Cold climate BMPs: solving the management puzzle

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Abstract Snowmelt runoff and rain-on-snow events present some of the highest pollutant loading and most difficult management challenges in the course of a year in regions with cold climate. Frozen conduits, thick ice layers, low biological activity, altered chemistry, and saturated or frozen ground conditions all work against effective treatment of melt runoff. Understanding the source, evolution and transition that occurs within a melt event, and defining the management objectives for specific receiving waters will help focus the search for effective management techniques. Solving the management puzzle means putting together a strategy for both soluble and solids-associated water pollutants.

Keywords BMPs; cold climates; snowmelt; urban runoff

Introduction

Research into the character of urban runoff and the impact it has on nearby receiving waters has largely focused on rainfall events and the rapid, high peak aspects of hydrologic response. Documentation on similar behaviour for the runoff resulting from the melting of urban snowpacks has been more scarce. Snowpacks accumulate water volume via snowfall and possibly rain-on-snow, and deposited material all winter, then release it quickly over a chemical-induced melt or slowly over a long period of high volume solar-driven melt. The snowpack also mobilises pollutants elsewhere within the runoff watershed, depending upon the hydrologic response within the urban area.

Once runoff begins its journey from the snowpack to a receiving water, problems occur because of ice formation in conduits and treatment systems, slowed biological activity, increased water density, frozen soils, and chemically altered water quality behaviour (Oberts, 1990; Novotny *et al*., 1999). At a time when all of these factors are evident and when receiving waters and BMPs are least able to handle pollutant inputs, a large inflow of highly concentrated meltwater occurs. Physical, chemical and biological systems are overrun and often unable to perform cleansing processes typical of other times in the year. Further discussion of the difficulties encountered in urban cold climates is given in Skretteberg (1990), Caraco and Claytor (1997), and UNESCO (2000 – Ch. 2 Bengtsson and Semadeni-Davies). The difficulties found in cold climates can be at least partially overcome by adapting our usual way of approaching urban runoff treatment, and by applying some alternative approaches to dealing with runoff during cold periods of the year.

Examining the problem

Accumulation of pollutants within a snowpack

The snowpacks that accumulate in an urban area can vary dramatically depending upon surrounding land use, traffic patterns, public works practices, snowpack orientation and local climatic variation. Bengtsson and Semadeni-Davies (in UNESCO, 2000) indicate that the high surface area of snow flakes at a slow fall velocity scavenges atmospheric pollutants more efficiently than raindrops, and at a time when increased inputs to the atmosphere occur from inefficient fuel burning and increased consumption. These flakes settle into an urban area where roads and urban uses contribute additional amounts of solids and related pollutants in massive numbers. Milina (in UNESCO, 2000) reports that up to 50% of the annual precipitation and runoff load of the pollutants in urban areas in cold climates can be stored in the annual snowpack prior to melt.

The three general areas of accumulation are roads and highways, near road areas and upland areas removed from heavy traffic, each with a pattern of pollutant accumulation that requires a different management approach. Road and highway areas contain a predominance of solid and solids-associated contamination (metals, phenols, polyaromatic hydrocarbons or "PAHs", cyanide, salts) that exceeds rainfall runoff because of the high volume of meltwater flow (Sansalone and Buchberger, 1996; Viklander, 1999). These areas are frequently assisted in the melt process by the addition of de-icing chemical (salt) and anti-skid material (sand). This area also accumulates a high solids load on the side of the road, where wind-blown particulates settle and are subject to runoff during low energy chemical melts and higher energy solar melts or post-melt rainfall events. The near road areas are the areas of most accumulation from roadways because of the common practice of plowing snow over to the side, in addition to wind-blown settling. The high solids content plowed, splashed and blown from the roadway is combined with urban debris (road pieces, litter), salt and dissolved chemicals, and exposed to many freeze-thaw cycles. Novotny *et al.* (1999) report that 90% of pollutants emitted by traffic are deposited within a 5 m band along the roadway, and that beyond 10 m the impact is minimal. Similar findings were reported in Norway by Lygren *et al.* (1984) and in a literature review by Lorant (1992). Sansalone and Buchberger (1996) also noted that metals in a roadside snowbank will eventually partition to adjacent solids and move with those solids. The upland areas away from high traffic roads do not have the high solids load associated with the previous two areas, but rather accumulate a high dissolved fraction reflective of airborne fallout occurring within urban areas (Viklander, 1999). These areas are typical of suburban or open space areas within an urban setting.

All of the above areas of accumulation have a common behaviour in that they store both water and pollution for long periods of the winter. The major concern in melt management then becomes the release of this substantial volume of material. Depending upon the character of the melt, this release can last from a few hours to a few weeks, and be dominated by solids or by soluble contaminants. The factors affecting melt behaviour are discussed in detail by Bengtsson and Westerström (1992), Viklander (1999), Semadeni-Davies *et al.* (2001) and Marsalek (2003a).

Release of pollutants from a snowpack

Urban snowpacks are inhomogeneous piles of frozen liquid that can contain high loads of solids and toxics. Behaviour of pollutants within a snowpack occurs according to a set of chemical and physical parameters in a process called by several names, including preferential elution, freeze exclusion, first flush and pollutant speciation (Colbeck, 1981, 1991). Generally, snowpacks are exposed to many freeze and thaw events both at the surface and within the snowpack itself. The formation of these layers can affect the flow of water through the pack, and repeated freezing and thawing causes reformed ice crystals to repel impurities to the edges of ice crystals. Once at the edge, these impurities are then able to be mobilised through molecular diffusion or mechanical dispersion by either a moving wetted front or by concentrated flow within preferential channels within the snowpack (Colbeck, 1981). The low energy movement that first occurs during the melt is capable of picking-up soluble material and moving it downward and out of the snowpack. Meltwater containing an acidic mix of soluble pollutants is likely to occur in this early stage of melt (Westerström, 1995). Concentrations of soluble constituents can exit the snowpack early in the melt at many times the concentration existing in the pack prior to melt (Daub *et al.*, 1994; Westerström, 1995; Viklander, 1999; UNESCO, 2000, Ch. 4 – Marsalek, Oberts and Viklander). Infiltration into an unsaturated soil under the pack is the natural way for the first parts of the melt to enter the hydrologic system and be reduced by natural soil adsorption processes. However, this infiltration can be impeded by frozen or saturated soils, or perhaps by the presence of a thick ice layer caused by the repeated addition of de-icing chemicals, resulting in overland flow away from the pack. The principal detrimental impact of this meltwater is felt by aquatic life and vegetation sensitive to elevated levels of metals, organic toxicants and salt. Managing this first flush of meltwater is best accomplished through a filtration/adsorption process in a treatment facility or through soil infiltration, where soil adsorption and microbiotic activity occur. U.S. EPA (1983) found in two of the Nationwide Urban Runoff Program (NURP) studies that most of the toxics contained in urban runoff were removed as water percolated towards the groundwater. However, some of the melt pollutants, such as Cl, will likely pass through the soil relatively intact. Figure 1 illustrates that management strategies for this early part of the melt should focus on infiltration, collection and dilution, and pollution prevention (such as chemical management and air pollution regulation). This management approach is especially pertinent for the urban areas removed from dense pollutions, high traffic and commercial-industrial areas.

During the central part of the snowpack elution event, water volume leaving the snowpack increases as the wetting front reaches the bottom. Most of the soluble constituents have been removed, and the solids begin to become the predominant pollutant of concern. Late in the event, particulate movement dominates, but energy decreases with the volume of runoff. However, the solids are very vulnerable to post-melt rainfall runoff, when energy becomes a major factor. Management of the middle and late parts of the snowpack melt should focus on collection and detention, filtration and pollution prevention (such as reduced sand application and timely sweeping).

The latter part of the melt and early spring rainfall runoff events can usually be treated effectively with commonly used BMPs that focus on settleable pollutants. The only difference between this runoff and that treated during rainfall events later in the spring through the fall is that there will likely be a higher level of adsorbed pollutants, such as PAHs and oil and grease that have resulted from winter build-up. Colbeck (1981) identifies a “worst-case” scenario for environmental damage occurring when a sequence of thaw-freeze cycles is followed by a slow melt or rain-on-snow. The repeated thaw-freeze cycles and slow melt accumulate dissolved materials at the bottom of the snowpack where they can be quickly moved away with a minimum amount of melt. The energy then associated with the rainfall could also generate movement of solids-associated pollution at nearly the same time, resulting in another kind of pollution loading event.

Defining the solution

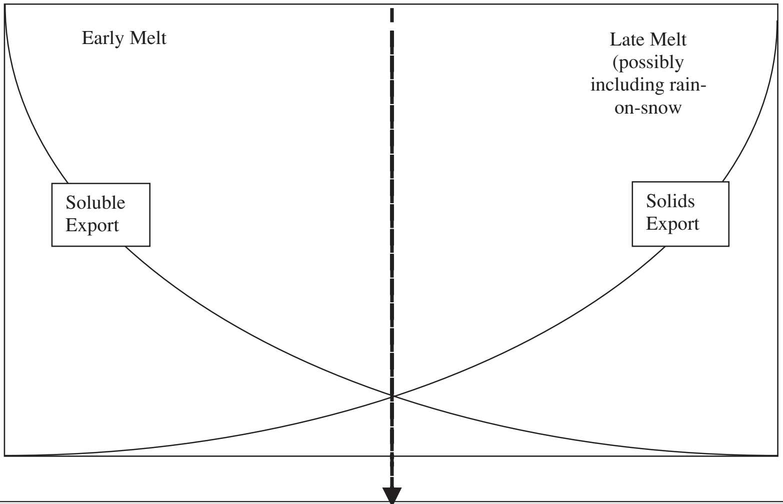
Why we need to change

Conventional surface water quality management techniques that depend on physical and biological treatment to reduce impact need to be altered in order to deal with the winter conditions described above. Several difficulties related to cold weather conditions must be overcome to properly treat meltwater runoff. Perhaps the most important factor is to keep in mind the nature of pollution within the area of concern and the behaviour of the melt sequence as described in Figure 1. An approach that aims to minimize the impact of highly soluble and toxic pollution at low-flow may differ markedly from one that focuses on solids and nutrient load reduction to lakes. Once an approach is selected, the previously mentioned difficulties of operating in a frozen environment must be kept in mind. In addition, high salt content reduces the partitioning coefficient of metals, creating a more toxic and mobile mix of soluble forms. Finally, a winter’s accumulation of pollutants can be washed away by the single largest volume of runoff in a year or during early spring rainfall, when urban surfaces and surface water conveyance facilities are flushed.

Design considerations

All of the above-mentioned difficulties with operation of management systems for snowmelt mean that some changes must be made in the normal ways of handling runoff. Caraco and Claytor (1997) collected the knowledge of surface water managers from cold climate regions of North America and developed a comprehensive list of needed changes in design approaches. In all cases, they recommend increasing water quality volume storage to account for the large volume of water moving in the spring from melt, rain-on-snow and rain-after-snow. The rule-of-thumb suggested is to oversize when the average annual snowfall depth is greater than the annual total precipitation depth. The authors suggest that no more than five-percent of the annual runoff volume should bypass some form of treatment during spring melt. Novotny *et al*. (1999) recommend capturing and treating 90% of the melt volume. Since melt can occur over a several week period, the routing of meltwater and design specifics of hydrograph storage are quite different than for intense rainfall events; that is, more total storage/treatment volume is required because of extended runoff.

Caraco and Claytor (1997) also showed that dry soils infiltrate about twice the volume of wet soils under melt conditions up to the point of saturation, whereupon pervious areas change to impervious and meltwater runoff occurs. The possibility of rain-on-snow further



Character	
High soluble content	High solids content
Low runoff volume, early infiltration	Large runoff volume (especially if rain-on-snow occurs), saturated soils
Initiated by chemical addition and/or solar radiation	Solar driven
Land Use Where Important	
Low density	High density
Residential/neighborhood	Roads, highways
Open space	Commercial
BMP Focus	
Infiltration	Filtration
Dilution	Volume control
Pollution prevention (salt, chemical application)	Pollution prevention (anti-skid application)
Retention	Detention/settling
Wetlands/vegetation (infiltration, biological and soil uptake)	Wetlands/vegetation (filtration, settling)

Figure 1 Generalized melt elution sequence (concentration vs. time)

complicates hydrologic design because of the additional volume of water added and the increased intensity of it entering the urban runoff hydrograph. A worst case design scenario would provide storage and treatment for a 10- to 100-year rainfall event on top of a statistically determined snowpack depth. Other factors recommended by Claytor and Schueler (1996) and Caraco and Claytor (1997) for inclusion in all runoff design facilities are pretreatment to settle coarse-grained solids, maximum pond depth of 2.5 m, maximum flow velocity of about 1.5 m/s anywhere in the drainage system, and use of vegetated buffers around all treatment facilities.

Possible BMP approaches/design adaptations

The approach taken to control or limit the amount of pollution occurring during snowmelt events depends largely on the phase of melt being focused upon and the location of the event. Effective treatment of cold climate meltwater runoff requires using new approaches that transcend those used to manage only rainfall runoff.

Pollution prevention. Perhaps the simplest set of BMPs to employ in anticipation of melt are those commonly referred to as “good housekeeping” and “pollution prevention”. The judicious use of both anti-ice and anti-skid materials is an essential first step toward reducing the amount of contamination associated with snowmelts. Application of less salt and anti-icers immediately means less chemicals reach impervious surfaces, but additionally means that some of the pollution mobilisation associated with road salt does not occur. An extensive discussion of alternative chemicals and alternatives to chemicals exists in Novotny *et al*. (1999). Elevated chloride levels not only create toxicity problems associated with the chloride itself, but also lead to dissociation of other contaminants into a more soluble, toxic phase. Chloride also changes soil character, leading to soil compaction and lack of biological productivity.

Additives to road salt include ferro- and ferri-cyanides for anti-caking, phosphorus for corrosion control, and nutrients for vegetation improvement. Movement of high levels of the extremely toxic free cyanide form has been observed in runoff from salt piles next to the Mississippi River in Minnesota (Cherryholmes, personal communication, 2000). Proper storage of salt and salt mixes (under cover, on impervious pad and well away from any receiving water) can prevent this.

Several advances in the technology of salt and anti-skid application show some promise for reducing the load of salt applied to urban roads. Trucks with temperature observation and geographic positioning equipment, salt and/or road pre-wetting with brine, road weather information systems (RWIS), direct spray onto troublesome road decks, and preventive anti-icing before snowfall are all being researched for broad application.

Removal of snow from urban areas to disposal sites can dramatically decrease the migration of pollutants during a melt by removing the contaminating material before it can migrate into the drainage system. Storage of snow on a flat pervious area, with good soil treatment, removed a suitable distance from a receiving water body is an effective way to eliminate urban melt loading, provided adequate safeguards are employed to promote infiltration and soil treatment.

Options for treatment of chloride-laden runoff are severely limited. Because chloride is a conservative element, removing it from the water in which it flows is virtually impossible. The only feasible method to address high levels of chloride in meltwater runoff, other than limiting its use, is to dilute its strength. This can be done by drainage system design in which runoff from areas with high chloride loads is combined with runoff from lower loading areas, in a ratio such that dilution below levels of concern results. Although not always possible, detaining chloride-laden runoff in a detention area, with slow release or concurrent release with a high volume melt flush can be effective at diluting the effect of the chloride.

Although sweeping anti-skid abrasives during a hard winter is not possible, getting sweepers out at the first opportunity in the spring to remove residual solids has both drainage and water quality benefits; that is, the debris will not be available to clog conduits or take up essential storage volume, and the sediment and adsorbed pollutants will be gone.

Other methods of simple pollution prevention are erosion control (stabilize landscape and un-vegetated areas before winter), establishment of chemical free zones for areas draining to sensitive waters, litter control (pets and human), and control of atmospheric pollutants.

Infiltration. The movement of soluble pollutants from the snowpack is one of the most perplexing challenges in dealing with the water quality of snowmelt. Looking at how and when these pollutants move from the snowpack is the key to determining treatment alternatives. Previous discussion in this paper referenced the saturation behaviour that occurs as a melt slowly proceeds, eventually leading to saturated conditions and whole-basin contribution to runoff. The condition of "frozen" soils varies from totally impervious to quite pervious, depending upon soil texture and moisture conditions at the time of freeze-up. Soils can also become saturated from the large volume of water moving in a melt, thus changing pervious portions of a watershed into impervious contributors to a melt event (Buttle, 1990; Bengtsson and Westerström, 1992; Viklander, 1999). The portion of the melt entering the soil prior to saturation can be critical to overall snowmelt management. In densely developed urban centres, the soluble content of the melt will likely be low because of the tendency for these materials to adsorb to the many solids available nearby in the pack (Sansalone and Buchberger, 1996; Viklander, 1999). However, in less densely developed residential areas, the proportion of solubles could be higher, thus promoting *in situ* infiltration or diversion of melt to infiltration basins as effective BMPs.

Treatment of soluble constituents through infiltration or constructed filtration takes advantage of the ion exchange capacity of soil and the microbial activity occurring within the soil. Oberts *et al*. (2002) reported that infiltration of pre-settled snowmelt in the very sandy portion of the Minneapolis-St. Paul region occurred at a rate up to 15 mm/hour in four regional infiltration basins, with no discernible impact on groundwater quality. Levels of chloride in the surface water infiltrating into these basins reached up to 130 mg/L, but groundwater samples taken to reflect local conditions after the seasonal melt reached a high of 81 mg/L in May 2002, receding to 32 mg/L by August. Marsalek (2003b) found, however, that chlorides in groundwater in Ontario accumulated to very high levels. Effective routing through a detention facility prior to introduction to any infiltration basin should be mandatory.

Perhaps the easiest way to manage highly soluble snowmelt runoff is to transport it via a pervious, albeit possibly frozen, drainageway to a pervious area where it can be given a chance to infiltrate. Capturing the initial melt and the dissolved pollutants associated with it, and allowing this fraction of the melt to infiltrate until the soils are saturated will lower overall runoff volumes and prevent toxic shock-type impacts in receiving waters. It is *essential* to exercise caution to assure that proper soil treatment will occur during infiltration so as not to harm groundwater. An example of design with a minimum structural approach is to route meltwater through an infiltration swale to a flow diffuser that spreads the meltwater over a naturally vegetated or wetland surface. Although the vegetation is dormant, the area should be able to infiltrate some water, especially if some detention storage is available. Because of the chloride and toxics content of this first flush, the vegetated area or wetland could undergo a species shift to less desirable plant species, so caution should be used if a sensitive or especially valuable area is being used (Isabelle *et al*., 1987).

Many different conditions must be in effect for infiltration to be effective in meltwater treatment. Caraco and Claytor (1997) suggest a minimum soil infiltration rate of about 1.3 cm/hour, with a clay content less than 30%. Flat slopes are essential to encourage seepage and clogging must be minimized, most likely by pre-settling. Soils dry at the time of freeze-up will have a more effective porosity because of the lack of ice in pore spaces, so any effort to drain water from soils that are part of an infiltration system will be beneficial. Granger *et al*. (1984) and Novotny *et al*. (1999) recommend keeping the top 30 cm of soil dry before freeze-up to retain soil infiltration capacity at melt.

The use of gravel filled trenches or basins can enhance infiltration. Installation of these structures can provide a pathway for water to get below the frostline, provided the gravel is kept dry prior to freeze-up. Use of geotextile material to wrap the gravel above and below will help to keep it from clogging, and provide an easier maintenance procedure if clogging does occur. The Sandsli-System in Bergen, Norway described by Thorolfsson (1997) makes use of infiltration to reduce overall runoff by 50% and peak runoff rates by 60%. Several "leaky pipe" systems are now available for sub-grade installation using corrugated metal or PVC. The possibility of plugging and the need to avoid installation in areas of sensitive groundwater present cautions that must be acknowledged before widespread use. These systems can be used to temporarily store runoff in large volumes while it seeps into the soil, and can be easily built into below grade retrofit drainage or treatment train schemes. Access ports for maintenance should be incorporated into the design.

James and Shahin (1998) evaluated three free-draining porous pavement blocks in Guelph, Canada to determine the pollutant removal for urban runoff draining through the pavement and sub-base material. Although snowmelt was not measured, the authors speculate that the application would be suitable for frozen conditions in low traffic areas. They found that the soil material in the sub-base plays a major role in ion exchange, adsorption, filtration and biological decomposition/transformation, depending upon the specific nature of the sub-base material. Lorant (1992) similarly found that sub-base material in porous surfaces and infiltration basins can be effective in treating melt.

Cautions that should be followed include: routing water from any source area that might release toxic material to groundwater; and avoiding saturated conditions, since repeated small melt events can saturate the soil prior to the major thaw or possibly create an impermeable layer at the surface (Marsh and Woo, 1984; Buttle, 1990; Kuchment and Gelfan, 1996).

Diversion. Diversion of flow to different BMPs can be designed according to the nature of the pollutants being carried, the type of control desired, and the potential receiving water. For example, a chloride- or toxics-laden early first-flush from a heavily-traveled roadway could be diverted to a holding area for later release when higher, less concentrated flow occurs, thus diluting the effects of the chloride. Similarly, the latter part of a melt that might come from an area of "clean" runoff away from any roadway can be diverted away from a structure that is limited in volume and used to treat only highly concentrated runoff.

Detention/ponding. Perhaps the most conventional method for urban runoff treatment is the use of detention or ponding. This technology developed almost exclusively for the treatment of solids from rainfall runoff and generally does not address the need for meltwater treatment in cold climates. Detention typically relies upon settling and biologic activity for treatment. However, the needs are far more complicated under winter conditions when an ice layer forms over the permanent storage pool and biological activity is slowed dramatically. Ponds have been shown to be less effective for treatment of snowmelt conditions unless adaptations are made to accommodate meltwater runoff (Oberts *et al*., 1989; Oberts, 1990; Marsalek, 1997). These adaptations can enhance treatment of meltwater, especially in areas receiving runoff from densely developed urban areas and roadways where solids are the predominant pollutant.

Relating the use of detention ponds to the character of meltwater is an essential first step in their use. Early in the melt sequence, a highly soluble first flush occurs, which ponds can store for later infiltration, dilution, slow release or settling. The salinity often associated with meltwater reduces settling velocity, oxygen levels and the partitioning coefficient for metals. The result is less settling of particulates, and possibly the release of metals from previously settled bottom material. Ponding for snowmelt conditions, therefore, would benefit from reduction of soluble pollutants and those associated with fine-grained particulate matter, both of which are difficult to accomplish. Following this is the movement of particulate material for which detention is better suited. Unfortunately, the conditions under which it is best suited do not exist, and adaptations are needed.

The primary difficulty associated with detention ponds in wintry conditions is the thick ice layer that can easily reach one metre in thickness and prohibit the effective use of the available storage volume in the pond by the incoming snowmelt runoff. The first increment of meltwater dives beneath the ice layer, potentially reaching a pressurized condition in which scour of possibly contaminated bottom sediments can occur if the sediment is loosely consolidated and the current is sufficient. Low oxygen conditions in the pond water, and low pH and high chloride in the inflowing water can also lead to release of previously settled metals from the sediment. After the available volume under the ice is filled, meltwater flows over the top of the ice, which leads to reduced treatment efficiency because the settling depth above the effectively impermeable ice layer is minimal and the settled material becomes available when the ice melts. In addition to the physical limitations of settling, biological activity in the pond is greatly reduced.

A thick ice layer also severs the air-water exchange, thus limiting the availability of oxygen to the water column, which can be depleted all winter long by organic decomposition, unless an adequate baseflow is available to replenish oxygen (Marsalek *et al*., 2000). The cold water flowing during the melt periods has a higher viscosity, thus reducing settling velocities of particles being carried into detention facilities. This decreases effectiveness and enables mobilisation of associated contaminants further down-gradient. Jokela and Bacon (1990) indicate that settling velocities are 50% faster at water temperatures of 20°C than at 4°C.

Marsalek (1997) and Marsalek *et al*. (2000) have conducted one of the few studies available for the physical and water quality behaviour of a detention facility under winter conditions. In their study of Kingston Pond in Ontario, Canada, the authors found that inflowing, warmer water can follow preferred flow paths and lead to ice thickness variation. The low velocity of this flow and the nature of the bottom material in the Kingston Pond did not result in any perceived scouring effects. The inflowing water did keep the pond aerated during all but the coldest of conditions, when the inflow channel also froze and aeration ceased. Under the ice during the winter, water was found to densely stratify due to high dissolved solids (salt) content, and reaeration from the surface ceased. The first ice to crack with increased melt inflow was along the axis of flow. This then allowed water from under the ice to escape and mix with inflowing water. Prior to a mix similar to this occurring at several sites in Minnesota, however, Oberts *et al*. (1989) observed the physical scour of bottom material from ice-covered ponds with unconsolidated, soft bottom material as inflowing water displaced pond water. The difference in ice break-through and scour potential behaviour seems to be a function of ice thickness, bottom roughness and material, and inflow character (volume, velocity, temperature and rapidity).

Oberts *et al*. (2000) describe an infiltration-detention pond that serves a double function starting with the early melt event. The system consists of a porous substrate with an under-drain to promote infiltration/filtration, and a controllable outlet structure that can be closed during the melt event to promote detention settling. As the melt event proceeds and reaches its peak end-of-season flow, the structure then becomes a detention facility, since inflow to the pond will exceed the infiltration capacity of the soil. The extra storage will help to settle some of the particulate pollutants that the runoff picks up as it flows over urban surfaces. The under-drain can be used to drain the soils in the fall below the critical moisture levels that are required to make an impermeable layer of frozen soil (Dunne and Black, 1971; Novotny, 1988), or to slowly release meltwater high in chlorides or dissolved pollutants when toxicity to downstream waters is an issue.

Oberts *et al*. (2000) also present a sample design of a "seasonal" detention facility within which water is drawn down in the fall via a controllable outlet to prevent the formation of a layer of ice at the normal summer elevation. A low-flow channel of adequate velocity to discourage the formation of channel ice will help to move baseflow and small melts through the structure during the winter and prevent ice build-up. A smaller pool during the winter limits the volume of potentially polluted water that is available for flushing by displacement. As the melt begins and meltwater flows begin to increase, the lower outlets can be closed, allowing the facility to act as an effective detention pond. This configuration allows for infiltration along the margins of the pond, as these slopes would be dry and typically able to accept infiltrating meltwater as the water level in the pond rises (Oberts *et al*., 2002). The effectiveness of detention ponds is a function of size relative to contributing area, and can be enhanced by flow diffusers, variable flow outlet structures, floatable skimmers, multiple in-line ponding, and enhanced infiltration (U.S. EPA, 1983; Oberts *et al*., 1989).

If drawdown is not possible or desirable, there are some design considerations for conventional detention ponds. First, the bottom should be sloped in such a manner that the deepest part of the pond is at the outlet to minimize scouring of bottom material as water emerges from under the ice on its way out of the pond. Installation of a baffle weir device or riser hood around the outlet can help by assuring that a constant movement of water from below the ice keeps an area around the outlet open to prevent the build-up of ice immediately adjacent to the outlet. Encouraging a constant baseflow through the pond will keep oxygen levels high, prevent stratification and prevent the flushing of anaerobic, highly saline water during melts.

Other adaptations of commonly used detention ponds suggested by Caraco and Claytor (1997) include a modified outlet to allow for drawdown in fall to prevent ice build-up or to dry the pond bottom for infiltration enhancement; buried inlet and outlet pipes below the frostline to prevent freeze-up; minimum one-percent slope on all conveyance pipes; prevention of splash in areas not insulated from low temperatures; oversized pipe diameter to retain design flow in the event ice forms in the pipe; use of minimum 15 cm pipe diameter; and use of a baffle weir and/or reverse slope outlet pipe from below ice. The use of stop-logs, weirs or modified outlet controls (valves, gates) are all adaptation possibilities. Safety can be addressed at facilities susceptible to thin or no ice through signage or fencing.

The use of moving parts in meltwater handling facilities should be considered carefully because of the potential for freeze-up at the time when they are most expected to function. If problems with moveable valves, plates/gates, flashboards or similar controls appear possible, an orifice or weir outlet control should be used and adapted to the situation.

Biologically based. Few modifications can be made in biological systems operating in cold climates because of the limits on biological activity during the winter. One useful application of biological systems is natural drainage swales that contain vegetation. These swales, although not effective for uptake of pollutants by aquatic organisms during periods of melt, are usually vegetated, mildly sloped, sump areas where some settling, filtration and infiltration can occur. Swales can be adapted to enhance treatment of snowmelt through the introduction of weirs or grade control structures to slow flow and allow for settling and infiltration. Planting of vegetation with deep roots enhances the likelihood of infiltration. Promotion of sheet-flow rather than channelized flow also improves the chances for pollutant removal. To maximize any benefit, Caraco and Claytor (1997) recommend side slopes flatter than 3:1; longitudinal slopes from 1–2%; and dense vegetation plantings of deeply rooted plants. They also suggest under-drains to enhance drying in the fall and remove infiltrated (filtered) water.

Surface water drainage systems that incorporate wetlands can also be adapted to improve performance during melt conditions. Lorant (1992) describes the treatment processes under way in wetland systems as sedimentation, decomposition, chemical adsorption and biological transformation. Under winter conditions, the biological activity and vegetative filtration are minimized, and the settling is altered by layers of ice and possibly frozen soils. Meltwater can also flush material from a wetland after vegetation decomposition during the winter or after some filtration and settling of baseflow or early melts occur during the winter. For wetland systems that contain some ponded water or maintained water level, Oberts (1994) recommends installing a controlled outlet structure that can be used to draw water levels down in the fall so that some detention storage will be available in the spring for melt and rainfall runoff. Caraco and Claytor (1997) recommend use of pre-treatment (settling) and incorporation of multiple cells within the wetland to enhance capture and infiltration possibilities. Installation of “permeable weirs” (weirs installed with a small gap between the boards) can temporarily detain flow with minimum impact on flood routing. Level spreaders can be used to spread the flow uniformly over the wetland to avoid concentrated flow and channelization.

Discharge of meltwater to any vegetated system has the potential for adverse impact on the vegetation. Isabelle *et al*. (1987) showed that discharge of meltwater to wetlands could cause species shifts to less desirable species. This also could lead to loss of biodiversity and chemical alteration of wetland soils.

Filtration, hydrodynamic structures and “treatment trains”. There is great potential for treatment of snowmelt runoff in filtering the runoff through a variety of increasingly available treatment train systems. A typical treatment train would include settling, straining, floatables removal, infiltration, and adsorption. Claytor and Schueler (1996) evaluated many different filtration configurations to determine normal water pollution behaviour associated with each. Although many filtration systems are effective in pollution removal, sub-grade (underground) filters have much more chance of succeeding with snowmelt than any structure built above ground. Systems evaluated by Claytor and Schueler (1996) and Urbonas (1997) showed that properly maintained and operated sand filters can achieve very good solid, nutrient, metal and hydrocarbon removals, but to be effective in cold climates, the filter media must be dried prior to freeze-up in the fall. Lau *et al*. (2000) saw excellent pollutant removal for highway runoff through a fine gravel bio-filter (bio-film growing on granular filter material).

Recommendations from Claytor and Schueler (1996) for design of filtration systems include pre-treatment for solids removal, average bed depth for filtration of 0.3–1.0 m, and exfiltration to groundwater when pollution levels are not a threat. Sansalone and Buchberger (1996) suggest such an approach for highway runoff using a partial exfiltration trench with adsorptive filtration through oxide-coated granular material. The incorporation of organic material (ex. peat) in the filter media can enhance the treatability of a filtration system through the removal of hydrocarbons, metals and organic chemicals; however, some release of soluble nutrients can occur from the organic media, so the trade-offs must be evaluated depending upon the specific water quality objectives of the installation.

A suite of new filtration appurtenances for roadway runoff has also become available in recent years. Typically, these devices insert directly into the runoff catchment system and filter flow on its way to a storm sewer or receiving water body. Pollutant removal is highly variable depending upon the design of the unit, with general success seen for solids and limited success for filtration of solubles in units with filter media. They can be an effective way to pre-treat runoff before getting to a more substantial facility where pre-treatment costs would rise. If freezing is likely, the units could be removed during the winter and replaced just prior to spring melt.

There are some structural devices that appear as good alternatives for the treatment of meltwater runoff. The possibility of getting self-contained treatment trains at sub-grade, below the frostline means that some effective treatment can occur for snowmelt even in densely developed urban centres, using very little space. Details on the numerous systems available, including vortex or swirl units, self-contained (vault) “treatment train” systems with differing configurations, and a number of appurtenances to improve treatment are discussed in UNESCO, 2000 (Ch. 6 Oberts).

The benefit of treatment trains for water quality management in cold climates comes from their ability to effectively treat all parts of a snowmelt event in a small-scale, self-contained facility. The use of filters capable of adsorbing soluble toxic pollutants addresses one of the principal weaknesses of most commonly used BMPs expected to treat meltwater.

Conclusions

There are many challenges confronting those interested in controlling the adverse impacts of snowmelt in cold climates. The best approach to managing this runoff is to keep it simple and attempt to duplicate natural behaviour. Treatment approaches should focus on the nature of the pollutant(s) of interest, its movement within a meltwater event, and the likely effectiveness of a BMP to reduce pollution load and/or concentration to the receiving water of concern. Although dramatic reduction in pollution associated with snowmelt in urban areas might not be possible, use of these approaches will begin to address these loads. Continued research and BMP development for cold climate runoff control is essential to solve this problem.

References

Bengtsson, L. and Westerström, G. (1992). Urban snowmelt and run off in northern Sweden. *Hydrol. Sci. Jour.*, **37**(3), 263–275.

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

Caraco, D. and Claytor, R. (1997). *Stormwater BMP Design Supplement for Cold Climates*. Center for Watershed Protection, Ellicott City, Maryland, USA.

Cherryholmes, K. (2000). Personal communication, Minnesota Pollution Control Agency.

Claytor, R.A. and Schueler, T.R. (1996). *Design of Stormwater Filtering Systems*. Center for Watershed Protection, for the Chesapeake Research Consortium, Inc.

Colbeck, S.C. (1981). A simulation of the enrichment of atmospheric pollutants in snow cover runoff. *Water Res. Research*, **17**(5), 1383–1388.

Colbeck, S.C. (1991). The layered character of snow covers. *Rev. Geophys.*, **29**(1), 81–96.

Daub, J., Förster, J., Herrmann, R., Robien, A. and Striebel, T. (1994). Chemodynamics of trace pollutants during snowmelt on roof and street surfaces. *Wat. Sci. Tech.*, **30**(1), 73–85.

Dunne, T. and Black, R.D. (1971). Runoff processes during snowmelt. *Water Resources Research*, **7**(5), 1160–1171.

Granger, R.J., Gray, D.M. and Dyck, G.E. (1984). Snowmelt infiltration to frozen prairie soils. *Can. J. Earth Science*, **21**(6), 669–677.

Isabelle, P.S., Fooks, L.J., Keddy, P.A. and Wilson, S.D. (1987). Effects of roadside snowmelt on wetland vegetation: An experimental study. *Journal of Environmental Management*, **25**, 57–60.

James, W. and Shahin, R. (1998). A laboratory examination of pollutants leached from four different pavements by acid rain. In *Advances in Modeling the Management of Stormwater Impacts, Vol. 6*, W. James, (ed.) Computational Hydraulics International, Guelph, Ontario.

Jokela, J.B. and Bacon, T.R. (1990). Design of urban sediment basins in Anchorage. *Cold Regions Hydrology and Hydraulics*, American Society of Civil Engineers, NY, pp. 761–789.

Kuchment, L.S. and Gelfan, A.N. (1996). The determination of the snowmelt rate and the meltwater outflow from a snowpack for modeling river runoff generation. *Jour. of Hydrol.*, **179**, 23–36.

Lau, Y.L., Marsalek, J. and Rochfort, Q. (2000). Use of a biofilter for treatment of heavy metals in highway runoff. *Water Qual. Res. J. Canada*, **35**(3), 563–580.

Lorant, F.I. (1992). *Highway runoff water quality literature review*. Research and Development Branch, Ontario Ministry of the Environment.

Lygren, E. and Damhaug, T. (1986). The swirl concentrator as an urban runoff treatment device. In *Urban Runoff Pollution*, H.C. Torno (ed.), J. Marsalek and M. Desbordes, Springer-Verlag, Berlin, pp. 713–724.

Lygren, E., Gjessing, E. and Berglind, L. (1984). Pollution transport from a highway. *Sci. Total Environ.*, **33**, 147–159.

Marsalek, J., Oberts G., Exall, K. and Viklander, M. (2003a). Review of the operation of urban drainage systems in cold weather: water quality considerations. *Wat. Sci. Tech.,* **48**(9) 11–20 (this issue).

Marsalek, J. (2003b). Road salts in urban stormwater: An emerging issue in stormwater management in cold climate. *Wat. Sci. Tech.,* **48**(9) 61–70 (this issues).

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

Marsalek, P.M., Watt, W.E., Marsalek, J. and Anderson, B.C. (2000). Winter flow dynamics of an on-stream stormwater management pond. *Water Qual. Res. J. Canada*, **35**(3), 505–523.

Marsh, P. and Woo, M.-K. (1984). Wetting front advance and freezing of meltwater within a snow cover 1. Observations in the Canadian arctic. *Wat. Res. Research*, **20**(12), 1853–1864.

Morrison, G.M.P., Ellis, J.B., Revitt, D.M., Balmér, P. and Gilbert, S. (1984). The physico-chemical speciation of zinc, cadmium, lead and copper in urban stormwater. In *Proceedings of the Third International Conference on Urban Storm Drainage; Volume 3, Planning and Control of Urban Storm Drainage*, Göteborg, Sweden, pp. 989–1000.

Novotny, V. (1988). Modeling urban runoff pollution during winter and off-winter periods. *Advances in Env. Modelling*, 1988, 43–58.

Novotny, V., Smith, D.W., Kuemmel, D.A., Mastriano, J. and Bartošová, A. (1999). *Urban and Highway Snowmelt: Minimizing the Impact on Receiving Water*. Water Environment Research Foundation (WERF) Project 94-IRM-2.

Oberts, G.L. (1990). Design considerations for management of urban runoff in wintry conditions. In *Proceedings, Int. Conference on Urban Hydrology under Wintry Conditions*, March 19–21, Narvik, Norway.

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

Oberts, G.L., Wotzka, P.J. and Hartsoe, J.A. (1989). *The Water Quality Performance of Select Urban Runoff Treatment Systems*. Metropolitan Council, St. Paul, Minnesota, Publication No. 590-89-062a, 170 p.

Oberts, G.L., Marsalek, J. and Viklander, M. (2000). Review of water quality impacts of winter operation of urban drainage. *Water Qual. Res. J. Canada*, **35**, 781–808.

Oberts, G.L., Emmons, B.H., Olson, J.L. and Correll, C. (2002). Basinwide infiltration as an effective cold climate urban runoff management practice. In *Proceedings – Ground Water/Surface Water Interactions*. An AWRA Specialty Conference, July 2002, Keystone, Colorado, pp. 393–398.

Sansalone, J.J. and Buchberger, S.G. (1996). Characterization of metals and solids in urban highway winter snow and spring rainfall-runoff. *Trans. Res. Record*, **1523**, 147–159.

Semadeni-Davies, A., Lundberg, A. and Bengtsson, L. (2001). Radiation balance of urban snow: a water management perspective. *Cold Regions Sci. and Tech.*, **33**, 59–76.

Skretteberg, R. (ed.) (1990). *Proceedings of an International Conference on Urban Hydrology Under Wintry Conditions*. Narvik, Norway, March 1990.

Thorolfsson, S.T. (1997). A study on the effects of urban runoff controls in the Sandsli Research Catchment, Bergen, Norway. *Wat. Sci. Tech.*, **36**(8–9), 379–389.

UNESCO (2000). *Urban Drainage in Specific Climates: Vol. II. Urban Drainage in Cold Climates*. Ed. by S. Saegrov, J. Milina and S.T. Thorolfsson. IHP-V, *Technical Documents in Hydrology*, No. 40, Vol. II, Paris.

Urbonas, B.R. (1997). Field evaluation of a stormwater sand filter. *Watershed Protection Techniques*, **2**(4), 536–538.

U.S. Environmental Protection Agency (EPA) (1983). *Results of the Nationwide Urban Runoff Program: Volume 1 – Final Report*. U.S. Environmental Protection Agency, Washington, D.C., 200 p.

Viklander, M. (1999). Dissolved and particle-bound substances in urban snow. *Wat. Sci. Tech.*, **39**(12), 27–32.

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