

SNOWMELT RUNOFF PROCESSES IN A SMALL PRECAMBRIAN WATERSHED

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ABSTRACT

The hydrologic response of a small Precambrian Shield watershed (Plastic-1) in the Muskoka-Haliburton region of south-central Ontario was examined during the 1985 snowmelt season. The primary purpose of the study was to identify snowmelt runoff pathways and demonstrate ways in which hydrologic processes can influence streamwater chemistry in environments subjected to acidic snowmelt inputs.

Many workers have used natural isotope tracers to show that only 20-40% of the total discharge from Shield watersheds during the snowmelt season can be attributed directly to meltwater and rainfall during that period (event water). The majority is supplied from previously stored (pre-event) water. Field surveys showed that saturated areas covered up to 31% of the Plastic-1 watershed during snowmelt in 1985, indicating that the majority of event water runoff could be accounted for by saturation overland flow. This conclusion was supported by the results of time-based hydrograph separations which showed quickflow comprised approximately 34% of total snowmelt season runoff. We believe that the majority of delayed flow was contributed by subsurface processes and would have consisted mainly of pre-event water. Some subsurface flow would also, however, have appeared as quickflow and would certainly have been important in sustaining the saturated conditions in the low-lying portions of the watershed.

The study has shown that a number of runoff mechanisms can contribute to streamflow in a watershed during snowmelt. Knowledge of the way in which water of various types mixes (surface and subsurface, event and pre-event) is necessary before streamwater chemistry can be interpreted meaningfully.

INTRODUCTION

Throughout extensive areas of Canada, northeastern United States, Europe and Scandinavia, the deposition of acidic rain and snow has been well documented (Wright et al., 1976; Whelpdale and Barrie, 1982; Lovett et al., 1986). Many workers examining the effects of acid deposition on watersheds have carried out mass balance studies with only basin inputs and outputs of water and solutes measured (e.g. Harvey et al., 1981; Dillon et al., 1984). Although numerous studies have identified a close relationship between chemical and hydrologic fluxes through a watershed (e.g. Johannessen and Henriksen, 1978; Dillon and Scheider, 1983; Cadle et al., 1984), few attempts have been made to identify the hydrologic pathways within a watershed, and relate this to solute transport through the system. This is an important consideration for many headwater lakes, since the source of streamflow runoff from the adjacent terrestrial watersheds will determine the amounts and rates of water and solute input to the lakes. On an annual basis, the spring melt represents the largest solute input to the system (e.g. Jeffries and Semkin, 1983; Jones et al., 1984). The time lag between the deposition of solutes in snow and those released in

snowmelt, is sufficient to accumulate large amounts of chemicals (e.g. Jeffries and Snyder, 1981) which then become released en masse during melt to cause conditions such as acid shock in streams and lakes (e.g. Jeffries et al., 1979).

Despite the extensive literature on various runoff mechanisms, recent evidence seems to suggest that the importance of groundwater in the total runoff yield has been underestimated. Based on chemical hydrograph separations using environmental isotopes (oxygen-18, tritium or deuterium), a large portion of the watershed runoff has been shown to have an isotopic signature similar to that of groundwater (e.g. Sklash and Farvolden, 1979; Bottomley et al., 1985; Sklash et al., 1986). In Plastic-1 a recent study by Sklash (1983) during autumn rains showed that approximately 80% of the peak discharge was isotopically similar to groundwater, suggesting that a large portion of watershed runoff may originate from water (pre-event) already in the watershed, and not from incident precipitation (event water). As an alternative approach, the separation of hydrographs using time-based graphical techniques (e.g. Hewlett and Hibbert, 1967) has been used in many environments to partition watershed runoff into quickflow and delayed flow components. Quickflow is generally assumed to represent water rapidly transmitted through the watershed and is therefore generally linked to surface runoff mechanisms and the expanding drainage network. Delayed flow is assumed to represent water routed via subsurface pathways, due to its slower transmission rates.

No study has yet been able to correlate results from standard hydrograph separation techniques and isotope analysis, with hydrometric field evidence conducted during snowmelt. The Canadian Shield represents an ideal location to carry out such a study given its: 1) dissimilar physiographic characteristics from environments where many of the conceptual runoff models were derived, 2) significant accumulation and release of snowmelt water, and 3) susceptibility to acid deposition, in both terrestrial and aquatic ecosystems.

FIELD SITE DESCRIPTION

The Plastic-1 watershed is a small (23.3 ha) headwater catchment located in the Muskoka-Haliburton region of south-central Ontario (Fig. 1). It is one of five subwatersheds draining into Plastic Lake, and has been monitored continuously for discharge and streamwater chemistry by the Ontario Ministry of the Environment since 1980, as part of the Acid Precipitation in Ontario Study (APIOS).

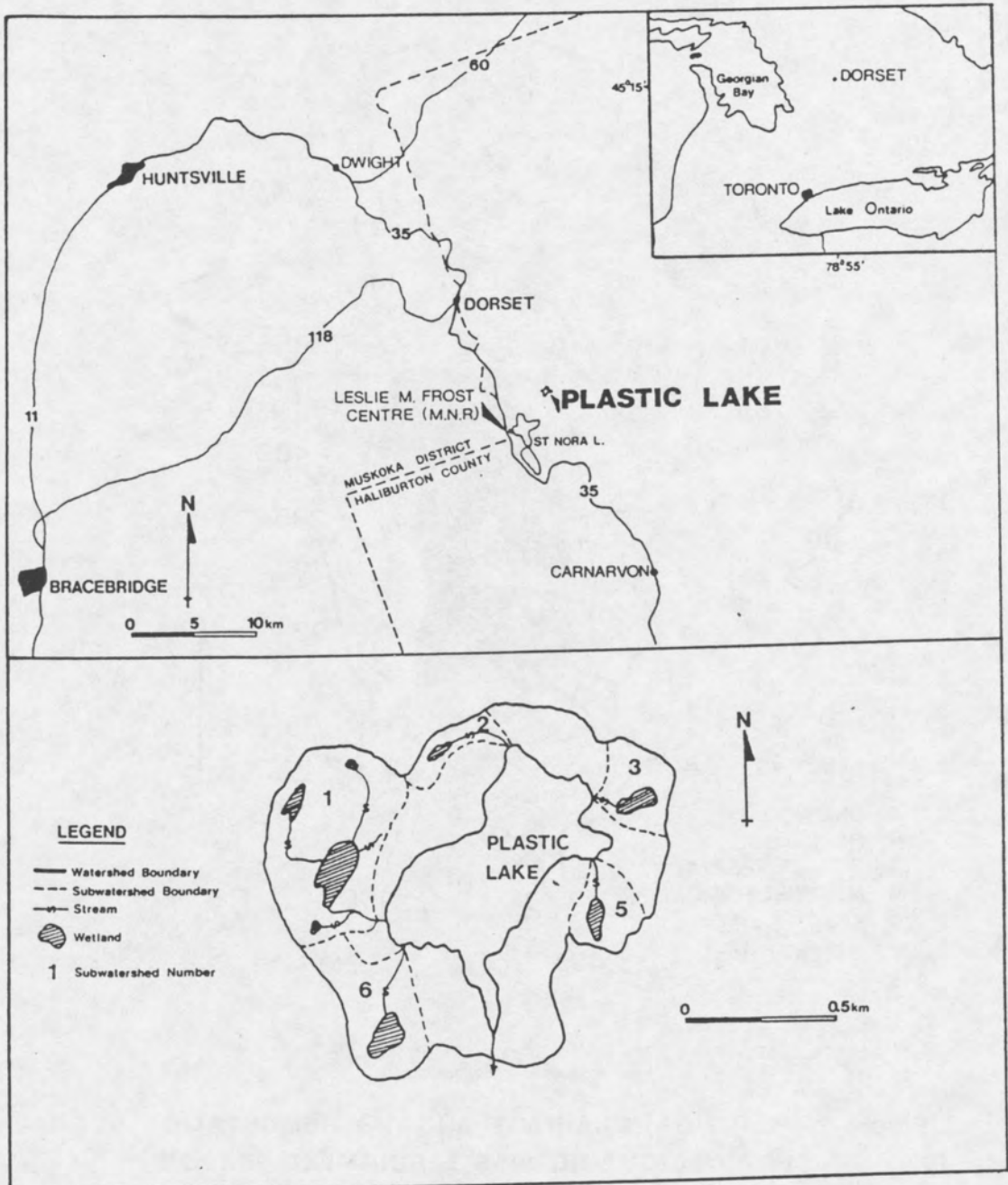
The watershed receives an annual precipitation of 900-1100mm, with a volume weighted pH of 4.0-4.2 (Dillon et al., 1984). Annual snowfall is between 2400-3000mm, with snowcover ablation occurring during mid to late April.

Drainage is structurally controlled and strongly influenced by a large (2.3ha) sphagnum-conifer wetland located in the centre of the watershed. Three ephemeral streams (PC-108, PC-4 and PC-3) drain approximately 79% of the watershed area, and are the major channelized inputs to the main wetland (Fig.2). The PC-108 subcatchment represents 15% of the watershed, with the PC-4 and PC-3 subcatchments together comprising 64%. Close to the watershed outflow (PC-1), and unconnected to the main wetland is an additional ephemeral stream (PC-2) (Fig. 2). All ephemeral streams drain upland wetlands of varying size, which remain present throughout the year.

The bedrock is orthogneissic in composition with outcroppings present in approximately 5% of the watershed. The surficial cover is invariably thin, with bedrock contact frequently less than 0.5m (McQuest Marine Sciences Limited, 1982). The spatial distribution of surficial cover can be seen by the differences between the two major subcatchments of the watershed (Fig. 2). The steeper PC-108 subcatchment supports a thinner soil cover than the flatter and larger PC-4/PC-3 subcatchment.

The watershed is naturally forested with open areas accounting for only 7% of the total catchment area. White pine (*Pinus strobus* L.) and eastern hemlock (*Tsuga canadensis* L.) represent the major tree species, and collectively may be found in approximately 54% of the watershed (Neary et al., 1987).

Figure 1. STUDY AREA LOCATION AND SUBWATERSHED MAP



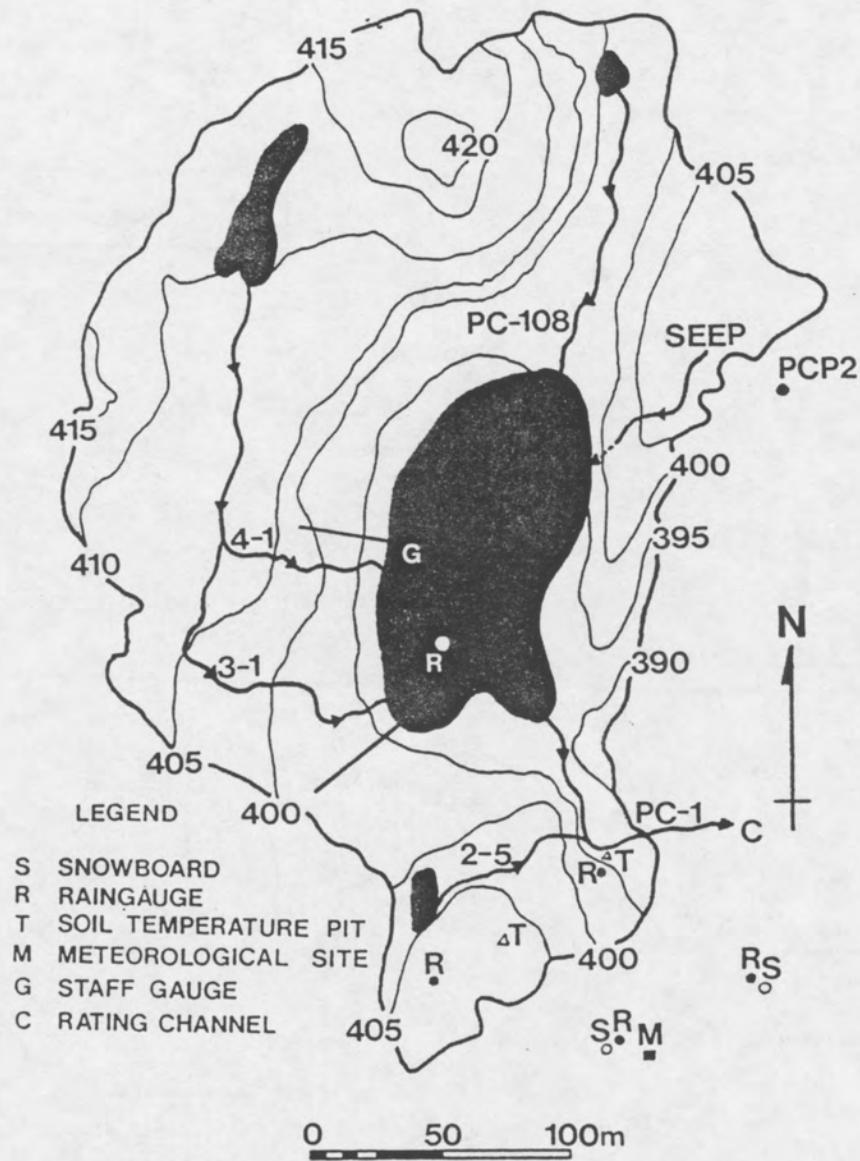


Figure 2. PLASTIC-1 DRAINAGE AND INSTRUMENTATION SET-UP FOR USE DURING 1985 SPRINGMELT SEASON

FIELD INSTRUMENTATION AND METHODOLOGY

Permanent on-site instrumentation at Plastic-1 was installed in 1980 and is continuously maintained by the Ontario Ministry of the Environment. A 90° V-notch weir and stilling well equipped with a Leupold Stevens stage level recorder was installed at the watershed outlet, and a meteorological station (PCP2) equipped with a Nipher snow gauge, Belfort tipping bucket raingauge, and a Lambrecht hygrothermograph was set up immediately outside the Plastic-1 field site.

The present study included complementary instrumentation to increase the spatial resolution for monitoring precipitation inputs to the watershed. Five Atmospheric Environment Service (AES) manual raingauges were used along with two snowboards. All precipitation volumes were measured and collectors were cleared daily. Two 0.5m x 0.5m soil pits were excavated and soil thermometers were inserted in vertical sequence into an open face of each pit. Soil temperatures were recorded daily at three depths: litter layer, 10cm and at the A-B horizon interface at approximately 20cm. Two lines of 1.6cm I.D. groundwater wells were installed along natural slopes normal to the main wetland perimeter. Line A with nine wells obtained a mean depth of 85cm along a 7° slope, while Line B had a mean well depth of 77cm along a 10° slope. A Beckman multimeter attached to a graduated circuit prod was used to measure the daily changes in depth to standing water in each well, from approximately peak melt up to the end of the melt season.

Estimates for snowpack water equivalent were obtained through a 29-point snow survey, conducted on an approximate daily basis, from February 21 to April 30, 1985. Corrections for areally-weighting individual point values and the remaining snowcover are discussed in Shibatani (1988). Computations for daily melt depths were complicated by inherent problems in the snow survey framework, and required the use of a budgeting procedure (Shibatani, 1985). Saturated areas were mapped every two to three days during the peak melt using field survey techniques based on those in the literature (e.g. Dunne et al., 1975; Moore et al., 1976; Taylor, 1982). Ephemeral stream discharges were measured daily using the standard velocity-area method (Hersch, 1985).

DATA ANALYSIS

The PC-1 discharge hydrograph from February 21 to May 4, 1985, was separated using the graphical technique described by Hewlett and Hibbert (1967). A time-based constant separation slope of $3.1 \text{ L}\cdot\text{s}^{-1}\cdot\text{day}^{-1}$ was used, and allowed for the partitioning of individual events into their respective quickflow and delayed flow components. Since total quickflow volume alone provides little insight into a watershed's ability to regulate precipitation and or melt, the quickflow response ratio (QFRR) was used. The QFRR in this study was used to represent: i) the proportion of the available water as quickflow and ii) the proportion of the total runoff as quickflow. Available water represented the combination of precipitation (rain only) and snowmelt which would have been available for runoff during an event, while total runoff simply represented the volume of water which had passed through the outlet weir (PC-1). All values were converted to an equivalent catchment water depth, with QFRR's reported as percentages.

RESULTS

The 1985 spring melt season produced 378mm of runoff. Five melt events occurred, each initiated by rain-on-snow (Fig. 3). Peak flow occurred on April 22 (Day 61) and had a peak instantaneous flow of $98 \text{ L}\cdot\text{s}^{-1}$. This last event represented the main melt event of the season and accounted for 50% of the entire season runoff. Over the course of the season, quickflow contributions accounted for 34% and 31% of the total seasonal runoff and available water respectively. Table 1 shows the quickflow relationships for each of the five melt events.

On an event basis, quickflow volumes and the QFRR's varied markedly in response to differing storage capacities (e.g. snowpack and wetland), and ground conditions (e.g. surface

Figure 3. 1985 SPRING HYDROGRAPH , HYETOGRAPH AND MEAN DAILY AIR TEMPERATURE TRACE

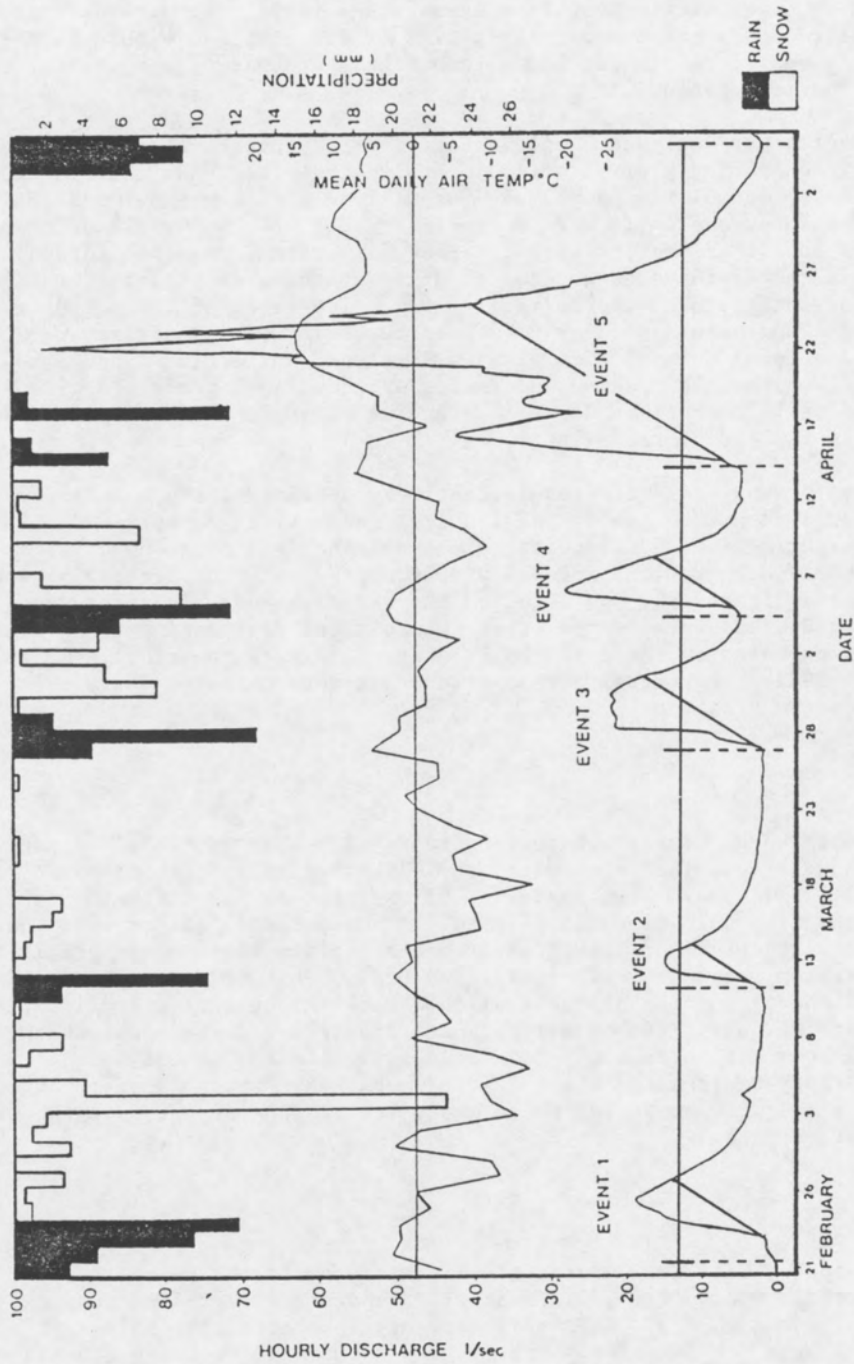


TABLE 1. 1985 Spring Melt Quickflow Relationships for Each Melt Event for Plastic-1 Catchment.

Event	Quickflow Runoff (QR) (mm)	Runoff (R) (mm)	Available Water(AW) (mm)	QFRR (QR/AW) (%)	QFRR (QR/R) (%)
1	9.1	42.5	70.9	12.8	21.4
2	5.4	30.5	45.4	11.9	17.7
3	14.3	43.0	40.2	35.6	33.3
4	13.7	45.4	36.2	37.8	30.2
5	84.3	216.2	211.5	39.9	39.0
TOTALS	126.8	377.6	404.2		
Seasonal Quickflow Response Ratio (QFRR)					
	Total Runoff (mm)	QFRR (Total QR/Total R) (%)	QFRR (Total QR/Total AW) (%)		
	377.6	33.6	31.4		

saturation and ground ice). Much of the early season available water went into storage, within the snowpack, wetlands, surface depressions and presumably into the soil as well. Quickflow volume and the QFRR (13-21%) during this time were low with any quickflow resulting from channel interception in addition to Horton overland flow promoted by impermeable ground frost and basal ice. As the season progressed, frozen ground conditions abated, but many saturated areas were formed as a result of increased meltwater inputs. Quickflow volume for the main melt event was the highest, but more importantly, the QFRR was also the highest.

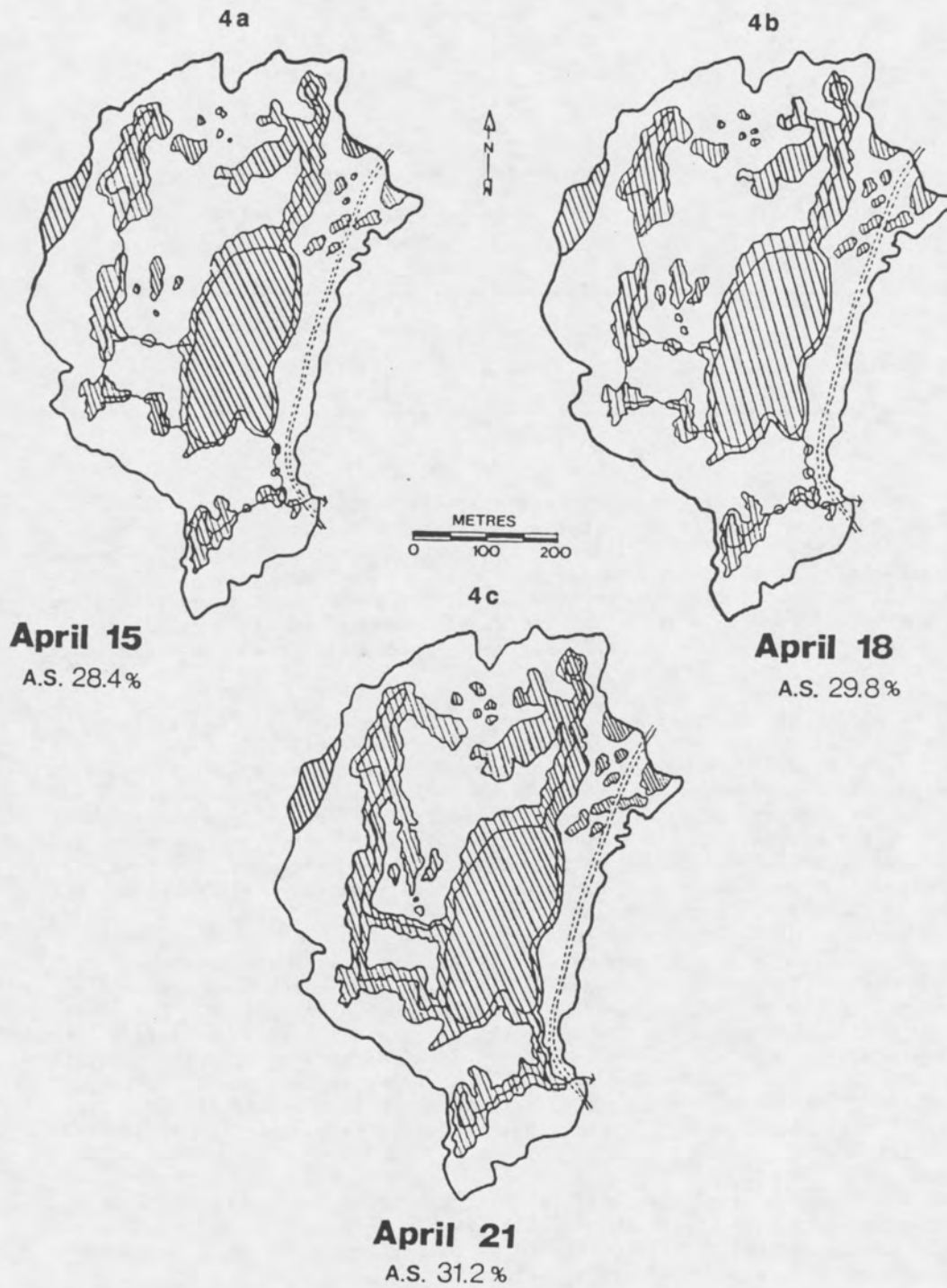
The progression of the mapped saturated areas over time are shown in Figures 4a-c. Areal saturation was 28% at the outset of the main melt event on April 15 and obtained a maximum of 31% six days later. Much of the initial expansion of the saturated areas was limited to the perennial wetland areas. As these areas filled, much of their overflow was drained by the ephemeral streams. The undulating topography in Plastic-1 and perhaps in other Shield watersheds produced isolated saturated zones in many upland areas removed from the perennial drainage network. Identified as upland seeps, these became linked to the drainage network only after their storage capacities had been reached. This cascading effect was observed on April 21 (Day 60) one day prior to peak flow.

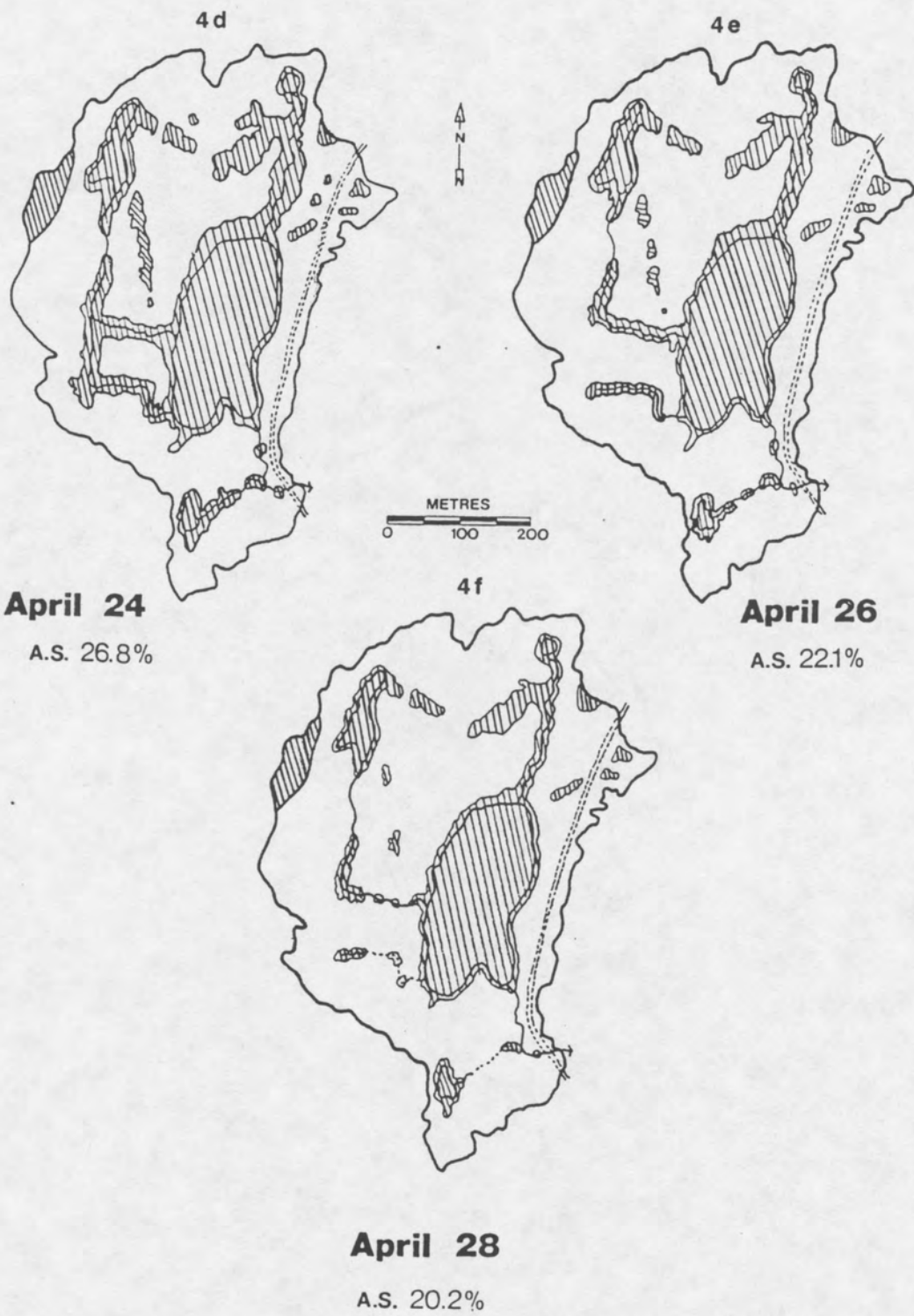
Mapped peak saturated areas in the two smaller subcatchments were 49% and 39% for PC-108 and PC-4/PC-3 respectively. For the entire main melt event, saturated areas were present in 40% and 30% of the PC-108 and PC-4/PC-3 subcatchments respectively. The time-weighted average watershed saturation for the main melt event was 25%. Assuming that saturation overland flow was a dominant contributor to the quickflow response, simple computation showed that approximately 64% (25% saturated area/39% quickflow response ratio) of the quickflow runoff during the main melt event could have resulted from runoff delivery via saturation overland flow. The remaining 36% must have resulted from other, subsurface processes.

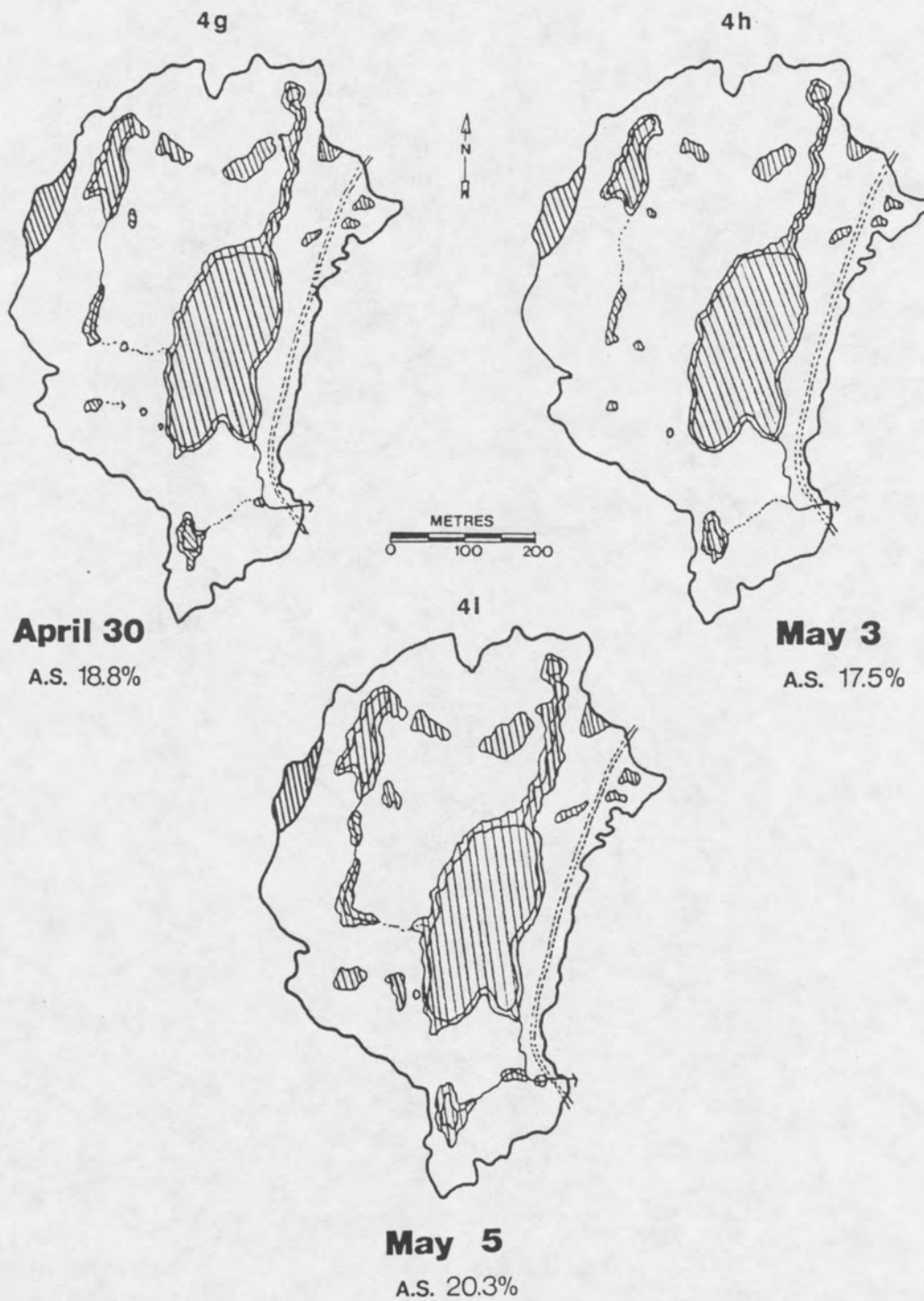
Delayed flow, over the course of the entire season, accounted for 64% of the total runoff. On an event basis, delayed flow contributions ranged from 61-79%. During the main melt event, delayed flow accounted for 61% of the total runoff. Clearly, this component was more important than quickflow in terms of its magnitude.

Since subsurface flow has been often regarded as a slower response mechanism than surface flow, it has been associated primarily with the delayed flow component of total

Figure 4. MAPPED SATURATED AREAS - TIME SEQUENCE







runoff. To help investigate this further, subsurface flow rates were modelled in two sub-catchments (PC-108 and PC-4/PC-3) of Plastic-1 using Darcy's Law. The results showed the varied response with which subsurface flow could contribute to the total runoff, depended on the surface conditions as well as the time scale chosen for investigation. In the PC-108 subcatchment, subsurface flow accounted for approximately 52% of the total subcatchment runoff during the main melt event. In the PC-4/PC-3 subcatchment, 74% was computed as subsurface flow. These proportions suggested that during the entire event, subsurface flow was the dominant mechanism. However, at peak flow on April 22 (Day 61), the computed fluxes for both the PC-108 and PC-4/PC-3 subcatchments were not as important as the surface water fluxes.

While the importance of subsurface flow in terms of its magnitude during the main melt event and over the entire melt season is clear, on a shorter term its importance may require re-defining. At peak flow, this was clearly shown. With the rapid expansion and contraction of the saturated areas, quickflow induced by saturation overland flow is a relatively short-lived process in comparison to the slower drainage via subsurface routes. At the event scale and certainly during the recession of the hydrograph, subsurface flow would be more important as the soils were being slowly drained. Quickflow computations, however, showed that a significant proportion of the quickflow response probably also resulted from subsurface processes. Rapidly produced subsurface flow has been reported in the literature resulting from macropore flow (e.g. Mosley, 1979; Roberge and Plamondon, 1987), translatory or piston flow (e.g. Horton and Hawkins, 1965; Hewlett and Hibbert, 1967) and rapid return groundwater flow (e.g. Sklash and Farvolden, 1979; Bottomley et al., 1985).

It seems probable from these results that during an isolated event the relative contributions of runoff from surface and subsurface mechanisms changes as the governing physical catchment characteristics change. Quickflow computed over the entire season (34%) and during each individual event (21-39%) roughly approximated the proportion of event water in the total runoff reported in the literature (e.g. Bottomley et al., 1985; Sklash et al., 1986). These isotope studies showed that approximately 20-40% of the total runoff was event water in composition. Our results suggested that 36% of the quickflow response did not result from surface processes (e.g. saturation overland flow) but must have contributed through some rapid response subsurface mechanism. In the absence of any detectable macropores, it was thought that the majority of the rapidly transmitted subsurface flow must have occurred as either return flow, rapid response groundwater or simple matrix flow via a translatory or piston flow mechanism. All of these would have exhibited a pre-event isotopic signature which would have mixed with the event water from saturation overland flow.

Further evidence showing the interrelationships between surface and subsurface flow processes could be seen by the maintenance of the saturated wedges in the low-lying portions of the watershed. Groundwater well data showed that standing water levels in the slope base wells were maintained long after peak flow (April 22) had passed (Fig. 5). Upslope wells, however, showed a gradual decline in water levels during the peak flow recession. This suggested that subsurface flow seemed to be important not only in producing the dominant flux for each event but also by sustaining saturated conditions at the slope base.

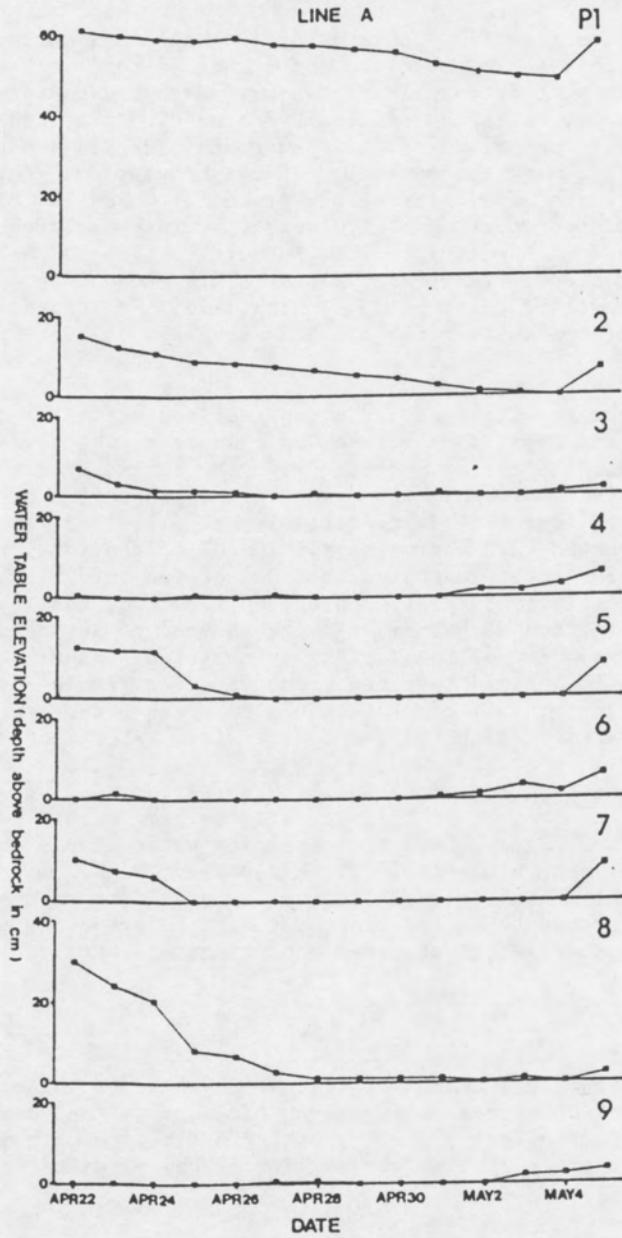
CONCLUSIONS

The study results have shown that a number of meltwater processes and runoff mechanisms can contribute to streamflow in a watershed at any given time during the snowmelt. The watershed response is strongly controlled by the temporal distribution of available water through rain and melt and the inherent spatial variability of the physical watershed characteristics.

Time-based hydrograph separations showed that 34% of the total season runoff was quickflow, with the dominant component being delayed flow. On an event basis, quickflow contributions ranged from 21-39% with delayed flow ranging from 61-79%. These proportions roughly approximated the event and pre-event water proportions in the total runoff as reported by many natural isotope tracer studies. The rough approximation of these proportions suggested that at any given time during the melt season, a certain degree of mixing between event and pre-event water probably occurred. Field mapping surveys showed that

Figure 5. GROUNDWATER PROFILES FOR
PEAK RECESSION FLOW

GROUNDWATER LEVELS



saturated areas covered up to 31% of the watershed during the melt season. During the peak flow event, 65% of the quickflow response could have resulted from saturation overland flow with an event water isotopic signature. Thirty-five percent however, must have resulted from rapid subsurface flow mechanisms of which the translatory or piston flow mechanisms have been suggested. With longer duration subsurface flow continually supplying soil water downslope, many of the saturated wedges would have been maintained. Further mixing of event and pre-event water therefore would have been possible within these slope base areas where saturation overland flow and return flow were occurring together.

We believe that the results from this study and others similar to it have shown the importance of process-oriented field studies in providing some appreciation of the ways with which water of various types can mix together (surface and subsurface, event and pre-event). In small structurally controlled Shield watersheds, these processes may be highly variable both in space and time and will most certainly affect the streamwater chemistry discharged from them.

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