

Article 3

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Influence of Snowmelt Dynamics on Stormwater Runoff Quality

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Potential water pollution associated with melting snow are a concern to watershed managers in northern climates. In fact, in some urban areas, substantial portions of the annual load of pollutants such as hydrocarbons, metals, solids, nutrients, and chlorides come from snowmelt and early spring runoff events. Thus the annual cycle of pollutant build-up and subsequent release during snowmelt can be a real threat to the attainment of water quality objectives.

This article examines the mechanisms involved in snow pollutant accumulation and the movement of various pollutants from the snowpack. With this knowledge practitioners can plan management actions to anticipate changing flows and pollutant concentrations. Techniques that can be incorporated include the designation of “salt-free” areas near key streams and wetlands, and dumping plowed snow in pervious areas where melt water can infiltrate.

The Snowmelt Sequence

Snowmelt can be described as a predictable process with three distinct stages (Figure 1). The first melt stage

is called *pavement melt*. As the name implies, it occurs when deicers are applied or the sun shines on heat-absorbing paved areas. These applications result in a winter-long sequence of chemically-driven melt events in which very saline water carries accumulated road pollutants into drainage systems and local receiving waters.

The second melt stage involves the more gradual melt of snow piles adjacent to road surfaces. *Roadside melt* contributes runoff intermittently as chemical splash and solar radiation gradually reduce piled snow. The final stage of the snowmelt sequence is the melt of non-paved pervious areas of the site, such as grassed lawns. The *pervious area melt* stage has the potential to contribute a substantial volume of runoff quickly, particularly when accelerated by a rain event.

Runoff Quantity

The volume of runoff generated by each of the three melt stages is dictated primarily by the amount of snow and the weather conditions (Table 1). In most cases, runoff produced during pavement melt is not substantial. The end-of-season melt of the snowpack (i.e.,

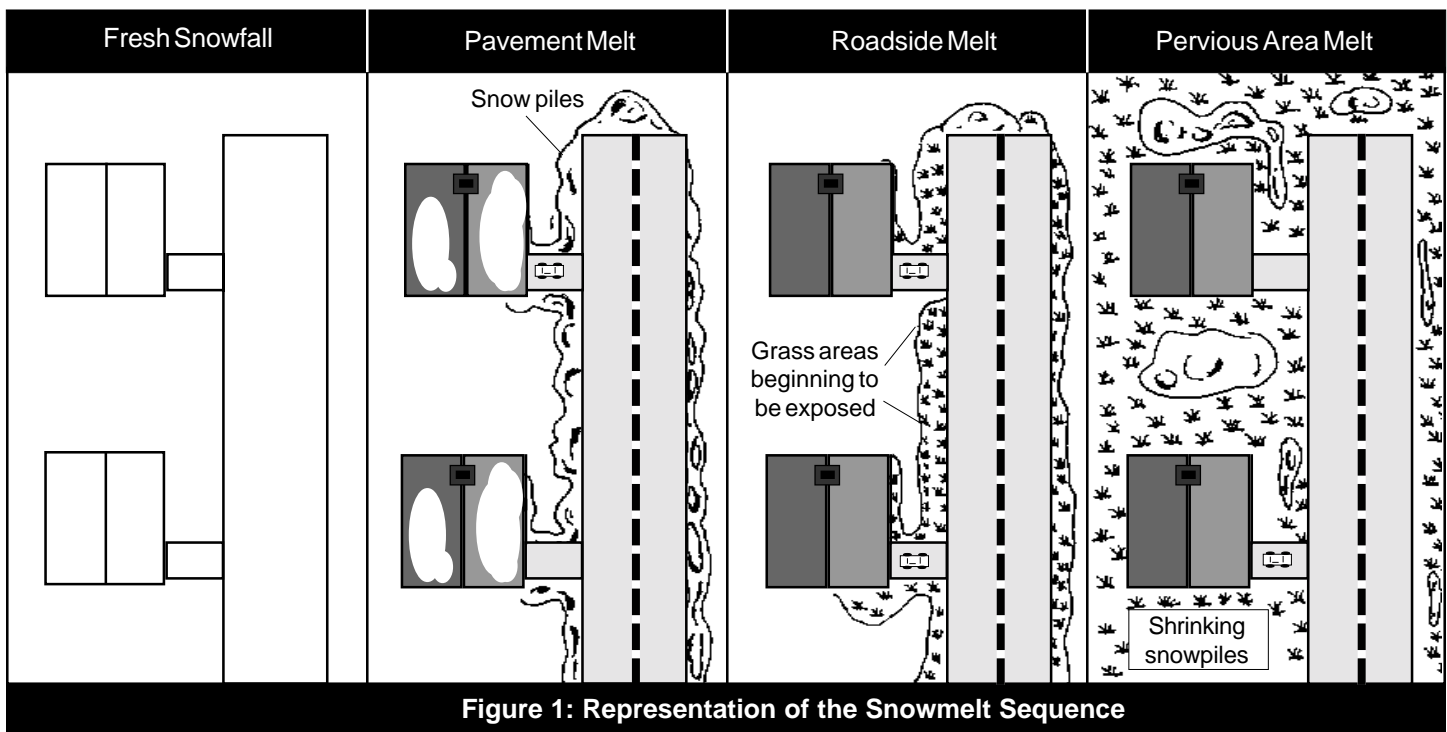


Figure 1: Representation of the Snowmelt Sequence

roadside and pervious area melt), however, often constitutes the largest single annual runoff event in northern climates. Often this melt lasts several weeks and can be magnified with concurrent rainfall (Bannerman *et al.*, 1983; Glancy, 1988; Westerstrom, 1984).

Figure 2 is an example of the significance of the large runoff produced by an end-of-season snowmelt event in an urban catchment in Minnesota (Oberts *et al.*, 1989). The importance of the melt event was magnified by several rain-on-snow events that occurred from mid-March to early-April, 1989. The snowmelt runoff is dramatic relative to the annual water budget, particularly when compared to runoff from the larger rain events (e.g., a 3.41 inch storm — 10-year frequency — that occurred in May, 1988).

Runoff Quality

Pollutant Sources

Pollutants accumulate in snow due to several processes. First, falling snowflakes are effective scavengers of both particulate and aerosol pollutants (Colbeck, 1978). After snow has fallen, the snowpack is subject to both episodic and continuous deposition of airborne pollutants from local urban emissions, as well as long distance transport of pollutants from activities unrelated to the locale (Couillard, 1982; Landsberger and Jervis, 1985; Schondorf and Herrmann, 1987; Vuorinen, 1986; Zajac and Grodzinska, 1981). Atmospheric deposition of toxic chemicals, nutrients, and solids have been noted on urban surfaces throughout the winter from sources such as fossil fuel combustion, refuse incineration, chemical processing, metal plating, and manufacturing (Boom and Marsalek, 1988; Horkeby and Malmqvist, 1977; Malmqvist, 1978; Novovny and

Chesters, 1981; Schrimpff and Herrmann, 1979).

Pollutants are also directly deposited on the snowpack and other cleared surfaces in winter. Most of the street surface studies, however, have not focused on the build-up of pollutants under snowy conditions. This omission is critical because street loads of sediment and toxic materials are at an annual peak at the onset of winter melt and early spring rainfalls (Bannerman *et al.*, 1983). Vehicular deposition of petroleum products/additives and metals, the direct application of salt and anti-skid grits, and roadway deterioration are major contributors to the pollution of road surface snow (Malmqvist, 1978; Oberts, 1986; Soderlund *et al.*, 1970).

“First Melt” Effect

Roadway snow is quickly removed by rapid melt through salt application, removal to a dump site, or plowing over the roadway curb/edge. The first action results in immediate runoff, usually involving small volumes of water and a minor portion of the annual pollution load, although concentrations may be high (Novotny and Chesters, 1981). For example, in 1980 small mid-winter melts in Minnesota accounted for less than 5% of the annual total phosphorous and total lead loads, respectively. In contrast the end-of-winter melt accounted for about eight to 20% of the annual phosphorus and lead loads (Oberts, 1982).

Runoff pollution from snow removed to a dump site is a topic that has been well studied, particularly in Canada. High levels of chloride, lead, iron, phosphorus, biochemical oxygen demand, and total suspended solids have been reported in snow dump runoff (La Barre *et al.*, 1973; Oliver *et al.*, 1974; Pierstorff and Bishop, 1980; Scott and Wylie, 1980; Van Loon, 1972).

Table 1: Runoff and Pollutant Characteristics of Snowmelt Stages

Snowmelt Stage	Duration/Frequency	Runoff Volume	Pollutant Characteristics
Stage 1. Pavement Melt	Short, but many times in winter	Low	Acidic, high concentrations of soluble pollutants, Cl ⁻ , nitrate, lead. Total load is minimal.
Stage 2. Roadside Melt	Moderate	Moderate	Moderate concentrations of both soluble and particulate pollutants
Stage 3a. Pervious Area Melt	Gradual, often most at end of season	High	Dilute concentrations of soluble pollutants, moderate to high concentrations of particulate pollutants, depending on flow.
Stage 3a. Rain-on-snow Melt	Short	Extreme	High concentration of particulate pollutants, moderate to high concentrations of soluble pollutants. High total load.

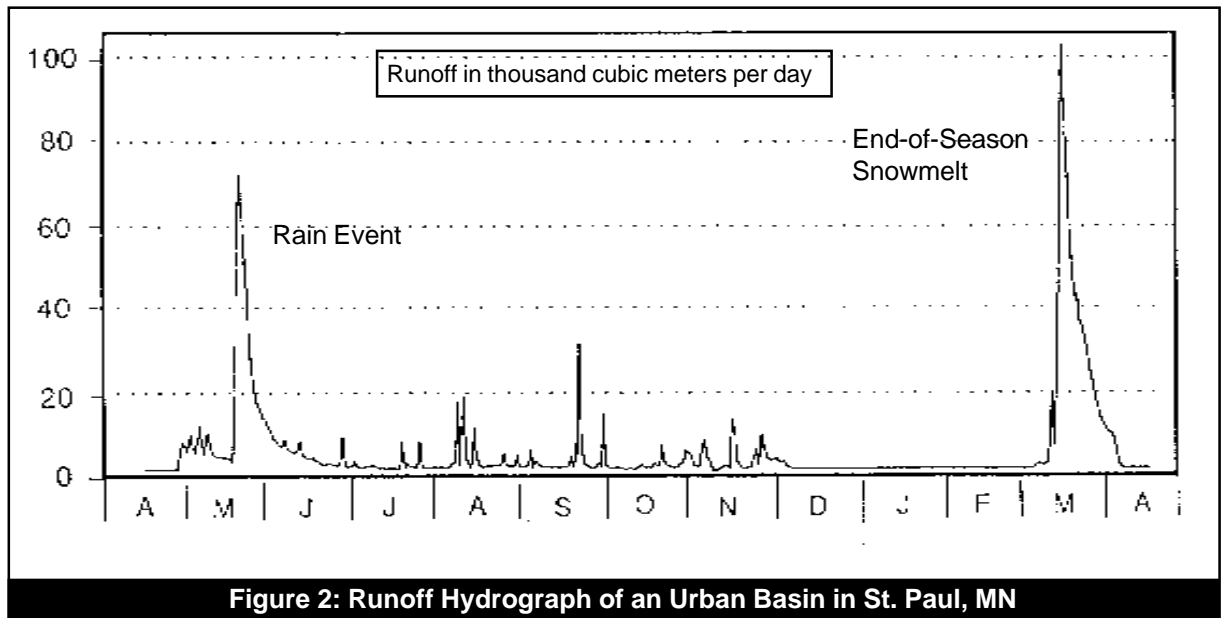


Figure 2: Runoff Hydrograph of an Urban Basin in St. Paul, MN

Roadside Snowpack

Plowing snow over to the roadside edge allows for the accumulation of debris, chemicals, grit, and litter over an entire winter. This material is easily mobilized in either short, chemically-driven melts or larger end-of-season runoff events. Material may also remain available for early spring rainfall washoff. Levels of contamination in a roadside snowpack can reach or even exceed that of a snowpack at a dump site (Oliver *et al.*, 1974; Pierstorff and Bishop, 1980; Scott and Wylie, 1980; Van Loon, 1972).

Once pollutants collect in a snowpack, a process of pollutant speciation associated with the freeze/thaw cycle begins to develop. This process has been called several different terms, including “freeze exclusion,” “preferential elution,” and “acid flushing.” All these terms refer to basically the same phenomenon wherein soluble pollutants are flushed from throughout the snowpack and concentrate at the bottom of the pack.

Several authors describe a process that begins when snowflakes respond to freezing and thawing cycles by metamorphosing (when ice crystals enlarge and round) (Colbeck, 1981; Hibberd, 1984; Schondorf and Herrmann, 1987). The reforming crystalline lattice does not allow impurities to be incorporated, so the impurities migrate to the outside of the crystal. They are loosely bound in this position and thus exposed for washoff by passing meltwater.

The heterogeneous nature of the snowpack allows for channelized meltwater to scavenge soluble pollutants randomly until the pack is saturated, whereupon pollutant mobilization becomes more uniform throughout the pack. In this condition, soluble pollutants are collected in a “wetted front” that moves through the pack, eventually reaching the bottom. At this position they intersect the soil or other surface and move from

the pack as a highly concentrated, usually acidic, pulse of meltwater. This “first flush” of concentrated snowpack meltwater will either infiltrate into the soil or runoff, depending upon the conditions of the surface soils underlying the snowpack.

The degree to which soluble pollutants are washed from the snowpack depends upon the number of freeze/thaw cycles during the winter and whether the pack receives any outside moisture. Repeated freezing and thawing “purify” the hexagonal crystals and any added moisture mobilizes the released pollutants more quickly. Johannessen and Henriksen (1978) found in both laboratory and field studies that about 40 to 80% of 16 pollutants were released from experimental snowpacks with the first 30% of the liquid melt. This process seemed to be independent of the initial snowpack concentration of the pollutants. Their studies also showed that pollutant concentrations in the initial melt were two to 2.5 times greater than those in the remaining snowpack (reaching as high as 6.5 times the snowpack levels in the very first fractions of melt).

Zapf-Gilje *et al.* (1986) found in their study of frozen secondary effluent that the first 20% of a melt contained 65% of the phosphorus and 90% of the total nitrogen. The removal was not related to initial pollutant content in the frozen effluent. In contrast, Schondorf and Herrmann (1987) reported that 90% of the particulate-associated polycyclic aromatic hydrocarbons (PAHs) in a snow column were contributed in the last 10% of the melt.

Particulate matter is filtered or coagulated with other particles as it moves through the snowpack and remains behind while the soluble component washes through. Pollutants such as tightly bound organics and metals adsorb to sediment and organic compounds. Schondorf and Herrmann (1987) also found that rain-on-snow

washes fine-grained particulate through the pack and flushes out metals and adsorbed organic pollutants.

Infiltration

Infiltration can occur at the bottom of a snowpack even into frozen or partially frozen soils. In fact, the very first portions of a melt generally infiltrate until the soil becomes saturated, leading to a progressive reduction in infiltration capacity (Bengtsson, 1984). Novotny (1988) explains that infiltration of substantial volumes of meltwater can occur into clay and loam soils, as well as sands, if impermeable frozen layers do not form before snow cover. The formation of these “concrete frosts” is a function of the amount of pore-water of the soil (Bengtsson, 1984).

Less soil moisture at freeze-up allows more meltwater to move through the available pore spaces. Once soils are saturated, however, the amount of runoff from the soil surface becomes a function of the degree of melt and the amount of downward movement of water through saturated soils. This situation can make the entire catchment 100% “functionally impervious” with the catchment actually contributing meltwater runoff. Bengtsson (1984) and Colbeck (1978) demonstrated that infiltration can vary from zero to 100%, depending upon the nature of the soil, the water content of the soil at freeze-up, and the degree of saturation reached during a melt event.

Runoff

The net effect of freeze exclusion is that meltwater moving from a snowpack has a different chemical quality depending upon the stage of the melt. Early in the melt, the primary movement out of the pack will be from soluble pollutants, followed by the particulate fraction. This applies only to water as it moves from the snowpack, however. It should be noted that the large volume of meltwater leaving the pack, particularly at peak melt, also can wash off accumulated pollutants from paved surfaces as well as picking up additional pollutants from saturated soil surfaces.

Because the initial stages of melt are generally slow, the first melt stage runoff exerts a concentration “shock” of highly soluble pollutants, but not a high pollution load. More runoff is produced in the latter stages of the melt, which can generate high concentrations and high loads because particulates are washed out of the pack.

Rain-on-snow

Extreme pollutant loads can be experienced during the end-of-the-season melt if rain falls on a deep, saturated snowpack that has undergone repeated freeze-thaw cycles (Couillard, 1982; Schondorf and Herrmann, 1987). This event leads to a sudden release of soluble pollutants from the wetted front at the same time that soluble and particulate pollutants are flushed from the snowpack by the rainfall.

The large volume of melt runoff associated with rain-on-snow events also flushes pollutants that have accumulated on paved and soil surfaces. The intensity

Table 2: Flow-Weighted Mean Snowmelt Concentrations in St. Paul Area by Site Type Compared With National NURP Study Averages. Data Reported in mg/l. (N)=No. of events.

	Total susp. solids	Volatile susp. solids	Chemical oxygen demand	Total phos.	Dissolved phos.	Total Kjeldahl nitrogen	Nitrate	Chloride	Total lead
Storm Sewers N=(20-40)	148	46	169	0.70	0.25	3.52	1.04	230	0.16
Open Channels N=(1-5)	88	15	82	0.56	0.18	2.36	0.89	49	0.2
Creeks N=(2)	64	---	84	0.54	---	3.99	0.65	116	0.08
MEDIAN	112	38	112	0.70	0.18	3.39	0.91	116	0.10
NURP*	---	---	91	0.46	0.16	2.35	0.96	---	0.18

*Runoff concentrations were obtained from over 2,300 rainfall events monitored at 22 project sites across the nation

of a rain-on-snow event is usually greater than a summer thunderstorm because the soil is saturated or frozen and the rapidly melting snowpack provides added runoff volume.

Levels of Pollution

Monitoring of pollutant concentrations in snowmelt runoff is much more scarce than monitoring of stormwater runoff. Research in the Minneapolis-St. Paul region of Minnesota over the last decade has shed more light on pollutant concentrations in snowmelt. Runoff data from 49 short-term January and February snowmelts and end-of-season March and April snowmelt events are provided in Table 2 (Oberts, 1982; Oberts and Osgood, 1988; Oberts *et al.*, 1989). For comparison, the table also lists national runoff concentrations obtained from NURP sites (USEPA, 1983). Snowmelt runoff contains elevated levels of solids, nutrient, and chemical oxygen demand (COD), in addition to the high levels of lead and chloride. Both total and volatile suspended solids concentrations in snowmelt runoff are considerably lower than the flow-weighted mean concentrations from rainfall events collected at the same sites. Concentrations of COD, organic nitrogen (TKN), and lead are higher in the melt events for most sites, and chloride and nitrate are much higher in the melt at all sites. Total and dissolved phosphorous are generally similar for both snowmelt and rainfall runoff.

A review of monitoring data from other locations shows that the Minnesota values are within the range of snowmelt runoff quality observed elsewhere. Snowmelt runoff measured in Ottawa revealed that even though high concentrations of lead and chloride accumulate in snow dumps and along roadsides, the actual levels in runoff are much lower (La Barre *et al.*, 1973; Oliver *et al.*, 1974). This is thought to be due to infiltration and adsorption of pollutants to soils during melt. For example, lead concentrations in Ottawa roadside and snow dumps reached levels as high as 113 mg/l, but concentrations from this snow after it had melted declined to <0.01 to 1.19 mg/l.

Sediment samples taken from a river near the dump sites showed lead levels as high as 1,344 mg/kg, but dropped to 183 mg/kg the year after dumping stopped near the site. Chlorides from this same study in Ottawa reached as high as 15,266 mg/l in a snowpack adjacent to a street in a commercial area and 2,500 mg/l at the dumps, but runoff levels from a storm sewer in the city declined to 219 mg/l (again close to the Table 2 values for runoff) and the dump averaged 500 mg/l.

Soderlund *et al.* (1970) reported snowmelt runoff in Stockholm reached levels as high as 450 mg/l chloride, 12 mg/l oil, and 1.0 mg/l total phosphorus. The authors found that rapidly rising temperatures generated a substantial volume of meltwater, which then washed a

tremendous amount of accumulated winter debris from street surfaces. Again, monitoring the rain events during or shortly after the melt of the snowpack yielded very high concentrations of many pollutants.

Pierstorff and Bishop (1980) reported that dump site melt runoff from Durham, New Hampshire and elsewhere reached as high as 664 mg/l Cl, 50 mg/l COD, and 13 mg/l oil and grease. Boom and Marsalek (1988) found that PAH levels in Sault Ste. Marie, Ontario, meltwater runoff (3 to 12 µg/l) differed little from the levels seen in the snowpack. Couillard (1982) noted that melt events exhibited very toxic levels of metals and that rain occurring during a melt tended to dilute the concentration, and hence the toxicity, of meltwater.

Alley and Ellis (1978) recorded mean meltwater lead levels of 0.7 mg/l, and similarly high concentrations of several other trace metals in Denver, Colorado. Bannerman *et al.* (1983) reported the highest annual concentrations of TSS, Cl, lead, and total zinc were recorded in meltwater and early spring rainfall events in most of their Milwaukee, Wisconsin monitoring sites. They also noted that significant loads of sediment and trace metals are produced during this short interval, with 20 to 33% of the annual load being contributed.

This finding is consistent with Minnesota meltwater where a substantial amount (about 65%) of the annual sediment, organic, nutrient, and lead load, and virtually all of the chloride load from urban areas are produced by snowmelt and early spring rainfall events (Oberts, 1982). Total loads of pollution are often of more concern than concentration, depending upon whether the receiving water is most sensitive to the strength of a pollutant or to total accumulation. For example, lakes respond to nutrient loads, whereas aquatic life in a stream are more likely to be concentration sensitive and react to the peak concentrations of the toxic materials.

Conclusions

Snowmelt runoff comes from short duration, chemically driven events and from longer duration, end-of-season events. Meltwater runoff carries pollutants that have accumulated all winter in the snowpack, as well as street and soil surface material that washes off of these surfaces. Atmospheric fallout, industrial activity, vehicular emissions/corrosion/fluid leaks, roadway deterioration, urban litter, and anti-skid grit and chemical deicers are sources of the solids, nutrients, and toxic materials that accumulate in a snowpack. Soluble pollutants are preferentially leached or purged from the snowpack in the early stages of the melt. Later melt stages carry the particulate fraction along with a large volume of meltwater, which also washes pollutants from the urban surface.

Table 3: Watershed Protection Techniques for Snow and Snowmelt Conditions

- Use of De-icing Compounds
 - Use alternative de-icing compounds such as CaCl₂ and calcium magnesium acetate (CMA)
 - Designate "salt-free" areas on roads adjacent to key streams, wetlands, and resource areas
 - Reduce use of de-icing compounds through better driver training, equipment calibration, and careful application
 - Sweep accumulated salt and grit from roads as soon as practical after surface clears
- Storage of De-icing Compounds
 - Store compounds on sheltered, impervious pads
 - Locate at least 100 feet away from streams and flood plains
 - Direct internal flow to collection system and route external flows around shelters
- Dump Snow in Pervious Areas Where It Can Infiltrate
 - Stockpile snow in flat areas at least 100 feet from stream or floodplain
 - Plant stockpile areas with salt-tolerant ground cover species
 - Remove sediments and debris from dump areas each spring
 - Choose areas with some soil-filtering capacity
- Blow Snow from Curbside to Pervious Areas
- Operate Stormwater Ponds on a Seasonal Mode
- Use Level Spreaders and Berms to Spread Meltwater Over Vegetated Areas
- Intensive Street Cleaning in Early Spring can Help Remove Particulates on Road Surfaces

An understanding of snowpack and snowmelt dynamics is useful to develop effective techniques for treating snowmelt runoff. Different techniques should be employed at each stage of the meltwater sequence, so as to effectively address the constantly changing flows and pollutant concentrations that occur as the melt progresses. A list of some effective techniques is provided in Table 3. **See also articles 71, 75 and 139.**

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