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Review of operation of urban drainage systems in cold weather: Water quality considerations

by J. Marsalek, G. Oberts, K. Exall and M. Viklander

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Review of operation of urban drainage systems in cold weather: Water quality considerations

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Abstract: Cold climate imposes special requirements on urban drainage systems, arising from extended storage of precipitation and pollutants in the catchment snowpack, processes occurring in the snowpack, and changes in catchment surface and transport network by snow and ice. Consequently, the resulting catchment response and runoff quantity differ from those experienced in snow- and ice-free seasons. Sources of pollutants entering urban snowpacks include airborne fallout, pavement and roadside deposits, and applications of de-icing and anti-skid agents. In the snowpack, snow, water and chemicals are subject to various processes, which affect their movement through the pack and eventual release during the melting process. Soluble constituents are flushed from the snowpack early during the melt; hydrophobic substances generally stay in the pack until the very end of melt and coarse solids with adsorbed pollutants stay on the ground after the melt is finished. The impacts of snowmelt on receiving waters have been measured mostly by the snowmelt chemical composition and inferences about its environmental significance. Recently, snowmelt has been tested by standard bioassays and often found toxic. Toxicity was attributed mostly to chloride and trace metals, and contributed to reduced diversity of benthic and plant communities. Thus, snowmelt and winter runoff discharged from urban drainage threaten aquatic ecosystems in many locations and require further studies with respect to advancing their understanding and development of best management practices.

Key Words: environmental effects, urban snowmelt, water quality, winter runoff.

Introduction

Discharges of urban stormwater from drainage systems may cause physical, chemical, biological and combined effects in receiving waters and thereby impair their quality, ecosystems, and beneficial uses. These effects differ in various climatic regions, but seem to be particularly severe during snowmelt or rain-on-snow events occurring in cold, Alpine and some temperate climates. This follows from the fact that during cold weather, precipitation accumulates on the catchment surface in the form of urban snowpacks, which store water, chemicals, solids, and other materials. Compared to snow-free seasons, the rates of chemical and material accumulation are higher in cold weather, because of higher releases of chemicals and materials caused, e.g., by heating, less efficient operation of motor vehicles, and application of de-icing and anti-skid agents (Malmquist, 1978). During snowmelt, or rain-on-snow events, accumulated water and chemicals may be suddenly released and contribute to acute and chronic impacts on receiving waters. These concerns were particularly well documented for salts used in winter road maintenance (Environment Canada and Health Canada, 2001). Thus, the assessment of water quality impacts of winter operation of urban drainage is of high interest in the protection of urban aquatic ecosystems.

In spite of the environmental significance of winter snowmelt and runoff, a literature review shows that relatively little has been published on this subject. For example, a recent UNESCO report on urban drainage in cold climates (Maksimovic *et al.*, 2000) lists less than 50 publications on urban snowmelt quality. The relative paucity of urban snowmelt quality papers follows from the fact that the majority of urban population lives in regions without snow, and the fact that studies of snowmelt and rain-on-snow are particularly challenging. Many such challenges are addressed in the following review of water quality aspects of urban snowmelt and winter runoff.

Quality of urban snowmelt and winter runoff

The urban hydrological cycle changes significantly during cold weather. Precipitation may be stored on the catchment in snowpack, in the form of ice and snow, and be transported not only hydraulically, but also by snow drift or snow removal. The resulting runoff, snowmelt and transport processes depend on climatic variables, including air temperature, wind and solar radiation, and anthropogenic effects in the form of sources of heat, chemicals and particulate matter affecting snowmelt in urban catchments (Oberts, 1990). Such processes and effects greatly vary in time and space, and consequently, urban snowmelt is highly non-uniform. Winter catchment conditions are characterised by reduced infiltration into frozen soils, and concomitant increases in the area contributing runoff and its time of concentration (Bengtsson and Westerström, 1992). Thus, design-type events, certainly with respect to runoff volume, may occur in late winter/early spring, often as rain-on-snow events, which coincide with snowmelt and may cause flooding (Milina, 1998).

Transport of urban pollutants is also affected by cold weather, particularly by snowpack processes, and may be controlled either by pollutant availability (e.g., soluble constituents), or by transport capacity (e.g., solids and hydrophobic constituents)(Oberts *et al.*, 2000). Other means of pollutant transport are effected by snow removal from urban areas during winter street/road maintenance and disposal in various ways. To mitigate the impacts of urban runoff and snowmelt on receiving waters, stormwater management has been introduced into urban drainage practice and somewhat modified for wintry conditions (Caraco and Claytor, 1997).

Pollutant Sources

Sources of pollutants to snowmelt and winter runoff are increased in winter months, compared to other seasons, and consequently, the winter season may produce up to 60% of the annual load of certain pollutants (Oberts, 1990). Sources of pollutants found in winter urban runoff and snowmelt include airborne fallout, roadway and roadside deposits, de-icing and anti-skid agents, and some secondary sources (e.g., litter).

Airborne Fallout. Falling snowflakes are effective scavengers of both particulate and aerosol pollutants (Colbeck, 1981), and the snowpack effectively traps airborne deposition from local as well as remote sources (Schöndorf and Herrmann, 1987; Viklander, 1997). Thus, urban snowpacks can be used effectively to study atmospheric deposition. Horkeby and Malmquist (1977) and Malmquist (1978) reported that a substantial portion of the toxic materials in runoff (and snowmelt) can be attributed to atmospheric sources, originating from fossil-fuel combustion, refuse incineration, chemical processing, metal plating, manufacturing, and fertiliser/pesticide application. PAH levels were particularly high in urban stormwater runoff, ranging from 10-320 μg/L (Horkeby and Malmquist, 1977). Similarly, Boom and Marsalek (1988) reported accumulations of PAHs (up to 7 μg/L) in the snowpack in the industrial city of Sault Ste. Marie, Ontario. Schrimpff *et al.* (1979), Sakai *et al.* (1988) and Daub *et al.* (1994) found regional patterns in the deposition of PAHs and heavy metals that were related to urban and industrial activities, with PAH concentrations an order of magnitude higher in melt runoff than in rain runoff, and TSS levels higher in melt water by a factor of two to five. Walker *et al.* (2003) reported elevated concentrations of metals associated with combustion ash in and around industrial towns in Northeast Russia, including Al, Ba, Sr, Cu, Ni, Pb, and Zn in snow-borne particulates, and As, Ba, Mn, and Sr in snowmelt. Considerable alkalisation of snow in the towns was also observed. On a smaller scale, Viklander (1997) noted that pollutant burden in snow increased towards the city centre.

Roadway and Roadside Deposits. Materials released by land use activities may become trapped in the snowpack. Most street surface deposition studies, however, have not considered the build-up of pollutants under snowy conditions. Vehicular deposition of petroleum products/additives and corroded or worn metals, the direct application of salt and anti-skid grits, and roadway surface deterioration are major contributors to the pollution of road surface snow (Malmquist, 1978; Oberts, 1986; Amrhein *et al.*, 1992; Viklander, 1997; Novotny *et al.*, 1999; Glenn and Sansalone, 2002). Accumulation of these chemicals or materials often increased with traffic density (Viklander, 1997), and was typically restricted to narrow bands (10 m) along roadsides (Novotny *et al.*, 1999).

Heavily polluted roadway snow is quickly removed by rapid melt through salt application, removal to snow dumps, or ploughing over the roadway curb/edge. Small melts in January and February accounted for <0.5% and 0.4-5% of the annual total phosphorus (TP) and total lead (TPb) loads, respectively, whereas the end-of-winter melt accounted for about 8-20% of the TP and TPb annual loads (Oberts, 1982). Sansalone and Buchberger (1996) noted that total element and solids concentrations were higher in snow washoff than in rainfall runoff, although metal elements in rainfall runoff were predominantly dissolved, but 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. These values were approximately two orders of magnitude greater than at a control site, and one to two orders of magnitude greater than in rainfall runoff samples.

Pollution from snow dumpsites has been extensively studied, with the reported levels of Cl (4-2500 mg/L), TPb (0.02-50 mg/L – high values obtained before Pb phase out), TFe (average 41.5 mg/L), TP (2.4-19.6 mg/L), BOD (8.2-57 mg/L), TS (256-10500 mg/L), and TSS (1570-2250 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).

De-icing and Anti-skid Agents. Common sodium chloride (NaCl) is the de-icer of choice in most of Canada and US, with Canadian use estimated at nearly 5 million tonnes per year (1997/98; Environment Canada and Health Canada 2001). The distribution of this quantity among the seven provinces with the largest use is shown in Fig. 1. The provincial salt uses reflect both the population and climate. Low uses can be found in the mild coastal climate (highly populated parts of British Columbia), or in a rather cold climate, in which road salting becomes ineffective and is less used in winter road maintenance (Alberta).

Road salt often contains the anti-caking agent, sodium ferrocyanide (~0.01% by dry weight). Sodium ferrocyanide itself is not toxic, but can transform to toxic free cyanide (HCN) when exposed to light (Novotny *et al.*, 1999). Other de-icers include calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), and calcium magnesium acetate (CMA), which are less corrosive, free of sodium ferrocyanide and more effective at lower temperatures, but are also more expensive. 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 have been shown to contain relatively high levels of phosphorus and several metals (Oberts, 1986).

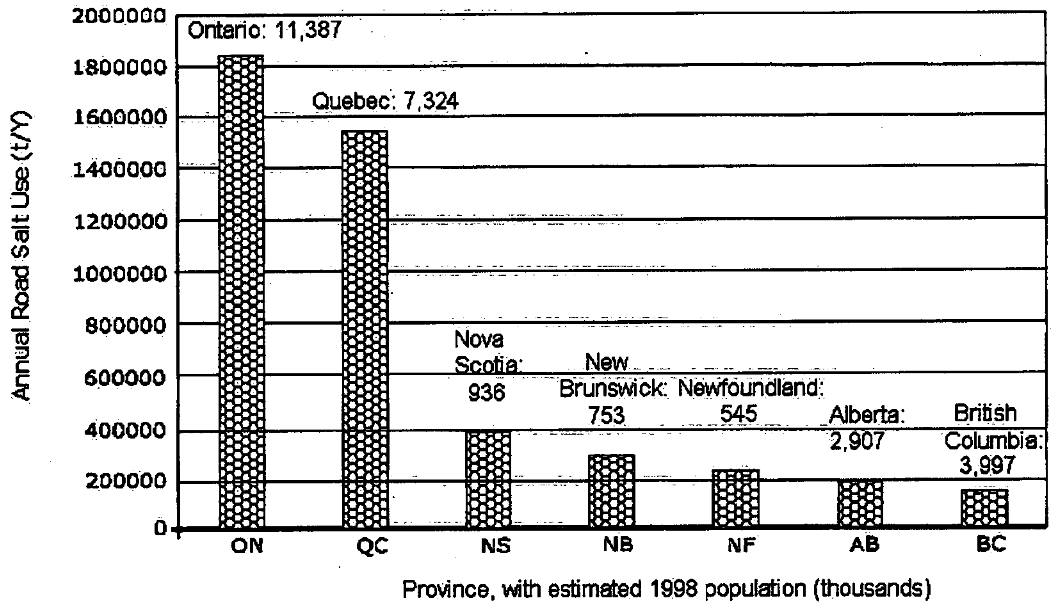

Figure 1. Annual road salt use in seven Canadian provinces, 1997/98 (Seven highest provincial salt uses plotted after Environment Canada and Health Canada, 2001; provincial populations in thousands adopted from Statistics Canada, 2002).

Secondary Sources. Secondary sources of pollution associated with snowmelt runoff include abrasion of roadway surface and urban litter. The repeated applications of salt, numerous freeze-thaw cycles, the pounding of ploughs on asphalt and concrete surfaces, and the use of studded tires during a winter season take a definite physical toll. Urban litter consists of a myriad of different materials, including animal faeces, vegetation and discarded food and beverage containers. Both types of sources are poorly documented (Oberts *et al.*, 2000).

Pollutant Release from Snowpacks

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 the final snowmelt, which fully depletes the snowpack (Viklander, 1997). The associated transport processes include snowpack elution, melt water infiltration into soils, and surface runoff. In snowpack elution, soluble pollutants are flushed from throughout the snowpack and concentrated at the bottom of the pack (Colbeck, 1981). In this process, snowflakes respond to freezing and thawing cycles with metamorphism, which leads to migration of impurities to the terminus of the crystal, where they are loosely bound and available for wash-off by percolating meltwater. Channelled meltwater may scavenge the soluble pollutants randomly until the pack is saturated, whereupon pollutant mobilisation becomes uniform throughout the pack. Soluble pollutants are collected in a "wetted front" that moves through the pack, and eventually from the pack as a highly concentrated, often acidic, pulse of meltwater. Dissolved pollutants preferentially eluted early in the melt are usually more toxic and far more mobile than the adsorbed material left behind, thus exerting a "first flush" of harmful contamination (Oberts *et al.*, 2000). High chloride levels in the urban snowpack may shift the speciation of metals into the soluble phase. Solids and associated hydrophobic substances, such as polycyclic aromatic hydrocarbons (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). Thus, two types of shock loads can be generated; soluble shock loads occurring early in the final snowmelt, and solids and hydrophobic substances shock loads occurring towards the end (or even after) the final snowmelt event.

The degree to which soluble pollutants are excluded and washed from the snowpack depends upon the number of freeze-thaw cycles (which purify the hexagonal crystals) and whether the snowpack receives any outside moisture (mobilising the released pollutants more quickly). Johannessen and Henriksen (1978) found in both laboratory and field studies that about 40-80% of 16 contaminants were released from experimental snowpacks with the first 30% of the liquid melt, and that this process seemed to be independent of the initial snowpack concentration of the pollutants in question. Similar concentration factors (5-8) were observed by Westerström (1995) in an urban field lysimeter (see Fig. 2), and early elution was reported by Droste and Johnston (1993) at snow dumps, and Schöndorf and Herrmann (1987) for rain-on-snow, which washed fine-grained particulates through the pack and flushed out metals and adsorbed organic pollutants. Such particulate material is filtered or coagulated with other particles as it moves through the snowpack and remains behind as the soluble component washes through (Viklander, 1997). 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. In snow samples, almost all substances were attached to particles, but in meltwater, a significant part of the chemical burden was in solution. Novotny *et al.* (1999) reported for the Water Environment Research Foundation (WERF) study sites 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 (Sharma *et al.*, 1991).

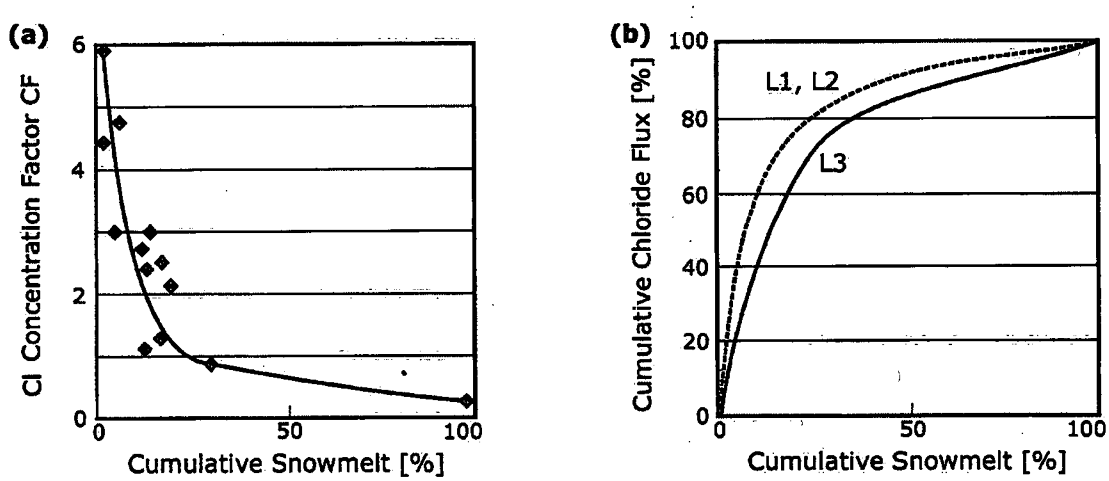

Figure 2. Preferential elution of chloride from: (a) field lysimeter (Westerström, 1995) and (b) laboratory lysimeters L1-L3 (Viklander, 1997)

Runoff

The 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, by diluting soluble pollutants, promoting the movement of particulates through the pack (Couillard, 1982; Schöndorf and Herrmann, 1987), and increasing 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.

Pollutant Removal with Used Snow

In contrast to rain runoff or in-situ snowmelt, used snow removal offers a management option to select 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 at 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 dump. Depending on the snow disposal operation, snow and the associated pollutants in the snow will be relocated and will impact on the environment in different ways (Oberts *et al.*, 2000). Snow removed from streets and parking areas may be either dumped in receiving waters (a less common practice) or on land. In on-land disposal, 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 dump sediments are allowed to accumulate over a long time, and are thus subject to slow leaching, or they are removed from the dump 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.

Snowmelt Quality and Environmental Effects

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 concentrations of TSS, 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).

	Concentration (mg/L)						
Source of data	TSS	COD	TP	TKN	NO_3	Cl	TPb
Minnesota sites	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	8-259	15-167	0.10-1.08	0.3-4.3	0.61-1.19	194-6242	0.02-0.057
NURP (50%)	100	65	0.33	1.50	0.68	---	0.144
NURP (90%)	300	140	0.70	3.30	1.75	---	0.350

Environmental Effects. 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). Such processes generally lead to destruction of the soil structure and lowered soil fertility. Salt-laden snowmelt also impacts on roadside vegetation, though some 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 were 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 causing, or contributing to, their densimetric stratification, which impedes vertical mixing and may turn some of these water bodies meromictic (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 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). The acidic melt also 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). 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. The salt alternative, CMA, exerts a very high demand for oxygen as it degrades, reaching a range of 0.6 - 0.7 g oxygen/g CMA (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, 1976; Couillard, 1982; Schöndorf and Herrmann, 1987). Novotny *et al.* (1999) found cyanides in roadside snow in concentrations ranging from 3 to 270 μg/L. Snowmelt releases of cyanides from roadside snow could exceed the U.S. EPA aquatic life protection criteria, which specify free cyanide levels (HCN) of 22 μg/L for acute toxicity, and 5 μg/L for chronic toxicity, both in fresh waters. 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 to snow 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.

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. In general, samples from sites close to major traffic routes exhibited positive responses, particularly after metabolic activation. There was a positive correlation between genotoxicity detection and the ambient levels of suspended particulates. It was speculated that fuel combustion by-products 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.

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. 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.

Poor water quality in 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 inflow of lower density, acidic meltwater entering the biotic zone and displacing cleaner water.

Conclusions

Cold weather affects profoundly design and operation of urban drainage systems, with respect to both water quantity and quality. In terms of water quality, urban snowmelt and winter runoff may carry disproportionately high loads of various pollutants at potentially toxic levels. De-icing agents (salt) or increased bioavailability of other chemicals in chloride-laden runoff may cause such toxicity. Ultimately, discharges of urban snowmelt and winter runoff lead to reduced biodiversity as indicated by benthic communities. To reduce environmental effects of winter operation of urban drainage, further development of best management practices (BMPs) is required. A BMP train should start with source controls and focus on adaptation of the existing stormwater best management practices for cold weather conditions, including high levels of pollutants and presence of chlorides.

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