NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL de RECHERCHE sur les EAUX

URBAN DRAINAGE IN COLD CLIMATE: PROBLEMS, SOLUTIONS AND RESEARCH NEEDS

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NWRI CONTRIBUTION 91-63

RRB 91-19

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APRIL 1991
NWRI Contribution 91-63

MANAGEMENT PERSPECTIVE

Urban drainage disrupts the hydrological cycle of urban areas and impacts adversely on water quality in the receiving waters. In cold climate, such impacts are particularly severe in winter months, when runoff transport is disrupted by freezing and pollutant loads are increased by high atmospheric deposition (due to heating and less efficient operation of motor vehicles), increased wear of road surfaces, and applications of deicing chemicals and materials. The report that follows presents a review of winter drainage problems, available solutions, and research topics needed to develop and refine these solutions. This review represents a first step in the UNESCO sponsored search for efficient and environmentally safe approaches to winter urban drainage. Such approaches are essential for achieving sustainable development of urban areas.

PERSPECTIVES DE LA DIRECTION

Le drainage urbain influe sur le cycle hydrologique des villes et a des effets néfastes sur la qualité des eaux réceptrices. Dans un climat froid, ces effets sont particulièrement graves pendant les mois d'hiver lorsque le transport des eaux de ruissellement est perturbé par le gel, et les charges de polluants sont accrues par des dépôts atmosphériques importants (à cause du chauffage et du fonctionnement moins efficace des véhicules automobiles), une plus grande usure des chaussées et des applications de produits chimiques et de substances de déglaçage. Le rapport qui suit est une analyse des problèmes de drainage en hiver, des solutions disponibles et des sujets de recherche nécessaires pour trouver des solutions et les perfectionner. Cette étude est une première étape dans le cadre des recherches parrainées par l'UNESCO pour trouver des moyens efficaces et sans danger pour l'environnement qui permettent le drainage urbain en hiver. Ces derniers sont essentiels si l'on veut réaliser le développement durable des zones urbaines.

ABSTRACT

The cold climate creates special requirements on urban drainage and such requirements can not be always met by the existing design approaches which were primarily developed for warm weather conditions. To remedy this situation, a review of problems, solutions and research needs connected with urban drainage in cold climate is presented. The main problems include an increased incidence of flooding and ineffective control of urban runoff pollution in cold weather. Solutions of such problems should follow from refinements of design flow computation procedures, the development of runoff controls for cold climate conditions, and improved maintenance operations. Research needs for the development of such solutions are also presented.

RÉSUMÉ

Le climat froid créé des exigences spéciales sur le drainage urbain et les moyens existants, conçus surtout pour des climats chauds, ne permettent pas toujours de les satisfaire. Afin de corriger cette situation, on présente une analyse des problèmes, des solutions et des besoins en matière de recherche liées au drainage urbain dans un climat froid. Les principaux problèmes comprennent une fréquence accrue des inondations et une surveillance inefficace de la pollution des eaux de ruissellement urbain dans un climat froid. Les solutions à ces problèmes devraient découler des perfectionnements des procédés informatiques des débits nominaux, l'élaboration d'ouvrages de surveillance des eaux de ruissellement pour des climats froids, et de meilleures méthodes d'entretien. On présente également les besoins en matière de recherche pour obtenir ces solutions.

URBAN DRAINAGE IN COLD CLIMATE: PROBLEMS, SOLUTIONS AND RESEARCH NEEDS

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ABSTRACT

The cold climate creates special requirements on urban drainage and such requirements can not be always met by the existing design approaches which were primarily developed for the temperate or warm climates. To remedy this situation, a review of problems, solutions and research needs connected with urban drainage in cold climate is presented. The main problems include the increased incidence of flooding and ineffective control of urban runoff pollution in cold weather. Solutions of such problems should follow from refinements of design flow computation procedures and the development of runoff controls for cold climate conditions. Research needs for the development of such solutions are also presented.

INTRODUCTION

Main functions of urban drainage include provision of convenience or minor drainage, usually by means of sewer pipes, and flood protection by means of major drainage, which comprises both man-made and natural conveyance channels. Such services should be delivered with minimal environmental impacts and in an economically efficient way. During the past 20 years, great progress has been achieved in studying and implementing this desirable approach to urban drainage. A closer examination of this progress shows that much of the past work focussed on temperate climatic regions. Consequently, more attention should be paid to the problems specific to other climatic regions, particularly those with cold and tropic climates. Such activities are currently promoted under a UNESCO project on urban drainage in various climates, which is coordinated by a UNESCO working group and the International Research and Training Center on Urban Drainage (IRTCUD) in Belgrade, Yugoslavia. The issues of urban drainage in cold climate are discussed in the paper that follows.

URBAN DRAINAGE PROBLEMS IN COLD CLIMATE

Cold climate affects urban drainage by changing the urban hydrological cycle, transport of runoff and stormwater pollutants, operation of runoff control facilities and sewage treatment plants in combined sewerage systems, 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 [1], becomes much more complex in cold weather. In particular, precipitation occurs in the form of rain or snow, may be stored on the catchment in snowpacks, and transported not just hydraulically but also by snow drifting or snow disposal. The resulting runoff, snowmelt and transport processes depend on climatic variables, including air temperature, wind and solar radiation, and man-made effects in the form of various heat sources and chemicals contributing to snow melting [2,3]. Winter catchment conditions, characterized by reduced soil infiltration, lead to increased runoff contributing areas and extended concentration times. Consequently, the design-type events causing excessive loading of the drainage system may occur during the winter months, often as rain-on-snow events coinciding with snowmelt, and cause flooding [2,4].

Fluxes of urban runoff pollutants and their transport are also affected by cold weather. Pollutant deposition and accumulation in urban areas increase 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 [5]. Subsequent transport of such materials depends on their characteristics, climatic conditions, and snow removal and disposal activities. Pollutants entering the snowpack are first stored and later preferentially eluted during chemical or climatic melts. Soluble pollutants, such as acidic depositions, are eluted from the snowpack in the early stages of snow melting [6]. On the other hand, hydrophobic substances, such as the polycyclic aromatic hydrocarbons (PAHs), stay in the snowpack until the last 5 to 10% of meltwater is leaving the snowpack [7].

Other pollutants are transported by removing used snow from urban areas and disposing it in various ways, including in-stream dumping [8]. This practice facilitates a quick entry of pollutants into the receiving waters. Where in-sewer snow dumping is used, the efficiency of treatment processes may be unduly lowered and this leads to an increased pollution of receiving waters [9].

Regardless of the transport modes, the loads of pollutants in winter runoff or snowmelt deserve increased attention. As reported by Oberts [10] and Zariello [11], winter runoff and snowmelt transport up to 60% of the annual runoff load of selected pollutants.

Conventional facilities for management and control of urban runoff do not perform satisfactorily in cold climate. Serious problems were reported for winter operations of stormwater ponds and wetlands [10]. The formation of ice in stormwater ponds affects flow patterns in such facilities by forcing the flow either under or over the ice cover. The former case leads to scouring of bottom sediment; the latter case results in shallow flows over the ice cover, with conditions unfavourable for pollutant settling. Similar difficulties were reported for frozen wetlands [10].

Finally, there are many operational problems encountered in urban drainage systems in cold weather. In particular, outfalls or culverts may freeze over and control valves may become inoperative. Some of these problems can be prevented by proper design, others have to be mitigated by the provision of emergency services. Solutions of winter drainage problems are slowly emerging from surveys of practice in various countries encountering these problems. Faster progress should be facilitated by international cooperation and information exchange under the earlier mentioned UNESCO project on urban drainage in various climates.

CONCEPTUAL SOLUTIONS OF COLD CLIMATE DRAINAGE PROBLEMS

The conceptual solutions of cold climate urban drainage problems are discussed under three headings dealing with the planning, design, and operation of drainage facilities.

Drainage Planning

The planning and design of urban drainage encompass a number of objectives, such as prevention of flooding, protection of environment, traffic safety, protection of structures against inundation, health and hygienic reasons, rehabilitation of urban areas, improvement of living conditions, and aesthetics [12]. The attainment of such objectives may require a combined effort linking urban drainage with water supply, and waste treatment and disposal. It is obvious that these objectives need to reflect the cold climate conditions, particularly when dealing with the prevention of flooding due to rain on snow or frozen ground, ice blockage of inlets, pollution impacts of snow disposal, and traffic safety requirements leading to snow removal during winter months.

In the past, the lack of coordination and fragmentation of the planning of urban drainage and land use resulted in many costly flood abatement programs. Effective flood control planning should be conducted for the whole basin as a unit by developing a master drainage plan which incorporates the whole drainage system, including the interconnections between major and minor drainage systems. Such a plan should be prepared for the entire basin at an early stage of development and regularly updated.

The information required in master drainage plans is extensive and includes such items as site plans of the watershed, land use patterns, storm flood lines for the proposed major drainage system; tables with pre- and post-development stages and discharges, benefit-cost matrices of drainage alternatives, sizes of control facilities; and, illustrations showing pre- and post-development peak flows and other relevant data [13].

Master plans have to account for cold climate in the selection of design events of longer durations corresponding to runoff contributing areas with frozen ground; consideration of rain-on-snow events, particularly during the melting season; and, the planning of flow control facilities accounting for runoff and snowmelt characteristics in terms of volumes and pollutant loads. Adequate consideration of cold climate factors in drainage planning can prevent many problems that would be otherwise encountered later in the operation of drainage systems.

Drainage Design

The design stage of drainage implementation is the most important phase during which all special features of drainage in cold climate need to be fully considered. Crucial decisions made at this stage include the selection of design events, computation of drainage flows, the selection of appropriate drainage structures, design of runoff/snowmelt control facilities, and design of snow removal/disposal.

<u>Drainage design events in cold climate.</u> In temperate climate, drainage design events, certainly for minor drainage, are short duration summer thunderstorms which produce high rates of runoff, mostly from impervious areas. Runoff generated by such events is computed by various procedures, among which runoff simulation dominates. In cold climate, the selection of design events may differ from the procedures used in warm weather. Such differences arise from changes in the runoff contributing area, reduced infiltration abstractions, and releases of water stored in the snowpack.

Runoff peaks from short high-intensity storms are caused by quick runoff from impervious areas representing a small part of the catchment. On the other hand, in snow-covered catchments, or catchments with frozen ground, a very large part of the catchment contributes runoff. This fraction may increase with progressing snowmelt and reach up to 100% of the snow-covered area [14,15].

Snowpack represents storage of water on the catchment surface. This water may be released fairly quickly, from 20 to 50 mm per a 12-hour period for return periods from 2 to 5 years [15], in later phases of runoff. Such releases, combined with rainfall, contribute to increased runoff peaks, high volumes of runoff, and extended runoff durations. High runoff volumes and long runoff durations, in conjunction with blocked inlets or full storage facilities, contribute to flooding [2].

Hydrologic abstractions, particularly infiltration, change dramatically in winter regime. Infiltration into frozen soils is largely a function of the air-filled soil porosity and is inversely related to the ice/moisture content of the shallow 0-300 mm soil layer [16]. This ice-moisture content depends on soil moisture at the time of early winter soil freezing. For initially low moisture, frozen soils retain a significant infiltration capacity. On the other hand, frozen soils with high initial moisture exhibit greatly reduced infiltration [16]. All the above factors, including snowmelt, increases in runoff contributing areas, and reduced hydrologic abstractions, indicate that longer duration events may cause the design-level hydraulic loading of drainage systems in cold climate [17].

Flow computations. To compute runoff under wintry conditions, the issues of design events, runoff contributing areas and hydrologic abstractions need to be addressed and joint probabilities of various outcomes evaluated. Obviously, the most adverse outcome is the occurrence of significant rain storms over catchments with frozen soils (low infiltration), and a melting ripe snowpack. While the methodologies for addressing such cases are not yet fully developed, recent studies show a number of promising approaches.

Probabilities of rain-on-snow events were investigated by Wisnowszky [18] and Thorolfsson [19]. For conditions in Central Europe, Wisnowszky found very low probabilities of rain-on-snow events and such probabilities excluded these events from considerations in urban drainage design, certainly for minor drainage. This finding is in agreement with Thorolfsson's [19] map of European climates showing regions of high and low probabilities of rain-on-snow events. High probabilities were indicated for coastal areas, particularly the West coast of Norway and these findings would have to be considered in drainage design. Further inland, such probabilities and significance of these events for design diminished. Global warming, contributing to increased variation of weather patterns, may increase the occurrences of rain-on-snow events with coincident snowmelt.

To estimate hydrologic abstractions and runoff contributing areas, the issue of infiltration into frozen soils needs to be addressed in the context of local climatic conditions. In areas with high moisture supply at the start of cold season, frozen soils will exhibit low infiltration and large runoff contributing areas can be expected.

Rainfall intensities of rain-on-snow events can be superimposed on snowmelting rates, which can be determined in several ways, including experimental observations and various computational methods. Instrumentation for concurrent measurements of snowmelt, rainfall, temperature and runoff, in a network of 18 catchments was described by Skretteberg [20].

The latest advances in snowmelt computations were reviewed by Buttle and Xu [3], Bengtsson [2] and Sand [21]. While the energy balance methods have clear advantages because of their physical basis, they are very demanding in terms of input data and this precludes their widespread applications. Furthermore, the existing experience with these methods relates mostly to rural basins and the effects of anthropogenic influences such as various heat fluxes, reduced albedo, and impacts of chemicals on snowmelt are little understood. These influences greatly vary in time and space and this complicates their considerations in snowmelt computations. Besides the melting of snow, the transport of meltwater through the snowpack has to be also properly represented. Such transport results in the lagging and attenuation of the meltwater hydrograph [21,22].

In view of the difficulties with the energy balance methods, simple methods, such as the degree-day method, seem to offer practical alternatives in urban areas. This method was used successfully to reproduce observed snowmelt in several catchments [2,3,14] and even to develop probabilistic data on snowmelt rates [15].

For practical applications in drainage design, empirical methods, expanded for some energy balance terms, seem to show a great promise. This was noted by Sand [21] in comparisons of various snowmelt computation procedures. A temperature index model, with a separate terms for shortwave radiation, combined with a cascade of two linear reservoirs, performed almost as well as the energy balance model.

Design of runoff and snowmelt control facilities. Stormwater management has evolved from simple removal of runoff to comprehensive management approaches employing various control measures which can be classified as source controls, collection system controls, and storage and treatment [23]. Design and operation of many such measures will be affected by cold weather.

Source controls are typically classified as nonstructural and structural/semi-structural controls. The former category includes such measures as urban development and resource planning, natural drainage, sewer ordinances and discharge permits, chemical use control, surface sanitation, and erosion and sedimentation control. Several of these measures will be affected by cold weather conditions, as discussed below.

The use of natural drainage elements in urban drainage involves integration of natural channels, vegetated swales, wetlands and ponds into the drainage network. In recent years, the use of wetlands has been particularly gaining on popularity. However, as pointed out by Oberts [10], the effectiveness of wetlands in cold climate is greatly reduced. In early winter, wetlands freeze over and during subsequent runoff, pollutants are washed through the facility during the periods of runoff or snowmelt. Consequently, it appears desirable to combine wetlands with storage facilities so that some control is maintained even after wetlands freeze.

Among sewer ordinances, attention should be paid to control of in-sewer snow disposal which is practiced in some cities [9]. Besides proper design of snow drop structures, the impact of such practices on the treatment plant operation has to be assessed. This form of disposal may be acceptable for sewer systems with physical/chemical treatment, but less suitable for biological treatment of which efficiency depends on temperature and toxicity of the treated media. Another concern is prevention of blockage of sewers by disposed snow.

Chemical use controls are important in the case of deicing chemicals. The use of salt is particularly common, because of low costs and good performance in breaking the bond between the ice and pavement. The currently pursued alternative options aimed at reducing the environmental impact of street and road salting include reduced salt dosages, the use of environmentally harmless chemical substitutes, and improved displacement plowing [24].

Surface sanitation typically deals with regular street cleaning, but in cold climate, it should also include removal of sand and debris, accumulated from street sanding, and removal of old snow. Snow remaining on streets toward the end of the melting period has elevated levels of hydrophobic contaminants, such as PAHs and heavy metals, and its removal and proper disposal should reduce the environmental impact of snowmelt [9].

Structural or semistructural runoff control measures include infiltration facilities, on-site storage, overland flow modifications and solids separation. Only the first two items are pertinent and were included in the following discussion. To retain some effectiveness of infiltration facilities in the winter, such facilities should be designed with underdrains reducing soil moisture prior to freezing [10]. Relatively dry soils will retain some infiltration capacity and capture some snowmelt volume after freezing.

Porous pavement and road superstructures can be used in two ways to control runoff - for treatment of snowmelt by filtration and for runoff storage. Runoff and snowmelt are effectively treated by percolation through porous pavements. Removals of solids and various chemicals result from filtration through the pavement and from chemical adsorption to pavement materials. Experience with permeable concrete block pavements [25] and porous asphalt pavements [26] indicates that about 50% of total solids, phosphorus and heavy metals, transported by runoff or snowmelt, are retained by these pavements.

Storage is one of the most common measures used for runoff control. It is practiced in diverse ways, such as on-site ponding, underground rock-filled facilities, dual-purpose facilities (rooftops, parking lots, manholes, playgrounds), and detention and retention basins or ponds. Even though the need for runoff detention may be reduced in the winter, the design and operation of storage facilities should account for cold weather conditions.

Special infrastructures, such as insulated utility channels and pervious pavements or road superstructures, can be also used for runoff infiltration and storage. Insulated utility channels were developed in Norway [27] to reduce costs of servicing houses in areas with rocky grounds. A shallow insulated channel, with crush-stone backfill, houses all service lines, including storm and sanitary sewers. The same channel can be used to store runoff and meltwater. A similar idea was applieded to runoff storage in a 80 cm thick macadam layer forming a part of the road superstructure. This structure was effective in storing runoff and after two years of testing, no problems with frost heaving or other damages were reported [28].

Design of stormwater ponds should take into consideration wintry conditions. The pond ice cover vertically divides the pond storage into two compartments of reduced depths. Depending on the position of the ice cover relative to the inlet, the flow is either forced under the ice, or over the ice. The former case leads to the scouring of bottom sediment, the latter case results is shallow flows over the ice cover with hardly any sedimentation taking place. These problems can be mitigated by designing ponds in conjunction with infiltration facilities and with special outfall arrangements allowing drawdown of the pond prior to freezing. Furthermore, ponds should have sufficient volumes to allow for sedimentation after the formation of ice [10].

Experience indicates that combinations of several control measures, including infiltration, wetlands and a pond, adapted to wintry conditions as discussed above, improve the effectiveness of runoff controls in cold climate. Examples of such approaches were reported by Oberts [10] for several facilities in Minnesota.

Besides the source controls discussed earlier, the other types of controls included collection system controls and storage and treatment. Among these controls, only treatment may require special considerations of cold climate conditions and deserves further discussion. Several of the earlier discussed source controls provide some runoff and snowmelt treatment - sedimentation in ponds, and filtration or adsorption in porous road structures. However, there are situations, where a higher degree of treatment of winter runoff and snowmelt may be required. Under such circumstances, Oberts [10] recommended to divert highly polluted snowmelt to the wastewater treatment plant. Lygren and Damhaug [29] tested the feasibility of using a swirl concentrator to treat highway runoff and snowmelt. Total suspended solids removals by the swirl concentrator were estimated from 6 to 69%.

Finally, it should be emphasized that the knowledge of drainage design for cold climate is limited and incomplete. Most of the information available is limited to conceptual descriptions. Actual sizing of facilities and operational experience will require further research and field testing.

Design of snow disposal. Snow removal and disposal are addressed here in conjunction with urban drainage, because snow represents precipitation stored on the catchment surface and its removal is a method of transport. Snow removal is practiced widely in cold climate cities with large volumes of snow removed annually [9,30]. Consequently, towards the start of the snowmelt period, the impervious surfaces are clear of snow and this contributes to fast runoff [3].

Removed snow is disposed of by such methods as in-situ melting, in-stream dumping, melting at central facilities, and on land disposal [31]. Environmental impacts of such practices are discussed below.

Mobile melters are used for in-situ melting with meltwater discharge into the gutters. When dealing with fresh snow (i.e. less than 24-48 hours old), the quality of meltwater is comparable to that of stormwater, except for enhanced levels of chlorides. Where chlorides do not pose an environmental threat, this practice should be acceptable for fresh snow.

Traditionally, in-stream snow dumping was the most common method of snow disposal. Concerns about environmental impacts of such a practice, caused by high levels of solids, chlorides, metals, acidity and other chemicals in used snow, led to discontinuation or curtailing of this practice. In-stream dumping may be acceptable in the case of fresh snow and in quantities appropriate to the stream transport capacity [8,9].

To control the discharge of meltwater, typically by diverting it to the sewage treatment plant, permanent snowmelt facilities are sometimes used. However, the operation of such facilities is rather expensive, because of snow hauling costs and the energy costs associated with snowmelting [31].

The last snow disposal method discussed is on-land disposal. This method is widely used and, if properly implemented, its impact on the environment is minimal. For such implementation, it is required to develop design criteria for site selection and facility design [32]. The site selection criteria include land availability, proximity to the urban area to keep snow hauling costs down, some remoteness from residential areas to avoid complaints about noise and traffic, and, finally, favourable hydrogeology. The definition of favourable hydrogeology depends on the utilization of ground water. Without ground water utilization, it is possible to allow seepage of snowmelt into the ground water. In other cases, the entry of snowmelt into the ground water aquifers is not acceptable [30,32].

Having selected the disposal site, the facility design can proceed. The main considerations include adequate snow storage area allowing to spread snow so it will melt by the summer, the surface grading should facilitate concentration of outflow at a single point (where the effluent could be treated, e.g. by sedimentation, if needed) and, where required, snowmelt entry into ground water should be prevented. Finally, the site must be protected against illicit garbage dumping by fencing and cleaned at the end of the melt period by removing debris [32].

Operation of Urban Drainage Systems in Cold Climate

Operation of urban drainage systems in cold weather is much more demanding than in warm weather. While the main aspect of such operation is keeping the system elements free of ice, some aspects of snow removal are also discussed here. Even though snow is removed from urban areas for traffic safety and convenience reasons and snow removal falls operationally under road maintenance, the implications are both hydrological and environmental. The methods of snow removal are diverse, with most common plowing to the sides and subsequent removal. Other removal methods include chemical melting by salt and pavement heating. Environmental impacts of street salting are well documented and raise serious concerns [33-36].

Much of the operational effort in winter focusses on keeping the drainage conveyance elements free of ice and operating at full capacities. Most problems are caused at inlets, which are typically protected by metal grates or racks. Such metal structures usually freeze up first. To prevent flooding, it is required to have emergency crews ready to be dispatched to problem areas and to free the blocked inlets [10]. Inlet blockages by ice are particularly frequent during repeated freeze-thaw cycles. Operational experience helps in planning emergency services.

Special attention needs to be paid to all movable control devices, such as valves and gates, used in drainage facilities. Cold weather may render them inoperative and provisions for alternate controls, using bulkheads, plates or stoplogs, need to be made [10].

The planning of winter operation can benefit from weather forecasts and field experience indicating which combinations of climatic factors cause operational problems.

RESEARCH NEEDS

Surveys of experience with urban drainage in cold climate countries indicate that attainment of further progress requires research on a number of key issues. Such issues were already mentioned in the earlier discussion and are briefly summarized below.

The sizing of drainage elements - further research is needed to improve methods for determining the design level flows in drainage systems. The key elements in this process include the selection of design-type events, determination of runoff contributing areas, determination of hydrologic abstractions for wintry conditions, computation of snowmelt rates, and snowmelt routing through the snowpack. Special attention should be paid to longer duration rain-on-snow events, coinciding with snowmelt and frozen ground conditions allowing low infiltration. In snowmelt computations, the methods that can be supported by widely available data should be emphasized.

The next group of research problems deals with adaptation of common runoff controls to cold climate. In particular, it is required to study the operation of infiltration facilities, permeable pavements, stormwater ponds and wetlands in cold climate. The ways of preserving some effectiveness of these measures in winter months need to be studied. Where required, these measures have to be applied in such combinations which will maintain some runoff control even during the winter season. In the case of infiltration facilities, provisions for emptying before the first frost may help to retain some capacity for snowmelt infiltration. For stormwater ponds, design arrangements allowing some settling of runoff even after the formation of the ice cover need to be developed. More information is needed on chemical and biological processes taking place in stored stormwater. Finally, the implications of the freezing of wetlands for runoff control need to established and alternative means of runoff control under such conditions should be developed.

Finally, improved understanding of operational requirements needed to keep drainage elements free of ice and development of new structures reducing the susceptibility of ice blockage need to be undertaken.

CONCLUSIONS

Rapid progress in urban stormwater management during the past 20 years focussed on warm climate conditions and led to the development of drainage design approaches providing flood protection and drainage convenience, with minimal costs and impacts on the environment. These approaches require further development or modifications when dealing with urban drainage in cold climate, which creates special demands on drainage systems. Such demands follow from changes in the urban hydrological cycle, hydraulics of drainage structures affected by ice formation, generation and transport of runoff and snowmelt pollutants, and environmental processes in runoff control facilities. The development of suitable solutions requires further research on design events and computational procedures for cold weather drainage design, adaptation of common runoff control measures to cold climate, and improved understanding of operational requirements of drainage systems in cold weather. The proposed research activities should benefit from increased international cooperation.

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