

AN INTEGRATED MODEL OF SNOWMELT QUALITY  
FOR BOREAL FOREST SITES

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ABSTRACT

An integrated model for snowmelt quality in boreal-forest sites has been developed by coupling a physical snowmelt model with a chemical model for the discharge of strong-acid anions from snowpacks during springmelt. The basic physical model is SNOW-17 (Anderson, 1973); the chemical model is derived from empirical relationships between the concentration of strong-acid anions in the snowpack and those found in successive snowmelt discharges during the runoff period. The physical model is a semi-empirical model in which the air temperature is used as an index to energy exchange across the snow-air interface. It includes mass transfer functions, energy exchange functions and water routing functions. Only two variables, air temperature and precipitation, are needed to simulate snow accumulation and ablation for each chosen output interval. Simulation using data taken during one season suggests that the model will be quick to calibrate. The chemical module is driven by a leaching coefficient  $k$ , the value of which is determined by a best fit between meltwater concentrations simulated by the conceptual model for ion discharge and meltwater concentrations measured in situ. Lysimeter studies in the field and laboratory have indicated that the values for  $k$  are related to the physical structure of the snow, both prior to, and during the circulation of free water through the pack. The model has been applied at the Lac Laflamme watershed in the boreal forest 80 km north of Québec city, Québec.

## INTRODUCTION

Recent research on acid precipitation in eastern Canada, has shown the existence of acid stress in aquatic ecosystems during the spring runoff period. Dramatic decreases in the pH of water by as much as 2 pH units have been reported (Papineau, 1985). The Québec region of the Inland Water Directorate (Environment Canada) has thus given priority to research on the snowmelt season. The main objective is the development of a model to evaluate the impact of spring melt on water quality in a boreal-forest environment. It will be a two-layer model, snowpack and hillslope systems being treated independantly. The upper layer of the model deals with the chemical composition of meltwater discharge from the snowpack. It is presently being jointly developed by research teams from Laval university and INRS-Eau.

## MODEL STRUCTURE

The model (fig.1) is the result of an integration of a physical module which simulates the evolution of snowcover and meltwater discharge (mm) from the pack and a chemical module which relates meltwater quality (concentration,  $\text{Mg.l}^{-1}$ ) to the quantity (mm) of meltwater discharge.

### Physical module

The purpose of the physical module is to estimate efficently, by numerical simulation, the evolution of the snowpack as well as the amount of water released at the ground level.

A temperature index type of model was preferred to an energy budget model, because the input data required for the former are more standardized and easily available. The model chosen is SNOW-17, a snowmelt model published by Anderson in 1973 as a subroutine of the HYDRO-17 (NWSRFS) hydrologic model. It is considered as one of the most advanced temperature index snowmelt models currently available.

A simplified flow chart of the whole snowmelt water quality model is presented in figure 1. The input required by the physical module (SNOW-17) is air temperature and precipitation. The physical functions can be grouped into three categories: the mass transfer functions, the energy transfer functions and the water routing functions.

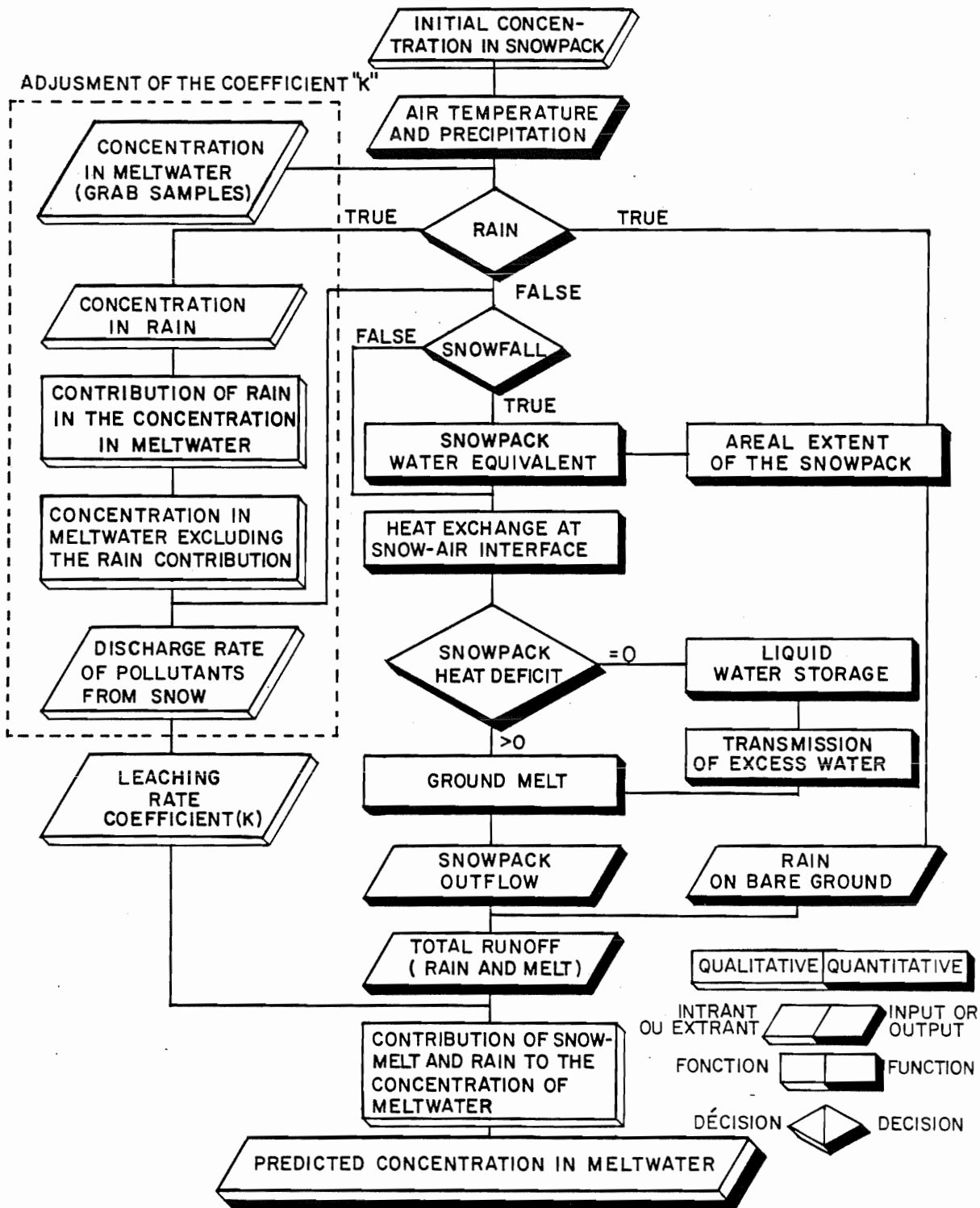


Figure 1: Flowchart of the integrated snowmelt model

The mass transfer functions include a function related to the area (%) of ground covered by snow. This is particularly important at the end of the snowmelt season when the snowpack is discontinuous.

The energy transfer functions evaluate the energy exchange at the snow-air interface. It also computes an energy deficit for the snowpack during cold weather (air  $T^0 < 0^{\circ}\text{C}$ ). This deficit has to be depleted before any other snowmelt can be generated. It also includes the melt generated by heat flux from the ground.

The water routing functions consider the capacity of the snow to hold free water and subsequently simulate empirically the lag induced by percolation of the water through the snowpack. As output, the model adds rain on bare ground to snow cover outflow during discontinuous snowcover conditions.

In contrast to most temperature index models for snowmelt and, more specifically to those using the degree-day method, air temperature is not used directly in SNOW-17 as an index to snowcover outflow but as an index to energy exchange at the snow-air interface.

The time step of the simulation is left to the choice of the user but it must be a multiple of the input-data time-series interval. This is usually between one hour and one day.

The model possesses 12 adjustment parameters, most of which are related to the physical characteristics of the site such as orientation and slope of the terrain and the type and density of forest cover.

#### Chemical module

The basic chemical parameters which control the final qualitative output of the model are concentration ([C] of meltwaters, snow or rain), water equivalent ([H] of meltwaters, snow or rain) and a leaching coefficient (k) which quantifies the rate of removal of pollutants from a pack by the passage of free water.

In a melt period without precipitation, the relationship between the concentration of any ion in a meltwater sample and the quantity of meltwater discharged from the pack in any given period of the melt is given by the expression:

$$[C]_{i \rightarrow i+1} = \frac{[C]_0}{(H_i - H_{i+1})} \left[ H_i e^{-k(H_0 - H_i)} - H_{i+1} e^{-k(H_0 - H_{i+1})} \right] \quad (1)$$

where:

$[C]_{i \rightarrow i+1}$  = concentration of the ion in a meltwater sample ( $H_i$  --  $H_{i+1}$ , mm) discharged during the melt period ( $\mu\text{eq.l}^{-1}$ );  $[C]_0$ , initial concentration of the ion in the snowcover immediately before any ablation of the snowcover takes place ( $\mu\text{eq.l}^{-1}$ );  $[H]_0$ , initial water equivalent of the snowcover before any ablation of the snowcover takes place (mm);  $[H]_i$ , water equivalent of the snowcover prior to the discharge of the meltwater sample (mm);  $[H]_{i+1}$ , water equivalent of the snowcover after the discharge of the meltwater sample (mm) and  $k$  is the leaching coefficient.

For melt periods during precipitation events, i.e. rain-on snow episodes the value of  $[C]_{i \rightarrow i+1}$ , i.e. the contribution of snowmelt to the final lysimeter samples, has to be calculated from the expression:

$$[C]_{i \rightarrow i+1} = \frac{[C]_L H_L - [C]_P (H_P - A)}{H_L - (H_P + A)} \quad (2)$$

where:  $[C]_L$  = ion concentration in the lysimeter sample ( $\mu\text{eq.l}^{-1}$ );  $H_L$ , quantity of  $L$  rain and meltwater collected by the lysimeter (mm);  $[C]_P$ , ion concentration in rainwater sample ( $\mu\text{eq.l}^{-1}$ );  $H_P$ , quantity of rain collected by the wet-only precipitation collector (mm) and  $A$ , quantity of rainwater retained if no further melt equivalent to the quantity  $A$  is produced after the rain episode terminates.

This expression assumes that the chemical composition of all rain which passes through the pack remains unchanged. The quantity  $A$  which can be retained under certain conditions can be estimated from the water equivalent and the density of the snowpack (Jones *et al.*, 1985) at the end of the melt period.

In cold periods with no melt, the model does not generate any meltwater discharge; if precipitation falls as snow, new snowfalls are integrated into the model by recalculating a mean concentration for any ionic species in the pack. This new value of  $[C]_0$  for the next melt sequence is given by:

$$[C]_0 = \frac{[C]_s H_s + [C]_n H_n}{H_0} \quad (3)$$

where:  $[C]_0$  = mean concentration of ion in the snowpack;  $[C]_s$ , concentration of ion in snowfall;  $[C]_n$ , concentration of ion in snowpack at the end of the previous melt period (measured or computed);  $H_s$  water equivalent of new snow;  $H_n$ , water equivalent of snowpack prior to new snowfall (measured or computed), and  $H_0 = H_s + H_n$ . This computed mean value of  $[C]_0$  from snowfall can be verified by the analysis of cores from the snowcover after any new snowfall event.

At the beginning of the melt  $H_0$  may be measured directly or computed from the physical module. As our present state of knowledge on the chemical evolution of snowcover does not allow us to compute  $[C]_0$  from the concentrations of individual snowfalls. The values of  $[C]_0$  are obtained directly from the chemical analysis of snow cores.  $k$  values for the model are determined by a bestfit of expression (1) to the measured relationship between the concentrations ( $H^+$  from pH,  $NO_3^-$ ,  $SO_4^{2-}$ ) and the quantity of meltwater samples from the field lysimeters. The bestfit exercise ignores data points which precede the maximum observed value for the concentration of meltwater after the start of any particular melt. In 1984, this represented one point only i.e. the meltwater sample collected on the first day of the melt period studied. The theoretical justification for this procedure has already been reported by Jones *et al.*, (1985).

## METHODOLOGY

The model was tested using data of spring 1984 from an experimental plot on the north slope of the Lac Laflamme watershed (Forêt Montmorency, Québec), 80 km north of Québec city. This site is located under a balsam fir cover, at an altitude of 800 m, in a boreal-forest environment.

The time step used for the physical simulation was one hour. The temperature was measured in a shelter under the canopy. The precipitation data were obtained from an heated pluviograph in situ as well as from a standard weather station located 1,5 km away. To evaluate the simulation results we monitored the outflow from a 20 m<sup>2</sup> snow lysimeter and estimated the average snow cover water equivalent from ten sampling points on the plot.

For the first attempt of simulation we gave the parameters a set of *a priori* values. The choice of these values was made according to guidelines provided by Anderson (1982) and based on physical knowledge of the site.

After the first simulation we carried out a sensitivity study of SNOW-17 to its parameters and then we proceeded with a series of calibration runs based on the 1984 melt season data. The adjustment of the parameters was obtained by a trial and error approach, according to the Anderson (1982) guidelines and with respect to the physical meaning of each parameter.

Precipitation (snow and rain) samples for chemical analysis were recovered from two Sangamo Type A wet-only collectors which were permanently installed outside the drip zone of the conifer trees. One collector was situated in an open area, the other beneath a balsam fir canopy. Snowcover samples were obtained by coring the snowcover with a large plastic (PlexiGlas) corer having a square (25 cm x 25 cm) cutting edge. No special precautions to remove surface debris from cores were taken except where twigs, lichen clumps and animal excrement interfered with the sampling operations. Meltwater was sampled from the discharge of a field lysimeter (fiberglass tank, 1 m x 1 m x 0,5 m deep) which had been installed before the first snow of autumn 1983. The organic layer of soil was removed down to a depth of approximately 10 cm and the lysimeter placed on the mineral horizon, levelled and connected by ABS tubing (10 cm diameter) to large plastic recipients (45 litres) buried in the lower soil horizons. To avoid any local heating of the fibreglass that can occur by solar radiation, polystyrene foam was used to cover any parts of the lysimeter that became exposed during the melt season.

Precipitation samples were collected on an event basis or, if the event lasted more than 24 hours, approximately every 24 hours. Lysimeter samples were collected approximately every 24 hours depending on the local meteorological conditions. The snowcover was sampled less frequently. Snow samples were kept frozen (-20°C) in polyethylene bags until melted;

liquid samples were kept at 4°C up to a maximum time limit of 48 hours. Melting of snow was carried out under an atmosphere of N<sub>2</sub> in large capped plastic bottles, pH was determined on unfiltered liquid samples by means of a pH meter radiometer pHM26. All liquid samples were filtered, (polycarbonate 47 mm, 0,4 µm) and the filtered samples analysed for NO<sub>3</sub><sup>-</sup> and SO<sub>4</sub><sup>2-</sup> by ion chromatography (Dionex 125).

## RESULTS

At the end of the SNOW-17 calibration process only two of the 12 parameters were altered. The maximum melt factor (MFMAX), a major parameter, which was originally fixed at 0,80 mm/°C/6 hr was increased to 0,85. The percent-liquid-water-holding-capacity for ripe snow (PLWHC), a minor parameter, was originally estimated at 0,05. The calibration brought it down to 0,03.

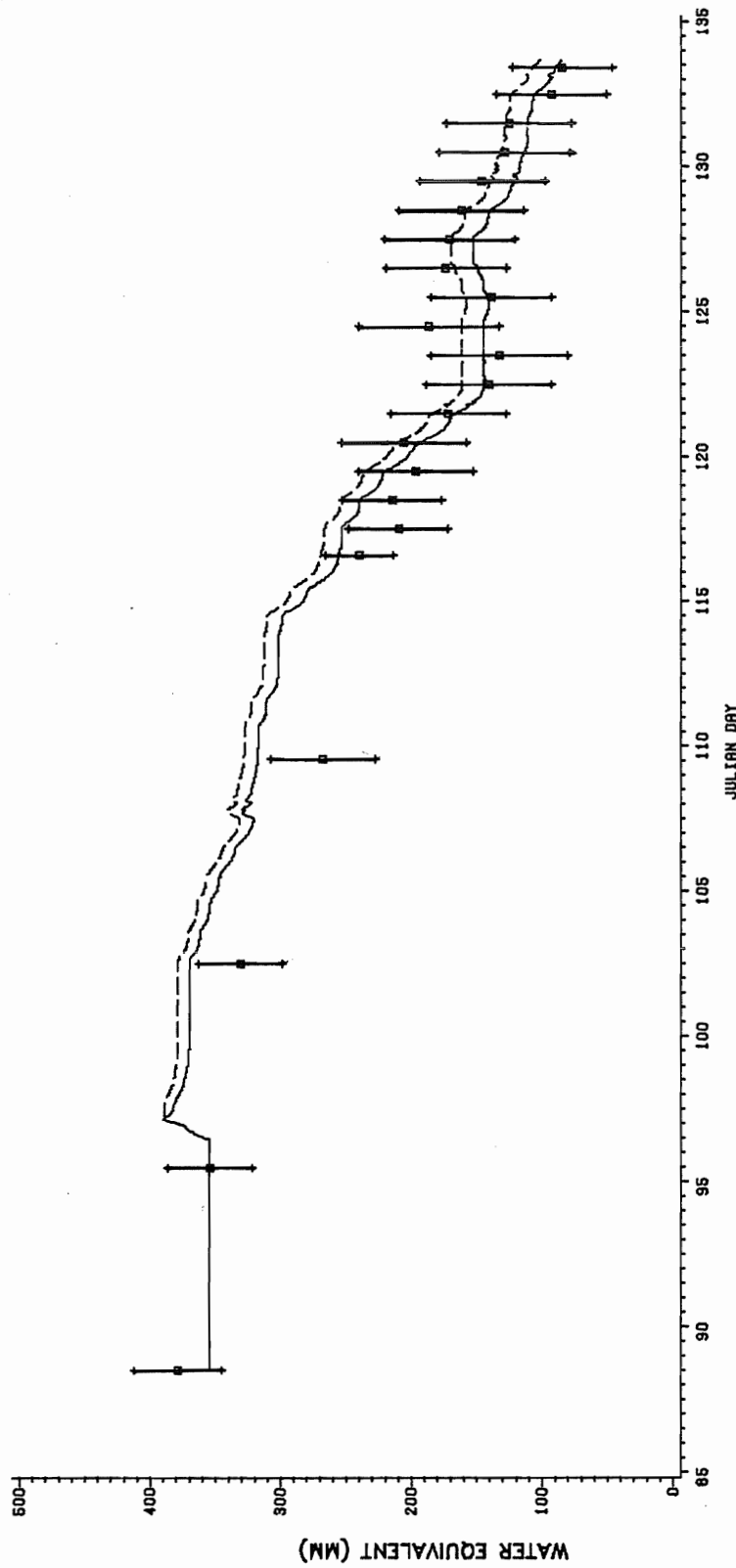
The physical simulation results obtained before and after the calibration have been compared with measured values of snowcover water equivalent and lysimeter outflow data. They are presented under three different aspects:

- the evolution of snowcover water equivalent (fig. 2)
- the cumulated outflow throughout melt season (fig. 3)
- the daily discharge (fig. 4)

Figure 5 shows the bestfit curve of expression (1) to the lysimeter measurements for SO<sub>4</sub><sup>2-</sup> for two melt periods (Julian Day [JD] 115, April 24 - JD 121, April 30th; JD 127, May 6 - JD 129, May 8, 1984). The two melt periods were separated by a non-melt period when new snowfalls were recorded. Both melt periods were terminated by heavy rain (April 30, May 8-9). We consider that the bestfit for the first period is due to the more precise measurements of concentration and water equivalent of the pack that can be obtained earlier in the overall springmelt than those recorded on a well-leached smaller pack that existed at the start of the second melt period. We subsequently used only the k value from data of the first melt period to simulate the quality of the meltwater discharge that commenced on JD 109 (April 18, fig. 6). The results, however, do show that the value of k is not constant and can change with the melt sequence under study (H.M. Seip personal communication). In addition the bestfit exercise as applied to the data on other ions (ex. NO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>) showed that k also exhibits different values for specific ionic species during the same melt period (Jones *et al.*, 1985). As all ions are completely soluble under the ambient chemical conditions of the melt, these results would not have been expected unless the ions are distributed in a different manner one to the other in



MARCH 28 TO MAY 12 1984 (DAYS 88 TO 133)

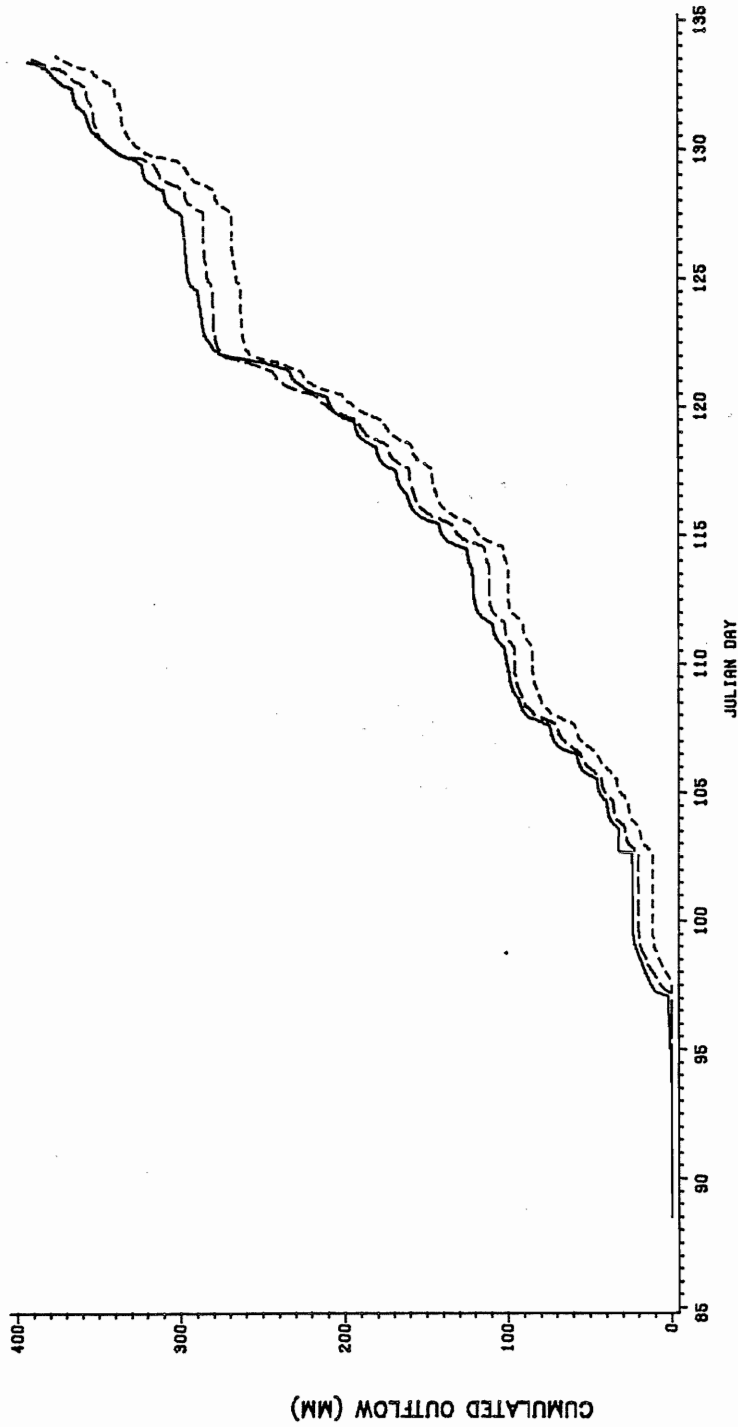


--- : SIMULATED BEFORE CALIBRATION  
— : SIMULATED AFTER CALIBRATION

THE SQUARES REPRESENT THE OBSERVED VALUES AND THE BARS, A 0.95 CONFIDENCE INTERVAL

FIGURE 2: MEASURED AND SIMULATED SNOWCOVER WATER EQUIVALENT

MARCH 28 TO MAY 12 1984 (DAYS 88 TO 133)



— : MEASURED  
- - - : SIMULATED BEFORE CALIBRATION  
- · - : SIMULATED AFTER CALIBRATION

FIGURE 3: MEASURED AND SIMULATED CUMULATED OUTFLOW

MARCH 28 TO MAY 12 1984 (DAYS 88 TO 133)

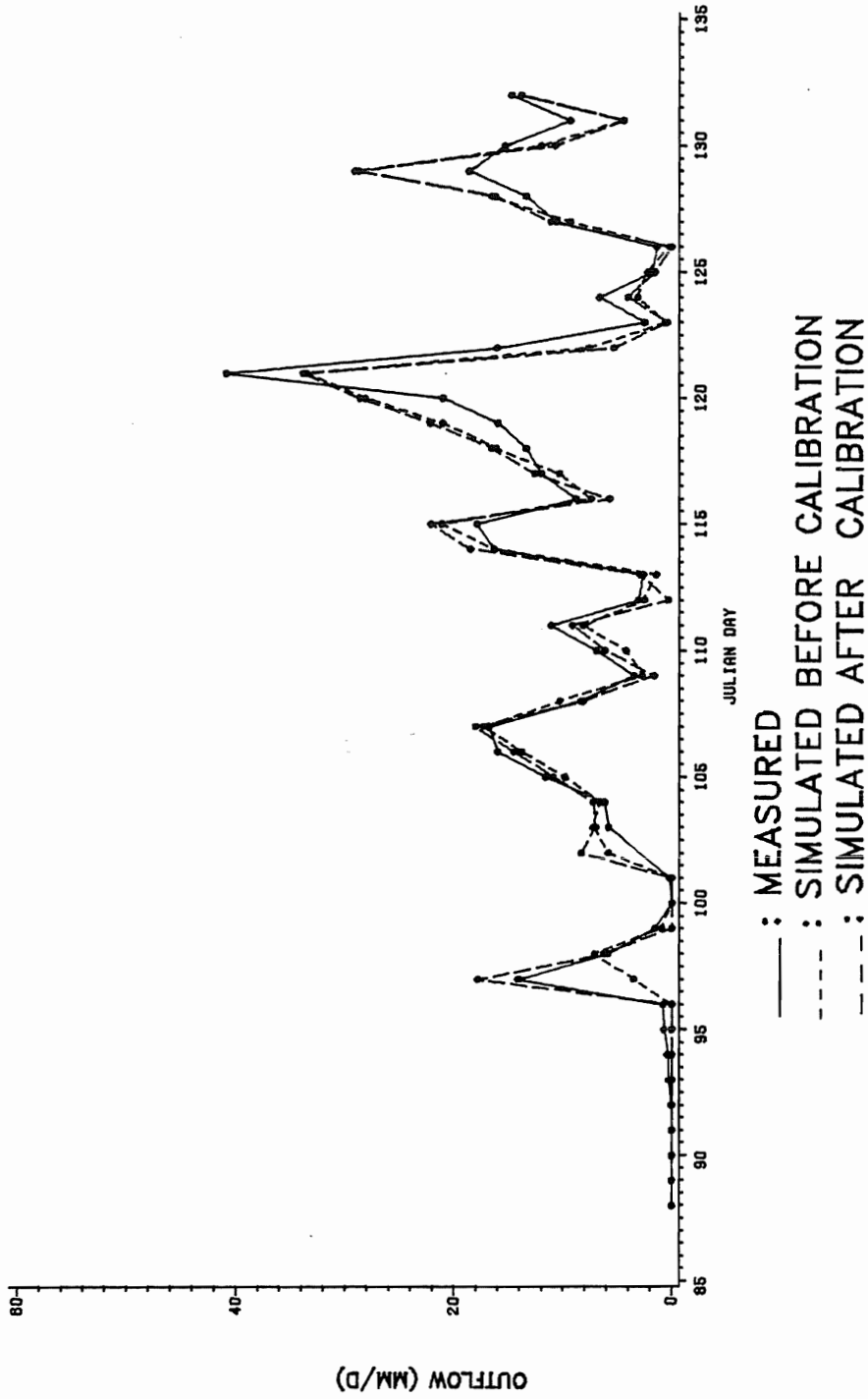


FIGURE 4: MEASURED AND SIMULATED DAILY OUTFLOW

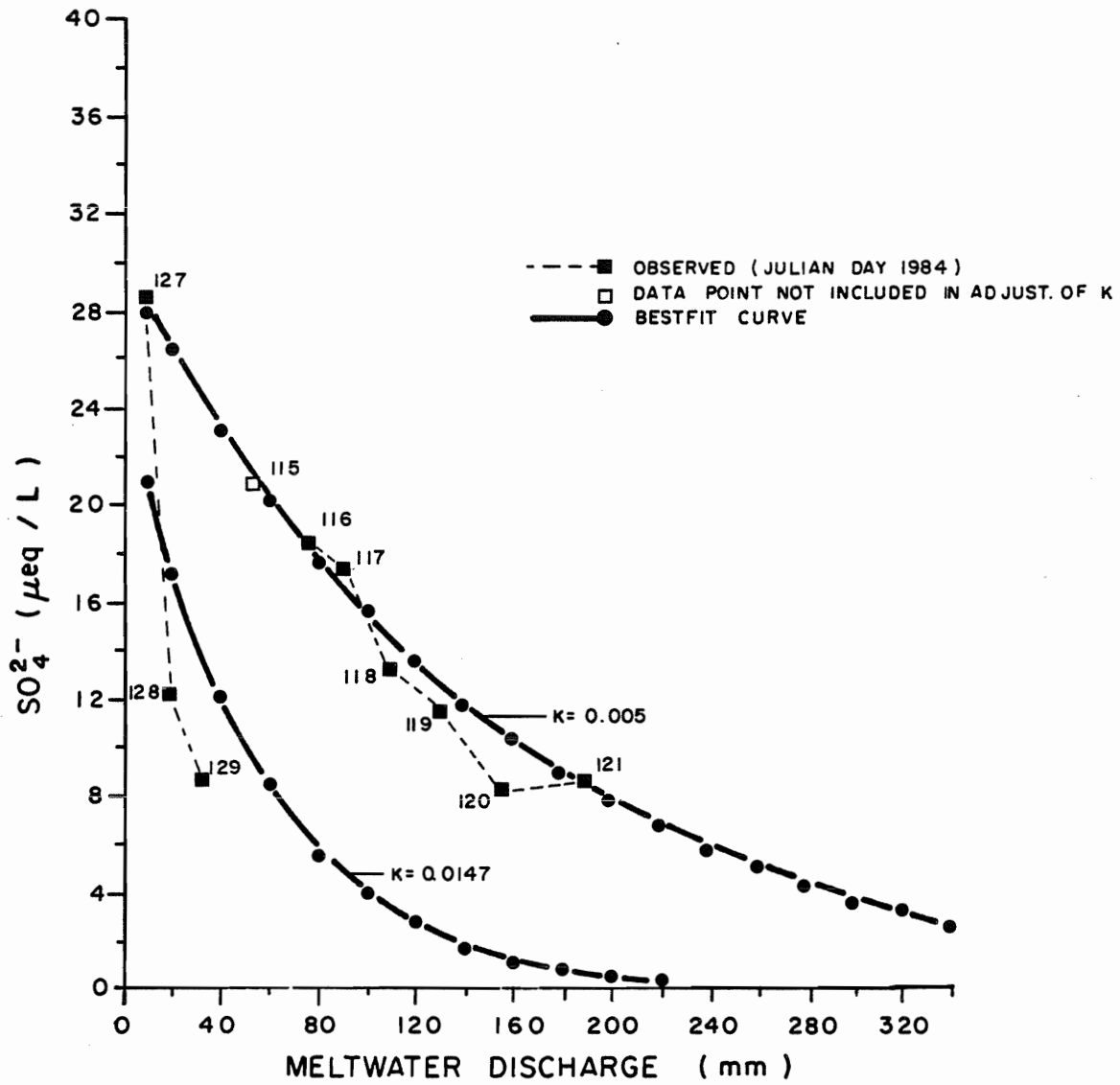


Fig. 5. Bestfit curve to the lysimeter measurements for  $SO_4^{2-}$  for two melt periods.

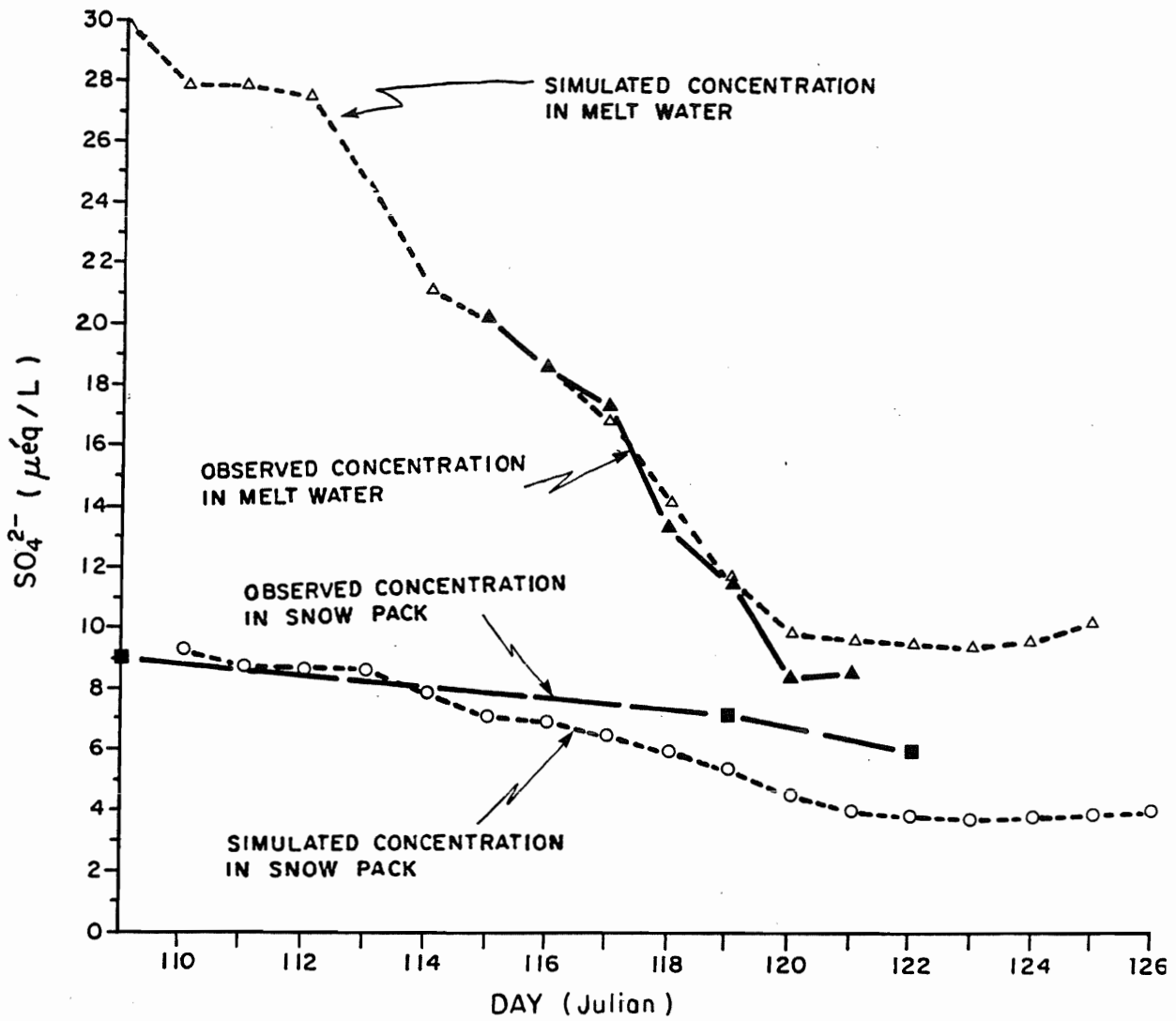


Fig. 6. Concentration of  $SO_4^{2-}$  in meltwater and snowpack, Lac Laflamme, from April 18th to May 5th 1984.

the snow crystals. Although, we have no present information on the distribution of ions within snow crystals before or after metamorphic change in the pack, the results of work elsewhere on snowmelt chemistry (Tranter et al., 1985) has indicated that preferential distribution and/or elution of ions does occur in snow.

## CONCLUSION

We consider that the results obtained for the quantitative discharge of meltwater from estimated values of model parameters are surprisingly good for a temperature index model. The preliminary calibration based on only one season allowed significant improvements in the simulation efficiency especially for the prediction of the cumulated flow (fig. 3).

Since the calibration required minor adjustment on only two parameters we can expect that in other boreal-forest sites, the parameter values can be efficiently approximated *a priori* assuming a minimum knowledge of site characteristics.

Work is presently in progress to include other melt seasons for the calibration and verification of the model. Meanwhile, SNOW-17 appears to be efficient enough to provide a reliable physical quantitative input to the chemical module.

It was observed that  $H^+$  showed consistently lower values for  $k$  than  $NO_3^-$  and  $SO_4^{2-}$  for the 1984 melt periods. These lower values have been attributed to other in-pack chemical and biological processes involving the  $H^+$  ion during the presence of free water in the pack (Jones et al., 1985) in addition to any physical processes for the preferential elution of ions.

Although we presently consider that the chemical module of the model is adequate to simulate satisfactorily the quality of meltwater discharge, the variability in the value of  $k$  and our inability to determine its value from other physical or chemical parameters of snow samples without physically simulating the melt of whole snow cores in the laboratory is the most acute problem in the predictive use of the model. A series of experiments to elucidate the relation between the value of  $k$  and the physical and chemical nature of the snowcover prior to any melt period is now being carried out.

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