NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

URBAN DRAINAGE IN COLD CLIMATE: CHALLENGES AND PROGRESS IN MANAGEMENT PRACTICES

J. Marsalek and G.A. Larkin

NWRI Contribution No. 98-043

URBAN DRAINAGE IN COLD CLIMATE: CHALLENGES AND PROGRESS IN MANAGEMENT PRACTICES

J. Marsalek and G.A. Larkin

National Water Research Institute,
Environment Canada
867 Lakeshore Road, Burlington, Ontario,
Canada L7R 4A6

A contribution to the UNESCO IHP-V Project 7.3: Integrated urban drainage modelling in different climates: tropical, arid, semi-arid and cold.

Management Perspective

Generation of urban non-point source pollution is strongly affected by the climate. Consequently, UNESCO has initiated a project on urban drainage in various climates. Among these, the cold climate deserves special attention, because it affects urban drainage in many ways, including changes in the urban hydrological cycle, generation and transport of runoff and stormwater pollutants, operation of runoff management facilities and sewage treatment plants, and disposal of runoff and pollutants. The report that follows was prepared at the request of UNESCO, as a contribution to the IHP-V Project 7.3: Integrated urban drainage modelling in different climates: tropical, arid, semi-arid and cold. The report focuses on progress that has been achieved since the publication of the first UNESCO report on this issue in 1991.

This report should be of interest to researchers and managers dealing with urban water management in cold climate.

Sommaire à l'intention de la direction

La pollution urbaine diffuse est fortement influencée par le climat. Aussi l'UNESCO a-t-il entrepris des travaux sur le drainage urbain sous différents climats. Le climat froid retient particulièrement l'attention parce qu'il influe à bien des égards sur le drainage urbain : modification du cycle hydrologique urbain, production et transport des polluants présents dans les eaux de ruissellement et les eaux pluviales, exploitation des installations de gestion des eaux de ruissellement et des usines de traitement des eaux usées, et évacuation des eaux de ruissellement et des polluants. Le rapport qui suit a été préparé à la demande de l'UNESCO dans le cadre du projet 7.3 de la phase V du Programme hydrologique international (PHI) : détermination par modèle intégré du drainage urbain sous différents climats : tropical, aride, semi-aride et froid. Le rapport est axé sur les progrès réalisés depuis la publication du premier rapport de l'UNESCO sur cette question en 1991.

Il devrait intéresser les chercheurs et les responsables de la gestion des eaux urbaines dans les climats froids.

Abstract

Cold climate imposes special requirements on the design and operation of urban drainage. However, such requirements can not be fully met using the existing knowledge base and design approaches that were primarily developed from research and experience in the temperate or warm climates. This situation is analyzed in a review of challenges in, and research progress with respect to, urban drainage in cold climate. Significant advances have been made in studies of urban snowpack processes and design and operation of stormwater management facilities. Future research needs include improved modelling of urban snowmelt, the hydrology of rain-on-snow events in urban and suburban conditions, snowmelt impacts on aquatic ecosystems, and refinement of stormwater management in cold climate.

Résumé

Le climat froid impose des conditions particulières à la conception et à l'exploitation du drainage urbain. Toutefois, il est impossible de remplir entièrement ces conditions si on utilise la base de connaissances et les méthodes de conception essentiellement élaborées grâce aux recherches effectuées dans les climats chauds ou tempérés et à l'expérience acquise à cet égard. Cette situation fait l'objet d'une analyse dans le cadre d'un examen des difficultés suscitées par le drainage urbain dans les climats froids et des recherches effectuées en la matière. Des progrès considérables ont été réalisés sur le plan des études des processus du manteau nival urbain ainsi que de la conception et de l'exploitation des installations de gestion des eaux pluviales. La recherche va devoir s'attacher aux volets suivants : amélioration des modèles de fonte nivale urbaine, hydrologie des épisodes de pluie sur fond de neige dans les conditions urbaines et suburbaines, effets de la fonte nivale sur les écosystèmes aquatiques, et raffinement de la gestion des eaux pluviales dans les climats froids.

Introduction

Historically, urban drainage systems were designed for a single objective – hydraulically and economically efficient removal of surface runoff from urban areas into the nearby receiving waters. Such systems protected urban dwellers against flooding and provided for their convenience by controlling runoff ponding in urban areas, but impacted severely on the receiving waters. The full understanding of impacts of conventional drainage on receiving waters has been attained only during the last 30 years. During that period, drainage impacts reached a critical magnitude arising from progressing development and the cumulative nature of these impacts.

The first attempts to address urban stormwater discharge impacts on receiving waters dealt primarily with flooding and erosion (physical impacts) caused by increased volumes and speed of runoff from urban areas. Subsequent research focused on chemical characterization of urban stormwater, with successive emphasis on solids, nutrients, heavy metals, hydrocarbons, and trace organic contaminants. The most recent concerns about stormwater discharges include acute and chronic toxicity of stormwater runoff (particularly from highways), export of faecal pollution from urban catchments, and thermal enhancement of stormwater in the urban environment.

Thus, stormwater discharge impacts can be characterized as physical, chemical and biological, and their significance depends on both the characteristics of the catchment producing such effluents (in terms of stormwater quantity and quality) and the characteristics of the receiving waters. The actual impacts have to be evaluated for each site and receiving water body, and may include the following: physical habitat changes (caused by sediment erosion and deposition, changes in stream morphology); water quality changes (manifested by dissolved oxygen depletion, or eutrophication); toxic pollutant impacts (both acute and chronic); public health impacts (faecal bacteria); thermal enhancement impacts (on cold water fish and other aquatic life); impacts on biological communities; and groundwater impacts. Finally, the assessment of these impacts should include reference to ecological criteria and recovery rates.

In spite of this progress in understanding the environmental implications of urban drainage, it is obvious that most of this work focused on temperate climate regions. Recognizing that the climate controls the requirements on urban drainage, more research is needed on the problems specific to other climates, and particularly in the regions with cold and tropic climates. The UNESCO and International Research and Training Centre on Urban Drainage (IRTCUD) in Belgrade, Yugoslavia have promoted such activities under the UNESCO project on urban drainage in various climates. In this program, the first progress report on urban drainage in cold climate was prepared in 1991 (Marsalek, 1991) and the progress achieved since then is reviewed in the paper that follows.

Urban Drainage Challenges in Cold Climate

Cold climate affects urban drainage in many ways, including changes in the urban hydrological cycle, generation and transport of runoff and stormwater pollutants, operation of runoff control facilities and sewage treatment plants, and disposal of runoff and pollutants. A brief summary of such impacts follows.

The urban hydrological cycle, usually described in the literature for warm-weather conditions (McPherson, 1975), becomes much more complex in cold weather. In particular, precipitation may occur as rain or snow, may be stored on the catchment in snowpacks, and transported not only hydraulically, but also by snow drifting or snow removal and disposal. 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 heat sources, chemicals and particulate materials enhancing snowmelt in urban catchments (Oberts, 1990; Conway et al., 1996). Furthermore, the processes affecting urban snowmelt greatly vary in urban areas, and this results in highly non-uniform snowmelt.

Winter catchment conditions are characterized by reduced infiltration into frozen soils, and this condition effectively increases the areas contributing runoff (Bengtsson and Westerstrom, 1992) and extends concentration times. Consequently, the design-type events overloading the stormwater management systems may occur during the winter months, often as rain-on-snow events coinciding with snowmelt, and cause flooding (Milina, 1998).

Fluxes of urban pollutants and their transport are also affected by cold weather. Oberts (1990) and Zariello (1990) estimated that winter runoff and snowmelt transport up to 60% of the annual runoff load of selected pollutants. These elevated seasonal loads can be explained by increased pollutant deposition and accumulation in urban areas in winter months, mainly because of heating, less efficient operation of motor vehicles, increased wear of road surfaces by studded tires, and application of deicing materials on roads (Malmqvist, 1983). Subsequent transport of such materials depends on their characteristics, climatic conditions, and snow removal and disposal activities.

During cold weather, pollutants are accumulated and stored in the snowpack and subsequently eluted during chemical or thermal melt. Dissolved pollutants, such as acidic depositions, are eluted from the snowpack in the early stages of snow melting (Jeffries, 1988). On the other hand, hydrophobic substances, such as polycyclic aromatic hydrocarbons (PAHs), stay in the snowpack until the last 5 to 10% of meltwater is leaving the snowpack (Schondorf and Herrmann, 1987). Through these preferential elution processes, pollution shock can be generated and released into the receiving waters. Other pollutants are transported with snow removed from urban areas during winter road maintenance and disposed in various ways; however, in-stream dumping, with direct input of snow pollutants into receiving waters, is now prohibited in most jurisdictions. Where snow is dumped into combined sewers, the efficiency of treatment at the wastewater treatment plant may be lowered and this leads to an increased pollution of receiving waters (Leduc and Delisle, 1990).

Conventional stormwater management practices, such as stormwater ponds and wetlands, require design modifications for good performance in cold weather (Oberts, 1994b). In particular, the freeze up of stormwater ponds affects flow patterns by forcing the flow either under or over the ice cover. The former case may lead to scouring of bottom sediment, and the latter case results in shallow flows over the ice cover, with poor conditions for pollutant settling. Similar difficulties were reported for frozen wetlands (Oberts, 1990).

Finally, there are many operational problems encountered in urban drainage systems in cold weather. Sewer inlets, outfalls or culverts may freeze up and control valves of stormwater management facilities may become inoperative. Some of these problems can be avoided by proper design, but others have to be mitigated by the provision of emergency services.

Progress in Research on Urban Drainage and Stormwater Management in Cold Climate

Since the first progress report was prepared under this UNESCO project (Marsalek, 1991), knowledge of various aspects of urban drainage and stormwater management in cold climate has been advanced. Such advances are reviewed in this section with respect to the hydrology of urban snowpacks and catchment hydrograph synthesis, the chemistry of urban snow and snowmelt, urban snowmelt impacts on receiving waters, and stormwater management in cold climate.

Hydrology of urban snowpacks and catchment hydrograph synthesis

The literature on snow hydrology is fairly extensive (Gray and Prowse, 1993), but it deals almost exclusively with rural or alpine regions. While the basic snowmelt processes in rural and urban areas may be the same, micro-climatic conditions as well as anthropogenic interventions are much different in urban areas and require special attention. The relatively small number of research studies dealing specifically with urban snow impedes progress in this field.

The location, development and melting of urban snowpacks are important processes affecting snowmelt dynamics in urban areas. One of the most difficult problems in dealing with urban snowpacks is their spatial distribution and distribution of energy fluxes. Several papers dealt with these issues, using various approaches. Oberts (1994a) conceptually described the phases of urban snowpack dynamics, comprising fresh snowfall covering the entire area, pavement melt, roadside melt, and finally, the pervious area melt. Pavement melt is fairly quick and results in low volumes of meltwater, roadside melt contributes moderate volumes of meltwater intermittently, and pervious area melt may contribute high volumes of runoff, particularly if accelerated by a rain event.

Two causes of spatial variation in thermal inputs to urban snowpacks were studied – reduced albedo and interference of urban structures with radiative energy. Bengtsson and Westerstrom (1992) noted in a test catchment in Northern Sweden that snow albedo in urban areas was much lower than outside of the city. Consequently, higher solar radiation energy was available to melt urban snow, compared to rural areas, and this led to an increase in daily melt by about 10 mm. Conway et al. (1996) conducted an experiment in which a clean snow surface was treated with soot and ash. This reduced the snow albedo to 0.18–0.41 initially (untreated snow value; 0.61) but as the particles moved with meltwater deeper into the snowpack, higher values of snow albedo were restored.

Semadeni-Davies and Bengtsson (1998) investigated spatial variation in radiative energy in urban areas. Three different types of exposure were defined – open ground (as common in rural areas), and the southern (sunny) and northern (shaded) sides of buildings. The south sides experienced radiation enhancement (by 15 $W{\cdot}m^{-2}$) and the northern sides experienced a decrease of 35 $W{\cdot}m^{-2}$. These differences were then reflected in the melt pattern. Thus, urban snowmelt seems to be influenced by variations in albedo, exposure to radiation, and the site location with respect to roads and potential input of snowmelting chemicals.

Rain-on-snow events receive continuing attention with respect to flood generation in urban and suburban catchments, recognizing that during such events on frozen ground, a large part of the total catchment area is contributing runoff (Bengtsson and Westerstrom, 1992). Such conditions and the resulting flooding were reported by Milina (1998) for a storm event in Trondheim. This event of 95 mm (March 31, 1997) occurred in a snow covered catchment and caused flooding in some parts of the city, including the site of a monitoring research station. Even though the return period of this rain event was estimated just between 10 and 20 years, the return period of the flood peak produced was about 50 years. Even in other cases, where runoff flow rates produced by snowmelt are not excessive, volumes of snowmelt events can be high and should be considered in design of storage facilities.

Buttle (1990) studied streamflow generation in a snow-covered suburban basin. The distinction between the properties of hydrographs associated with snowmelt only and rain-on-snow events became more pronounced with progressing urbanization. Rain-on-snow generated higher maximum peak flows and lower average peak discharge per unit input compared with snowmelt. To advance the understanding of these rain-on-snow events, Buttle et al. (1995) separated the catchment hydrograph into the event (rain) water and that contributed by snowmelt, by an isotopic hydrograph separation method. It was noted that event water supplied about 55–63% of the peak discharge, and 48–58% of total runoff from a suburban catchment ($A = 1.066$ km^2) with a 14% directly connected impervious area. These findings contrast those that are typical for rural basins, in which the outflow hydrographs are dominated by pre-event stored water.

The sensitivity of streamflow simulations in a watershed with a winter-long snowpack to changes in temperature and precipitation, arising from an assumed climate change scenario, were studied by Ng and Marsalek (1992) using the HSPF model. Temperature increases barely affected the annual streamflow, but led to larger and earlier winter runoff when precipitation was stored in the snowpack, and increased winter/spring streamflow peaks driven by snowmelt.

Chemistry of snow and snowmelt

Many anthropogenic pollutants accumulate over extended periods of several months in urban snowpacks and are released relatively quickly during short periods of snowmelt (2–3 weeks). To advance the understanding of the snowpack chemistry, several processes are of interest: urban snow quality, pollutant elution from the snowpack, and the residue under the snowpack. Furthermore, these processes were studied at various scales in the laboratory, research snow courses or lysimeters, snow packs in cities, and at snow dumps.

Most studies focused on the quality of snow found in urban areas. In sampling design, both temporal and spatial variations are of interest. The results of these studies can be used to estimate atmospheric deposition of special pollutants (Boom and Marsalek, 1988), or the chemical burden in the snowpack and its potential impacts on receiving waters (Delisle et al., 1997).

The chemistry of urban snow was studied by several researchers, usually in relation to such sources of pollution as traffic or industry. Viklander (1997) studied snow quality in the City of Luleå (Northern Sweden) to determine pollutant burdens in urban snow. Snow samples were collected in the city centre, in a residential suburb, and along several traffic routes with various traffic densities. It was noted that traffic density was the main factor controlling snow quality. Along major traffic routes, snow contained higher concentrations of suspended solids and exhibited higher pH. In general, concentrations of pollutants in snow increased with time, unless snow was disturbed by plowing or removal.

A similar survey was conducted by Hautala et al. (1995) along a road with traffic density of 9,100 vehicles per day. They concluded that on roadsides, there was deposition caused by traffic emissions and winter maintenance, and this deposition exceeded normal background deposition. Traffic emission deposition decreased with the distance from the road.

Loranger et al. (1996) studied Mn in urban snow near an expressway, but could not find a clear link between motor vehicle emissions and the concentration of Mn in snow (Mn originated from combustion of MMT, methylcyclopentadienyl manganese tricarbonyl, an additive in unleaded gasoline).

Viklander (1997) also examined snow samples melted in the laboratory. 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. The laboratory study further showed that melt-freeze cycles delayed the release of chemicals from snow. In snow samples, almost all substances were attached to particles, but in meltwater, a significant part of the chemical burden was in solution. No acid shock was observed.

Elution of chemicals from snowpacks has received much attention, particularly in connection with the so-called acid shock found in some rural watersheds. For urban conditions, similar data were collected at two scales – in the laboratory (e.g., Schondorf and Herrmann, 1987) and in an urban lysimeter (Westerstrom, 1995). Westerstrom (1995) observed typical release of dissolved ions from the snowpack, with high concentrations released during the early phase of snowmelt and the corresponding concentration factors ranging from 5 to 8. This information could be used in control of snowmelt quality; by intercepting and treating the first quarter of the total melt volume, almost two thirds of the pollutant load would be controlled.

Akan (1994) developed a model for enrichment of soluble pollutants in a snowpack. It is based on liquid water flow, heat transport, and pollutant transport equations. These nonlinear partial differential equations were solved using a difference scheme. This model can handle melt-freeze cycles, but so far, it has not been verified with actual data.

Oberts (1994a) described the relationship between pollutant sources and snowmelt quality, with reference to the urban snowpack distribution in space. Pollution processes included the scavenging of atmospheric pollutants by snowflakes, and deposition of atmospheric pollutants, particularly from fossil fuel combustion, refuse incineration, chemical processing, metal plating, and manufacturing. Other pollutants deposit on snowpacks or surfaces without snow. Vehicular deposition of petroleum products, gasoline additives and metals, the direct application of salt and anti-skid grits, and roadway wear are the major contributors to the pollution of road surface snow. High loads of total phosphorus (TP) and total lead (TPb) were observed in urban snow and were not washed out until the final phase of snowmelt. Concentrations of chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN) and Pb were particularly high in snowmelt transported by storm sewers and significantly exceeded those reported for rain-generated urban runoff in the U.S.A.

The chemodynamics of trace pollutants in snowmelt from roof and street surfaces was studied by Daub et al. (1994). Concentrations of suspended solids in snowmelt driven runoff were 2–5 times higher than in rain runoff. However, the specific metal concentrations in suspended solids in snowmelt were lower than in runoff suspended solids (except for Zn). There were no other differences in concentrations of metals in snowmelt and runoff, except for Cd whose concentrations increased in the presence of high concentrations of macro ions. Higher concentrations of PAHs in meltwater followed from longer equilibrium times available during snowmelt compared to runoff, and enhancement of PAH solubility by dissolved organic carbon. The physical and chemical properties of roofing materials affected temporal variations of PAHs.

Sansalone and Buchberger (1996) studied the chemistry of highway snow and spring runoff. Total elements and solids concentrations were higher in snow washoff than in rainfall runoff. This was explained by low rates of snow washoff, long periods of pollutant accumulation in snow, and entrapment of various materials during percolation of rain or snowmelt through snow banks. Metal elements in rainfall washoff were predominantly dissolved, but bound to particulates in snow washoff.

Droste and Johnston (1993) analyzed the chemistry of snow at four urban snow dumps by analyzing snow samples for biochemical oxygen demand (BOD), total and fecal coliforms, chlorides, sulphates, specific conductance, suspended solids, and metals. Samples of snowmelt were also analyzed. Compared to snow samples, the constituent concentrations in the outflow were reduced by 50–70%. Dissolved substances in snowmelt were discharged at high levels during the initial stages of snowmelt, but quickly diminished. The settleability of both snow and snowmelt samples was tested for settling times ranging from 1–24 hours. Removals of suspended solids and metals exceeded 90%.

Urban snowmelt impacts on receiving waters

Novotny et al. (1997) investigated potential impacts of urban snowmelt on receiving waters. The major concerns identified included direct impacts of elevated salt concentrations, cyanides, increased toxicity of metals, first flush effects (preferential elution), acidic leaching of chemicals, and stratification of urban lakes. Cyanides are usually contained in anti-caking additives to road salt and were found in roadside snow in concentrations ranging from 3 to 270 $\mu g \cdot L^{-1}$. Snowmelt releases of cyanides from roadside snow could exceed the U.S. EPA aquatic life protection criteria, which specify the cyanide levels as low as 22 $\mu g \cdot L^{-1}$ for acute toxicity, and 5 $\mu g \cdot L^{-1}$ for chronic toxicity, both in fresh waters.

Road salts contribute to mobilization of metals and organic materials in roadside soils (Amrhein et al., 1992). Regardless of the leaching sequence (NaCl followed by water, or water followed by NaCl), several metals Cr, Pb, Ni, Fe, Cd and Cu were leached out from roadside soils.

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) to snow, a novel index used to assess and compare the toxic potential of industrial effluents. The authors concluded that used snow had a low toxicity.

Recognizing that chemical protocols do not reflect contaminant speciation and bioavailability, the assessment of potential effects of urban snowmelt was done by genotoxicity testing (White and Rasmussen, 1995). Snow samples from the Montreal area were extracted with dichloromethane and genotoxicity of these extracts was tested by 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 byproducts were the main cause of genotoxicity.

Rochfort et al. (1997) studied toxicity of urban stormwater from various sources using a battery of tests including *Daphnia magna*, Microtox™, sub-mitochondrial particle bioassays, SOS chromotest, fathead minnow and *Ceriodaphnia dubia*. Among the various sources tested, highway runoff was the most toxic. Confirmed severe toxicity was found only for winter snowmelt or rain-on-snow samples, as indicated by *Daphnia magna* and sub-mitochondrial particle testing.

Another type of impact was described by Hayhoe et al. (1995) – erosion. Using climatic data and computer simulations, they developed snowmelt runoff erosion indices for Canada. In some northern regions of Canada, snowmelt runoff accounted for up to 96% of the total annual runoff and up to 80% of the total annual soil loss. In southern climate and urban conditions, these concerns would be less significant, but do deserve some attention.

Stormwater management in cold climate

The need to mitigate stormwater discharge impacts led to the development of stormwater management measures that are also referred to as best management practices (BMPs). BMPs include both structural and non-structural measures designed to mitigate the impacts of urbanization, including increased discharges and volumes of runoff, and increased production and export of pollutants and heat from urban catchments. For best performance, two or more BMPs may need to be combined in a treatment train to achieve the desired level of stormwater quantity and quality control (Schueler, 1987).

Difficulties with operation of stormwater ponds and wetlands BMPs in cold climate (Minnesota) were reported by Oberts (1990, 1994b). He noted that for majority of pollutants, including solids, nutrients and Pb, pollutant removal under snowmelt conditions was about one half of that for rainfall events. This was explained by reduced settling in ponds, because their storage was reduced by ice formation, pressurized flow under ice, or shallow flow over ice. Furthermore, biological activity in the pond was substantially reduced. The same forces worked against the performance of wetlands systems. This was particularly obvious for first two rainfall events after snowmelt conditions.

Marsalek (1997) studied the winter regime of an on-stream pond in Kingston, Ontario. Water quality surveys indicated that pH in the pond was slightly alkaline and this followed from the limestone geology of this area. The creek passing through the pond supplied enough oxygen to maintain aerobic conditions at the sediment/water interface during practically the whole winter. The ambient water quality in the pond did not promote metal release from bottom sediment. Water in the pond was stratified, mainly because of high concentrations of chlorides ($> 1200\ mg \cdot L^{-1}$) in bottom layers. This stratification would hinder sediment settling. The pond freeze up occurred in late fall, with the ice thickness varying from 0.25 to 0.4 m. Ice cover was slowly eroded by warmer creek water in early spring and eventually was broken up by spring runoff events. It was concluded that the winter regime and associated conditions in the pond did not cause any operational or environmental problems at this facility.

Oberts (1994a) recommended some basic measures for stormwater management in cold weather, including proper management and storage of deicing materials, disposal of snow or meltwater on vegetated areas away from streams, street cleaning in early spring to remove residue, and proper operation of ponds and wetlands. In environmentally sensitive areas, alternative compounds should replace salt, deicing materials should be properly stored, and any salt or sand residue should be cleaned from streets after the winter.

Design of stormwater ponds should take into consideration cold weather conditions. To avoid the situation where the pond ice cover divides the pond storage into two layers, Oberts (1990) recommended special outlet controls that allow drawdown of the pond water level prior to freezing. Other beneficial measures include designing ponds in conjunction with an infiltration basin, which could be used for treatment of polluted water. The infiltration bed should be designed with underdrains that can be used to reduce soil moisture prior to freezing and thereby to partially preserve soil infiltration capacity. Cold-weather wetlands should be designed with some detention storage to maintain some flow control after wetlands freeze.

The U.S. Center for Watershed Protection (CWP) held a special workshop on cold climate BMPs and the workshop findings are summarized below (CWP, 1997). Among the cold climate design challenges, the following were listed: cold temperatures, deep frost line, short growing season, and significant snowfall. Cold temperatures may cause pipe freezing, ice cover formation, and reduced biological activities, oxygen levels and settling. Deep frost line leads to frost heaving, reduced soil infiltration, and pipe freezing. Short growing season reduces time for establishment of vegetation and dictates the use of plant species suitable for cold climate. Finally, significant snowfall leads to high runoff volumes from snowmelt and rain-on-snow events, high pollutant loads during spring snowmelt, impacts of road salt/deicers, and increased demands on BMP storage.

The adjustments required in BMP design for cold climate start with proper sizing criteria, accounting for spring snowmelt and rain-on-snow events. For ponds, other modifications include protection of inlet and outlet structures against icing, increasing the forebay and treatment volumes, preventing sudden releases of meltwater into the receiving waters, and providing regular maintenance. For wetlands, the modifications are similar to those listed for ponds. Wetlands should be planned in combination with a grassed infiltration area for treating meltwater shock loads. The selection and planting of vegetation must match these conditions.

Extensive use of stormwater infiltration in cold climate is not encouraged. The main concerns include input of chlorides, influx of sand from sanded surfaces, and need for pretreatment. Filtration facilities may experience similar difficulties in winter operation.

Recognizing the highly polluted character of snowmelt, the feasibility of snowmelt treatment by other systems than BMPs was also considered. Oberts (1990) suggested diversion of highly polluted snowmelt to the wastewater treatment plant, and in another case, the feasibility of using a swirl concentrator to treat highway runoff and snowmelt was considered (Lygren and Damhaug, 1986).

Finally, it should be emphasized that the knowledge of BMP design for cold climate is limited and incomplete. Most of the information available is limited to conceptual descriptions. Further research and field testing are required to develop design criteria.

Research Needs

Surveys of experience with urban drainage in cold climate countries indicate that continuing progress requires research on a number of issues which are summarized below.

Further advances in urban snowmelt modelling appear to be feasible. Such models should consider several types of urban surfaces reflecting spatial distributions of snow depth, albedo, solar radiation and chemical inputs, with respect to snowpack dynamics and elution of pollutants.

More work is needed for the assessment of snowmelt impacts on receiving waters. During the period reviewed, traditional investigations of snowmelt chemistry were supplemented by toxicity measurements. For this purpose, guidance is needed on the selection of test organisms and exposure conditions. Further research is needed on identifying the sources of toxicity; the results obtained so far point to chlorides and traffic byproducts (dissolved metals and hydrocarbons).

Finally, the common BMPs require further refinement and testing to improve and sustain their performance in cold weather. Effective treatment trains for cold weather may be quite different from those currently in use. Some of the BMP combinations listed in the preceding section, e.g., ponds with adjacent infiltration areas, or wetlands with storage and adjacent infiltration areas, require further study. Relatively little is known about water quality processes in ice-covered ponds, or wetlands.

Conclusions

Urban stormwater management has evolved quickly during the past 30 years and offers a range of solutions best applicable to urban drainage problems in temperate climate. These approaches require further development and modification for applications to urban drainage in cold climate, which creates special demands on drainage systems. Towards this end, further research is needed on modelling urban snowmelt quantity and quality, the assessment of snowmelt aquatic impacts, including those caused by snowmelt toxicity, and adaptation of the existing stormwater best management practices for cold weather conditions. International collaboration is needed to make the best use of limited funds available for this purpose in relatively few countries.

References

Akan, A.O. 1994. Modeling enrichment of soluble pollutants in snow covers. Water Air Soil Pollut. 73: 225–234.

Amrhein C., J.E. Strong, and P.A. Mosher 1992. Effects of deicing salts on metal and organic matter mobilization in roadside soils. Environ. Sci. Tech. 26: 703–709.

Bengtsson, L. and G. Westerstrom. 1992. Urban snowmelt and runoff in northern Sweden. Hydrol. Sci. 37(3): 263–275.

Boom, A. and J. Marsalek. 1988. Accumulation of polycyclic aromatic hydrocarbons (PAHs) in an urban snowpack. Sci. Tot. Env. 74: 133–148.

Buttle, J.M. 1990. Effect of suburbanization upon snowmelt runoff. Hydrol. Sci. 35(3): 285–302.

Buttle, J.M., A.M. Vonk, and C.H. Taylor. 1995. Applicability of isotopic hydrograph separation in a suburban basin during snowmelt. Hydrol. Process. 9(2): 197–211.

Center for Watershed Protection (CWP). 1997. Stormwater BMP design supplement for cold climates. CWP, Ellicott City, MD 21043, USA.

Conway, H., A. Gades, and C.F. Raymond. 1996. Albedo of dirty snow during conditions of melt. Water Resour. Res. 32(6): 1713–1718.

Daub, J., J. Foerster, R. Herrmann, A. Robein, and T. Streibel. 1994. Chemodynamics of trace pollutants during snowmelt on roof and street surfaces. Water Sci. Technol. 30(1): 73–85.

Delisle, C.E., C. Chenevier and P. Andre. 1997. Synthèse des données physico-chimiques sur les neiges usées au Québec et leurs répercussions environnementales. Vecteur Environnement 30(6); 33–44.

Droste, R.L., and J.C. Johnston. 1993. Urban snow dump quality and pollutant reduction in snowmelt by sedimentation. Can. J. Civ. Eng. 20(1): 9–21.

Gray, D.M and T.D. Prowse. 1993. Snow and floating ice. Chapter 7 *in* D.R. Maidment (ed.), Handbook of hydrology. McGraw-Hill, New York.

Hautala, E.-L., R. Rekilä, J. Tarhanen, and J. Ruuskanen. 1995. Deposition of motor vehicle emissions and winter maintenance along roadside assessed by snow analyses. Environ. Pollut. 87: 45–49.

Hayhoe, H.N., R.G. Pelletier, and D.R. Coote. 1995. Estimating snowmelt runoff erosion indices for Canada. J. Soil Water Conser. 50(2): 174–179.

Jeffries, D.S. 1988. Snowpack release of pollutants. National Water Research Institute, Report No. 88–06, Burlington, Ontario, Canada.

Leduc, A. and C.E. Delisle. 1990. Quality of used snow from city streets and sidewalks in Montreal. Proc. Int. Conf. on Urban Hydrology under Wintry Conditions, Narvik, Norway, March 19–21, 1990.

Loranger, S., M. Tetrault, G. Kennedy, and J. Zayed. 1996. Manganese and other trace elements in urban snow near an expressway. Environ. Pollut. 92(2): 203–211.

Lygren, E. and T. Daumhag. 1986. The swirl concentrator as an urban runoff treatment device. Pages 713–724 *in* H.C. Torno, J. Marsalek and M. Desbordes (eds.) Urban Runoff Pollution, Springer Verlag, Heidelberg.

Malmqvist, P.A. 1983. Urban stormwater pollutant sources. Chalmers University of Technology, Goteborg.

Marsalek, J. 1991. Urban drainage in cold climate: problems, solutions and research needs. Pages 299–308 *in* C. Maksimovic (ed.), New Technologies in urban drainage, UDT'91. Elsevier Applied Science, New York.

Marsalek, P. 1997. Special characteristics of an on-stream stormwater pond: winter regime and accumulation of sediment and associated contaminants. M.Sc. Thesis, Queen's University, Kingston, Ontario, Canada.

McPherson, M.B. 1975. Special characteristics of urban hydrology. Pages 239–255 *in* Prediction in Catchment Hydrology, Australian Academy of Science, Canberra.

Milina, J. 1998. Runoff based flood analysis in urban catchments subject to the effects of cold climate conditions. A poster submitted to the 1998 IAWQ Biennial, Vancouver, June 20–26, 1998.

Ng. H.Y.F. and J. Marsalek. 1992. Sensitivity of streamflow simulation to changes in climatic inputs. Nordic Hydrology 23: 257–272.

Novotny, V., D. Muehring, D.W. Smith, and R. Facey. 1997. Impact of urban nonpoint source snowmelt on receiving waters. A paper presented at the Center for Watershed Protection Workshop on BMP design for cold climate, St. Paul. Minn., Sept. 22–23, 1997.

Oberts, G.L. 1990. Design consideration for management of urban runoff in wintry conditions. Proc. Int. Conf. on Urban Hydrology under wintry Conditions, Narvik, Norway, March 19–21, 1990.

Oberts, G.L. 1994a. Influence of snowmelt dynamics on stormwater runoff quality. Watershed Protection Techniques 1(2): 55–61.

Oberts, G.L. 1994b. Performance of stormwater ponds and wetlands in winter. Watershed Protection Techniques, 1(2): 64–68.

Rochfort, Q., J. Marsalek, B.J. Dutka, A. Jurkovic, and R. McInnis. 1997. Toxicity characterization of combined sewer overflows and stormwater discharges. National Water Research Institute, February 1997.

Sansalone, J.J., and S.G. Buchberger. 1996. Characterization of metals and solids in urban highway winter snow and spring rainfall-runoff. Transportation Research Record 1523: 147–159.

Schondorf, T. and R. Herrmann. 1987. Transport and chemodynamics of organic micropollutants and ions during snowmelt. Nordic Hydrology 18: 259–278.

Schueler, T.R. 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Washington Metropolitan Water Resources Planning Board, Washington, D.C.

Semadeni-Davies, A., and L. Bengtsson. 1998. Snowmelt sensitivity to radiation in the urban environment. Hydrol. Sci. 43(1): 67–89.

Viklander, M. 1997. Snow quality in urban areas. Ph.D. Thesis, Luleå University of Technology, Luleå, Sweden.

Westerstrom, G. 1995. Chemistry of snowmelt from an urban lysimeter. Water Qual. Res. J. Canada, 30(2): 231–242.

White, P.A. and J.B. Rasmussen. 1995. Genotoxicity of snow in the Montreal metropolitan area. Water Air Soil Pollut. 83: 315–334.

Zariello, P. 1990. Seasonal water quality trends in an urbanizing watershed in upstate New York, USA. Proc. Int. Conf. on Urban Hydrology under Wintry Conditions, Narvik, Norway, March 19–21, 1990.

NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

National Water Research Institute
Environment Canada
Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
Canada L7R 4A6

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
Canada S7N 3H5

Institut national de recherche sur les eaux
Environnement Canada
Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington; (Ontario)
Canada L7R 4A6

Centre national de recherche en hydrologie
11, boulevard Innovation
Saskatoon; (Saskatchewan)
Canada S7N 3H5

Environment Canada Environnement Canada

Canada