Early Spring Snowmelt in a Small Boreal Forest Watershed: Influence of Concrete Frost on the Hydrology and Chemical Composition of Streamwaters during Rain-on-Snow Events

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ABSTRACT:

The hydrology and geochemistry of meltwaters and streams during rain-on-snow events in a small boreal watershed in eastern Canada indicated that rapid runoff might occur during pre-melt and early melt periods due to the presence of concrete frost in litter and upper organic soil horizons. The approximate extent of concrete frost cover in the catchment was estimated from prevailing meteorological conditions for the winter–spring periods in 1982–83 as "high" (>75% cover); in 1983–84 as "medium" (≈50% cover) and in 1984–85 as "low" (<5% cover). When concrete frost coverage was medium to high then runoff was 20% to 40% of melt + rainfall to the concrete frost area of the basin. The efficiency with which runoff from concrete frost "contributing" areas reached the stream was 25–50%, but increased to near 100% for a high rain on snow event. However, the "efficiency" of chemical relocation in runoff from contributing areas varied from 60% to 600% depending on the species used as a tracer. This large range of values can be ascribed to the leaching of ground cover, litter and organic soil above or embedded in the frost cover, the patchiness of frost cover, erosion of the frost cover and flow through riparian zones. It is concluded that simple direct routing techniques will not always be able to successfully describe the complex phenomenon of runoff from variable frozen ground at small to medium scales.

Keywords: frozen soils, concrete frost, infiltration, runoff, snowmelt, snow chemistry, interflow routing, spring freshet.

INTRODUCTION

In eastern Canada, snow meltwaters can be a major factor in the availability and redistribution of nutrients and solutes in forested watersheds. For example, snow only contributes 35% of the annual precipitation in the Forêt Montmorency Boreal Forest Experimental Research Area (Lac Laflamme watershed) in southern Quebec but more than 50% of annual runoff occurs in the spring (Papineau, 1989). At the time of maximal accumulation prior to melt, the snow cover also contains up to 45% of the annual nitrogen [N] precipitation load (18%, NH_4; 27%, NO_3; Papineau, 1987). Although some losses of readily bio-available N (NH_4, NO_3) are due to microbiological assimilation in melting snow (Jones, 1999), meltwaters can deliver up to 30% of the annual N precipitation load to the forest floor during the short (2–3 weeks) spring runoff. In addition, solutes and nutrients leached from soil horizons and litter are also made available (Taylor and Jones, 1990).

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The overall efficiency of nutrient uptake by forest floor communities is dependent on many competing and complex processes such as biological assimilation rates, physical adsorption and desorption and removal by hydrological transport. Nutrient uptake, e.g. N, will be favoured by relatively long residence times in the soil horizons during melt that allow microbiological communities to achieve growth and roots to assimilate N. In the case of runoff that travels rapidly over the soil to the streams and lake the soil residence time of the meltwaters will be less and biological uptake of N should be reduced. Reduced soil residence times will thus lead to increased export of nutrients and solutes from snow and litter to the streams and lakes of the hydrological network. While many hydrological routing schemes transfer meltwater directly from a land element to streams or lakes (e.g. Kite and Kouwen, 1992) or use implicit routing across a soil gradient (e.g. Beven and Kirkby, 1979; Creed and Band, 1998); successful small to medium scale hydrological and hydrochemical routing techniques in forests are tending towards routing sequentially from soil unit to soil unit in order to capture the dynamics of both runoff and chemical transformations in such complex environments (Tague and Band, 2001). There is evidence that this approach is also required to calculate runoff from patchy mosaics of frozen and unfrozen soil (Stähli et al., 2001)

If soils are fully frozen during melt then seasonal infiltration of meltwater is inversely proportional to the total moisture content (water + ice) of the soil at the time of melt (Zhao and Gray, 1999). Infiltration in Alaskan boreal forests is reduced compared to unfrozen soils depending on the moisture content of the soils prior to freezing. (Kane and Stein, 1983). Janowicz et al. (1997) found a tenfold increase in peak spring runoff from a Yukon catchment when saturated frozen ground was present compared to a year with similar snow accumulation but drier frozen soils. Shanley and Chalmers (1999) found that basin-scale runoff was not enhanced in years with significant occurrence of frozen ground in Vermont. They did not however consider the effect of year-to-year variations in frozen soil moisture content. Nyberg et al. (2001) found that spring rain on frozen ground events in Sweden infiltrated rather than produced runoff. Gray et al. (1985) distinguished frozen soil infiltration into three classes in agricultural soils; *unlimited* where macropores permit infiltration of all meltwater, *limited* where infiltration is controlled by meltwater supply and soil moisture content in the top 30 cm of soil and *restricted* where ice lenses on top of soil or at shallow depth limit infiltration to negligible amounts. These classes explain the behaviour of field evidence from a large range of environments (e.g. Burn, 1990; Janowicz et al., 1997; Nyberg et al., 2001) and relate strongly to the scaling parameters that must be considered when applying point infiltration equations to the basin scale (Gray et al., 2001).

Concrete frost occurs when rain or meltwater enters frozen soil zones and refreezes to form an impeding layer to infiltration prior to application of the primary bulk of meltwater or percolating rainfall. Water may freeze in the organic soil or it may penetrate the organic horizon and freeze back up to the surface when low infiltration leads to ponding and freezing at the mineral/organic interface (Kane and Stein, 1983). Gray's "restricted" infiltration case corresponds to observations of concrete frost (frozen litter and upper soil horizons) in the boreal forest. Concrete frost has been shown to occur in the Lac Laflamme watershed under certain meteorological conditions but is not a regular occurrence (Stein et al, 1994; Proulx and Stein, 1997). Gray et al. (1985) showed that prevalence of the restricted snowmelt infiltration case in soils resulted in the largest peak streamflow events of the year in relatively large prairie catchments. The wide-spread occurrence of concrete frost in a boreal forest might therefore be expected to generate large amounts of "quickflow" of melt and rainwater moving either at the surface or in shallow subsurface flow to streams and lakes. Depending on storage and routing within the hydrological system these quickflow events at the plot scale could be reflected by distinctive stream runoff and chemistry responses at larger basin scales, in comparison to situations without concrete frost or frozen soils (Maulé. and Stein, 1990; Prévost et al, 1990). However, Stein and coworkers (Stein et al, 1997) only measured concrete frost in the Lac Laflamme watershed during one winter (1989–1990); Proulx and Stein (1997) then simulated the potential for concrete frost formation in years prior to 1990 from meteorological data. During the previous years no field surveys or experiments had been carried out in the watershed with the object of relating runoff characteristics to concrete frost formation. Prior to 1990, data on surface waters during the spring runoff was primarily compiled

with regard to the Lac Laflamme experimental programme on lake acidification and for the input–output budgets for major anionic and cationic species (Papineau, 1987). Subsequent to the realisation that concrete frost could play a significant role in surface runoff and therefore the mechanism for export of N, we proceeded to re-examine the past data sets on surface waters in the light of simulated concrete frost occurrence during spring snowmelt at Lac Laflamme.

In the following paper we analyse the hydrological responses and the chemistry of stream waters of the Lac Laflamme basin in springtime to the estimated occurrence of frozen soils under the snow cover during a three-season period, 1982–83, 1983–84 and 1984–85.

STUDY SITE

Lac Laflamme (47° 19' N; 71° 07' W; 780 masl) is a shallow headwater lake, 0.06 km^2 situated 80 km north of Québec City. The whole basin (0.68 km^2) is forested (Black Spruce) and rests on impervious charnockitic gneiss covered by sandy till. Mineral soil is overlain by organic soil (5–10 cm) and the ground cover consists mainly of lichens and mosses. The average annual mean temperature and precipitation are 0.2^oC and 1424 mm and days with frost number 234. Approximately one third of the precipitation falls as snow. The snow cover starts to form in late October and at the end of the accumulation season the snow cover reaches on average from 100 to 150 cm depth and 350 to 420 mm of snow water equivalent (SWE). The melt season generally extends from the end of March to mid-May. Drainage in the basin is poorly developed except for the stream draining the lake. Up to 94% of groundwater flow recharges the lake—the rest, 6%, exiting the basin through the deep till under the lake. However, during large influxes of meltwater from rain-on-snow events in early melt, some, or all, of the streams entering the lake (main stream, ET9; subsidiary streams R6, R9, R12, R13) may run intermittently. In addition, numerous hypodermic streams, pipe flows and surface runoff attain the lake surface at the shoreline during the main melt period when the water table is high (Roberge and Jones, 1991).

METHODOLOGY

Lake discharge data were obtained from the Environment Canada Lac Laflamme report series (Couture, 1994). Stream discharges were not gauged but the lag time of the lake outlet to stream inputs during rain-on-snow events in early melt is short (a day or so) due to laminar flow underneath the ice cover and the short distances (200–330 m) from stream mouths to the lake exit (Roberge and Jones, 1991). Streams were sampled during and after rain-on-snow events for chemical analyses, while samples for the chemical composition of meltwaters during rain-on-snow events were obtained by the use of snowmelt lysimeters. A description of the methodology may be found in Jones (1987).

Estimation of concrete frost is based on the work of Proulx and Stein (1997). The original methodology of Proulx and Stein, which is based on the consideration of precipitation, warm and cold events during snow accumulation and melt periods was slightly modified. The criteria were expanded to take into account the amount of meltwater discharged to soil as estimated from the relationship between snow-cover water equivalent and the amount of rain deposited on the pack during warm precipitation events, and to the time and mean temperature between the estimated formation of concrete frost during mid-winter and the spring melt period. It was assumed that the longer and warmer the period between formation and spring snowmelt, the lower is the probability that concrete frost will remain intact at the surface of the litter layer. The probability of occurrence of concrete frost prior to early melt was classed as "high" (H) > 75%; "medium" (M) ≈ 50%; "medium-low" (ML) ≈ 25% and "low" (L) < 5%. Each probability class was expressed as a % of the surface area of the basin estimated to be covered by concrete frost based on the surface area covered by concrete frost (76%) measured in the spring of 1990 by Stein et al (1994). The method of estimation is approximate and the figures should be considered more as indicators of the degree of concrete frost formation rather than an accurate computation of the extent of frost-covered area.

RESULTS

Occurrence of concrete frost

Table 1 shows that a high probability of concrete frost occurred at Lac Laflamme in the spring of 1983 and 1990; there were 3 years of medium probability, in the spring of 1984, 1986, and 1988, and 3 years of low probability, 1982, 1985, and 1987. We chose the yearly sequence 1983–1984–1985 for this study i.e. a three-year period where the probability of concrete frost formation declined from high to medium to low in a progressive manner and for which our data sets on the hydrology and chemistry of the stream waters was compatible.

Table 1**: Areal coverage of concrete frost (% of total area) during winter-spring in the Lac Laflamme Basin, 1981–82 to 1989–90**

Year	81-82	82-83	83-84	84-85	85-86	86-87	87-88	88-89	89-90
Frost cover	<5	>75	≈50	<5	≈50	<5	≈50	≈25	>75

Temperature and precipitation records for the winter–spring periods of 1982–83, 1983–84 and 1984–85 suggest a contrasting sequence of weather patterns. The 1982–83 winter was characterized by low snowfall (37 cm) and a large number (12) of rain events; snow cover depth at the start of the melt period was 0.45–0.70 m depending on the canopy cover (Jones, 1987). In 1983–84, snowfall amounted to 49 cm; there were seven rain events and the depth of the snow cover reached 1.05–1.15 m. In 1984–85, snowfall was 43 cm but there were no rain events between the start of snow cover accumulation and the beginning of melt; the snow cover depth at the commencement of melt was 1.10–1.40 m. The precise events that led to the formation and persistence of concrete frost in 1982–83 are believed to be the precipitation of January 10–11 (44 mm) followed by the cold period of January 12–23 (mean temperature, –14 $^{\circ}$C) and February 2–3 (60 mm) followed the cold period of February 4–13 (mean temperature, –16 $^{\circ}$C). The major rain event of March 20 (38 mm), which was followed by a cold period (–15 $^{\circ}$C, to March 25) was also conducive to the formation and persistence of concrete frost. In 1983–84, two precipitation and/or melt events followed by cold periods could have resulted in concrete frost. These are the rain event of February 15 (20 mm) during the warm melt period, February 12–19, followed by the cold period of February 20–March 14 (mean temperature, –13.6 $^{\circ}$C) and the precipitation of March 22 (14 mm) followed by the cold period of March 24–29 (mean temperature, –8 $^{\circ}$C) just prior to the melt period. In 1984–85 there were no real conditions conducive to the formation of concrete frost; the main precipitation of April 14–15 (57 mm) occurred during the warm melt period. In 1983 the melt period was from April 9 to May 11, in 1984 from April 6 to May 6, and in 1985 from April 15 to May 9.

Hydrological response of surface waters to rain-on-snow episodes.

Ice masses in upper soil layers initially grow but then progressively melt and degenerate during application of meltwater and cannot persist throughout a melt period (Zhao et al., 1997). In the case of Lac Laflamme, depths of frozen soil are relatively shallow and the effects of frozen ground would become relatively small once the shallow soil ice layers had melted. Thus any influence of concrete frosts would be most likely observed during pre-melt or early melt periods. In pre and early melt the largest inputs of water occur during rain-on-snow events. We identified two rain-on-snow events in 1983 during the pre-melt and early melt period (Figure 1A): March 20, 38 mm, and April 17–18, 20 mm; there were two rain-on-snow events in 1984: March 22, 14 mm, and April 6–7, 20 mm; in 1985 there was one event: April 15–16, 57 mm.

There is evidence from the daily discharge at the lake outlet during these 3 years that the degree of concrete frost is reflected by the flashiness (rates of rise and fall of discharge) and volume of water exported from the lake during precipitation events. Figure 1 shows the daily discharge during the entire melt period (Figure 1A) and the discharge during only the pre-melt and early

melt periods (Figure 1B). In the pre-melt and early melt of spring 1983, the lake discharge showed 3 distinct peaks (Figure 1B). The first, Figure 1B, 83A, is the response of the watershed to the precipitation event of 38 mm (March 20); the second, 83 B, to a warm melt period and the third, 83C, to the rain event of 20 mm (April 17–18). In 1984 the responses to the rain events of March 22 (14 mm; 84A) and April 6–7 (20 mm, 84B) are only one-third the size of 83A and 83C. In 1985 there was a very small response to the rain event of April 15–16 even though the amount of rain was considerable, 57 mm.
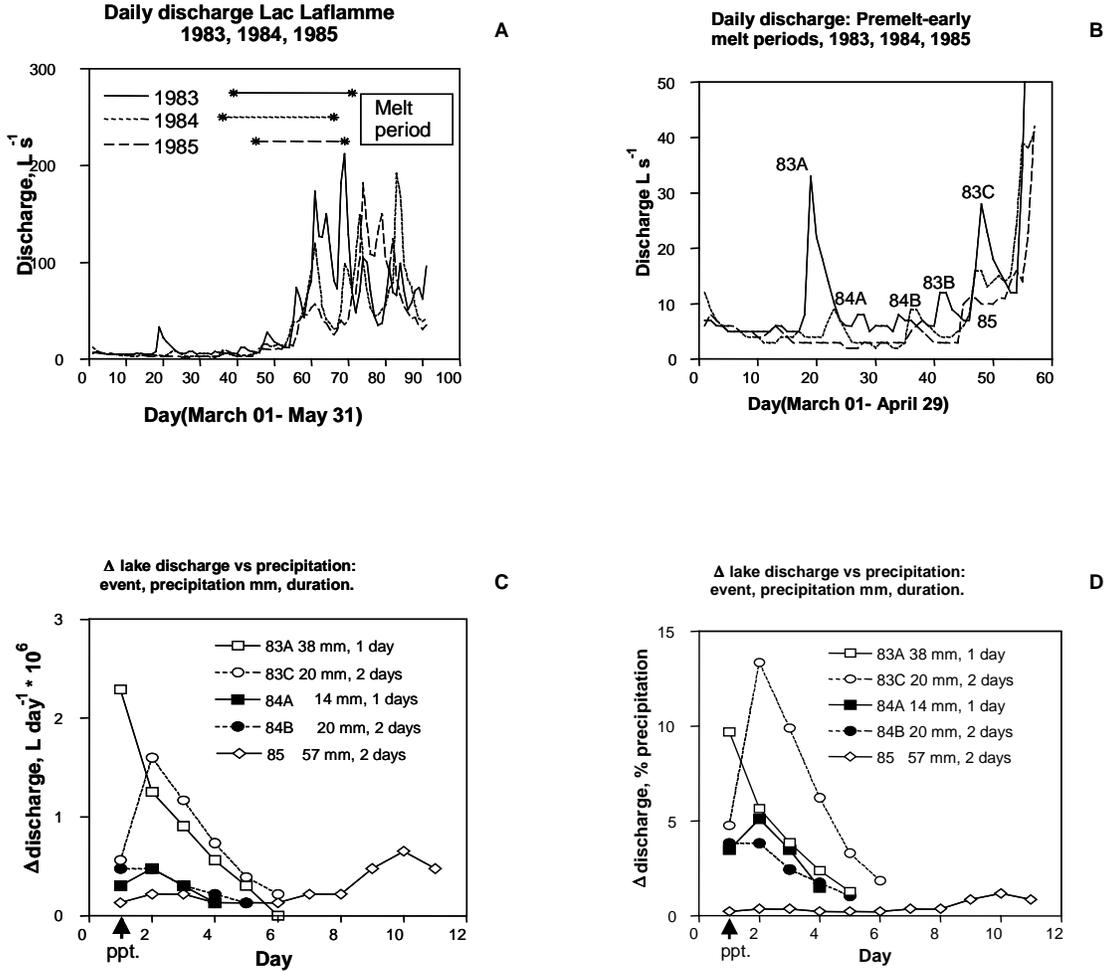

Figure 1. Lake discharge, spring snowmelt period, Lac Laflamme, Québec, 1983, 1984, 1985.

In an attempt to separate the hydrographs to show the influence of quickflow events, Fig. 1C shows the subsequent change of daily discharge to a rainfall event, ΔQ where

$$\Delta Q = Q_i - Q_0 \qquad (1)$$

and Q_i is daily discharge in the days following each rain event and Q_0 is base line discharge (L s^{-1} 10^6) as recorded before and after each event. ΔQ for 83C is much larger than that for 84B even though the precipitation inputs were identical at 20 mm over 2 days. In 1983 and 1984 the response time, the time that peaks rise from, and fall to, base line values, was between 4–6 days. In 1985, the year with no concrete frost, the input of rain, 57 mm, completely infiltrated the soil and practically no change in discharge was observed.

To better evaluate the influence of concrete frost on runoff generation from rain on snow, runoff ratios, R, were calculated as

$$R = 100\left(\frac{Q_i - Q_0}{P_i - P_0}\right) \tag{2}$$

where Q_i is the amount of discharge that flowed through the lake on day i, less that beforehand Q_0, and P is the corresponding rainfall. R-values are shown in Fig. 1D, which shows the greatest relative runoff ratio was for event 83C; the ratios diminished progressively for events 83A, 84A and 84B. The largest runoff ratios were also associated with the sharpest rise and fall in runoff. No such pattern was observed with event 85 which showed a negligible response to rainfall.

Event based runoff ratios (integration of Eq. 2 for events 83A, 83C, 84A, 84B, and 85) are shown in Table 2. The results indicate a trend in that the higher R values are consistently associated with higher classes of concrete frost occurrence probability and the lowest R values is for an event with an extremely low probability of concrete frost. The runoff ratios are consistently lower than the percentage area of concrete frost cover; suggesting that the estimated concrete frost areas were either not completely impermeable or/and that runoff from concrete frost areas did not freely and directly drain to the lake without intermediary storage.

Table 2**: Concrete frost percentage and total runoff as a percentage of incident precipitation for rain-on-snow events, pre-melt and early melt periods 1983, 1984, and 1985.**

Event	Precipitation, P, expressed as volume over plots, L x 10^6	Response, days	Total runoff from plots, Q L x 10^6	R %	Frost, %, estimated
83A	23.56	5	5.31	22.5	>75
83C	12.40	7	4.89	39.4	>75
84A	8.68	4	1.21	13.9	≈50
84B	12.40	5	1.60	12.9	≈50
85	35.34	11	1.87	5.3	<5

Chemical composition response of surface waters to rain-on-snow episodes.

We could not directly relate the chemical composition of the lake discharge to the precipitation events, 83A, 83C, 84A, 84B, and 85. Although the quantity of the lake outlet discharge will reflect the amount of rain and meltwater inputs to the watershed less storage and evaporation, the chemical composition of the lake outlet waters cannot directly reflect those of the precipitation events as the lake discharge draws not only on surface runoff and stream waters but also on lake ice meltwaters, lakeshore snowbank meltwaters and shallow and deep groundwater inputs both during and after the rain events (Roberge and Jones, 1991). However, the data sets for 1983 and 1985 included the chemistry of stream waters for the main tributary, ET9, and the intermittent streams R6, R9, R12, and R13. The latter streams flow only during the snowmelt period and are fed by surface runoff and particularly by hypodermic flow when the water table is high (Roberge and Jones, 1991). Figure 2A shows the conductivity for these streams in the pre-melt and early melt period of 1983. A decrease in conductivity at the time of flow contribution by runoff from an estimated 75% coverage of concrete frost into the streambeds is clearly recorded for all of these waters. No data was available for 1984. The conductivity of the two streams ET9 and R13 in 1985 (Figure 2B) also reflects the rainfall 85 event but to a lesser extent than the stream responses in 1983. This is in concurrence with the smaller estimated area of concrete frost in 1985 (50%). Ca,

Mg, Na, and Cl concentrations generally followed the same pattern as conductivity. NO_3 values for stream waters (Figure 2C, 2D) vary less than the pattern for conductivity but the individual runoff events can still be recognized.
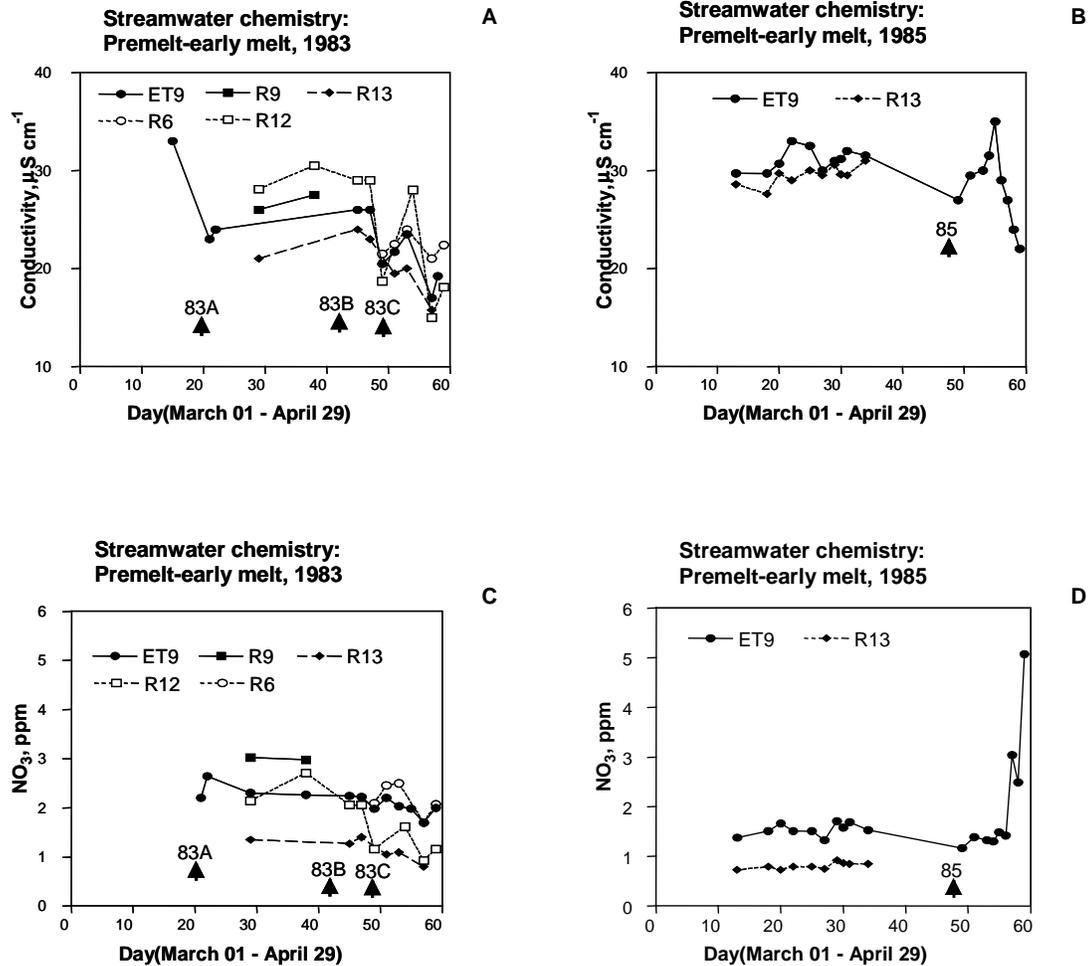

Figure 2. Streamwater chemistry, spring snowmelt period, Lac Laflamme, Québec, 1983 & 1985

IMPLICATIONS FOR ROUTING SNOWMELT RUNOFF AND CHEMISTRY

The assumption inherent in many current "grouped response unit" semi-distributed hydrological models, such as WATFLOOD and SLURP, is that all land surface types within a grid or sub-catchment are freely and completely draining to a stream or lake (Kite and Kouwen, 1992; Kouwen et al., 1993). Though addition of physically based frozen soil infiltration routines improves model performance for spring snowmelt periods (e.g. PBS-SLURP: Pomeroy et al., 1999), the assumption is still that all runoff from the plot scale contributes to streamflow. Routing to the stream is based on travel time estimations from the hydrograph. This assumption was examined for its ability to explain early melt discharge from rain on snow by assuming that concrete frost areas contribute all of their snowmelt + precipitation inputs to streamflow over a period of several days until the hydrograph has receded to baseline levels and that non-concrete frost areas do not contribute flow (complete infiltration or storage). A runoff efficiency ratio, E_Q was defined as

$$E_Q = \frac{\int_0^n (Q_t - Q_0)/P_t \, dt}{A_{fs}} \qquad (3)$$

where t denotes time, n is the end of the hydrograph rise and A_{fs} is the area of concrete frost. The resulting values of E_Q are shown in Fig. 3 along with ratiometric runoff ratios, R/100 (Eq. 2). Interestingly the runoff ratio did not vary with rain on snow amount. The runoff efficiencies range for most events from 0.25 to 0.5, but for the largest rainfall event (also with the smallest area of concrete frost), E_Q rises to near 1.0. The lower efficiency for larger concrete frost areas and smaller rainfall amounts are likely due to storage requirements during flow from the concrete frost zones to the stream. These storage requirements are unaccounted for in direct routing from impermeable surfaces and depend on the characteristics of unfrozen ground between the stream and concrete frost patches. Presumably, the largest rainfall event managed to satisfy storage requirements resulting in the relatively high efficiency for that event.
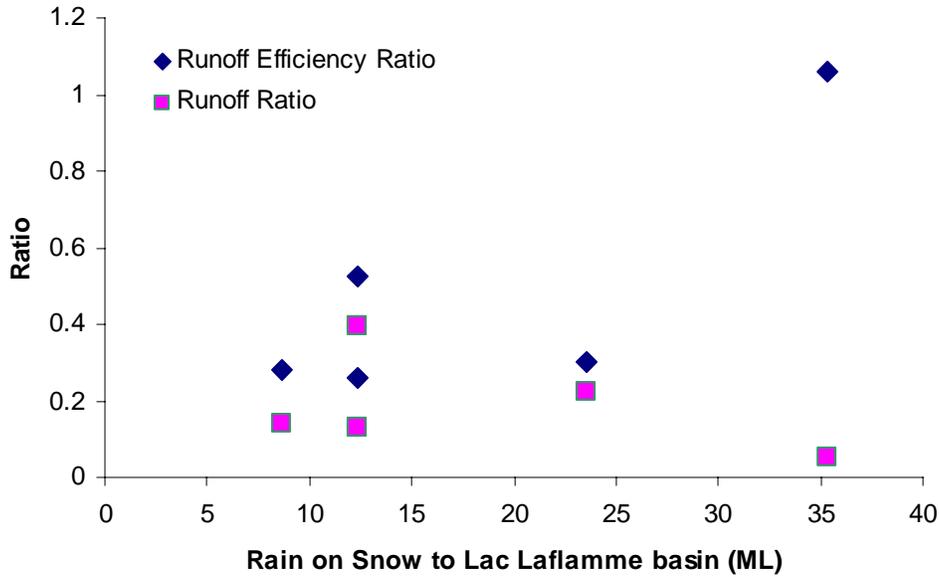

Figure 3. Runoff efficiency, E_Q, from concrete frost areas and runoff ratio R for the basin. Lac Laflamme, Québec, 1983, 1984, 1985.

Extending the concept to the chemical load and flux results, it was formalised in that the concrete frost-covered area of the watershed was assumed to control the relationship between the chemical load carried by quickflow and the stream chemical load of the species in question during and after the rain-on-snow event. Defining an efficiency of chemical runoff $E_{QC(x)}$ of species x:

$$E_{QC(x)} = \frac{\int_0^n \frac{Q_t \, C_t(x) - Q_0 \, C_0(x)}{P_t \, C_{lys}(x)} \, dt}{A_{fs}} \qquad (4)$$

where $C_{lys}(x)$ is the mean concentration of x in the lysimeter runoff and C otherwise refers to stream concentration at time t. Measurements of discharge and Cl, SO_4, Na, and Ca for the main stream ET9 (Figure 2) in the 83C event were used to estimate chemical runoff efficiency for the 6-day period after the event (Figure 1C). These species are relatively conservative tracers of

meltwater routing. Nitrate cannot be used in this fashion as it is known to decrease in meltwaters due to microbiological activity (Jones, 1999).

The chemical runoff efficiencies for this event were 0.6 for Cl (similar to the runoff efficiency of 0.52) and 1.1 for SO_4. However, the $E_{QC(Na)}$ was 6.0 and $E_{QC(Ca)}$ was 4.5; indicative of relatively increased leaching of these latter species probably from unfrozen soil forest litter between patches of concrete frost and/or the local input of soil waters from riparian zones during the rain-on-snow events. Routing of runoff water over patchy concrete frosts could induce a storage withdrawal from discharge that could possibly be accommodated by routing frozen ground runoff downslope through an unfrozen soil zone with a storage term. However the patchiness of concrete frost has even greater repercussions on the chemical composition of waters entering the streams. Transformations of water chemistry moving through unfrozen soil patches and possible contributions of highly concentrated water near the stream can confound any attempts to estimate stream chemistry from lysimeters discharge and knowledge of frozen ground—particularly if the concrete frosts patches are relatively removed from stream reaches. The hydrochemistry results seem to confirm the necessity of the explicit landscape partitioning and "profile array" routing approach suggested by Tague and Band (2001) and Stähli et al. (2001) respectively. The spatial distribution of frozen ground attributes and its effect on both runoff generation and chemical mobility through catchments is a major problem and future research should take into account the distribution of concrete frost and its spatial relationship to stream reaches and recharge areas.

CONCLUSIONS

The hydrology and chemistry of streams in a small boreal forest watershed shows that rapid runoff associated with "impermeable" concrete frost may occur during rain on spring snowmelt during the pre-melt and early melt periods. Hydrological data in the Lac Laflamme basin indicated that when concrete frost covers 50–75% of the catchment then runoff ratios of 0.2 to 0.4 prevail for these rain on snow events, the highest values corresponding with the highest coverage of concrete frost. The efficiency with which runoff from concrete frost areas reached the stream is 25–50%, but increased to near 100% for a high rain on snow event. This suggests that intermediary storage during transit from concrete frost zones to the stream may play an important role in attenuating runoff. When the efficiency of chemical transport from snowpacks over concrete frost to streams is examined, tremendous variability is evident. Possible reasons are differential rates of leaching of solute whilst the solution flows through intermediary unfrozen soils to the stream. The patchy nature of concrete frost distribution is thought to be a major factor in selection of appropriate routing methods for runoff and runoff chemistry in this terrain and would seem to suggest that explicit distributed routing across soils of varying infiltration capacity is necessary in some instances.

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