As requested by the Ontario Procedure B-4-1, Guidelines for Snow Disposal and Deicing Operations in Ontario (MOE, 1975), and recommended by Transportation Association of Canada (TAC) best management practice 8.0 Snow Storage and Disposal, the Richmond Hill SSF provides a treatment train for snowmelt leaving the melting pad through a well-defined outflow pathway. The treatment train comprises settling in a quasi-sheet flow on the melting pad, sediment and floatables separation in the oil and grit separator (OGS) treating the entire snowmelt flow, and settling and vegetation bio-uptake in the treatment pond receiving outflow from the OGS. Before addressing the treatment train, it is of interest to describe the principal pollutants in urban snowmelt and their treatability.

As discussed in Section 2 (literature review), the main snowmelt quality constituents of potential environmental concerns are TSS and sediment (e.g., sand from maintenance operations), chloride, and heavy metals and PAHs associated with traffic by-products. Among these parameters, TSS and sediment, and associated metals and PAHs, can be partially removed by sedimentation, but

none of the common passive stormwater treatment processes remove chloride. Thus, the treatment train at the study site should work well for capturing a high percentage of solids and suspended metal and PAH loads, but with respect to chloride, the train can only temporarily detain and redistribute chloride fluxes. Such a performance is in compliance with the Ontario Procedure B-4-1.

A large proportion of solids contained in snow settles and stays on the melting pad surface. Snowmelt flows are generally very low (a short-duration peak discharge through the OGS was about $0.040 \text{ m}^3/\text{s}$; on the melting pad, this discharge is spread over a large width) and do not provide sufficient scouring and transport capacity to remove coarser solids from the pad surface. This is evident at the end of the melt season, when large quantities of sediment remain and need to be mechanically removed and properly disposed of.

Within the stormwater pond, plants aid removal of contaminants physically through enhancement of settling, as well as biologically through uptake of dissolved metals and nutrients. Since the roots of the macrophytes contained the highest metal concentrations, and little was transferred to the shoots, typical harvesting techniques would not likely provide much benefit in terms of metal removal and could actually reduce the enhancement of settling of solids. It is possible that other macrophytes (such as those known as metal hyperaccumulators) would take up a greater proportion of the sediment metal concentration and transfer the metals to shoots that could be easily removed and managed, but this idea would need to be explored further to determine its viability and overall benefit.

Chloride release and transport. High concentrations of chloride washed out of the pack and passed through the pond early in March, although the bulk of chloride was released during the high volume, low concentration melt near the end of the season. The conductivity probe readings at the pond outlet can be used as a surrogate for chloride concentrations and show a similar trend – high readings in early March and rapid decline over next 6 weeks. High concentrations of chloride contribute to densimetric stratification in the treatment pond (i.e., high concentrations along the bottom and much lower concentrations on the top), but the stratification did not persist long. Weak stratification of the pond remained in early May, but was gone by the end of June. The distribution of chloride concentrations in the outflow could be managed by modifications of the outlet structure; e.g., allowing pond outflow from some intermediate depth above the bottom.

Recent discussions addressed the possibility of recovery of dissolved chloride from snowmelt ponds and its reuse in brine production. The feasibility of such recovery could be enhanced by strengthening the pond stratification and chloride detention by outlet modifications allowing discharge from upper water layers containing low chloride concentrations. There are at least three arguments against this control option: (a) From the environmental point of view, source controls and/or deicing material substitutions applied throughout the catchment are much more effective measures than a limited recovery at the point of discharge into the environment, (b) pond water laden with chloride may also contain unacceptably high concentrations of dissolved metals (e.g., cadmium) and may be unsuitable for reuse, without some removal of metals, and (c) economically, potential recovery of even a large part of the 16 tons of chloride leaving the pad (about 6% of the chloride applied within the municipality) would be infeasible. In other words, the resources applied on reuse would be better spent on promoting and implementing chloride source controls.

Concerning the first point, many of the currently promoted best practices in road salting (often termed as "smart" salting) result in reduced applications of road salt, and new deicing products on the market (without chlorides, but more expensive than salt) are currently promoted and tested for more widespread municipal applications. Furthermore, by applying controls at the source, environmental benefits are distributed throughout the catchment and the receiving waters. Reuse of snowmelt pond brine may require additional treatment to reduce dissolved metals and toxicity of the recovered brine and ascertain that the reuse of pond water does not violate environmental laws and does not increase the risk of toxic effects at the point of use. The cost of additional treatment required for removing solids and/or other contaminants from the pond water would also need to be considered and would make the reuse option even less attractive. Nevertheless, these issues could be addressed in future studies exploring whether the current obstacles to chloride reuse can be overcome.

Treatment residue. The main residues of the existing treatment train are contaminated solids and sediments. The bulk of the solids and metals remained with the snowpack until the end of the melt. While such issues as the proportion of solids remaining on the paved surface or the efficiencies of the OGS or stormwater pond in terms of solids removal may be of interest to the municipal staff, they fall outside of the scope of this study (see the study scope and objectives in Section 1.2). Addressing the issues of removals would require much more intensive and costly data collection. Continued study in 2008 may indicate differences in the particle sizes of solids found in each location (paved area residue, OGS and pond sites), which could provide further understanding of solids transport behaviour. It is clear that the metals concentrations observed in the OGS and near the inlet of the pond were much higher than those near the outlet of the pond, indicating some removal of contaminants is taking place at the facility; therefore discharge of those contaminants into receiving waters is reduced. Similarly, substantial toxicity was observed only in the sediments collected from the OGS, and not in those from the stormwater pond.

Environmental overview. Stormwater management facilities typically treat stormwater by immobilizing and storing pollutants, including contaminated sediments. Thus, it is always useful to examine pathways of pollutants through such facilities, and the findings of these examinations are most useful in designing a suitable maintenance program, which keeps the facilities fully operational and reduces potential ecological risks associated with the presence of pollutants. The same rationale applies to the RHSSF, where the main retained residues are contaminated sediments. Tests of sediment quality and toxicity and their effects on benthic organisms indicated that there are points in the treatment train, where sediments may contain pollutants at the levels potentially causing toxic effects. Two examples of such locations are inside the OGS and by the inlet of the treatment pond. The former location does not cause environmental problems, because it is regularly maintained and the contaminated sediments are properly disposed of. Pond sediment may require a closer scrutiny by regular inspections of not only sediment accumulations, but of their toxicity as well. The latter condition may trigger removal of polluted sediments before the reductions in the pond treatment volume would call for such an action. The observed sediment chemistry and toxicity varied throughout the pond, with the lowest concentrations occurring by the pond outlet. This confirms the effectiveness of the pond in retaining contaminated sediments and reducing their loads on the downstream receiving waters.

The other constituent of environmental significance is chloride originating from road salting. The Ontario procedure B-4-1 recognizes the challenges in controlling chloride in snowmelt and consequently does not call for chloride removal, but just balancing of its release concentrations. The results of this study indicate that, to a fair extent, such balancing is occurring at the SSF facility and more data will be forthcoming from the second-year SSF report. Further manipulations of outflow chloride concentrations could be achieved by modifications of the pond outlet; such modifications would be in place just during late winter/early spring, when snowmelt occurs.

Facility operation and maintenance. Facility protection by a fence contributed to good control of access to the site and prevented illicit dumping of snow or waste. The facility is designed for ease of maintenance at the end of the melting season, when TSS and sediment are swept and removed from the melting pad, and the OGS is cleaned out with a vacuum truck. By comparison, dredging of the pond to remove accumulated sediments is a more expensive and elaborate operation; thus, inclusion of the OGS upstream of the pond may reduce the frequency of pond dredging.

Finally, a summary of observations on the RH SSF compliance with the Ontario Procedure B-4-1 and TAC best Practice 8.0 is included in the Conclusions.

7. Conclusions

The snow pile stored at the RHSSF was monitored from January to April 2007. The water balance of the facility was established with an accuracy of 10-15%, and indicated that the facility stored snow for about 82 days from January 17 to April 7, 2008. In total, about 7,200 m³ of water passed through the facility. Of this amount, about 2/3 were contributed by dumped snow and the remaining third by direct precipitation over the storage and surrounding area. Continuous monitoring of runoff indicated that chloride exhibited preferential elution from the snowpack, but that the first flush samples were not acidic. Chloride concentrations in runoff from the storage pavement averaged 2500 mg/L over the entire melt period. The bulk of the solids remained with the snowpack until the end of the melt period, along with most of the metals. Cyanide, TPH and PAHs were all present at concentrations near or below the method detection limits, so it could not be determined if these constituents were present at concentrations exceeding Canadian aquatic guidelines.

Profiles of the OGS and stormwater pond taken in May showed stratification of the OGS and near the pond inlet at RHSD1. Chloride concentrations increased with increasing depth and were very high near the sediment-water interface at these locations. By the end of June, it seems that much of the chloride had been washed out of the pond as concentrations were much lower. Conductivity measurements taken at the outlet of the pond indicated that the highest salt concentrations passed through the pond early in March, but conductivity levels at the pond outlet continued to decrease until late May.

In May, cadmium and copper concentrations greatly exceeded the CCME guidelines for the protection of aquatic life in all OGS and pond water samples, while iron and zinc displayed exceedances only in the OGS and RHSD1. Except for cadmium, most samples taken in June contained metal levels below the CCME guidelines.

Sediment samples taken from the OGS, the stormwater pond and the drainage ditch showed that metal and PAH concentrations decreased along the length of the pond and were below the CCME sediment quality guidelines by the outlet of the pond. Copper, fluoranthene and pyrene all showed elevated levels in the drainage ditch, however, and this could be caused by accumulation of fine sediments released from the pond.

Macrophyte samples collected from the stormwater pond were tested for copper, lead and zinc. Concentrations were highest in the root tissue, then the shoot tissue. Negligible amounts were detected in the root plaque. As was seen in the sediment samples, metal concentrations in root tissues generally decreased along the length of the pond. Near the inlet of the pond, metal concentrations in root tissues were somewhat lower than in the sediment, while near the shore and near the outlet of the pond, metal concentrations in root tissues exceeded levels in the sediment.

The benthic community total abundance and taxon richness showed the strongest pattern in 2007: the benthic community is most sparse at the pond site closest to the inflow (RHSD1), most dense and taxon-rich at mid-pond site RHSD2, intermediate at site RHSD3 near the pond outflow, and further decreased in the drainage ditch. Acute toxicity of sediment was absent, except possibly for samples from sites RHOGS and RHSD2, major chronic (sublethal) toxicity was observed in 2 of 18 cases, and minor chronic toxicity in 5 of 18. Only the sample from the RHOGS showed substantial toxicity potentially attributable to sediment contaminants.

Overall, the system appears to function well with respect to the MOE Guidelines for Snow Disposal and Deicing Operations in Ontario (Procedure B-4-1; MOE, 1975) and the TAC Syntheses of Best Practice 8.0 Snow storage and disposal (TAC, 2003), with respect to:

- (a) Controlling and managing snowmelt runoff from the site, by providing a paved base for the facility and curb along the perimeter, ensuring that all runoff is channelled into the treatment train;
- (b) Managing quality of snowmelt/runoff from the site by the treatment train comprising an oil & grit separator (OGS), and a stormwater/snowmelt management pond with a sediment forebay. The OGS retained some of the more contaminated sediments (as documented by benthic toxicity testing), and other contaminants were retained with sediment in the pond. Trace metal and PAH concentrations in pond sediment significantly decreased in flow direction from inlet to the outlet. The pond also regulates release of chlorides from the site; early in the winter, chloride laden water is stored in the pond, and it is gradually purged when snowmelt/runoff increases. To confirm this phenomenon, a second conductivity probe was installed at the pond outlet in time for the second year of study (2008).
- (c) Facilitating easy cleanup of debris and litter at the end of the snowmelt period.
- (d) Finally, site location and protection by a fence contributed to good operation and security of the site.

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Appendix A – Analytical methods

The following methods have been condensed from the official Environment Canada Wastewater Technology Centre Analytical Laboratory (WTC-AL) Standard Operating Procedures. All methods include such quality control measures as blanks, reference samples and duplicates.

INW13 Method for the determination of anions in water

Scope and application / Parameters measured

Ion chromatography may be used for the rapid, sequential measurement of common anions such as bromide, chloride, fluoride, nitrate, nitrite, phosphate, sulphate and thiosulphate. It effectively distinguishes among the halides (Br^- , Cl^- and F^-) and the oxy-ions (SO_3^{2-} , SO_4^{2-} , or NO_2^- , NO_3^-).

This method is applicable, after filtration to remove particles larger than $0.2\ \mu\text{m}$, to surface, ground and wastewaters.

The following is a list of the anions that can be analysed using this method:

F^- (fluoride)	Cl^- (chloride)	NO_2^- (nitrite)
Br^- (bromide)	ClO_3^- (chlorate)	SO_4^{2-} (sulfate)
NO_3^- (nitrate)	PO_4^{3-} (phosphate)	$\text{S}_2\text{O}_3^{2-}$ (thiosulfate)

Summary / principle of method

A small portion of a filtered, homogenous, aqueous sample or a sample containing no particles larger than $0.45\ \mu\text{m}$ is injected into an ion chromatograph. The sample merges with the eluent stream and is pumped through the ion chromatographic system. Anions are separated on the basis of their affinity for the active sites of the column packing material. Conductivity detector readings (either peak area or peak height) are used to compute concentrations.

Equipment

Dionex ICS-2000 Ion Chromatography System, equipped with an ASRS-Ultra II 4mm Suppressor, an AS40 Automated Sampler, an IonPac AS15 Column and Dell Computer with Chromeleon IC System Software.

Method detection limit for chloride: 0.156 mg/L

INW06 Method for the determination of cyanide in water

Scope and application

"Cyanide" refers to all of the CN groups in cyanide compounds that can be determined as the cyanide ion, CN^- , by the methods used. Total cyanides include complex cyanides such as $\text{K}_4\text{Fe}(\text{CN})_6$ (Potassium Ferro cyanide) and simple cyanides, like NaCN (Sodium cyanide). Distillation for total cyanide occurs under $\text{pH} = 4 \pm 0.2$. The weak acid dissociable cyanides are liberated from a slightly acidified ($\text{pH} = 4.5$ to 6.0) sample under prescribed distillation conditions. The method does not recover CN from tight complexes that would not be amenable to oxidation by chlorine.

Summary / principle of method

By this method complex cyanides (with the exception of gold and cobalt complexes) are converted to HCN gas through a reaction with sulfamic acid and EDTA at $\text{pH} 4.0$. The HCN liberated by distillation is trapped in 1N sodium hydroxide and converted to CNCl by reaction with chloramine-T at $\text{pH} < 8$. On addition of isonicotinic-barbituric acid reagent, CNCl forms a red-blue colour. Colourimetry is used for quantitation for samples containing $< 5 \text{ mg/L CN}$; for higher concentrations, the sample can be diluted.

Equipment

Microblock Simultaneous Distillation Apparatus, Shimadzu UV 160 spectrophotometer.

Method detection limits: Total Cyanide 0.02 mg/L ; Free Cyanide 0.02 mg/L

INW14 Method for the determination of total and dissolved metals in water by inductively coupled plasma (ICP-OES)

Scope and application / Parameters measured

Inductively coupled plasma (ICP) techniques are applicable over a broad linear range and are especially sensitive for refractory elements. The following elements can be analysed using this ICP method. Results are reported in µg/L.

Silver (Ag)	Manganese (Mn)
Aluminium (Al)	Molybdenum (Mo)
Arsenic (As)	Sodium (Na)
Boron (B)	Nickel (Ni)
Barium (Ba)	Lead (Pb)
Beryllium (Be)	Antimony (Sb)
Bismuth (Bi)	Silicon (Si)
Calcium (Ca)	Tin (Sn)
Cadmium (Cd)	Strontium (Sr)
Cobalt (Co)	Tellurium (Te)
Chromium (Cr)	Titanium (Ti)
Copper (Cu)	Thalium (Tl)
Iron (Fe)	Uranium (U)
Potassium (K)	Vanadium (V)
Lanthanum (La)	Tungsten (W)
Lithium (Li)	Zinc (Zn)
Magnesium (Mg)	Zirconium (Zr)

Summary / principle of method

Total Metals: A suitable aliquot of sample is digested by the addition of HNO₃ and H₂O₂ and concentrating down to a known volume. Digestion is necessary to break down organic matter and to convert metal associated with particulates in a sample to a dissolved form that can be determined by inductively-coupled plasma spectroscopy (ICP). The sample is then diluted to an appropriate final volume.

Dissolved Metals: The sample is first filtered through a 0.45 µm filter and preserved to a pH<2 with HNO₃. A suitable aliquot sample is then analyzed without further digestion.

The sample is pumped into the ICP, where a sample aerosol is generated in an appropriate nebulizer and spray chamber and is carried into the plasma. The plasma consists of a flowing stream of argon gas ionized by an applied radio frequency field. It is inductively coupled to the ionized gas by a water-cooled coil surrounding a quartz "torch" that supports and confines it.

The high temperature of the plasma excites atomic emission efficiently and the ionization of a high percentage of atoms produces ionic emission spectra. The efficient excitation provided by the ICP results in low detection limits for many elements. The light emitted from the ICP is focused onto the entrance slit of a monochromator that effects dispersion. A precisely aligned exit slit is used to isolate a portion of the emission spectrum for intensity measurement using a photomultiplier tube.

Equipment

ICP-OES Perkin Elmer Optima 5300DV, Milestone High Performance Microwave Digester MLS 1200 MEGA, Environmental Express Hot Block Digester.

Method detection limits for metals included in RHSSF study:

Cadmium	0.22	µg/L
Calcium	4.78	µg/L
Chromium	0.15	µg/L
Copper	0.5	µg/L
Iron	2.21	µg/L
Lead	0.64	µg/L
Manganese	0.09	µg/L
Nickel	0.26	µg/L
Sodium	11.37	µg/L
Zinc	0.95	µg/L

GCWS 1 Method for the determination of total petroleum hydrocarbons (TPH) in solid and liquid samples

Scope and application

This method describes the determination of total petroleum hydrocarbons in solid and liquid samples.

Summary / principle of method

One litre liquid samples are spiked with surrogate and serially extracted with three 60ml portions of dichloromethane. For solid samples, a twenty-gram sample is likewise spiked with surrogate and extracted with 80 ml of dichloromethane in an Erlenmeyer flask using a platform orbital shaker.

The extract generated is dried by passing through anhydrous sodium sulphate. The extract is concentrated to an appropriate final volume. All sample extracts and standards are analysed by GC/FID.

A standard is prepared in dichloromethane of organic based materials submitted for identification purposes. The standard is analysed and the resulting chromatographic profile is compared against known standards of a variety of fuels.

Equipment

Gas Chromatograph - Hewlett Packard 5890 Series II equipped with autosampler, split/splitless injector, and flame ionisation detector.

Chromatography column - 30 m DB-5 (0.25 I.D. x 0.25 micron film thickness)

Method detection limit for TPH: 0.5 µg/mL

MSW1 Method for the determination of polynuclear aromatic hydrocarbons in water by GC/MS

Scope and application / Parameters measured

This method is for the determination of polynuclear aromatic hydrocarbons (PAHs) in liquid samples using liquid-liquid extraction and gas chromatographic / mass spectrometry (GC/MS) analysis.

The following is a list of the compounds that can be analysed for in this method.

Target compounds & Target ion		Surrogates & Target ion
Naphthalene 128	Pyrene 202	Naphthalene-D ₈ 136
2-Methylnaphthalene 142	Benzo(a)anthracene 228	Acenaphthene-D ₁₀ 162
1-Methylnaphthalene 142	Chrysene 228	Fluorene-D ₁₀ 176
Acenaphthylene 152	Benzo(b)fluoranthene 252	Phenanthrene-D ₁₀ 188
Acenaphthene 154	Benzo(k)fluoranthene 252	Pyrene-D ₁₀ 212
Fluorene 166	Benzo(a)pyrene 252	Chrysene-D ₁₂ 240
Phenanthrene 178	Indeno(1,2,3-c,d)pyrene 276	
Anthracene 178	Dibenzo(a,h)anthracene 278	
Fluoranthene 202	Benzo(g,h,i)perylene 276	

Summary / principle of method

A one litre sample is spiked with a surrogate mixture and serially extracted three times with dichloromethane (DCM) under basic conditions. The combined extracts are dried over sodium sulphate.

The solvent is evaporated from the extract to a final volume of 2 millilitres. The extract is then combined with an internal standard and analysed by GC/MS.

Equipment

Gas chromatograph/mass spectrometer system:

Gas chromatograph - 6890 Hewlett Packard Gas Chromatograph

Column - DB-5, 30m narrowbore column (0.25mm I.D.), 0.25 micron film thickness.

Mass spectrometer - Hewlett Packard 5973 Mass Spectrometer

Method detection limits for PAHs included in RHSSF study:

Acenaphthene	0.372	µg/L
Acenaphthylene	0.384	µg/L
Anthracene	0.682	µg/L
Benz(a)anthracene	0.678	µg/L
Benzo(a)pyrene	0.829	µg/L
Benzo(b)fluoranthene	0.604	µg/L
Benzo(ghi)perylene	0.981	µg/L
Benzo(k)fluoranthene	0.972	µg/L
Chrysene	0.685	µg/L
Dibenzo(ah)anthracene	0.999	µg/L
Fluoranthene	0.707	µg/L
Fluorene	0.444	µg/L
Indeno(1,2,3-cd)pyrene	1.029	µg/L
Naphthalene	0.541	µg/L
Phenanthrene	0.540	µg/L
Pyrene	0.687	µg/L

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