Effects of Varying Snowpack and Watershed Conditions on Snowmelt Runoff Response

J.J. McDonnell and C.H. Taylor

Watershed Ecosystems, Trent University, Peterborough, Ontario K9J 7B8

Introduction

The spatial and temporal variability of snowmelt and runoff generation in the Precambrian Shield region of south-central Ontario makes modelling these processes very difficult both on an annual basis and during discrete melt episodes.

A number of investigations have identified this problem in various climatic regions (Dunne et al., 1976; Price et al., 1978; Bengtsson, 1982). In terms of operational streamflow forecasting, a number of models have been developed for synthesizing or simulating streamflow from snowmelt (see Fleming, 1975). Gray et al. (1984) note that in Canada there is no unanimity among Provincial water management agencies in the choice of a model that best satisfies their requirements and produces the most reliable and accurate results.

A recent application of these snowmelt subroutines has been associated with aquatic acidification and material flux through watersheds. An examination of the suitability of 18 such routines used in existing models is being undertaken by the Ontario Ministry of Natural Resources (MacLaren Plansearch, 1984). A detailed knowledge of the processes and pathways of snow cover ablation and meltwater runoff is required for their improvement and calibration. It is hoped that the results of the study described here will be useful in this connection.

Study Site and Instrumentation

The Harp 4 watershed (120 ha) used in this investigation is located near Dorset, Ontario (Figure 1) and has been gauged both chemically and physically since 1976, as part of the Ontario Ministry of the Environment's Acid Precipitation in Ontario study. The watershed is largely forested except for open wetlands and bare rock areas. The surficial geology is characterized by a thin veneer of discontinuous basal till with some isolated deposits of deeper sands and silts.

The variable climate and non-uniform surficial geology of the area result in a complex snowmelt runoff system with large annual and seasonal variation in melt regime. This investigation focuses on one melt season (spring 1984) and the effects of varying snowpack and watershed conditions on the snowmelt runoff response.

A number of different techniques were used to quantify the rates, volumes and pathways of the various melt and runoff components during snowmelt, 1984, which extended from February 13 to April 24.

Inputs were measured at a M.O.E. meteorological station located on the basin divide and by daily measurements on a 32-point snow course (Figure 1). Outflow was monitored at a flume and stilling well assembly at the basin outflow. In order to help identify runoff processes and pathways, groundwater effluent areas were mapped throughout the watershed, and groundwater level measurements were made at a transect of shallow wells up a selected slope.

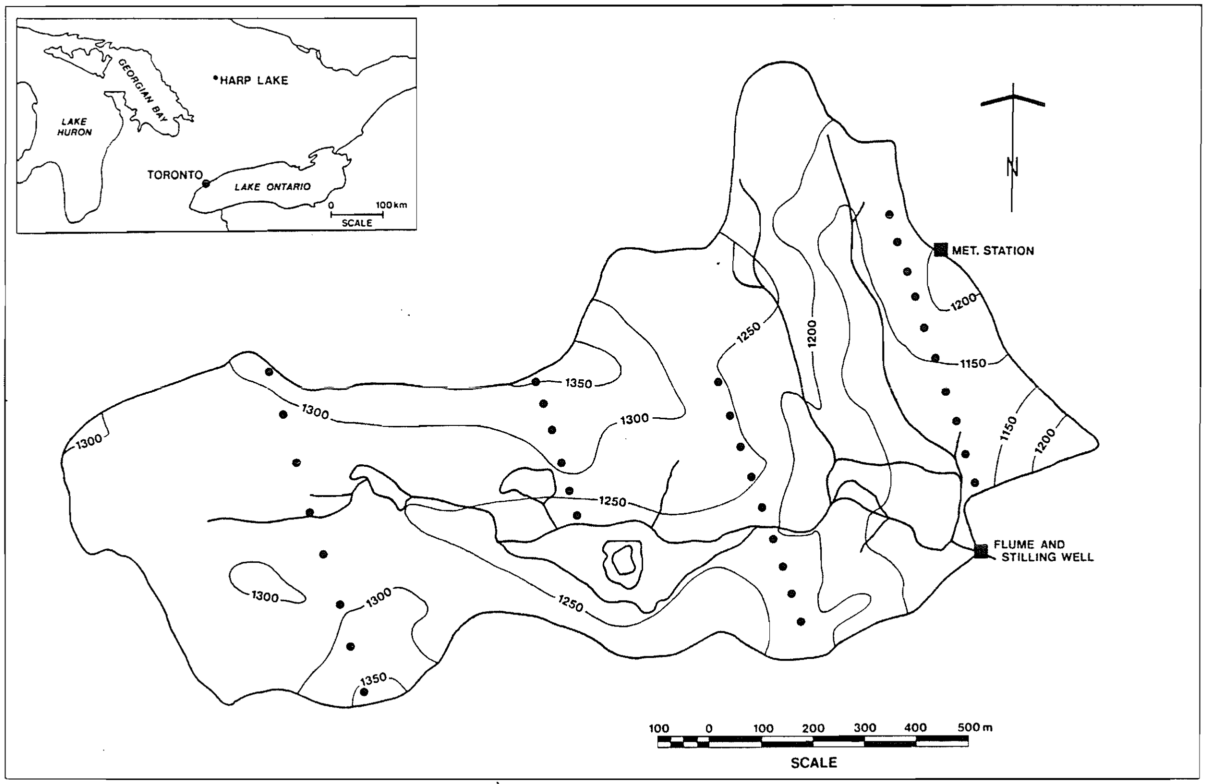


Figure 1. Location, physical characteristics and instrumentation of Harp 4 study watershed. Dots represent snow sampling locations.

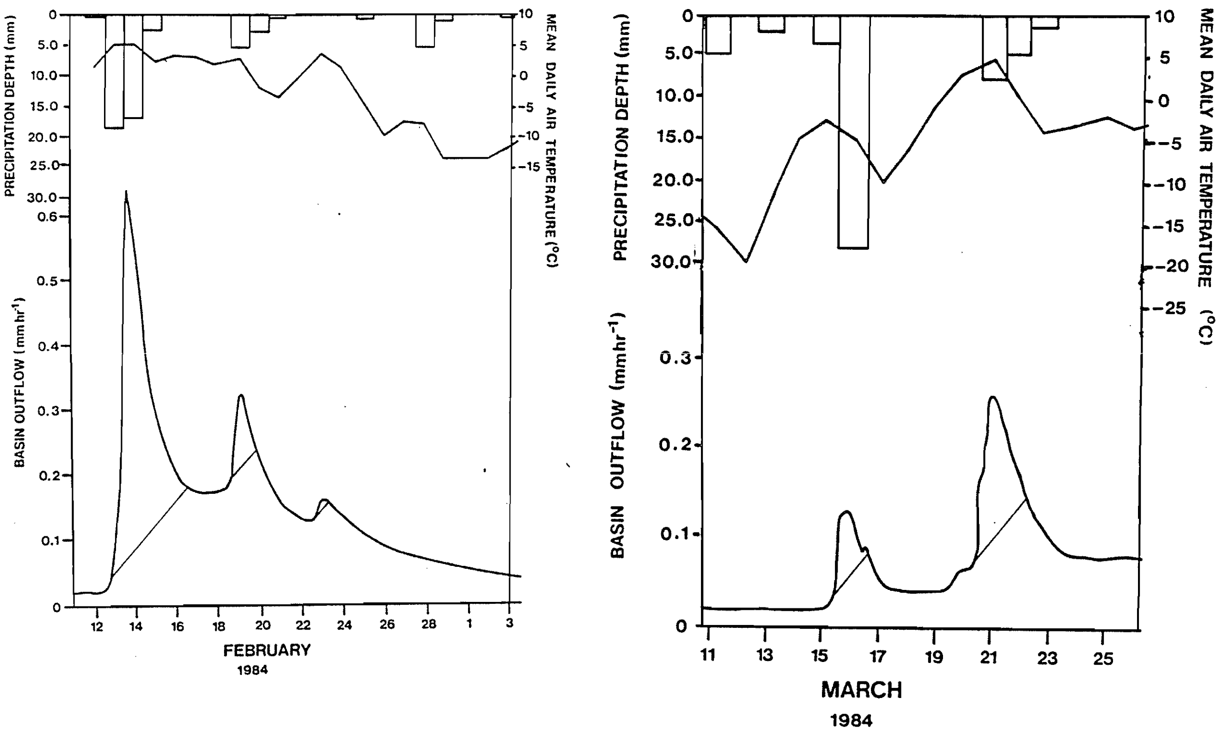
Results

Examination of the 1984 melt data show that three distinct melt periods dominated the season, each representing different rainfall, soil, snowpack and antecedent conditions. Ground surfaces remained unfrozen throughout the winter months and were overlain by a deep (762 mm) homogeneous snowpack. The three melt periods were defined as February 13-24 (M1), March 15-27 (M2) and March 28-April 24 (M3), (Figures 2a-c).

Table 1 summarizes the inputs, outputs and storage changes for the three melt periods, and also for individual peaks within them. Quickflow volumes were obtained for the peaks by means of Hewlett and Hibbert's (1967) time-based separation technique.

In M1 (Figure 2a) initial water infiltrated freely in response to an early season rain-on-snow event. Approximately 25% of the snowpack was lost during this event and peak flow rates exceeded 0.64 mmhr^{-1}. From groundwater effluent area mapping performed later in the melt and water volume relationships (Table 1), it is assumed that quickflow in this period was generated as surface runoff over saturated surfaces near the channels and wetland areas, with a large portion of the water input (38%) remaining in storage.

Cold temperatures between M1 and M2 resulted in widespread basal ice and severe structural discontinuities in the snowpack, with considerable storage available in the watershed. The hydrograph for the first peak in M2 (Figure 2b) shows the effects of these antecedent conditions on the runoff response, with much of the water input from March 15 and 16 remaining in storage. Wetter conditions, including more extensive surface saturation, contributed to a much greater runoff response on March 21 (Table 1).



(a) Melt period 1 (M1)

(b) Melt period 2 (M2)

(c) Melt period three (M3)

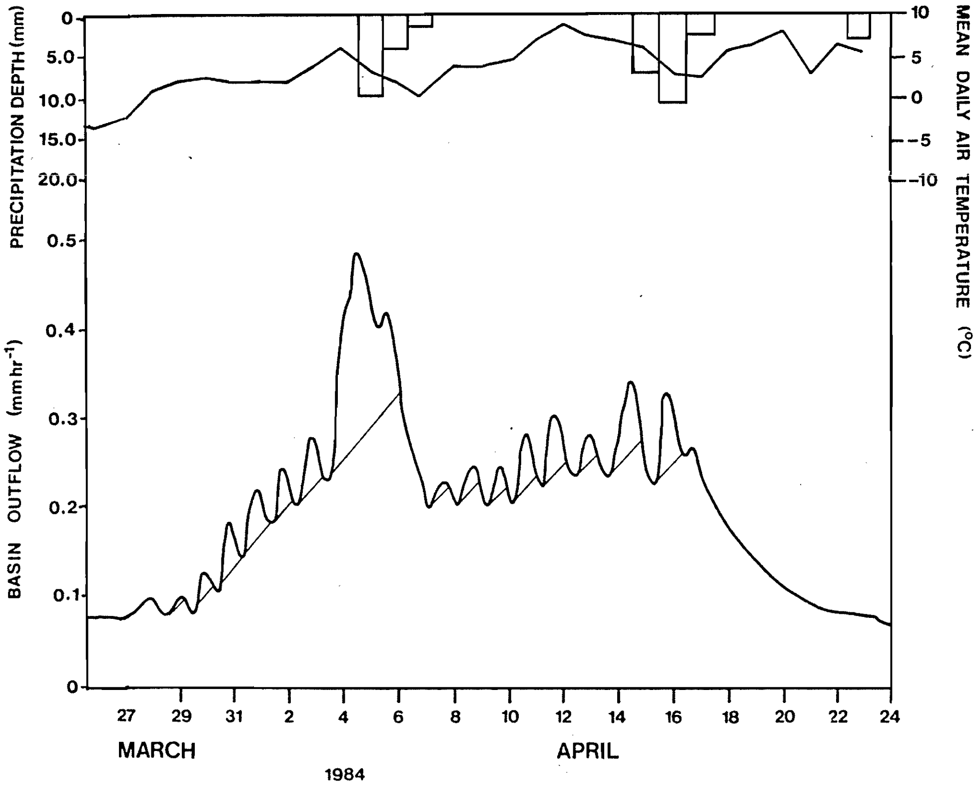


Figure 2. Outflow hydrographs for the three melt periods.

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

			INPUTS			OUTPUTS		STORAGE CHANGE	
Melt Period			Melt (mm)	Rain (mm)	Total (mm)	Total (mm)	Quickflow Response (%)	(%)	(mm)
M1		Feb 13-24	47.5	46.8	94.3	58.2	17.7	+ 38.2	36.1
M2	(i)	Mar 15-21	10.0	22.5	32.5	5.1	3.0	+ 84.3	27.4
	(ii)	Mar 21-27	15.6	13.7	29.3	19.7	12.3	+ 32.0	9.6
Total			25.6	36.2	61.8	24.8	7.5	+ 60.0	37.0
M3	(i)	Mar 27	3.9	0	3.9	1.8	-	+ 55.1	2.1
	(ii)	Mar 28	6.2	0	6.2	2.2	0.5	+ 65.0	4.0
	(iii)	Mar 29-30	16.5	0	16.5	5.0	1.0	+ 69.6	11.5
	(iv)	Mar 31-Apr 1	8.2	0	8.2	8.0	13.1	+ 2.3	0.2
	(v)	Apr 2	5.9	0	5.9	5.6	7.1	+ 5.2	0.3
	(vi)	Apr 3	12.7	0	12.7	5.4	5.2	+ 57.3	7.3
	(vii)	Apr 4-8	21.9	15.3	37.2	39.1	20.8	-	-1.9
	(viii)	Apr 9	3.6	0	3.6	5.2	7.9	-	-1.6
	(ix)	Apr 10	5.1	0	5.1	5.0	4.2	+ 1.8	0.1
	(x)	Apr 11	5.5	0	5.5	6.2	11.6	-	-0.7
	(xi)	Apr 12	3.9	0	3.9	7.3	19.1	-	-3.4
	(xii)	Apr 13	3.6	0	3.6	5.1	5.7	-	-1.5
	(xiii)	Apr 14-23	5.0	23.2	28.2	44.6	5.0	-	-16.4
Total			102.0	38.5	140.5	139.3	9.7	+ 0.8	1.2

The final melt period (M3) was characterized by a series of 15 radiation melts along with three minor rain-on-snow events (Figure 2c). Table 1 shows increasing volumes of water moving into storage until April 5, when the basin was at its maximum retention capacity. Quickflow peaks superimposed on the general increase in groundwater flow are a result of overland flow over saturated surfaces. In this period, as in the earlier ones, quickflow responses (up to 21%) conform quite well with the surveyed extent of basin saturation (14.4% on April 10).

Discussion

Results indicate that most of the water output over the whole 1984 season (86%) left the watershed as delayed flow, presumably via subsurface pathways, while the water comprising the rapid individual runoff peaks (14%) could be accounted for by overland flow on saturated surfaces mapped throughout the basin.

As seen in the hydrographs and Table 1, the runoff response varied throughout the melt period. This can be accounted for mainly by different snowpack, soil and groundwater conditions affecting the ability of the watershed to store water. In addition, varying moisture conditions on the sideslopes affected rates and volumes of subsurface flow, and the varying extent of surface saturation in the valley bottoms controlled the volumes of rapid runoff delivered by overland flow.

The effects of varying snowpack and watershed conditions on snowmelt runoff response must be accounted for in the application of snowmelt runoff models. Results of this study agree with those of Braun and Slaymaker (1981) that at the small watershed scale, streamflow during snowmelt is primarily a function of snow phenology and variable runoff generation pathways.

The various models available for use differ from each other in some form, either as they calculate hydrological components or simulate the processes of snow cover accumulation and ablation, evaporation, infiltration, changes in soil moisture storages, and flood routing (Gray et al., 1984). Even when a model is applied to a watershed similar to where it was developed, extensive calibration and testing of its performance is necessary. The results of this study indicate that large variations in snowmelt and runoff processes even within a single melt season, can complicate the modelling process and must be taken into account during calibration periods.

References

Bengtsson, T., 1982. Groundwater and meltwater in the snowmelt-induced runoff. Hydro. Sci. Bul. 27(2) : 147-158.

Braun, L.N. and H.O. Slaymaker, 1981. Effect of scale on the complexity of snowmelt systems. Nord. Hydrol. (12): 225-234.

Dunne, T., A.G. Price and S.C. Colbeck, 1976. The generation of runoff from subarctic snowpacks. Water Resour. Res., 12(4): 677-685.

Fleming, G., 1975. Computer simulation in hydrology, Elsevier, New York.

Hewlett, J.D. and A.R. Hibbert, 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In W.E. Sopper and H.W. Lull (eds.), Forest Hydrology, Pergamon, 275-290.

Gray, D.M., P.G. Landire and R.J. Granger, 1984. Simulating infiltration into frozen Prairie soils in streamflow models. Can. J. Earth Sci., (22): 464-472.

MacLaren Plansearch, 1984. Snow hydrology study phases I and II : study methodology and single event simulation. Report for Conservation Authorities and Water-Management Branch, Ministry of Natural Resources, Province of Ontario, Toronto, Ontario, pp. 1.1-8.8.

Price, A.G., L.K. Hendrie and T. Dunne, 1978. Controls on the production of snowmelt runoff. Proc. Modeling of Snow Cover Runoff, S.C. Colbeck and M. Ray (eds.), Hanover, N.Y., 257-268.