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SNOWMELT RESEARCH AND MANAGEMENT: READY FOR THE NEXT BIG STEP

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ABSTRACT: Tremendous strides have been made since the first international conference in Narvik, Norway in 1990 dedicated completely to the understanding and management of snowmelt in urban areas, to Maine in 2003. But with every discovery comes the need to know more. The advent of sophisticated computers and software that can predict the sun's effect on a snowpack, the chemical data to finally know what that snowpack will yield to a receiving water, and the behavior of that water as a slug of heavily polluted meltwater enters are all recent advances in the science. But knowing these things merely whets the appetite to delve further. Drawing from participation in the series of conferences and workshops beginning with Narvik, and from experience in the field, observations will be made on what we have learned and how it applies to everyday practical application in cold climate regions. Accompanying this will be the identification of the many information needs that still exist for both theoretical and practical aspects, including: accurate modeling of the spatial mechanics of melt generation within an urban area and the runoff it generates; better definition of the nature, partitioning and fate of pollutants as they move from snowpack into and through receiving waters (recipients); improved chemical handling and the impact of chemicals on surface and ground water; the effectiveness of MTPs (meltwater treatment practices) and how they differ from STPs (stormwater treatment practices); the potential impact of climate change; and technical transfer of information to a limited world audience. The very positive result of identifying these needs is that today someone is working on every one of these elements and new collaborative efforts are under way among those interested in cold climate hydrology and water quality. We have moved past the problem recognition stage and are on the verge of truly understanding how meltwater generation and runoff can be anticipated and managed. This keynote address will set the stage for the conference, which focuses on lessons learned and practical applications for the future.

Key Words: snowmelt, management practices, urban hydrology

INTRODUCTION

Understanding what happens when snow accumulates, melts and runs off is the key to proper water management for much of the world's population living in cold climates. Because much of the science of hydrology developed to predict response from drastic rainfall events, the impacts of snowmelt have not historically received the attention that we would like.

There has been much improvement in our understanding of snowmelt accumulation and melt behavior over the past several decades. However, much of this work has been undertaken in non-urban environments, and similarly has not addressed the rapidly emerging area of runoff quality management to mitigate adverse receiving water impacts. Instead, we have relied upon research and management evaluations from moderate or even warm climates, where the nature of runoff and the constituents it carries are far different during much of the year.

The need to better address year-round water quality issues and the realization that cold climates present very harsh management conditions in need of special attention has led to a resurgence in cold climate runoff management, as exemplified by this conference.

HISTORY OF PROGRESS

Citing historic works in any field is a risky proposition because no matter how many "historic" references are listed, many more will be left off. The following list is not meant to be comprehensive, but merely a summary of those pieces of work that the author has found to be classic pieces of work that catapulted the field of cold climate runoff management and research forward. Many, many additional researchers deserve credit, but cannot be individually identified because of the need to limit the scope of this paper.

Early Work. Even though cold climate hydrology is in its infancy compared to rainfall runoff hydrology, sophisticated research into the genesis of snowpacks and the runoff that results when they melt has been under way since the 1940s. Research into cold climate hydrology began in earnest in the U.S. with the activities of the Eastern Snow Conference (ESC - http://www.easternsnow.org/) in the early 1940s. This long and successful series of annual conferences recently conducted its 60th annual event in Quebec. This series has produced a myriad of papers that began the modern era of research into snow build-up and melt models.

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL - http://www.crrel.usace.army.mil/) also has a long history of studying the physical processes associated with snow, including the classic works of S.C. Colbeck and many others, helped to define the physics of snow accumulation and the movement of water and its contents from that snowpack after it melts. In 1966, a CRREL publication (Bates and Bilillo, 1966) noted that nearly half of the land mass in the Northern Hemisphere, and essentially everything north of 40˚N latitude can be classified as "cold regions" based upon air temperature, snow depth, ice cover and frozen ground.

Both ESC and CRREL have contributed substantially to the development of basic snow-related physics and hydrology, particularly in non-urban, alpine regions. The large number of conferences and publications of these two prolific groups has provided a sound base for understanding the physical nature of snow and the general movement of meltwater. However, those interested in urban water management and water quality have needed to go beyond this to explore application in urban receiving water situations: hence, the need for this conference.

Meltwater runoff management has been the topic of several sessions at IAHR/IAWQ international conferences on urban storm drainage, including those in Banff in 1972, Gothenburg in 1984 and Niagara Falls in 1993.

Scandinavian research blossomed through the 1970s and 1980s with the work of such individuals as S. Thorolfsson on the Risvollan catchment and snowmelt runoff in Norway, P-A. Malmqvist on pollution character, and G. Westerström and L. Bengtsson on the behavior and content of Swedish snow. Much of this Scandinavian research provided the basis for discussion at the Narvik (Norway) conference in 1990.

Canadian research on water quality in cold climates has consistently been led by J. Marsalek, who has worked with many Canadian colleagues to define the chemical character of meltwater and the material it transports, and its impact on receiving waters. The work of J. Buttle on watershed response to snowmelt, and R.J. Granger and D.M. Gray on infiltration have provided the standard reference material used by subsequent researchers.

Recent Efforts. The 1990s and early 2000s have seen a continuation of much of the work described in the previous section, plus several advances in the exploration of cold climate hydrology and water quality. The first international conference devoted to the topic, however, occurred in Narvik, Norway in 1990. Since that time, publications on the topic have been published by the Center for Watershed Protection (Caraco and Claytor, 1997), the Water Environment Research Foundation (WERF) (Novotny et al., 1999) and UNESCO (2000). A second Scandinavian sponsored conference was held in March 2003 in Riksgränsen, Sweden. At this conference, a follow-up workshop was held in which participants discussed issues and defined some focal points for future action. Many from this workshop have become members of an International Water Association/International Association for Hydraulic Research (IWA/IAHR) Working Group on Urban Drainage in Cold Climate, and several of the conference papers occur as a series in the IWA journal *Water Science and Technology*, Vol. 48(9).

The North American Eastern Snow Conference series continued, and a Western Snow Conference began, and CRREL continues to build its incredible research base.

Throughout the recent period, most of the previously referenced researchers continued their work, and many mentored new researchers, such as M. Viklander and A. Semadeni-Davies (Sweden), B. Matheussen in Norway, and J. Sansalone (U.S.), and many others who have made significant new contributions to the field. Graduate programs throughout the world are now developing a whole new group of knowledgeable individuals poised to

carry new research efforts forward. This fact contributed to the optimism leading to the title of this paper.

All of the above efforts have become the launching spots for much of the research being reported upon at this Maine conference. A wide range of topics will be presented, and the tremendous new research under way throughout the cold climate world will be discussed. The new computer and geographic information system (GIS) tools we have at our disposal have opened many new doors that we only dreamed of as recently as ten years ago. The explosion of new products designed to treat nonpoint source runoff and the research associated with many of these products gives us new optimism that pollution can in fact be managed.

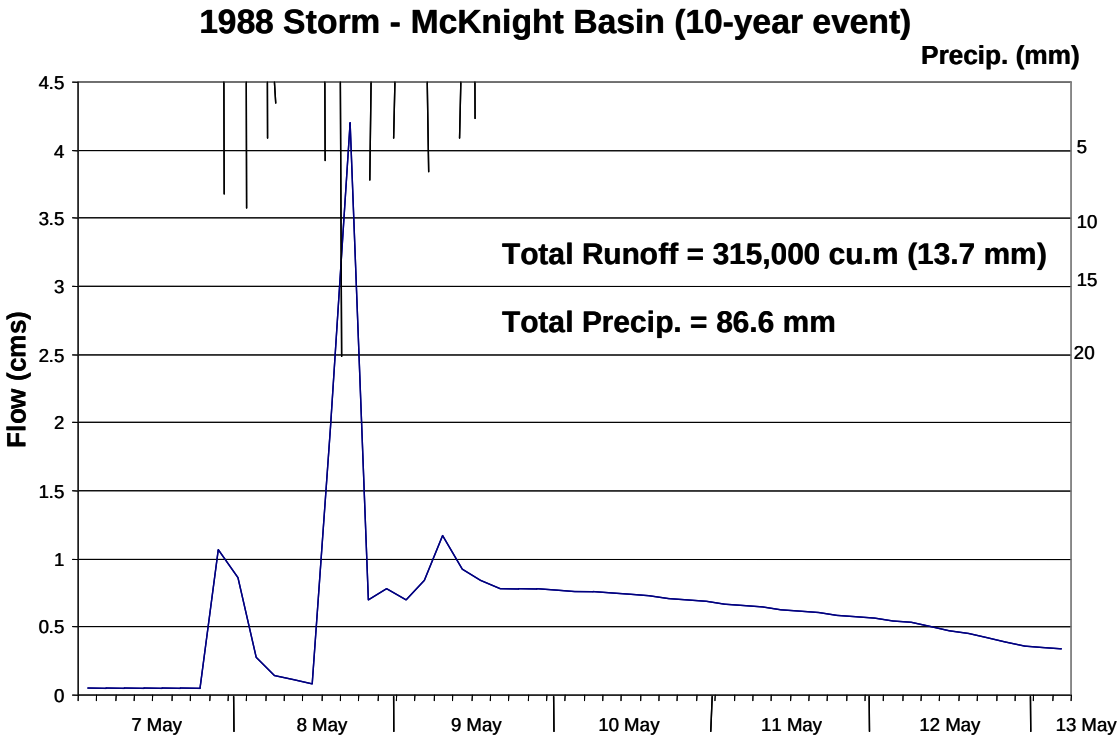
The material that follows is far from comprehensive because any claim to that effect always leaves out some landmark piece of work. Rather, it is an attempt to define what the nature of the cold climate runoff problem is as it relates to mostly urban areas where water management problems affect the most people. It will also briefly suggest some focal areas in need of continued research efforts.

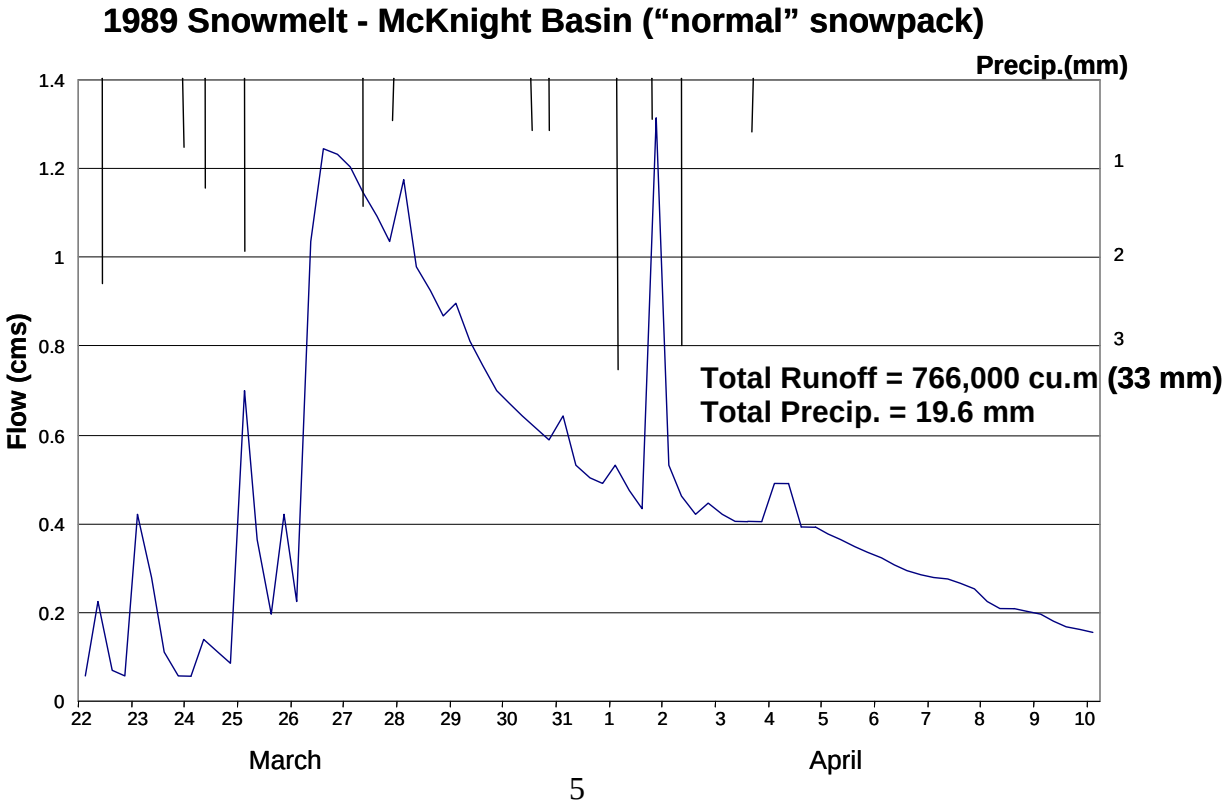
NATURE OF THE COLD CLIMATE PROBLEM

Hydrology of Melt. The heart of the problem with snowmelt runoff is that water volume in the form of snow and ice builds for several months and suddenly releases with the advent of warm weather in the spring or during short interim periods all winter long. Figure 1 shows this situation as it occurs in Minnesota, but a similar graphic could be developed anywhere that snow occurs. This comparison shows the runoff from a 10-year rainfall event (about 87 mm) on an urban Minnesota watershed compared to a "normal" snowpack (about 300 mm) melt event during which an additional 20 mm of rain fell. Note that although the snowmelt peaks are substantially less than the rainfall, the total event volume is about double.

This behavior of seeing a major portion of the annual runoff occur during the relatively short period in the year when the snowpack melts is typical of cold climates. Factors influencing the nature of this melt and the speed with which it occurs include solar radiation, the distribution of snow cover, the addition of de-icing chemical to the pack, and the amount of freeze-thaw cycling. Each of these processes can be modeled and predictions generated on the volume of water that will be available for wash-off. The development of better distributed models that describe the details of snow accumulation and subsequent melting is one of the most significant areas of emerging research. Many details of this development occur in the publications listed in the opening section, as well as the proceedings of this conference. Excellent summaries of snow accumulation and melt processes, and the extensive work in this field, are contained in Chapter 2 (A. Semadeni-Davies and L. Bengtsson) and Chapter 3 (J. Milina) of the UNESCO 2000 report on *Urban Drainage in Cold Climates.*

Figure 1. Volume Comparison of Rainfall Versus Snowmelt Hydrographs (Oberts et al., 1989)





Quality of Melt. The water quality problems associated with melt occur because the large volume of water released during melt and rain-on-snow events not only carries with it the material accumulated in the snowpack all winter, but also material it picks up as it flows over the land's surface. Figure 2 illustrates the accumulation of surface material on a snowpack compared to that occurring on the same urban surface during the rainfall season. The winter accumulation can occur directly on a standing snowpack or on the side of a roadway where it is plowed. In either case, the material builds for several months prior to wash-off. Since snow is a very effective scavenger of atmospheric pollutants, literally any airborne material present in a snow catchment will show up in meltwater when it runs off. Add to this the any material applied to, or deposited upon the land surface, for example to melt snow or prevent cars from sliding, and the wide range of potential pollutants becomes apparent. As with the volume of meltwater, a major portion of annual pollutant loading can be associated with spring melt events.

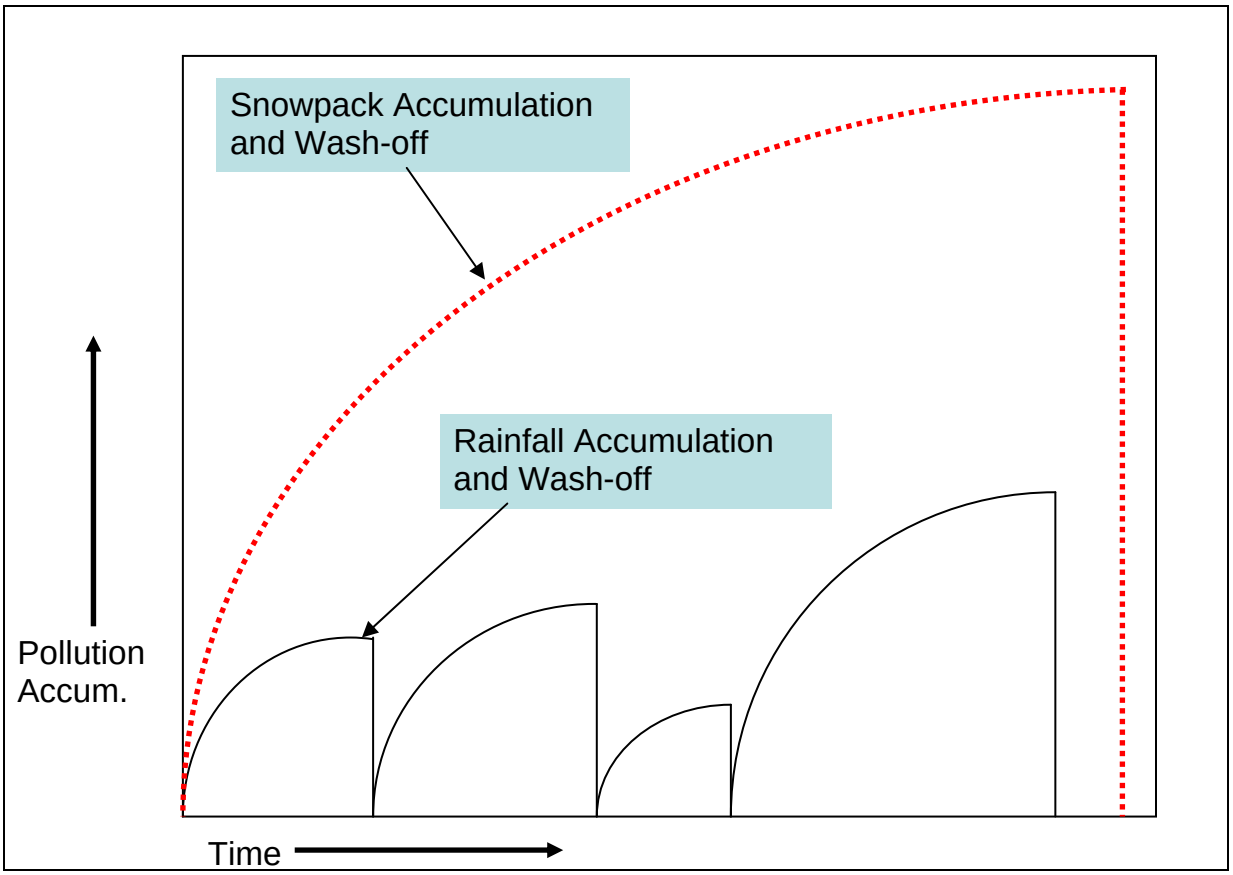


Figure 2. Snowpack Pollution Accumulation and Wash-off as Compared to Rainfall.

Major discussion of the water quality associated with these events and references to many associated pieces of literature occur in Novotny et al. (1999) and UNESCO (2000). Marsalek et al. (2003) summarized the state of knowledge in the Riksgränsen proceedings, reflecting on studies from the U.S., Canada and Sweden.

The conventional pollutants of concern for most urban runoff situations are supplemented in meltwater runoff by additional contaminants added during the winter. Pollutants of concern are particulates (organic and inorganic), nutrients (nitrogen and phosphorus) and

toxics that can either associate with particulates (ex. polynuclear aromatic hydrocarbons or PAHs, some heavy metals, phenols) or occur in a soluble state after being intentionally added to the snowpack (ex. chloride and cyanide).

The complex melting pattern that occurs within a snowpack results in the release of pollutants at different times during the melt, thus further complicating an already difficult management scenario. The variability of snow character and the repeated freeze-thaw cycles that occur throughout a long winter create a very heterogeneous snowpack, with many different flow paths available for melt water to move along (Figure 3). The freeze-thaw cycles also result in the re-crystallization of snow and the subsequent exclusion of "impurities" to the outside edge of the crystals, whereupon they become available for wash-off by the melting front as it passes. This process has been extensively documented in classic works by Colbeck (1978, 1981, 1991), Marsh and Woo (1984), and Jeffries (1988), among others. The process has been called by many different names, including "preferential elution", "freeze extraction" and "first flush".

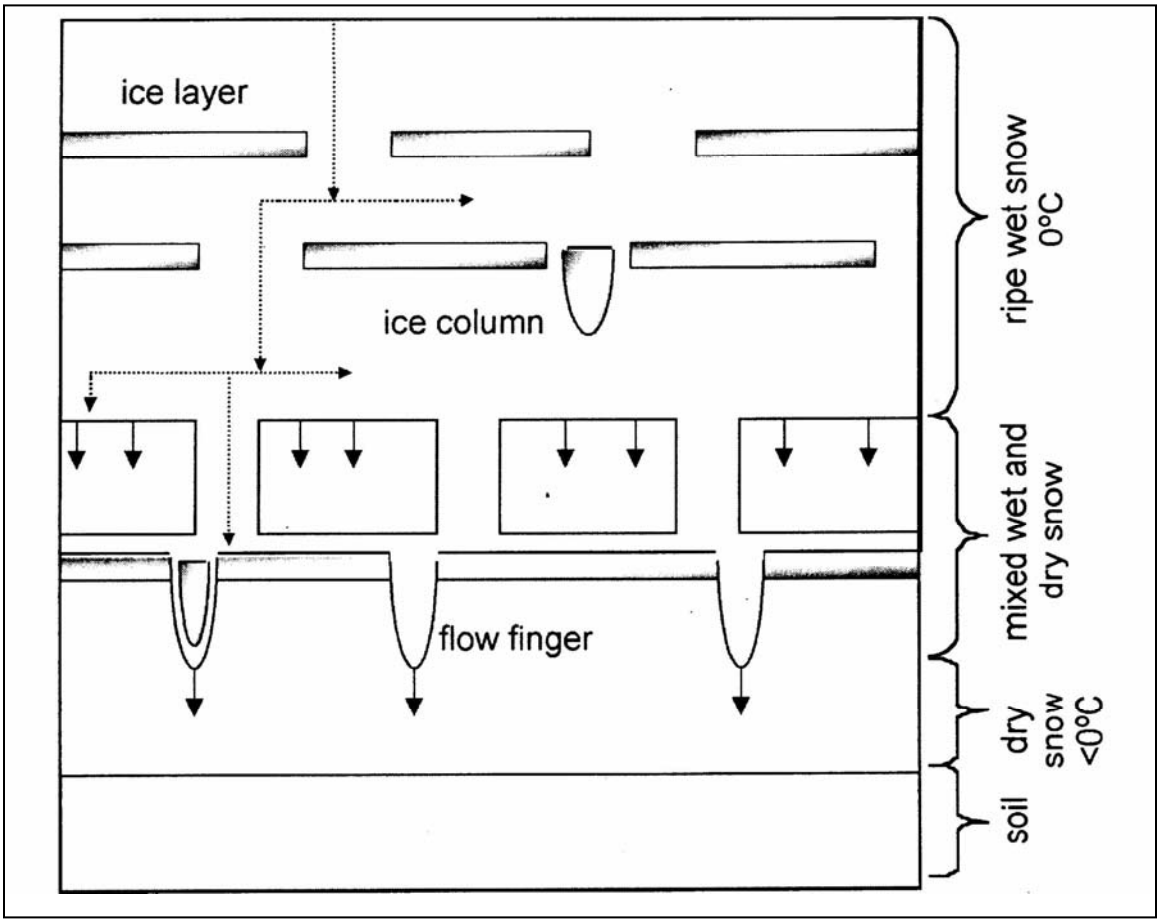
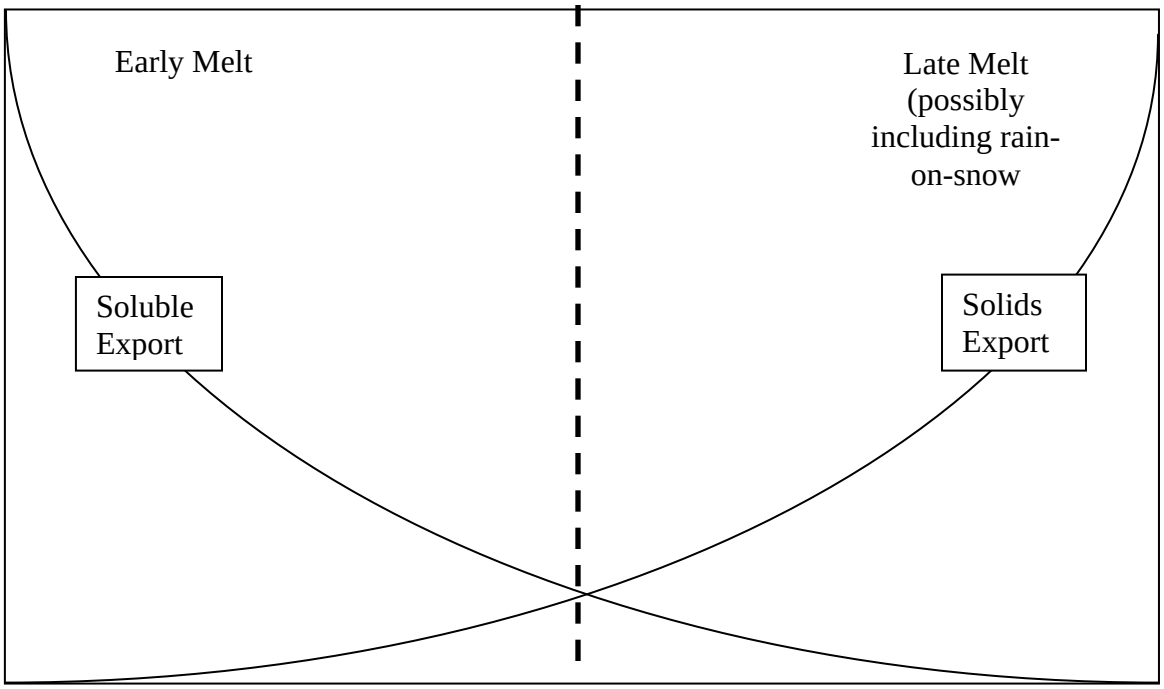


Figure 3. Percolation of Water Through a Snowpack, from UNESCO 2000 (Chapter 2, Semadeni-Davies and Bengtsson, as adapted from Marsh and Woo, 1984).

The management implication of the preferential elution process is illustrated in Figure 4. The graphic shows that the early part of the melt involves the very efficient elution of soluble constituents (ex., Cl, dissolved metals and nutrients, dissolved organics) at the crystal edges, resulting in a substantial release of the soluble component of a snowpack, often resulting in a shock effect as these pollutants reach a receiving water body. Following the release of solubles is a period when much of the liquid volume of the snowpack releases and carries with it the remaining solubles along with the beginning portion of finer-grained solids and associated contaminants (ex. hydrophobic PAHs). This inner-melt period generally has the largest portion of water runoff associated with the melt, and the mobilization of solids begins and continues as long as sufficient energy is available to move the particles. Because energy dissipates with the meltwater, much of the medium- to coarse-grained particulate material in a snowpack can remain after the snowpack is gone, leaving it, however, available for wash-off during the first rains of spring.

Part of the severity of the water quality problem associated with melt is that it occurs when the hydrologic system is least able to deal with it. Routine assumptions on biological activity, aeration, settling, and pollutant degradation are altered by the cold temperatures, cold water and ice covered conditions that prevail for many months. An end of the season rain-on-snow event often presents the worst-case scenario whereupon rain falls onto a deep, possibly saturated snowpack. The movement of a well defined, rapidly moving wetted front through the snowpack results in the mobilization of soluble constituents, plus the energy associated with the rainfall is sufficient to mobilize the fine-grained or possibly larger solids and associated contaminants. This wave of melt also washes over urban surfaces and picks up material that has been deposited on these surfaces all winter. Comprehensive reviews of the quality of snowmelt are presented in Chapter 4 (Marsalek, Oberts and Viklander) of the UNESCO 2000 report and in Novotny et al. (1999).

Figure 4. Generalized melt elution sequence (concentration vs. time) from Oberts, 2003.



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)

(Mis-)Management of Melt. For many years the old adage "one size fits all" was tried for the management of all runoff management. Once the effects of this approach were scrutinized, however, it became apparent that applying traditional rainfall runoff "best management practices" or BMPs were not working in spite of their success with rainfall (Oberts, 1990). Complications encountered in cold climates simply work against many of the commonly used BMPs, reinforcing the need for the development of "meltwater treatment practices" (MTPs?) better suited to address runoff in cold climates. Additionally, the behavior exhibited in Figure 4 is rarely considered when management approaches are designed.

Factors contributing to the failure of many traditional treatment practices include frozen conduits, the development of a thick ice layer, reduced biological activity, frozen or near-frozen soils, increased water density, and highly concentrated in situ and runoff quality pollutants (Caraco and Claytor, 1997). Typical results of these conditions include flow by-passing and flooding, lack of reaeration in the water column, decreased settling and biological uptake, flushing of previously settled material, and reduced infiltration capacity. Difficulties associated with management are discussed in detail in Chapter 6 (Oberts) of the UNESCO 2000 report.

Clearly, new approaches designed specifically to address these short-comings are needed if we ever hope to effectively manage meltwater runoff. This conference will present new research related to the effectiveness of management practices better suited to cold climate use, as well as the author's work in a presentation on management for cold climates.

RESEARCH NEEDS

Presenting the results of an exhaustive literature review of past research into meltwater management is far beyond the scope of this paper. Rather, a summary of a workshop following the Riksgränsen conference is given, and supplemented with additional thoughts. The workshop (March 2003) brought together a large group of cold climate researchers and meltwater practitioners to identify the future needs for research and collaboration. The following section summarizes the thoughts gathered at that workshop (in which the author participated), as well as some additional thoughts on where we should go from here.

Meltwater Character. The accumulation of snow and ice, and the manner by which it melts and runs off have been the subject of substantial research, yet we still struggle with accurate descriptions and predictive long-term models. Single event snapshots rather than continuous simulation have been the norm. The development of progressively sophisticated computer technology means that we are now able to build models that can accurately describe the behavior of snow over long time periods, and route the melt that occurs over an annual cycle of small mid-season and major end-of-season events. The details that are input to these models and the algorithms that define them, as well as connecting them to rainfall runoff models for an accurate annual water balance, all merit continued developmental research. New applications, such as the application of image processing and neural networks (Matheussen and Thorolfsson, 2003) to map and follow

the progression of snowfall through melt, show tremendous promise as our computer and imaging technologies improve.

The physical and chemical processes under way in a snowpack present an extremely complicated and variable set of phenomena. The freeze-thaw cycle and the elution of chemicals that it drives have been understood for many years, but details on the migration of the many chemicals of concern from the snowpack would benefit from a new focus on better field data. Management of these pollutants could be a key to improvement of regional meltwater quality.

The toxicity of the meltwater and the effects that these chemicals have on various receiving waters and related biological resources is still poorly understood. Through the works of J. Sansalone, J. Marsalek and many other researchers, we understand that meltwater can be extremely concentrated in many different toxic substances (metals, PAHs, organics, free cyanide, chloride). However, we know little about the impact of these substances on streams, lakes, groundwater and wetlands, and even less about their impact on plants, invertebrates, fish and other biological life.

The effects of road salting, especially the conservative element chloride (Cl), becomes increasingly important as the number of vehicles worldwide increases. With the increased number of vehicles comes a need to provide ever safer traffic-ways, which translates into ice-free roads for several months in cold climates. The increase in road salt has even led the Government of Canada to recommend the inclusion of Cl as a toxic substance because of the impact of this chemical on ground and surface waters. Associated with Cl is the anti-caking salt additive, sodium ferrocyanide. Although not toxic itself, ferrocyanide can break down to free cyanide, which is extremely toxic at low levels. Recent data (Table 1) collected in Minnesota from a group of large salt storage facilities (Minnesota Pollution Control Agency, unpublished data) and limited data from two County public works facilities during 2002-2003 (Oberts - unpublished data) has shown that chemicals associated with salting operations can reach very high levels in runoff from sites where salt is stored and handled, even if recommended handling procedures are followed. Additional data on this type of runoff is needed to better assess the impact of these common operations and to develop more effective management practices.

Table 1. Unpublished Water Quality Data from Minnesota Salt Storage and County Public Works Facilities.

Date (sample type, N=number of samples)	Sodium - mg/L Na	Chloride - mg/L Cl	Free Cyanide - µg/L FCN
1999 (MPCA* sampling of runoff in the vicinity of four large salt storage piles; N = 9)	--	--	120 - 1,500
7/10, 8/9, 8/21 and 11/8/02 (pre-season baseline samples in pond receiving public works facility runoff; N = 5)	14 - 150	19 - 230	ND - <100
11/8/02 (three shallow groundwater samples at public works facilities; N = 3)	71 - 4,210	188 - 7,540	ND
2/2/03 (mid-season melt event, surface water runoff during salting operations at public works facilities; N = 5)	6,260 - 16,700	15,400 - 29,400	ND (2 samples) - 21.0
3/14 and 3/20/03 (rainfall runoff immediately after snow/ice gone from public works facilities; N = 3)	346 - 1,470	530 - 2,200	ND

(*K. Cherryholmes, personal communication, 1999)

Management Approaches. Traditional "best management practices" or BMPs have been shown by many researchers to have serious short-comings when it comes to meltwater management. BMPs designed to treat rainfall runoff, as most were originated to do, are not well suited to deal with cold climate conditions, such as thick layers of ice, frozen conduits, greatly reduced biological activity and highly concentrated meltwater at a low temperature. Dealing adequately with cold weather runoff will require the evolution of an adapted set of "meltwater treatment practices" or MTPs that are specifically designed to operate under the rigors of cold climate.

The most commonly used rainfall runoff BMP has been detention ponding. Although much discussion and speculation on the performance of detention ponds during meltwater movement has occurred, the only fully equipped study of such a pond was done in Kingston, Ontario by Marsalek et al. (2000). Understanding better the dynamics of

sedimentation and resuspension will be necessary to building better detention systems in the future, and to retro-fitting the thousands in place already. Data collection on some of the meltwater treatment adaptations, such as seasonal detention, variable outlets, under-ice circulation, and first melt diversion into or around a treatment system, is greatly needed if we are to ever identify MTPs that are effective.

As mentioned above, the fate of toxics and Cl in meltwater is not well understood. Data collected on the performance of MTPs should include a definition of the toxic and Cl behavior associated with the treatment. Basic information on the dissociation dynamics of previously settled, particulate associated metals in highly Cl-concentrated pond water under ice, or the effectiveness of dormant wetland or swale vegetation at reducing PAH migration is needed.

Perhaps the most vexing problem facing cold climate water managers today in many parts of the world is the accumulation of Cl from the ever-increasing application of road salt (see Table 1 and the previous discussion). As a conservative element, Cl moves readily through all commonly used treatment devices and into both ground and surface waters. The only effective means to remove Cl is through reverse osmosis, which does not lend itself at all to the large volume of runoff associated with a melt event. The treatment approaches that seem to have some likelihood of success are less use (logical, but not in favor by many transportation managers), dilution (mix high load runoff with low load runoff) or detention and slow release to avoid toxic shock. Alternative chemicals have shown some promise in the past, but each alternative seems to bring associated impacts once scrutinized. However, the search for, and evaluation of alternative chemicals or artificial substances for de-icing or anti-icing must continue if we ever hope to reduce our reliance on NaCl. "Smart salting" is the pre-emptive application of deicer to prevent ice from forming. In Minnesota, the use of liquid $MgCl_2$ spray on bridge decks has proven to be an effective way to avoid repeated NaCl application at high doses. Continued data collection on the presence of Cl in receiving waters is essential to the development of a reasonably protective Cl strategy. Other routinely mentioned alternatives to NaCl use are calcium chloride ($CaCl_2$), calcium magnesium acetate (CMA), potassium formate (KFo), potassium acetate (KAc) and urea (used almost exclusively at airports).

Many new management systems are flooding the market today with promises of year-round effectiveness. Many of these proprietary systems are promising, yet most are untested in cold climates. Perhaps the most promising practices for meltwater are the treatment trains that incorporate settling, floatables skimming, and filtration through some kind of organic or synthetic media. Theoretically, these systems should be able to settle the solids associated with anti-skid grit added over the winter, then remove a fair portion of the soluble toxics also washing off in a melt. Unfortunately, conservative elements like Cl will move through these systems unchanged. This conference will hear from several of the proprietary system developers on the promise of their systems. In the U.S., the Environmental Technology Verification (ETV) program of USEPA has begun to test the claims of many proprietary units. The need for actual field data on cold weather performance must be stressed as part of the testing procedure on the effectiveness of these systems. The testing of the Austin Sand Filter by the California

Department of Transportation for alpine climates (Larsen and Alderete, 2003) is a good example of the many such efforts currently underway.

The movement in runoff management toward less structural, "low impact" development techniques shows a great deal of promise, yet the effectiveness of this approach when meltwater flows over fully or partially frozen soils has been questioned. More data on infiltration of meltwater in pervious parts of a watershed would yield valuable insights into how use of alternative or natural treatment systems could be used to better manage cold climate runoff from the entire year.

Finally, decision support for the selection, effectiveness assessment, and operation and maintenance (O&M) of MTPs is needed by practitioners in cold climates. Getting user-friendly information into the hands of those managing this runoff is essential. The information most requested by these managers seems to be data on the expected performance-specific practices. This is especially critical in light of the need to meet regulatory requirements for pollutant removal at a specified level.

Groundwater Impact. The most damaging meltwater component affecting groundwater appears to be the two elements associated with the most commonly used road salt - Na and Cl. The damage begins at the soil interface where Na can displace Ca and Mg and disrupt the physical structure of the soil column, and Cl can lower pH and dissociate heavy metals into more soluble and mobile forms. Although both of these chemicals can continue to migrate downward, it is mostly the Cl that presents a major threat. Much more data are needed before we can truly understand the complexity of the Cl threat. Although the threat is very real and has been documented with groundwater data in many places (summarized well in Marsalek, 2003), in other places, even within the same region, the threat is variable. Within the Twin Cities region of Minnesota, for example, groundwater from two watersheds shows some similar and some different results. A groundwater flowpath within the western Minneapolis-St. Paul region's Shingle Creek watershed (Figure 3, Andrews et al., 1999) has shown groundwater levels as high as several hundred mg/L Cl, which subsequently discharges as baseflow to the Creek at levels consistently between 20-100 mg/L throughout the year (Figure 4). Surface water Cl content has reached as high as 35,000 mg/L in recent stormsewer inflows to the Creek and similarly reached several thousand mg/L in the Creek itself (preliminary data from the Shingle Creek Watershed Management Commission, 2003). The South Washington Watershed District in the eastern part of the same region of Minnesota has shown groundwater Cl levels (Figure 5*) associated with a regional infiltration basin reaching lower peak levels (close to 100 mg/L), but has maintained levels in the same 20-100 mg/L range as Shingle Creek baseflow (groundwater). Site CDP85 shown in Figure 5 collects pumped runoff from a large urbanized basin prior to infiltration, while CDP69 collects localized runoff within a smaller urban area. Chloride levels in the groundwater at both SWWD sites remain within the range of surface water (SW) draining to the facilities. However, the three long-term CDP85 monitoring wells appear to be rising in

* Note in Figure 5 that "SW" = surface water site associated with the infiltration basin, and that "GW" denotes a series of groundwater monitoring wells around the infiltration basin at various depths.

Cl concentration, although some recent values are certainly within the range of those collected in the early- to mid-1990s. Since the character of the surficial material in the Shingle Creek and SWWD areas is essentially the same, the major difference appears to be in the amount of salt applied to the surface and the routing of salt-laden runoff before it infiltrates. Additional data collection continues on both of these areas within the Twin Cities region. Exploration of factors determining the behavior and accumulation of Cl in groundwater will help shed light on how to avoid contaminating the source that many relay upon for drinking water.

Figure 3. Chloride Behavior along an Urban Groundwater Flowpath in Minnesota (July 1997, from Andrews et al., 1999).

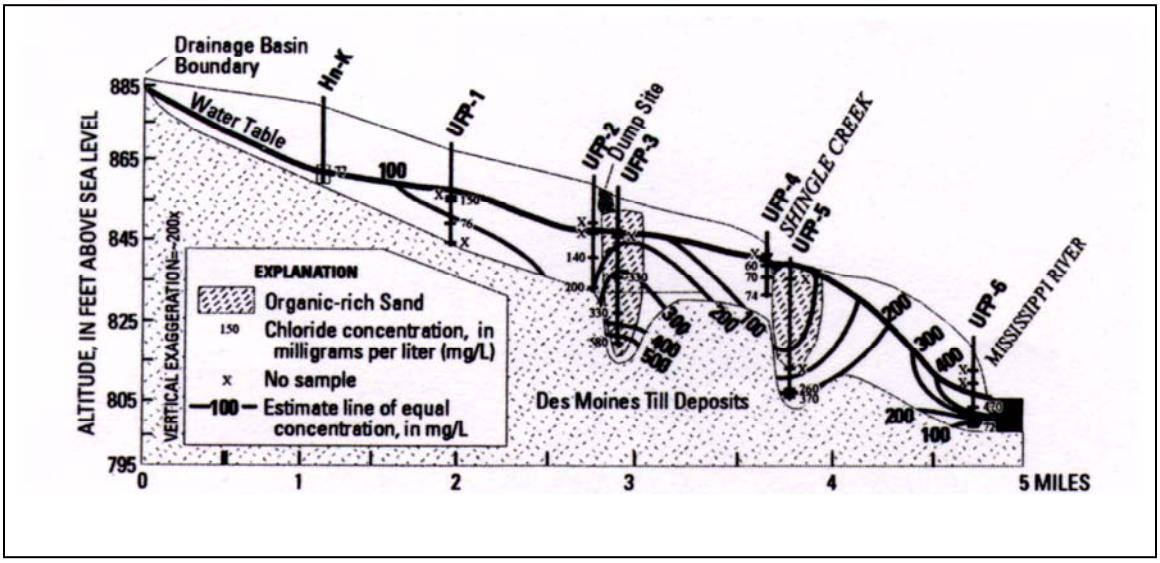


Figure 4. Shingle Creek (surface water) Chloride Data (Shingle Creek Watershed Management Commission data).

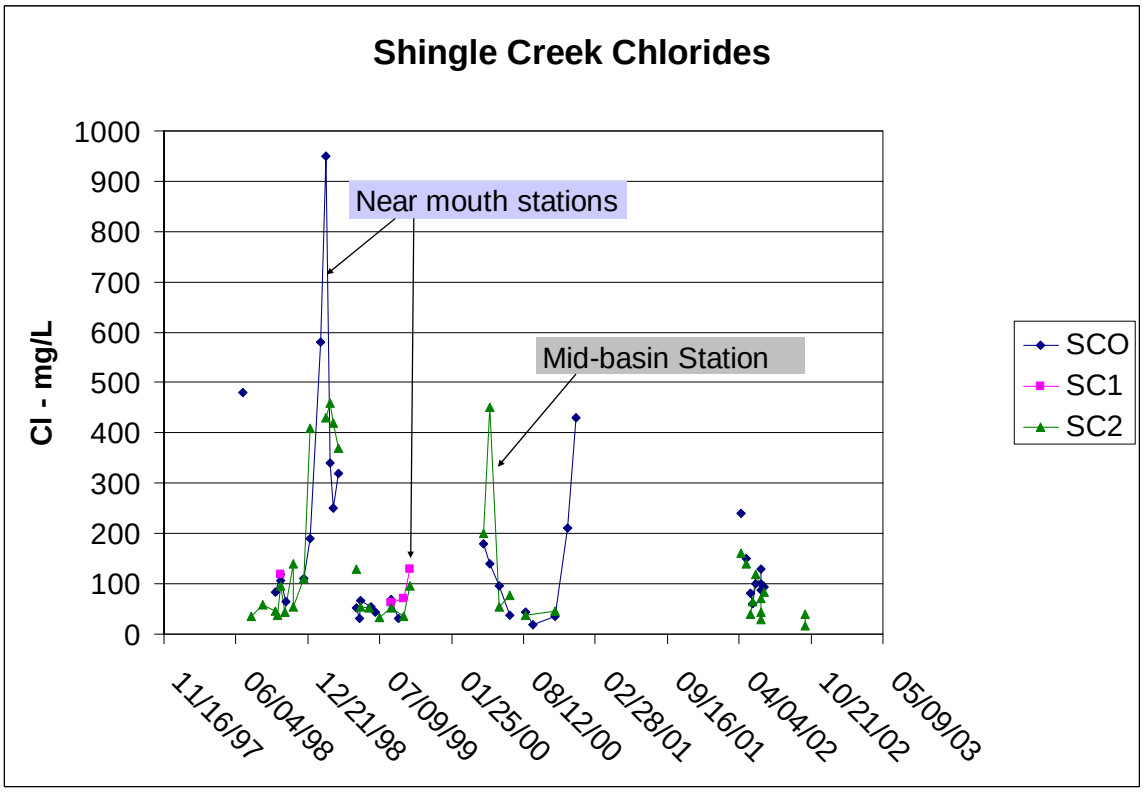
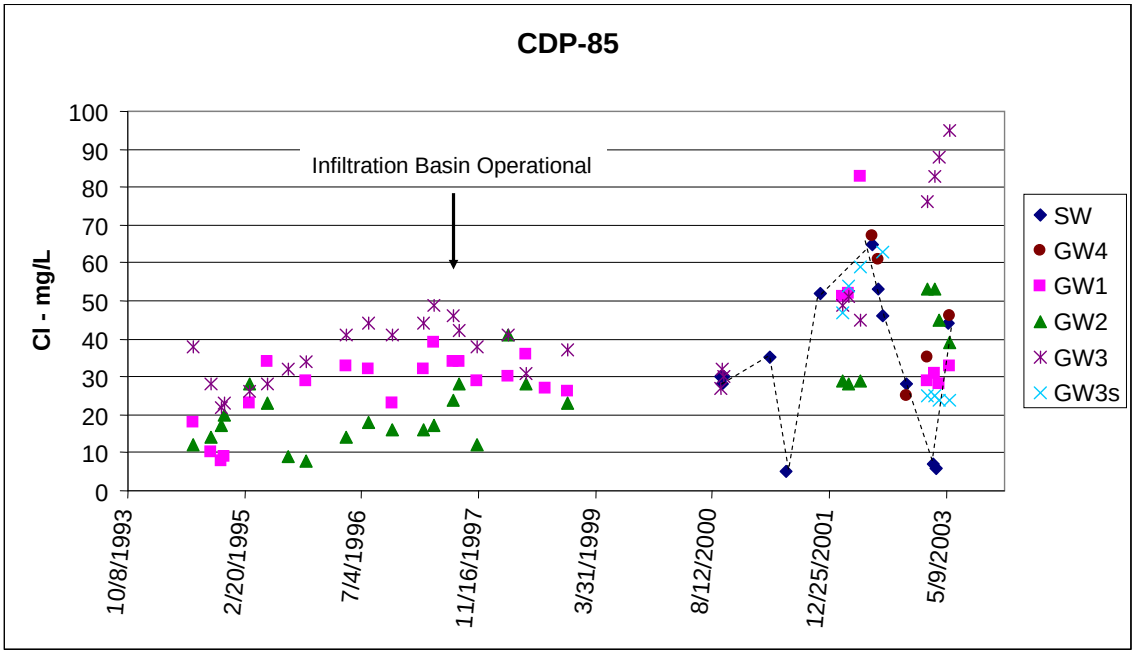
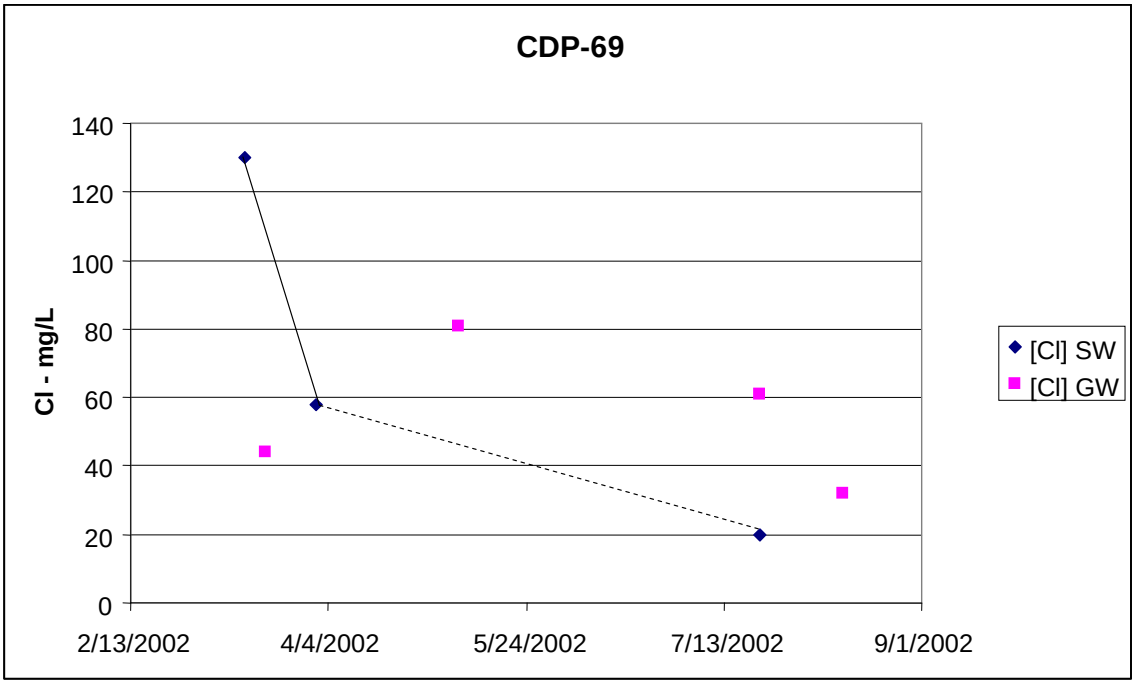


Figure 5. Comparison of Cl in Surface and Ground Water at Two Minnesota Infiltration Sites (South Washington Watershed District, Minnesota data).





Wetland, Open Space and Biological Impacts. There are scant data available on the impact of meltwater on wetland systems and associated open space areas. The classic work by Isabelle et al. (1987) defines the potential damage that meltwater presents, but follow-up data collection in other systems and other geographic areas has not occurred to a large extent. This information is critical as we enter a period when the use of "natural systems" for runoff management is increasingly promoted. Is this a wise thing to suggest for meltwater routing, or should these areas be avoided for the portion of the annual cycle involving snowmelt? Marsalek (2003) summarizes the impacts of meltwater runoff on wetlands and receiving water biota. Among these impacts are species shifts to less desirable species, increased toxicity to various biota, and decreased diversity.

Snow Management. The plowing, relocation and collection of snow presents some very real management questions in need of support data. In most urban areas, a number of approaches are followed depending upon the level of urban density. In residential areas, snow is generally plowed to the side of the road and allowed to accumulate there all winter long. However, in commercial/industrial zones, snow is often plowed to a corner of a parking lot, and in densely-developed urban centers, snow is often removed to a totally different, often remote area, where it is dumped for an entire winter season. The pros and cons of these different approaches were described in several presentations at Riksgränsen, yet local practices seem to vary considerably based on tradition, expectations and the cost of removal operations. Assuming snow is collected, the design of "snow dumps" must take into account the fact that snow eventually melts and will need somewhere to flow, either off of the land surface or into the ground. Some suggestions for design were proposed by Wheaton and Rice (2003) based on the Anchorage, Alaska experience, but much more data are needed to build a good suite of sampled designs. Of particular need is data on the impact of these facilities on both ground and surface waters. Until adequate data are available, commonly accepted snow dump practices include location well away from surface water bodies and well above the groundwater table, spring clean-up of debris left after the snow melts away, and location on a flat slope with well drained soils, although location on an impermeable pad, followed by collection and treatment can also be a viable option (Wheaton and Rice, 2003).

Climate Change. Regardless of the results of the debate raging on the cause of changing climate, it is clear that we are in a period of global warming. The results of this phenomenon on the character of snow accumulation and melt could be substantial in the long-term. It seems clear that snow will fall in changed patterns and that which falls will accumulate less; that snowfall terminus lines will shift northward, and upward in elevation; that the mix of ice storms and rain-on-snow will increase; that the timing and rate of snowmelt will vary from current conditions; and that the likelihood of catastrophic flooding events associated with rainfall during spring melt will increase. This is a future that could also imply more chemical use to provide road safety, less chance for effective storage of snowmelt for later use, and altered annual water balances. It is also assured that any scenario for the future will include a substantial amount on uncertainty, which we must define if we ever hope to plan with any success (Jones, 2000; Semadeni-Davies, 2003a). In fact, Roads et al. (2003) in analyzing various U.S. climate simulation models, found model predictions of runoff often with errors from 50-100%. Uncertainty will

include both climatic factors and social factors as we implement solutions to perceived and real problems. Clearly, better cold climate data analysis, continued input of data into the development of future scenarios, assessment of the variability associated with those scenarios and the repercussions for cold climate hydrology and water quality, and identification of possible management changes are all important research needs that must feed into the continuing discussions on the possible effects of climate change. Local/regional impact evaluations, similar to those conducted for northern California (Miller et al., 2003), for Sweden (summarized in Bergström, 2003) and locally for Lycksele, Sweden (Semadeni-Davies, 2003b), should be done for all areas potentially impacted by changes in the character of snow accumulation and depletion. Hedstrom et al. (2001) used the Cold Regions Hydrological Model to assess potential prairie hydrologic changes on a watershed scale near Lethbridge, Alberta. These kinds of evaluations are needed to bring global and national scale modeling into local perspective, and conversely, these data are needed as input to improve the larger-scale models.

Planning and Education. All of the above research and work will be meaningless if the results do not get properly interpreted and distributed, both to the local officials making decisions and to the public that must live with those decisions. For example, a public clamoring for ice-free roads is in direct conflict with a reduced salt strategy. Local officials also need data and technical assistance to make good decisions on meltwater management. A design manual designed for this purpose was prepared by the Center for Watershed Protection in 1997 and will be updated as a result of a workshop held as part of this conference. Preparation of more of this kind of "on-the-ground" technical information in the hands of everyday managers is essential if we ever hope to improve water management in cold climate areas.

HOPES FOR THE FUTURE

This conference provides an excellent opportunity for discussion of both past revelations and exciting new findings. It is the hope of this author that many results will come from these discussions. Success will be achieved if in the next decade we can see:

- Closer work between those developing models of snow physics and hydrology, and those assessing the water quality impacts;
- Fully descriptive snow and meltwater quantity and quality models in the hands of all interested users;
- A substantial database on the performance of a whole new suite of meltwater treatment practices;
- An understanding of what will happen in cold climate regions of the world as the climate continues to change;
- Full knowledge of the fate of chloride and toxic material carried in meltwater and development of management systems that mitigate those effects;
- Better technical assistance available for cold climate water managers; and
- An understanding of the biological repercussions of routing snowmelt into biological systems.

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