Surface and Subsurface Water Contributions During Snowmelt in a Small Precambrian Shield Watershed, Muskoka, Ontario

Jeffrey J. McDonnell[1] and Colin H. Taylor
Watershed Ecosystems Program
Trent University
Peterborough, Ontario K9J 7B8

[Original manuscript received 27 June 1986; in revised form 11 March 1987]

ABSTRACT *The rates and pathways of snowmelt runoff on Precambrian Shield watersheds are not fully understood. The results of a detailed field study and numerical analysis of these processes are presented for a small watershed located in Muskoka, Ontario, that has been gauged both chemically and physically since 1976 by the Ontario Ministry of the Environment as a part of its Acid Precipitation in Ontario Study. Field data show that in many areas, soils with very high hydraulic conductivities contributed significant amounts of subsurface flow to the hydrograph during and shortly after melt. Quickflow in the first phase of snowmelt was generated by a combination of saturation overland flow and saturated-unsaturated subsurface stormflow from shallow side slopes; however, most of the total water volume was delivered via slower ground-water flow. In the final phase of the melt period, the streamflow was mainly due to ground-water flow recharged on a forested area and delivered over limited distances through shallow, highly permeable overburden materials. Quickflow peaks superimposed on this general trend could be accounted for mainly as surface runoff over ground-water effluent areas mapped throughout the watershed. In support of ongoing hydrochemical studies by the Ontario Ministry of the Environment, these data and interpretations will aid in modifying and improving hydrologic submodels by adding to our understanding of water movement in acidified watersheds.*

RÉSUMÉ *Les taux ainsi que les parcours des ruissellements de la neige fondue dans un bassin hydrographique situé dans le bouclier précambrien ne sont pas très bien compris. Les résultats d'une étude exécutée sur le terrain, ainsi que d'une analyse numérique de ces processus sont présentés pour un petit bassin hydrographique situé à Muskoka en Ontario dont les mesures des caractéristiques chimiques et physiques ont été effectuées depuis 1976 par le Ministère de l'environnement de l'Ontario dans son étude sur les pluies acides en Ontario. Les données prélevées sur le terrain révèlent que dans plusieurs endroits, les sols possédant une haute conductivité hydraulique étaient responsables d'une bonne partie des écoulements souterrains enregistrés par l'hydrographe durant, et immédiatement après la fonte. Au cours de la phase initiale de la fonte de la neige, l'écoulement rapide est généré par la double action de la saturation de l'écoulement superficiel et le débit d'orage souterrain saturé-non saturé des pentes douces latérales; cependant la majorité du volume d'eau était*

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[1] Current address: Department of Geography, University of Canterbury, Christchurch, New Zealand.

ATMOSPHERE-OCEAN 25 (3) 1987, 251–266 0705-5900/87/0000-0251$01.25/0

généré par les ruissellement de surface peu rapides. Au cours de la phase finale de la période de la fonte, l'écoulement était dû à l'écoulement souterrain rechagé sur une région forestière et délivré sur de courtes distances par une couche peu profondement et fortement perméable de matières surchargées. Les pointes des écoulements rapides, superposées à cette tendance générale peuvent être expliquées comme étant des ruissellements de surface sur des régions d'effluents des eaux souterraines cartographiées pour tout le bassin hydrographique. Ces données et analyses permettront dans le cadre des études hydrochimiques continues du Ministère de l'environnement de l'Ontario, la modification et l'amélioration des sous-modèles hydrologiques qui nous permettront d'approfondir notre compréhension de la circulation de l'eau dans les bassins hydrographiques acidifiées.

1 Introduction

Over the past two decades snowmelt and snowmelt runoff have received a substantial amount of attention in the literature, and as a result our ability to model these processes has improved greatly. The most important use of these models is associated with the study of aquatic acidification and material flux through watersheds. Stream water chemistry models (e.g. Christophersen and Wright, 1981) critically depend on an adequate hydrologic submodel, because most of the chemicals entering and leaving watersheds are in solution.

Studies of mass flux through watersheds in the Muskoka-Haliburton area in Ontario, by the Ontario Ministry of the Environment, have been ongoing since 1976. The effects of acidic deposition on the various components of the hydrologic cycle have been documented by Scheider et al. (1979), Jeffries et al. (1979) and Dillon et al. (1982). A growing awareness of the need for physical hydrologic investigations in this area has resulted in a number of recent studies dealing with snowmelt simulation (Scheider et al., 1983b; Buttle and McDonnell, 1987), and runoff production (Sklash, 1983; Bottomley et al., 1984), however, this work has not yet included the processes associated with snowmelt runoff generation.

Scheider et al. (1983a) report mean annual precipitation for the Muskoka-Haliburton region as 900–1100 mm, with approximately 25 to 30% of this occurring as snow. The snowmelt period, from sometime in mid-March to early May, generates an average of 49 to 77% of the annual runoff (400–500 mm) within a six-week period. This represents the most important event of the hydrologic year as the lakes, wetlands and limited ground-water bodies of the region are recharged with meltwater. Annual evapotranspiration is in the range of 500–600 mm (Scheider et al., 1983a).

Given that chemistry flux closely follows hydrologic flux, Dillon and Scheider (1983) noted that some 44 to 72% of the annual input of Ca, Mg, Na, K and Cl to Harp Lake in Muskoka also occurred during the March to May period in 1976–1980. In addition, intensive studies have identified the potential for significant biotic effects during spring melt, when the pulse of waters of low pH and elevated aluminum are introduced into the aquatic system (Marmorek et al., 1984).

2 Background

In the design of many empirically based models available for predicting peak flows and total discharge during snowmelt events, there has been a tendency to view

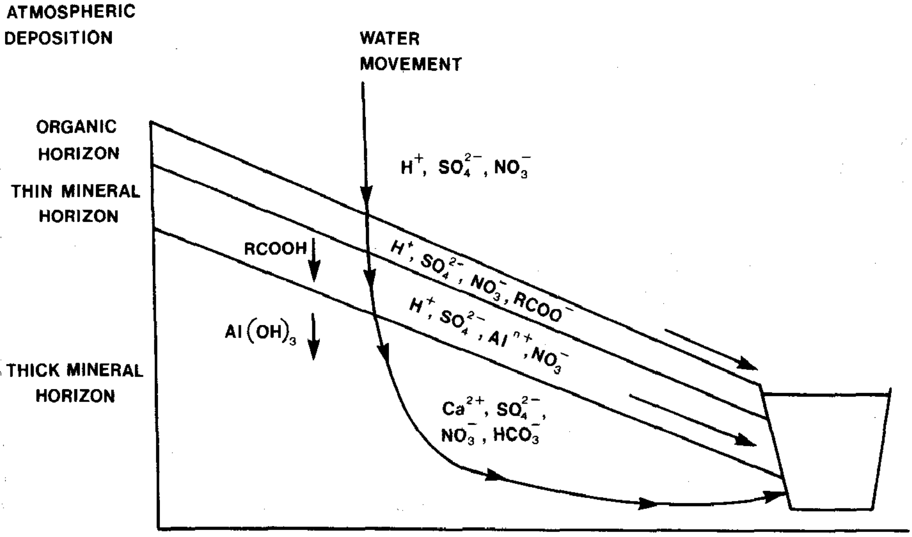

Fig. 1 Chemical transformations associated with water flow paths to a hypothetical Shield stream (after Driscoll and Newton, 1985).

studies of runoff processes as being of greater academic interest than of practical importance (Abdul and Gillham, 1984). Clearly, however, the development of models that serve to combine water routing and water quality algorithms requires a more detailed knowledge of these related pathways.

Bottomley et al. (1984) noted that ground-water discharge to a small stream in Muskoka had a major ameliorating influence on the acid input to Harp Lake by storm runoff from the watershed. Very little pH depression was observed in the runoff from low intensity events because of the domination of the ground-water component. However, during high-intensity rain events, a larger depression of stream pH was observed because of the greater proportion of runoff contributed directly by the rain.

The effects of these inferred flow paths are illustrated in Fig. 1 where direct precipitation onto saturated surfaces and the resulting overland flow maintain chemical compositions similar to the atmospheric deposition. As the water containing these materials migrates through organic soil and peat, the resulting solution will contain mineral and organic acids. Water moving through shallow acidic soils, depositing organic solutes and mineral acids, will solubilize Al, causing a solution with concentrated levels of H^+ and Al.

Driscoll and Newton (1985) noted that if acidic solutions are transported through thick mineral soil, H^+ and Al will be neutralized by the release of basic cations. Bottomley (1984) reported that ground waters in the Turkey Lakes watershed, Ontario, generally exhibited a deficit in alkalinity relative to base cations, which suggests that strong acid neutralization exchange reactions may occur in the unsaturated zone during ground-water recharge periods.

Present concepts regarding the generation of storm and snowmelt runoff appear somewhat discordant (Taylor, 1982; Price and Hendrie, 1983; Bottomley et al.,

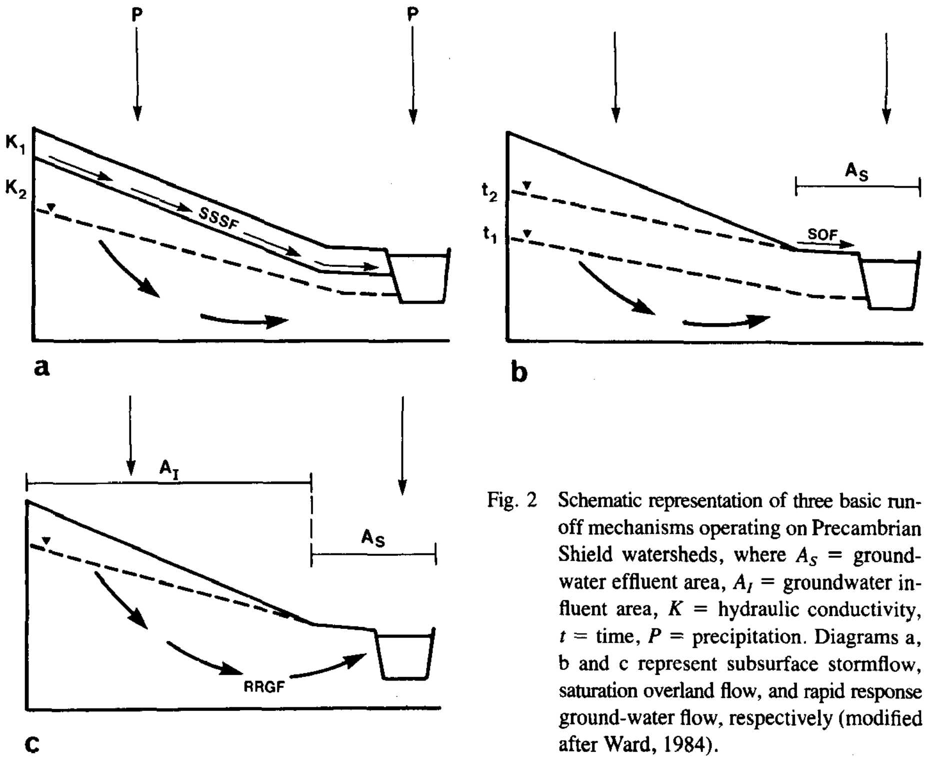

Fig. 2 Schematic representation of three basic runoff mechanisms operating on Precambrian Shield watersheds, where A_S = groundwater effluent area, A_I = groundwater influent area, K = hydraulic conductivity, t = time, P = precipitation. Diagrams a, b and c represent subsurface stormflow, saturation overland flow, and rapid response ground-water flow, respectively (modified after Ward, 1984).

1984) with the major discussion concerning the relative contributions of surface and subsurface water to event hydrographs. The traditional concepts of storm runoff production have received extensive reviews (Freeze, 1974; Dunne, 1978; Ward, 1984) and include: (i) Hortonian overland flow from partial catchment areas, (ii) variable source area saturation overland flow, (iii) subsurface stormflow, and (iv) rapid response ground-water flow. Figure 2 illustrates the operation of some of these processes on a Precambrian Shield watershed.

Hortonian overland flow (not shown in Fig. 2) is now known to be important only under limited conditions over frozen ground or over bare rock. Subsurface stormflow (Fig. 2a) is important in zones characterized by steep straight slopes with thin cover, underlain by impermeable bedrock (e.g. Weyman, 1974). This flow may be either saturated-unsaturated Darcian flow through the porous soil matrix (e.g. Harr, 1977) or turbulent flow through macropores (e.g. Beven and Germann, 1982). Saturation overland flow (Fig. 2b) is important in locations with thin soils, concave footslopes and wide valley bottoms (e.g. Dunne, 1978). This process occurs where infiltrating rain or snowmelt raises the water-table until it intersects the soil surface. Any additional water falling onto the expanding saturated (ground-water effluent) area is rapidly translated into streamflow via flow over a saturated surface. Rapid response ground-water flow (Fig. 2c) occurs when water previously stored in the watershed (phreatic, vadose and surface water) is displaced by incoming precipita-

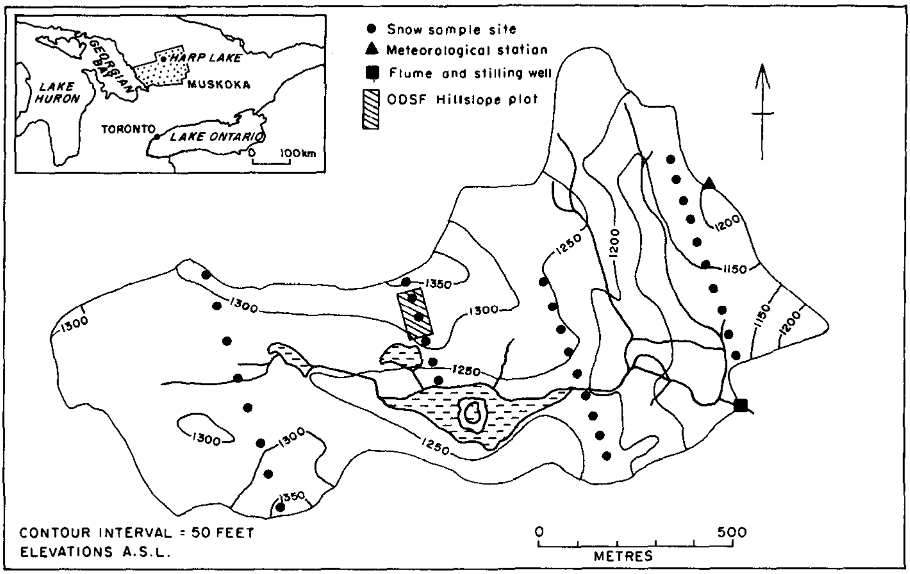

Fig. 3 Location of the Harp-4 catchment illustrating the snow survey network (dots), the ODSF hillslope plot, and the instrumentation.

tion to form the major portion of the event hydrograph. This is particularly important under shallow water-table regimes, where the tension-saturated capillary fringe extends to the ground surface (Sklash and Farvolden, 1979; Gillham, 1984).

Central to the latter two mechanisms is the expansion and contraction of surface saturated zones both seasonally and during discrete storm and snowmelt events. As shown by Rodhe (1981) and Taylor and Pierson (1985), when saturation overland flow is the primary mechanism for producing rapid runoff, it is possible to establish a close accordance between the percentage of a catchment that is surface-saturated, and the proportion of a rainfall or snowmelt input that is generated as quickflow, as defined by the time-based hydrograph separation technique of Hewlett and Hibbert (1967). The Hewlett and Hibbert technique, which has been widely used in many environments, does not in itself specify runoff pathways, but can be used, in combination with field observations, to infer them.

By using simple manipulations of easily collected field data, this study attempts to extend our interpretations of runoff-producing processes in the Canadian Shield. Particularly, it aims to comment on the relative importance of surface versus subsurface water movement during spring snowmelt, and thereby aid in the discussion of their significance to aquatic acidification.

3 Study area and instrumentation

The field experiment was conducted on an Acid Precipitation in Ontario Study watershed in Muskoka, Ontario (Fig. 3). The Harp-4 (H4) catchment is 119.8 ha in area and largely forested with sugar maple (*Acer saccharum*), yellow birch (*Betula* *alleghaniensis*) and beech (*Fagus grandifolia*), with some hemlock (*Tsuga canadensis*) and balsam fir (*Abies balsamea*) in poorly drained areas. Approximately 4% of the watershed is covered by wetland and the relief is relatively severe with a 5% grade (Jeffries and Snyder, 1983). The bedrock geology is typical of this Shield region mainly consisting of amphibolite and schist with some biotite and hornblende gneiss.

The surficial geology is characterized by a thin veneer of discontinuous basal till, with exposed bedrock common in many areas. The depth of overburden to bedrock ranges from an average 1 m to 10 m near the basin outlet. Water balance estimates based on our study and other data (Scheider et al., 1983a) suggest there is negligible loss via deep ground-water flow. Some of the streams are structurally controlled and most of the wetlands occupy bedrock depressions. The dominant soil types are acidic brunisols and podsols, with organic soils confined to zones of very poor drainage (Jeffries and Snyder, 1983). Profile development is poor or absent and thickness varies considerably from over one metre to only a few centimetres of overlying bedrock.

Temperature and precipitation were continuously recorded at an Ontario Ministry of the Environment meteorological station located on the basin divide (Fig. 3). Hourly streamflow was recorded at a flume and stilling well assembly located at the basin outlet. Direct heat was supplied to the flume pool to prevent freezing under subzero conditions. A snow course consisting of 32 points at 50-m intervals along four transects (Fig. 3) was sampled daily during periods of active melt using a Meteorological Service of Canada (MSC) snow sampler. Although Goodison (1978) notes that there are errors involved in the use of this technique (average error: 6%; error range: −1.8 to 13.0%), it was possible to use measurements of mean daily snowpack water equivalent to estimate daily meltwater inputs to the catchment surface. A full description of our snow survey technique is given by McDonnell (1985).

Much of the H4 watershed is characterized by thin overburden material lying on essentially impermeable bedrock. Under spring conditions, these normally unsaturated zones become saturated owing to a transient ground-water recharge. On sloping hillsides, this transient ground-water flow process is spatially and volumetrically important to the hydrologic response of the catchment. A small hillslope plot (Fig. 3) was monitored to examine the processes associated with saturated/unsaturated flow in some detail. Overburden thicknesses on the 18-degree slope averaged less than 1 m and were underlain by relatively impermeable amphibolite and schist bedrock. A series of open stand-pipe piezometers (I.D. 2.5 cm) was installed laterally up the hillslope to monitor ground-water level fluctuations on a daily basis and on an hourly basis during rain events.

4 Results

The spring runoff period was defined as extending from the first pronounced rise in the hydrograph from snowmelt and/or rainfall runoff until the occurrence of low flow levels following the last hydrograph peak that could be attributed to snowmelt. During this time in 1984 (February 13–April 23), approximately 151 mm of precipitation fell, which combined with the water available in the snowpack at the time of peak survey on February 14 to make 326 mm available for runoff. Of this total input, 250 mm passed out of the flume by April 24, 1984; using the separation technique of Hewlett and Hibbert (1967), 14% of the total runoff was characterized as quickflow and 86% as delayed flow. The following paragraphs discuss these water volume relationships in light of the recent theory of water movement within drainage basins.

a *Ground-Water Responses*

Saturated surfaces (ground-water effluent areas) were mapped in the field on three occasions, using the technique described by Dunne et al. (1975). Figure 4 shows that basin saturation was at 14.4% on April 10. Based on topography and some point measurements, we think that the saturated zone may have covered an additional 5% of the catchment earlier in the melt period, but it was not possible to map it easily under the continuous snow cover. The saturated zone then shrank through the later part of the melt period to 10.2% by May 12 and to only 4.2% of the total watershed area by July 1.

Ground-water level observations on the experimental hillslope plot (Fig. 3) could not begin until April 3 when the snowpack had depleted sufficiently to expose the piezometers. Ground-water levels declined quite rapidly after melt (Fig. 5), with only the downslope portions of the area (piezometers 1–3) remaining responsive after melt. Rain events on April 16 and May 7 show minor fluctuations superimposed on this general trend. More specifically, the rate of response for a given piezometer varied with its distance upslope, piezometers toward the top of the slope responding most rapidly to surface inputs and maintaining the highest rates of recession. Farther downslope, response was delayed by water draining as saturated-unsaturated Darcian flow over the impermeable amphibolite and schist boundary. In addition, the lower piezometers showed a disproportionately large rise in water-table elevation because of this process and also because of higher soil antecedent wetness.

A schematic representation averaged over the entire melt season is presented in Fig. 6. Immediately after melt (Fig. 6a), infiltrating meltwater was perched on the largely impermeable bedrock, resulting in considerable saturated subsurface (i.e. transient ground-water) flow. During this period, sideslopes remained saturated at the surface, and lower swale portions produced overland flow during rain events. One week after melt (Fig. 6b), the water-table elevations had declined somewhat, with much of the original meltwater draining freely. High hydraulic conductivities were still maintained in the lower hillslope portions, but the extent of the effluent area had declined. In Figs 6c and d (two and three weeks after melt, respectively), rapid drainage had allowed ground-water elevations to drop closer to background levels.

b *Melt Periods*

Ground surfaces remained unfrozen throughout the winter months and by the end of winter were overlain by a deep (mean W.E. on February 14 = 175 mm, SD =

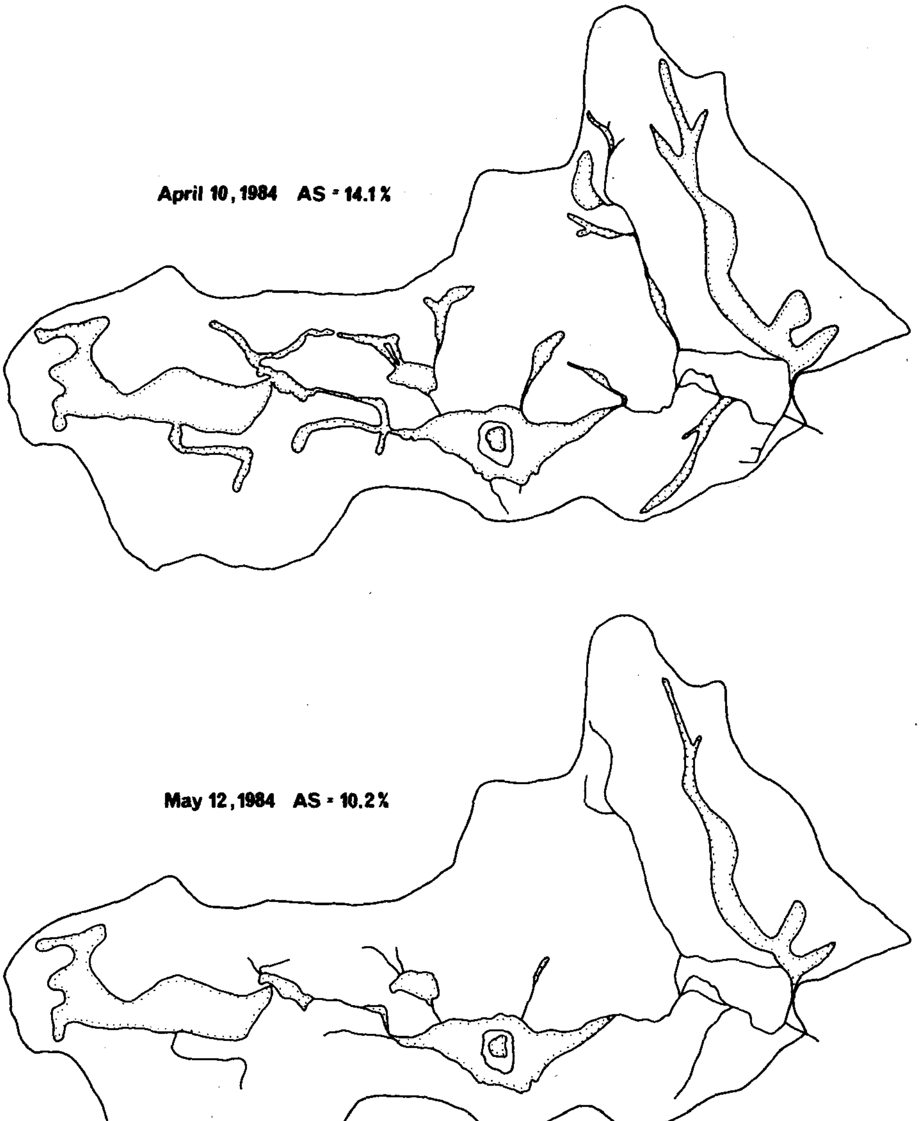

Fig. 4 Ground-water effluent area mapping for periods during and after the 1984 melt, where A_s is the percentage of ground surface saturated, and the stippled areas enclose zones of surface saturation.

19 mm) homogeneous snowpack. Three distinct periods made up the 1984 melt season, each representing different rainfall, soil surface, snowpack and antecedent conditions (Fig. 7). The three melt periods were characterized by: (i) a rain-on-snow event over a relatively homogeneous snowpack with unfrozen ground, (M1)

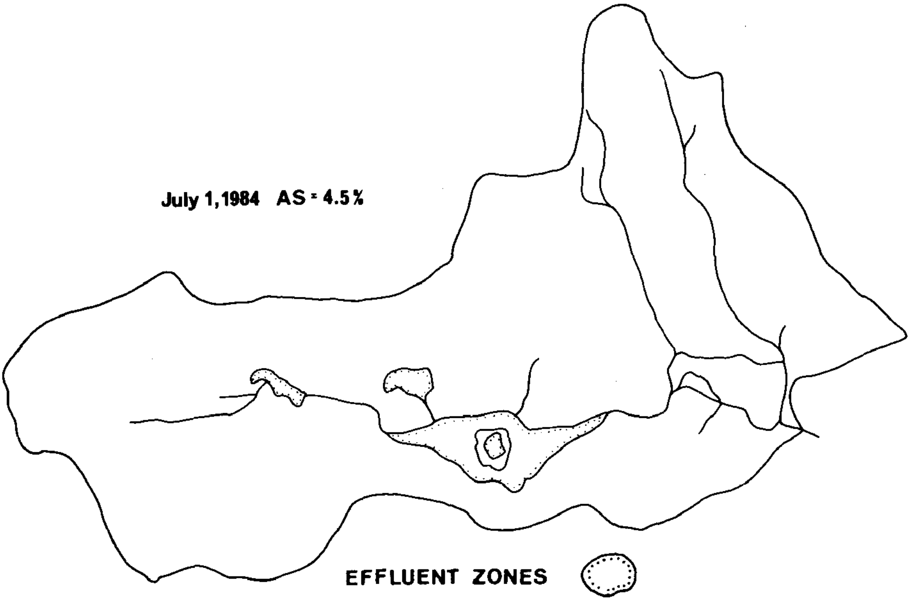

Fig. 4 (*Concluded*).

February 13–24, (ii) a rain-on-snow event over a severely crusted snowpack with partially frozen ground, (M2) March 15–27, and (iii) a radiation melting period over an isothermal snowpack with unfrozen ground, (M3) March 28–April 24.

In M1, initial water infiltrated freely in response to an early season 47-mm rain-on-snow event, resulting in a 25% loss of the snowpack and peak flow rates exceeding 0.64 mm h^{-1} (Fig. 7). Quickflow during this period (17.7% of the total available water) could be accounted for as surface runoff over ground-water effluent areas near stream channels, including the pond and wetland areas. Water infiltrating on the hillslopes in many shallow overburden areas would have also contributed to this response along with previously stored water displaced by incoming melt. On balance, however, a significant proportion of the meltwater input remained in storage, since only 58.2 mm of the 94 mm available from rain and snowmelt emerged as streamflow (Table 1).

The intervening cold temperatures between melt periods one and two (M1 and M2) resulted in structural discontinuities within the pack. On March 15, a 4-mm rainstorm was totally absorbed into the snowpack, but another 23-mm event the next day caused a runoff response (Fig. 7). A total of 33 mm of water was available for runoff during M2a, but only 5.1 mm emerged at the flume with 27.4 mm going into storage; the quickflow accounted for 20.9% of the total runoff. M2b was another small rain-on-snow event (14 mm) but yielded a much larger runoff volume than M2a, with 32% of the available water going into storage and with quickflow accounting for 18.3% of the total runoff. This suggests that overland flow over ground-water effluent areas was the probable major mechanism involved in rapid runoff, since this percentage corresponds very well to the proportion of the watershed area that was saturated when mapping was done later in the melt (see Fig. 4).

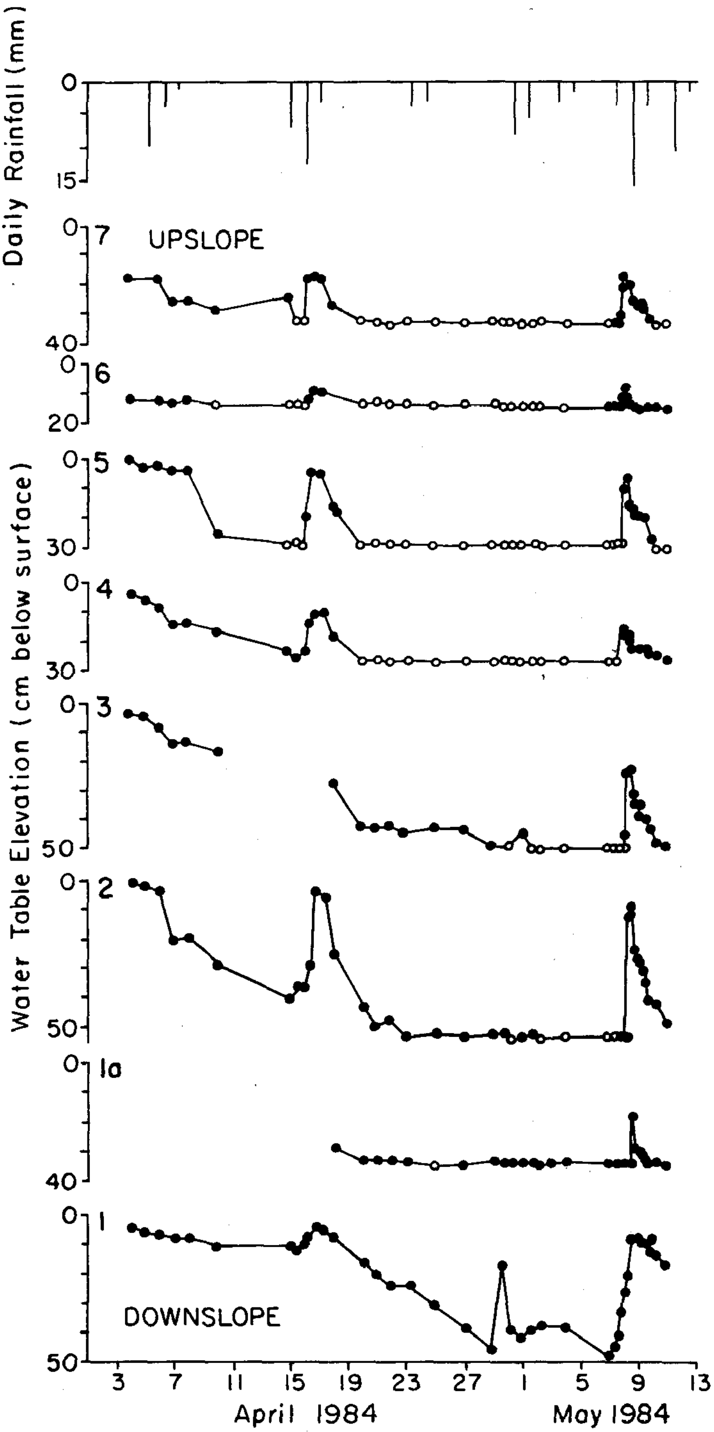

Fig. 5 Ground-water level fluctuations after snowmelt at the ODSF representative site. Open dots indicate a dry reading at the bedrock interface.

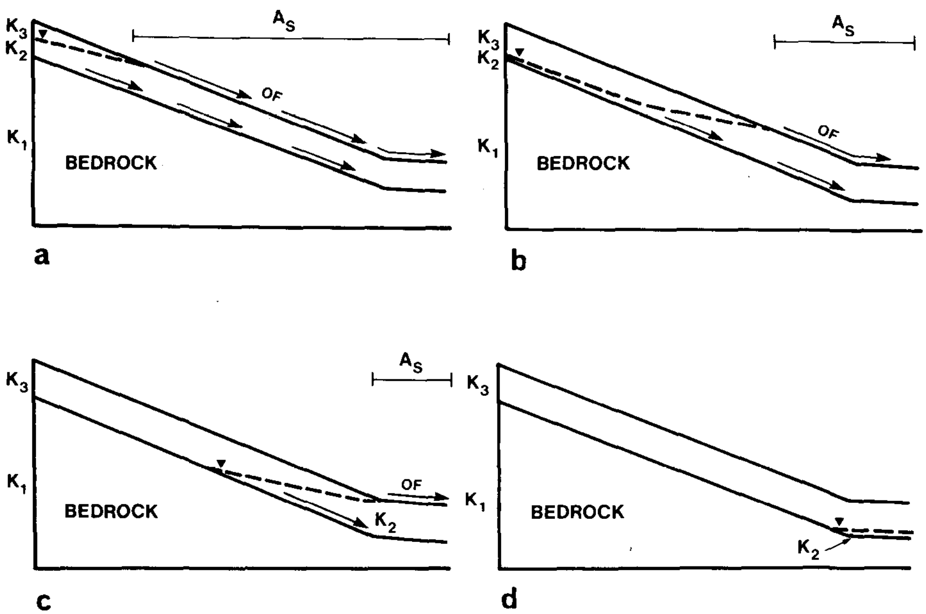

Fig. 6 Simplified schematic representation of hillslope flow processes at a representative site averaged over the entire study period, where A_s = surface saturated zone, OF = overland flow, K = hydraulic conductivity with K_1, K_2 and K_3 corresponding to flow through bedrock, saturated soil and unsaturated soil, respectively.

The main and final 24-d melt period (M3) was characterized by a series of 15 radiation melting events along with three minor rain-on-snow events (Fig. 7). A total of 141 mm was available from melt and rainfall during M3, and 139.3 mm emerged as runoff with 9.8% in the form of quickflow. As radiation melting progressed and pack ripening continued, the time-to-peak of the diurnal melt hydrograph decreased considerably, also as a result of the increased extent of saturated surfaces and more efficient water routing. In addition, infiltrated meltwater continued to drain through shallow soils over bedrock on the sideslopes.

M3 illustrates a hydrograph form different from those of M1 and M2. Streamflow showed a continuous rise until April 5, and then a steady decline to baseflow conditions, with quickflow peaks superimposed on this general trend. Table 1 shows increasing volumes of water moving into storage until April 5, when the basin was at its maximum retention capacity. In the first week of M3, storage change was highly positive while later in the melt as storage was filled, it became highly negative. Quickflow peaks superimposed on this general increase in groundwater and subsurface flow are a result of overland flow over saturated surfaces. In this period, as in earlier ones, quickflow responses (up to 21%) conform quite well with the surveyed extent of basin ground-water effluent areas (14.4% on April 10).

Bengtsson (1982) observed these same features for a small watershed in southern Sweden where overland flow was noted in the lower saturated portions of the basin,

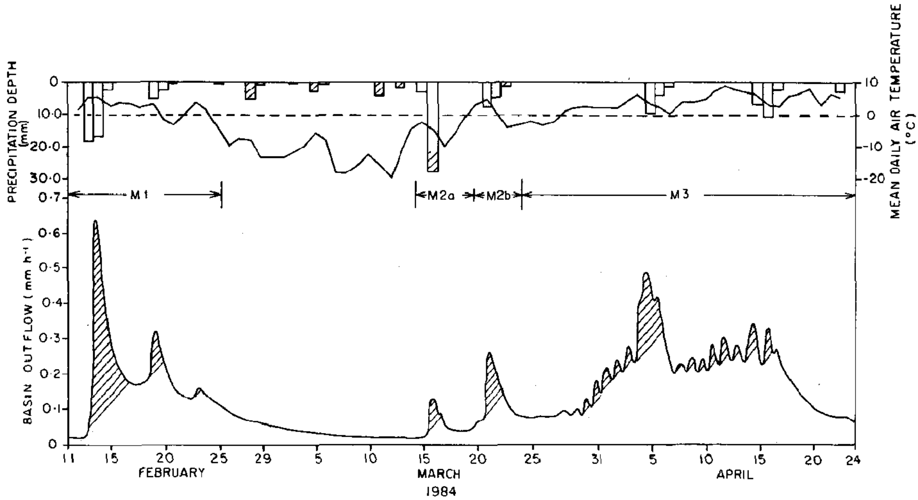

Fig. 7 Harp-4 runoff, temperature and precipitation records for the entire 1984 melt. M1, M2 and M3 represent different melt periods (see text). Hatching on the hydrograph indicates quickflow separations and on the hyetograph indicates precipitation in the form of snow.

however, the streamflow response to fluctuations in snowmelt intensity was small (similar to this study's), since most of the water was fed by subsurface outputs.

Figure 8 illustrates, in some detail, these subsurface responses at the piezometer transect for the April 16 rain-on-snow event. At this point, less than 10% of the basin was snow-covered and the study slope was essentially bare. Ground-water elevations can be seen to be time-linked with soil surface inputs, but are visibly lagged and dampened. More specifically, the upslope piezometer shows a rapid rise in water level and a slow recession to base-level conditions. In contrast, the downslope piezometer shows a much slower but more substantial increase in water-table elevations since water from upslope portions of the site flowed in the form of saturated subsurface flow (subsurface stormflow or translatory flow by displacement) to contribute water to the shallow swale area. This saturated (ground-water effluent) area at the base of the slope (swale area) showed a 10-m headward expansion as a result of this upslope contribution and the locally rising shallow water-table.

These interrelated changes in soil water storage, water-table elevations and water-table slope are also reflected in the basin outflow (Fig. 8). Although integrated over the entire watershed (representing a number of slope processes), the basin outflow shows a rapid rise from surface inputs because of high antecedent wetness conditions. As rain changed to snow (at about 1800 LST, April 16) basin response slowed significantly and declined 6 h later, until another small rain event caused a subsequent hydrograph rise. In this case, the time-to-peak of the hydrograph and the rate of recession in the basin were dampened as a result of new snowcover and greater storage potential.

5 Conclusion

The causes of the recent acidification of surface waters in several parts of the world,

TABLE 1. Tabulated summary of water volume relationships for the three 1984 melt periods

			Inputs			Outputs		Storage Change	
Melt Period			Melt (mm)	Rain (mm)	Total (mm)	Total (mm)	Quickflow Response (%)	(%)	(mm)
M1		Feb. 13–24	48	47	94	58.2	17.7	+38.2	36.1
M2	(a)	Mar. 15–21	10	23	33	5.1	3.0	+84.3	27.4
	(b)	Mar. 21–27	16	14	29	19.7	12.3	+32.0	9.6
M3	(a)	Mar. 27	4	0	4	1.8	—	+55.1	2.1
	(b)	Mar. 28	6	0	6	2.2	0.5	+65.0	4.0
	(c)	Mar. 29–30	17	0	17	5.0	1.0	+69.6	11.5
	(d)	Mar. 31–Apr. 1	8	0	8	8.0	13.1	+2.3	0.2
	(e)	Apr. 2	6	0	6	5.6	7.1	+5.2	0.3
	(f)	Apr. 3	13	0	13	5.4	5.2	+57.3	7.3
	(g)	Apr. 4–8	22	15	37	39.1	20.8	—	−1.9
	(h)	Apr. 9	4	0	4	5.2	7.9	—	−1.6
	(i)	Apr. 10	5	0	5	5.0	4.2	+1.8	0.1
	(j)	Apr. 11	6	0	6	6.2	11.6	—	−0.7
	(k)	Apr. 12	4	0	4	7.3	19.1	—	−3.4
	(l)	Apr. 13	4	0	4	5.1	5.7	—	−1.5
	(m)	Apr. 14–23	5	23	28	44.6	5.0	—	−16.4

including Scandinavia (e.g. Overrein et al., 1980) and North America (e.g. Likens et al., 1979) are still a matter of considerable controversy. A better understanding of the acidification mechanisms can be obtained by a combination of field studies and mathematical modelling (Seip et al., 1985). Since hydrological processes are an integral part of any deterministic hydrogeochemical model, a more detailed understanding of water movement through study catchments will result in improved chemical flux estimates. The residence time of water in a catchment strongly controls the water chemistry (Marmorek et al., 1984). Bottomley et al. (1984) have previously pointed to the strong ameliorating influence of ground-water discharge on the acid input from rainstorms in the H4 catchment. Using data from the same catchment, Whitehead et al. (1986) have also shown that the proportion of channel flow derived from subsurface sources has a large effect on its acidity.

A general assessment of the 1984 melt season for the H4 catchment indicates that of the total runoff, 14% occurred as quickflow. The time-based separation technique upon which this is based does not establish runoff pathways, but it is interesting to note that quickflow for the whole period accounts for 10.7% of the total precipitation and snowmelt – a figure quite close to the mapped extent of ground-water effluent areas in the watershed. Using the reasoning of Dickinson and Whiteley (1970), Rhode (1981) and Taylor (1982), this does suggest that most of the rapid runoff that contributed to the peaks of the hydrographs could have been generated by water resulting from snowmelt and rainfall directly onto saturated surfaces and moving over them as overland flow. The remainder of the runoff, therefore, can be interpreted as having moved at various speeds via subsurface pathways.

From an inspection of water volume relationships and field observations, it is assumed that most of the subsurface water discharged from these areas is meltwater

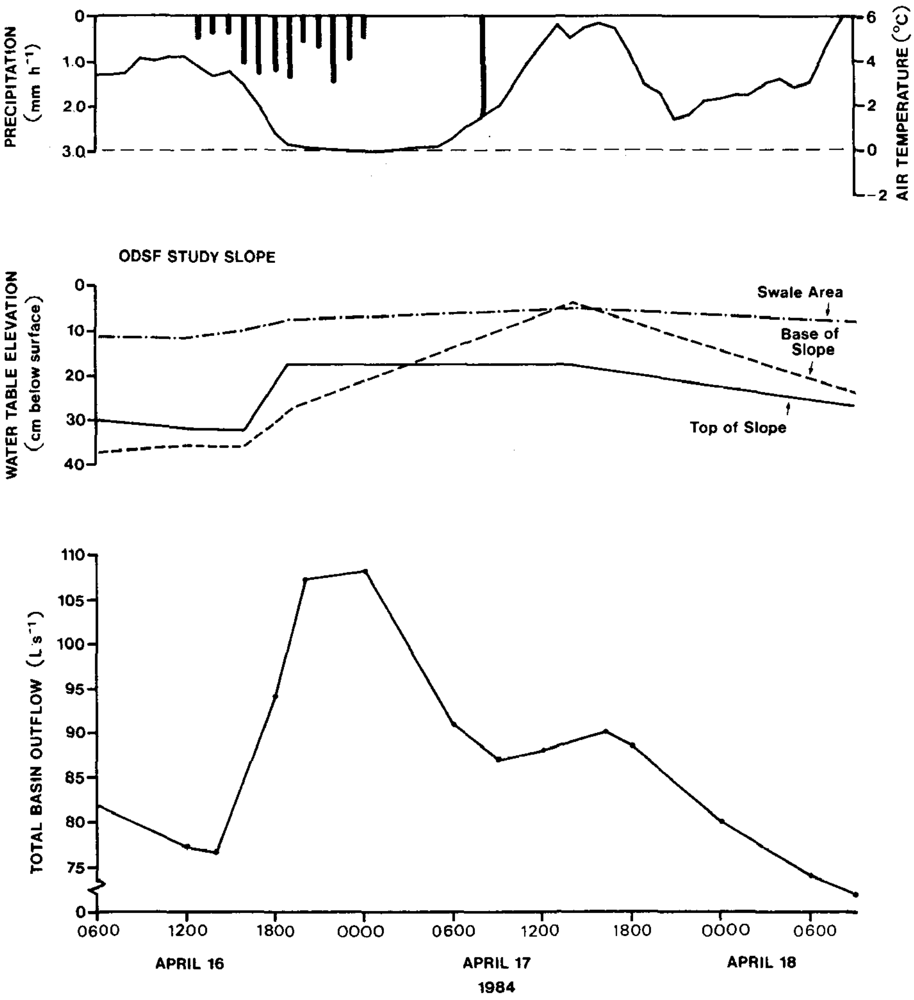

Fig. 8 Water volume and water depth relationships for the April 16, 1984 storm event.

that had infiltrated earlier in the melt season and was then delivered as a transient ground-water flow or saturated-unsaturated subsurface stormflow toward the end of the melt period through the shallow overburden materials.

Overall, the results of this study using hydrograph separation and ground-water effluent area mapping appear consistent with other studies involving the use of stable isotope tracers (e.g. Sklash and Farvolden, 1979), mathematical simulations (e.g. Stephenson and Freeze, 1974) and stream water temperature separations (e.g. Kobayashi, 1985). In particular, Rodhe (1981) used a combination of stable isotope tracers and ground-water effluent area computations for two forested watersheds in Sweden, and determined that the discharged volume of meltwater equalled the total melting over 10–15% of the basin – a figure representing the fraction of saturated areas in the catchment.

Detailed studies of watershed processes are required to improve the development and calibration of hydrogeochemical models (Marmorek et al., 1984) and our understanding of streamflow generation on Precambrian Shield catchments. In the Muskoka-Haliburton area in Ontario, field research needs to be pursued more vigorously in a wider range of physiographic environments and under a broader range of conditions than are currently acknowledged. This will allow basin representativeness to be determined and model extrapolations to other watershed areas to be made more realistic.

Acknowledgements

This study was funded by the Natural Sciences and Engineering Research Council of Canada, and also supported by the Ontario Ministry of the Environment and its Acid Precipitation in Ontario Study. Particular thanks go to Mr Wolfgang Scheider and Dr Peter Dillon of the Dorset Research Station for generously providing much of the required data and technical assistance. The field assistance of Gary Ward is also gratefully acknowledged. This paper was originally presented at the Canadian Waters: The State of the Resource Symposium, Toronto, May 28, 1985.

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