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APPLICATION OF HYDROLOGICAL MODEL TO ACIDIFIED TURKEY LAKES WATERSHED

by

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MANAGEMENT PERSPECTIVE

The development of watershed acidification models is central to the design of management strategies to reduce sulphate loadings from emission sources. This paper addresses the important issue of meteorological influences and hydrological responses which are shown to be highly variable in space and time. A highly accurate hydrological model is presented here with predictive capability as confirmed with extensive observational data bases, not only from surface stream runoffs but also from snowpack and groundwater regimes. The results bring a closer understanding of the uncertainties and probabilities of episodic occurrence of the snowmelt acid shock phenomenon.

ABSTRACT

A hydrological model has been applied to Turkey Lakes Watershed at different locations. The calculated model results agreed with streamflow, groundwaterflow, snowpack and snowpack chemistry and the agreement is reasonably good. The model results are consistent with the observed data and with many of the episodic events that have occurred in the watershed. In particular, the snowpack sulphate concentration is simulated with a simple sulphate model linked to the hydrological model. Contrasts have also been made on the different calibrated coefficients at several locations in the watershed. An attempt to relate them to the geology and soil characteristics at the site has led to realistic estimation of the soil contact times.

INTRODUCTION

Earlier hydrological models have been developed mainly for flood forecasting purposes (e.g. Crawford and Linsley, 1966; Dawdy and Lichty, 1968; Jaimieson and Amerman, 1969). These models are specially developed for short-term simulations and for predicting the total runoff. Several major difficulties may arise if they are to be interfaced with hydrogeochemical models (e.g. Christophersen et al., 1984) to simulate watershed acidification. For example, the simulation of hydrogeochemical processes requires an accurate description of the flow rate and contact time in the various soil layers and water compartment, not just the streamflow. Each of these layers and compartments in turn requires strict water balances which are not usually achieved in some of these early models.

As discussed out by H.M. Seip during a recent workshop on predicting soil and water acidification (Johnson et al., 1985), a satisfactory knowledge of the hydrology is extremely necessary in understanding acidification. Thus, we have adopted a modelling approach (Lam and Bobba, 1985) in which both the accuracy of the hydrological model and its linkage to hydrogeochemical models are emphasized. The hydrological model which we have developed (Bobba and Lam, 1984) includes these new considerations and applies to different Canadian watersheds (Bobba et al., 1986).

The objective of this paper is to report on the results of testing the model with observations, wherever available, conducted in the soil layers and water compartments such as those in groundwater, water equivalent in snowpack and streamflow. In addition, several watersheds that have been selected from Turkey Lakes Watershed have been chosen for verification purposes in order to test the general applicability of the model. Understandably, some of the model coefficients may have to be changed during the model calibration for a new watershed. However, it is anticipated that once the coefficients are calibrated, they can be held fixed and applicable for subsequent years. More importantly, we must know how these coefficients change from watershed to watershed, and sometimes from one location to another even within the same watershed. Can they be related to the soil types? Do they conform to the kinematic rates measured in the laboratories of the field? It is only when questions on the accuracy of the flow predictions and versatility of the hydrological model coefficients are answered that we are able to link up the hydrological and hydrogeochemical models.

TURKEY LAKES WATERSHED

The hydrological model has been applied to the Turkey Lakes Watershed. The watershed is located approximately 60 km north of Sault Ste. Marie, Ontario and the watershed bundaries are shown in Figure 2. It has an area of 10 sq km and consists of five lakes joined by a main stream. A detailed description of the watershed was given by Jeffries and Semkin (1982).

The highest elevation is Batchawana Mountain on the northern boundary at 645 m and the lowest elevation in the watersehd is 245 m. The total watershed was divided by four subwatersheds and stream gauges were installed at the mouth of each subwatershed. The Water Survey of Canada has been collecting the stream flow data from 1981 onwards. The bedrock in the watershed is Precambrian rocks and consists of felsic, igneous and metamorphic rocks. The bedrock is overlain by surfacial unconsolidated deposits and the thickness is generally a meter or more. The bedrock is exposed on the steepest slopes and on the top of some hills. The soils are predominantly ferro hermic podzols.

The texture of the uppermost portion of profiles are loam to silt-loam. The coarser texture soils such as sandy loams and sands generally occur at depths of more than 50 to 60 cm. The textural contrast is attributed to the presence of two tills throughout. In lower to moderate elevations, a fine textured till overlies a coarse and compact basal till.

The soils are generally fine grained, light coloured and well foliated. They occur in all of the samples and mineralogically consist of quartz and felspar with a minor mafic component.

HYDROLOGICAL MODEL

The description of the hydrological model has been given in Bobba and Lam (1984). The primary elements considered in our hydrological model are precipitation (rainfall or snow), evaporation, a set of reservoirs of determinable capacities that hold water temporarily and gradually recede as their contents are diminished by infiltrations, recharge, evapotranspiration and lateral drainage. These zones and the fluxes of water balance for each zone are shown conceptually in Figure 1. The vertical zones include a surface/snow storage reservoir, an upper soil reservoir and groundwater reservoir. The model consists of mass balance calculations for snow accumulations and melting, soil moisture budgeting, runoff generation and hydrological routing in these reservoirs.

The separation of the runoff regime into three reservoirs is a salient feature of our model, not only because of the physical considerations but also because we can conveniently associate them in the known regions of chemical processes. For example, generally speaking, humus formation may occur in the upper soil reservoir, cation exchange in the upper and lower soil reservoir and soil weathering in the groundwater reservoir.

A SIMPLE SNOWPACK SULPHATE MODEL

The detailed linkage of the hydrological model to hydrochemical model is presented in Lam et al. (1987). However, to illustrate the sulphate ion pathway in the snowpack, a simple linkage model is presented here. The atmospheric deposition of air pollutants occurs in both the dry form and the wet form. It is assumed that for each time step, the contaminants from both dry deposition and wet deposition are accumulated and added to the snowpack contaminant concentration. In the case of sulphate ions, a simple mass balance equation for the sulphate concentration in the snowpack is:

$$\frac{d(VC)}{dt} = \sigma C_d A + P C_w A - m C_m A \qquad (1)$$

where V = volume of snowpack (m^3) as computed from the hydrological model, C = concentration of sulfate in snowpack (g/m^3), A = area of the watershed (m^2), σ = dry deposition rate (m/day), C_d = dry deposition concentration (g/m^3), P = precipitation rate (m/d), C_w = precipitation concentration (g/m^3), m = melting rate (m/d), C_m = concentration of the snowpack (g/m^3).

The dry deposition rate, dry deposition concentration, and wet deposition concentration were based on the CANSAP data (Sirois and Vet, 1987). Field and laboratory observations of the snowmelt enrichment process reported by Semkin _et al._ (1987) have suggested that 50 to 80 percent of the total snowpack contaminants are removed by the first 30 percent of meltwater.

Thus, the melting rate m in Eq. (1) is an important model parameter. In general, potential snowmelt is what occurs if the snowpack is not limiting, i.e.,

$$m = 0 \qquad T < 0 \qquad (2a)$$

$$m = aDD \qquad T > 0 \qquad (2b)$$

where m = daily snowmelt rate (m^3/day)

a = proportionality constant for snowmelt per degree day (m^3/°C-d)

T = air temperature (°C), estimated as the average of the daily maximum and minimum temperature

DD = degree-days per day (°C-d/d), computed as the integral of air temperature with time over those portions of the day when the temperature is above the freezing point.

Since the fluctuation of air temperature during the dirunal cycle is not always known, a triangular distribution can be assumed (to approximate an expected sinusoidal variation). The resulting expression for degree-days is

$$DD = 0 \qquad T_{max} \leq 0 \qquad (3a)$$

$$DD = \frac{1}{2} \frac{T^2_{max}}{(T_{max} - T_{min})} \qquad T_{min} < 0 < T \qquad (3b)$$

$$DD = T \qquad 0 \leq T_{min} \qquad (3c)$$

where T_{max} = maximum air temperature (°C), and T_{min} = minimum air temperature (°C). The proportionality constant, a, is a model parameter to be determined during model calibration. Thus, snowmelt at any point in time is highly dependent upon the condition of the snowpack as well as the heat energy flux. The snowpack condition is generally identified in terms of its "cold content" and water holding capacity of liquid-water deficiency. Basically, energy is required to raise the snowpack temperature to 0°C and to melt enough snow to satisfy the water-holding capacity of the snowpack, before liquid water can reach the soil surface. Once these conditions are met, any additional heat input to the snowpack causes snowmelt-runoff. Although these processes of a snowpack are generally difficult to quantify, Eqs. (2)-(3) represent a simple approach to define the melting rate.

RESULTS

The model has been applied to the major stream stations (S1 to S4) for four years (1981 for calibration and 1982-84 for verification). For example, Figure 3a shows the calibration (1981) and verification (1982-84) results for the total runoff at a headwater stream station, S1. These results can be contrasted with those at a downstream station (S3, Figure 3a). In both cases, the computed hydrograph fits well with the observed, in terms of the episodic frequencies and the magnitudes of high flows. However, the computed portions of surface, interflow and groundwater flows expressed as percentages of the total runoff are drastically different at these two stations. The headwater station consistently shows that the majority (about 70%) of the runoff originiates form the top soil layers (Fig. 3b), whereas only about 30% of such input occurs in the downstream station (Figure 3b). Indeed, the proportion of surface flow, interflow and groundwater flow differs from station to station and varies with seasons (Figure 3b).

As a part of the investigation on the accuracy of the submodel components, we have also compared the computed water equivalent of the snowpack with the observed data averaged for the whole Turkey Lakes Watershed for the period December, 1982 to April, 1983 (Fig. 4). The observed snow accumulation and thawing sequences are reproduced quite closely by the results of the snow accumulation and ablation submodel. The relative mean square error between observed and computed data is 14.5%. Figure 5 shows the observed data and the sulphate concentration computed by the simple snowpack sulphate model (Eq. 1) in the snowpack averaged for the whole watershed and for the same duration. The agreement is also reasonably good. The relative mean square error between observed and computed data is 15%. In particular, the accumulation of snow in the months of December and January tends to build up the sulphate content in the snow and the thawing in late February causes a rapid drop in concentration. The simulated groundwater discharge has also been compared with observed groundwater data collected near station S1 for the period March 28 to April 8, 1981. The groundwater flow data was estimated by the ^{18}O isotope method (Bottomley *et al.*). Again, the computed groundwater results conform well with the estimated (Fig. 6). The relative mean square error between observed data and computed data is 14.7%. Thus, both the snow portion and the groundwater portion are simulated well for Turkey Lakes Watershed. However, since the measurements for the snow and groundwater components are more difficult to obtain than those for the total runoff, further statistical evaluation on these model components cannot be carried out. Thus the model calibration and confirmation are evaluated with the observed total runoff data only.

DISCUSSIONS

During calibration, the model coefficients are set by mathematically minimizing the least-squares variance between the computed and observed results for each watershed. For example, Figure 3 showed the calibration (1981) and verification (1982-84) results for the total runoff at a headwater stream station, S1. The computed hydrograph produces a satisfactory fit with the observed data (e.g. rank correlation coefficient, r=0.84 and the slope, s=0.95 for confirmation period, Table 1). In particular, the episodic events during spring snowmelt for all four years are accurately simulated as well as other episodes due to heavy rainfall. The magnitudes at these peaks are also predicted reasonably well (e.g. the mean relative error, e=10.5% with the coefficient of efficiency E=0.51 indicating an improvement of 51% over the mean-as-model for the confirmation period, Table 1). Similarly, the computed hydrograph for a downstream station, S3 at the same watershed produces a good fit with the observed data (e.g. r=0.91, s=0.93 for the confirmation period, Table

1). Note that the calibrated constants for infiltration (between top and middle layers, Table 2) for S1 and S3 are several orders of magnitude different and so are the calibrated constants for deep infiltration. These differences are due to the compact clayey till texture, the shallower soil depths and the sometimes exposed bedrock at S1, typical of many headwater watersheds in the area.

Table 2 also lists the calibrated hydrological coefficients for the various stations in the Turkey Lakess Watershed. For exmaple, the infiltration coefficient which regulates the flow from the upper soil zone to the lower soil zone ranges between 1 to 2 cm day^{-1} for all locations except station S1 in the Turkey Lakes. However, the deep infiltration coefficient which regulates the flow from the lower soil reservoir to the groundwater reservoir varies substantially between 0.00004 to 0.042 cm day^{-1}. Yet these values conform to the values reported in the literature (e.g. Freeze and Cherry, 1979) for the type of geology concerned. For example, the soil zone B of station S1 in Turkey Lakes pertains to headwater glacial soil of clay-silty loam texture, whereas downstream soil such as station S3 has a larger deep infiltration coefficient because of the silty sand texture. At station S2, the interflow constitutes about 20 to 25% of the total runoff, much more than at other stations (Fig. 3b), because the soil depth for soil zone B at that station is thicker than at other stations and the clay silt texture has a lower hydraulic conductivity as indicated by the relatively lower deep infiltration coefficient (Table 2).

The half-life water residence times of the three soil reservoirs can be computed using the flow coefficients (Table 2). In all cases, as expected, the groundwater reservoir has a longer residence time. These estimated residence times are therefore also consistent with geology of these watersheds.

CONCLUSIONS

The hydrological model has been applied successfully to four mean stream stations. The model has produced encouraging results showing reasonable agreement with the observed data on stream flow, groundwater and snow pack. The calibrated model coefficients and the estimated residence times are fairly consistent with known geological characteristics at these watersheds. Statistical evaluation of the model results with subsequent data has confirmed the validity of these calibrated coefficients.

In particular, the snowpack sulphate concentration is simulated with a simple model, using the predicted snowpack volume and observed dry and wet deposition. Most importantly, these test results have encouraged us to link the hydrological model to hydrogeochemical models for studying acidification problems in Turkey Lakes Watershed (Lam _et al_., 1987).

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Table 1. Statistical Evaluation of Computed Hydrograph with Observed Runoff

Station	Calibration Period	Rank Correlation		Mean Relative % Error	Coefficient of Efficiency (E)	Confirmation Period	Rank Correlation		Mean Relative % Error (e)	Coefficient of Efficiency (E)
		Coefficient (r)	Slope (s)				Coefficient (r)	Slope (s)		
S1	1981	0.85	0.93	18.4	0.50	1982-84	0.84	0.89	10.5	0.51
S2	1981	0.88	0.89	25.4	0.81	1982-84	0.81	0.95	24.5	0.77
S3	1981	0.91	0.91	15.5	0.78	1982-84	0.91	0.93	16.8	0.76
S4	1981	0.90	0.94	21.1	0.92	1982-84	0.88	0.90	19.7	0.93

Table 2. Geology and the Calibrated Model Constants

Station		Station #1	Station #2	Station #3	Station #4
Area (km^2)		2.05	3.62	5.48	8.60
Slope		steep	steep	steep	steep
Geology	A	clay-loam	clay-silt loam	sandy-silt loam	sandy-silt loam
	B	clay silt with till	clay silt with glacial till	silty sand with glacial till	silty sand with glacial till
	C	very compacted till with weathered bedrock	compacted till with sandy silt	glacial till with gravel and sand	glacial till with gravel and sand
Soil Depth (m)	A	0.1	0.20	0.25	0.35
	B	0.5	2.5	1.5	2.00
	C	1.0	2.0	3.5	3.75
Calibrated Constants					
Infiltration A-B		0.0002	0.05	1.00	0.75
Deep Infiltration B-C		0.00004	0.015	0.025	0.03
Surface Flow		0.55	0.52	0.54	0.572
Interflow		0.35	0.32	0.30	0.375
Groundwater Flow		0.25	0.225	0.20	0.157
Computed Half Life					
A		1.3	1.3	1.3	1.21
B		2.0	2.2	2.3	1.85
C		2.8	3.1	3.5	4.42

FIGURE LEGEND

Figure 1 Schema for the hydrological model (after Bobba and Lam, 1984).

Figure 2 Sampling locations in the Turkey Lakes Watershed.

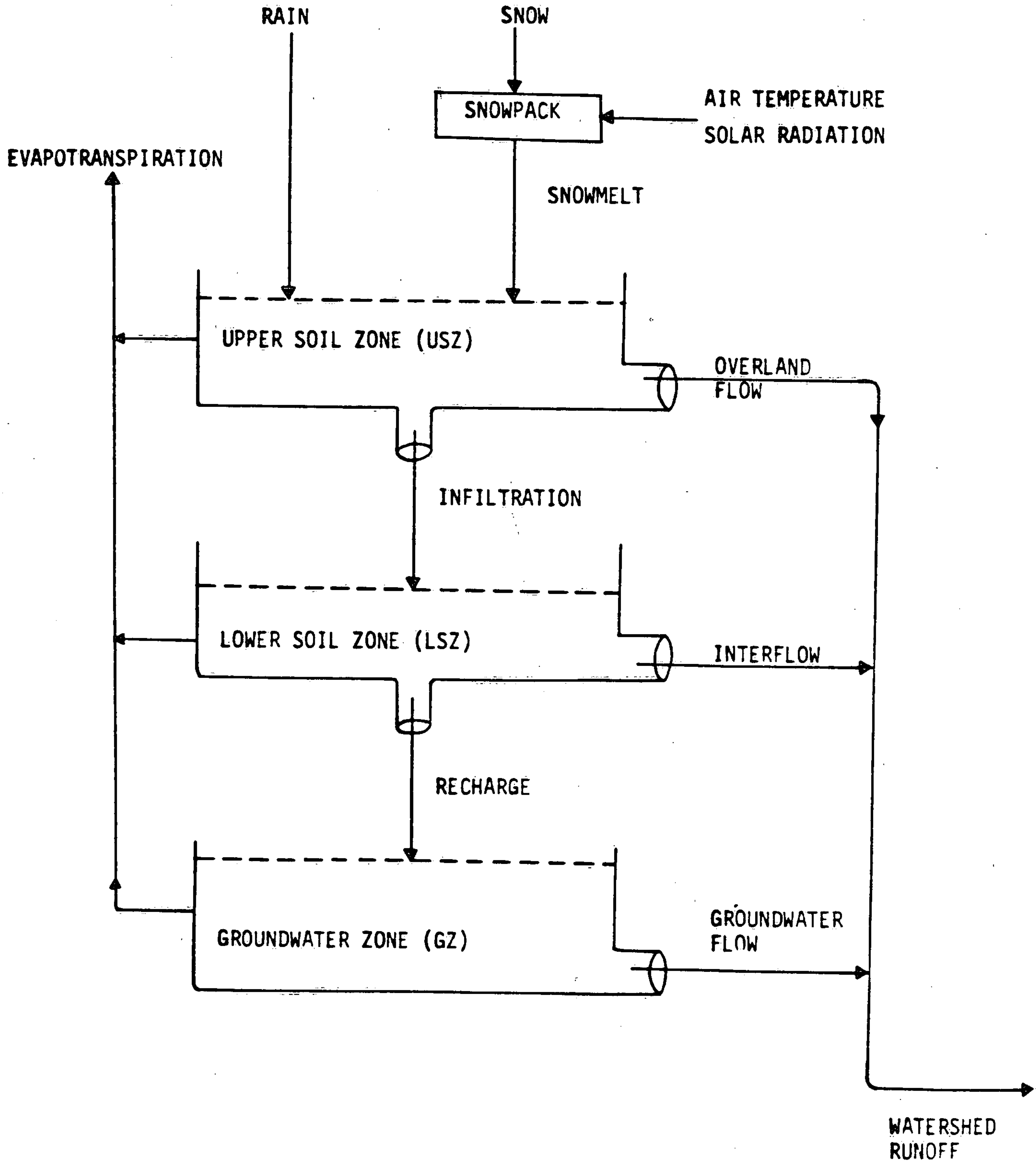
Figure 3 (a) Computed and observed total runoffs at S1-S4;

(b) Computed overland flow, interflow and groundwater flow as percentages of the computed total runoff at S1-S4.

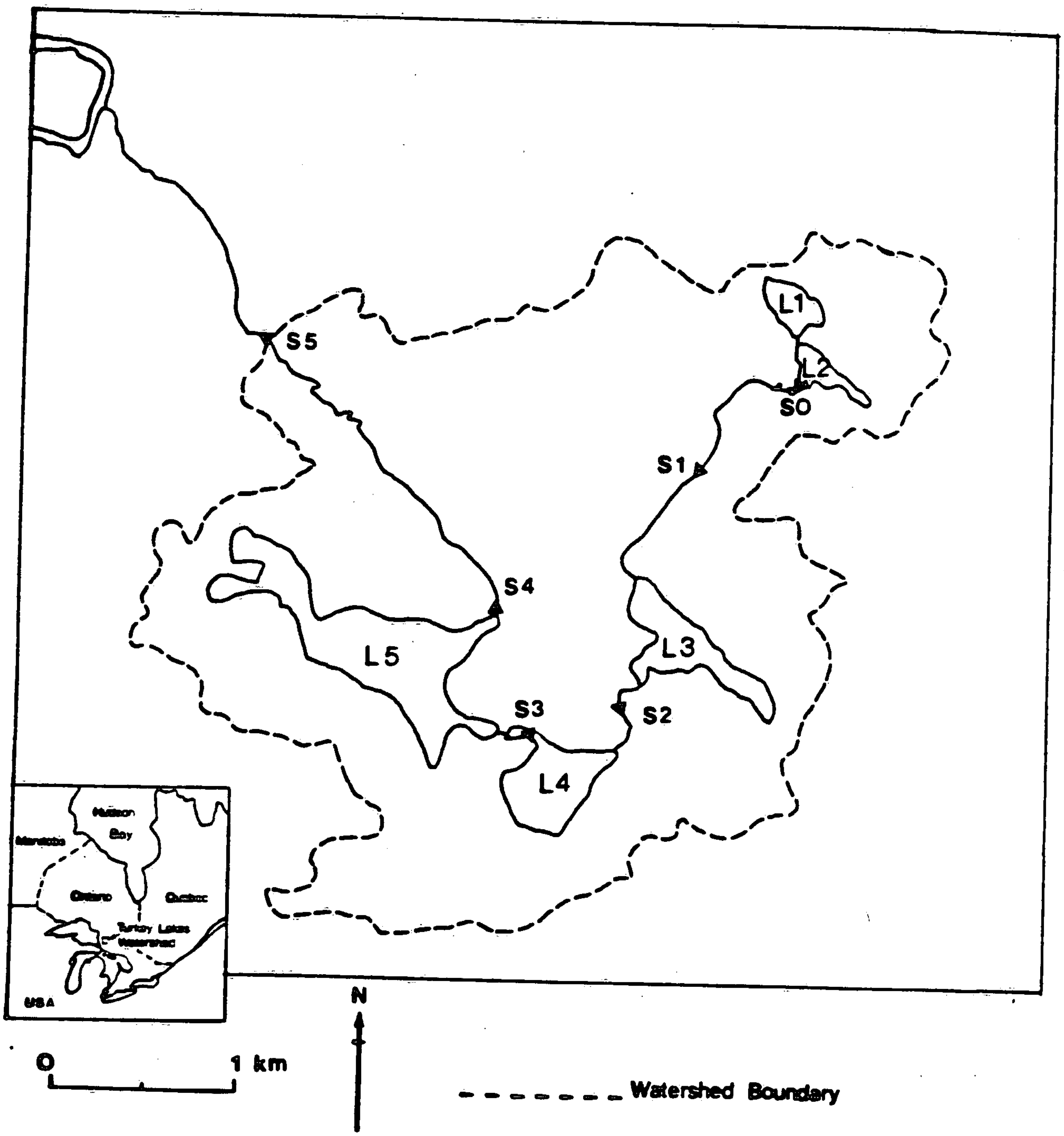
Figure 4 Computed (solid line) and observed (bars) water equivalent of snow for the period December, 1982 to April, 1983 averaged over the Turkey Lakes Watershed.

Figure 5 Computed (solid line) and observed (bars) sulphate concentration for the same period and location as in Figure 4.

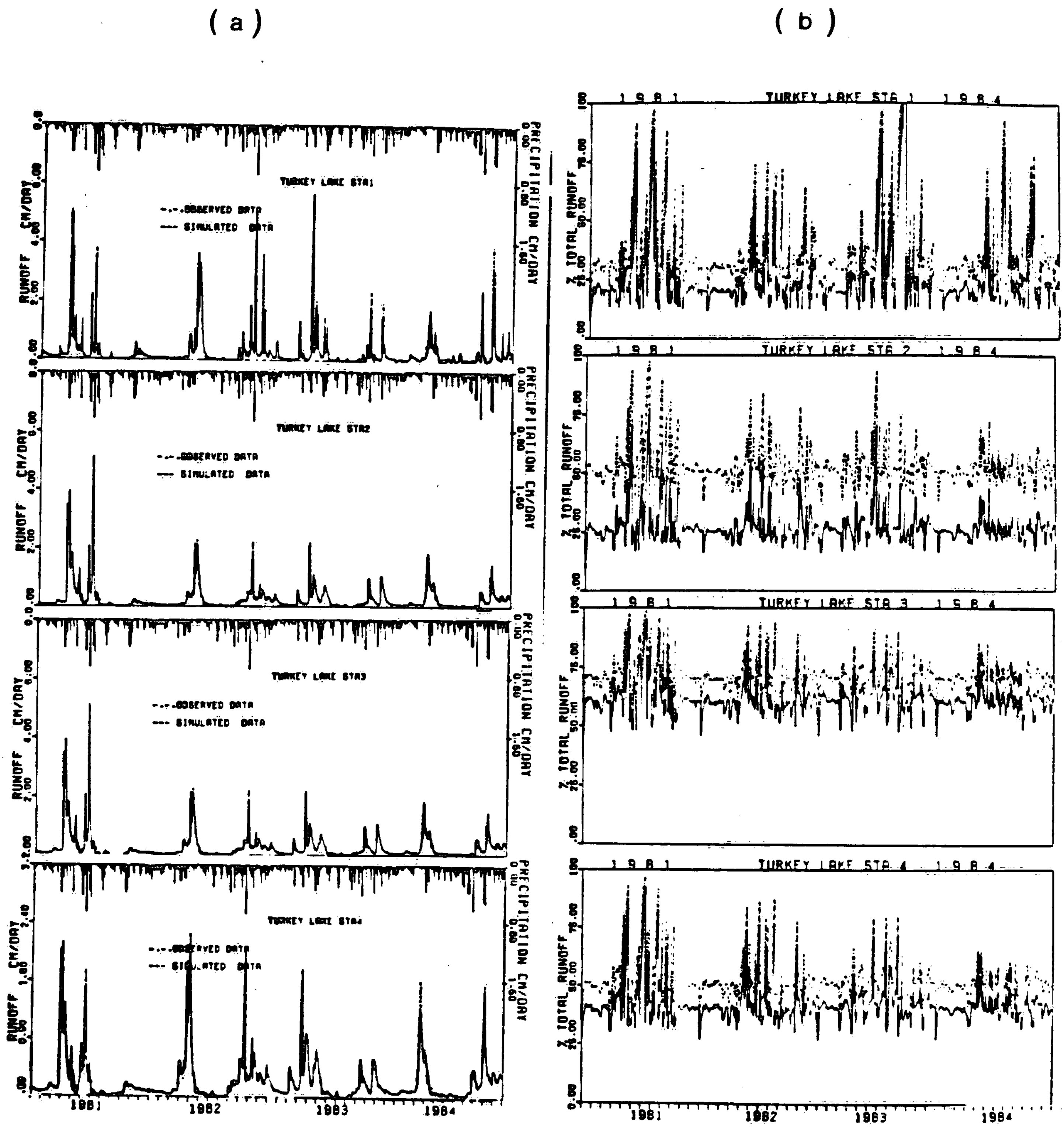
Figure 6 Comparison of computed groundwater flow with observed groundwater flow (^{18}O data) and observed total runoff for 28 March 1981 to 8 April 1981 at S1.



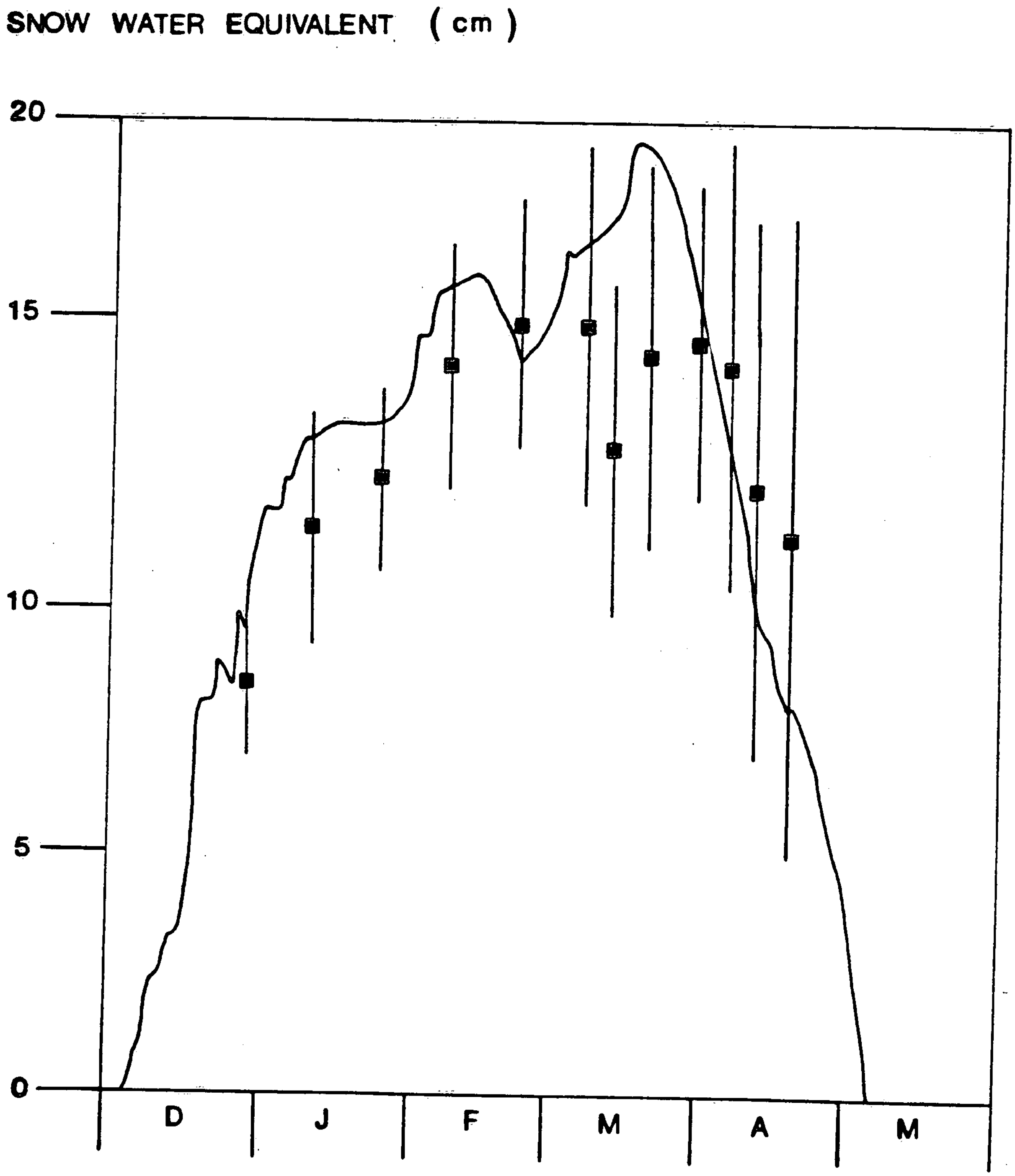
RAIN
SNOW
SNOWPACK
AIR TEMPERATURE
SOLAR RADIATION
EVAPOTRANSPIRATION
SNOWMELT
UPPER SOIL ZONE (USZ)
OVERLAND FLOW
INFILTRATION
LOWER SOIL ZONE (LSZ)
INTERFLOW
RECHARGE
GROUNDWATER ZONE (GZ)
GROUNDWATER FLOW
WATERSHED RUNOFF

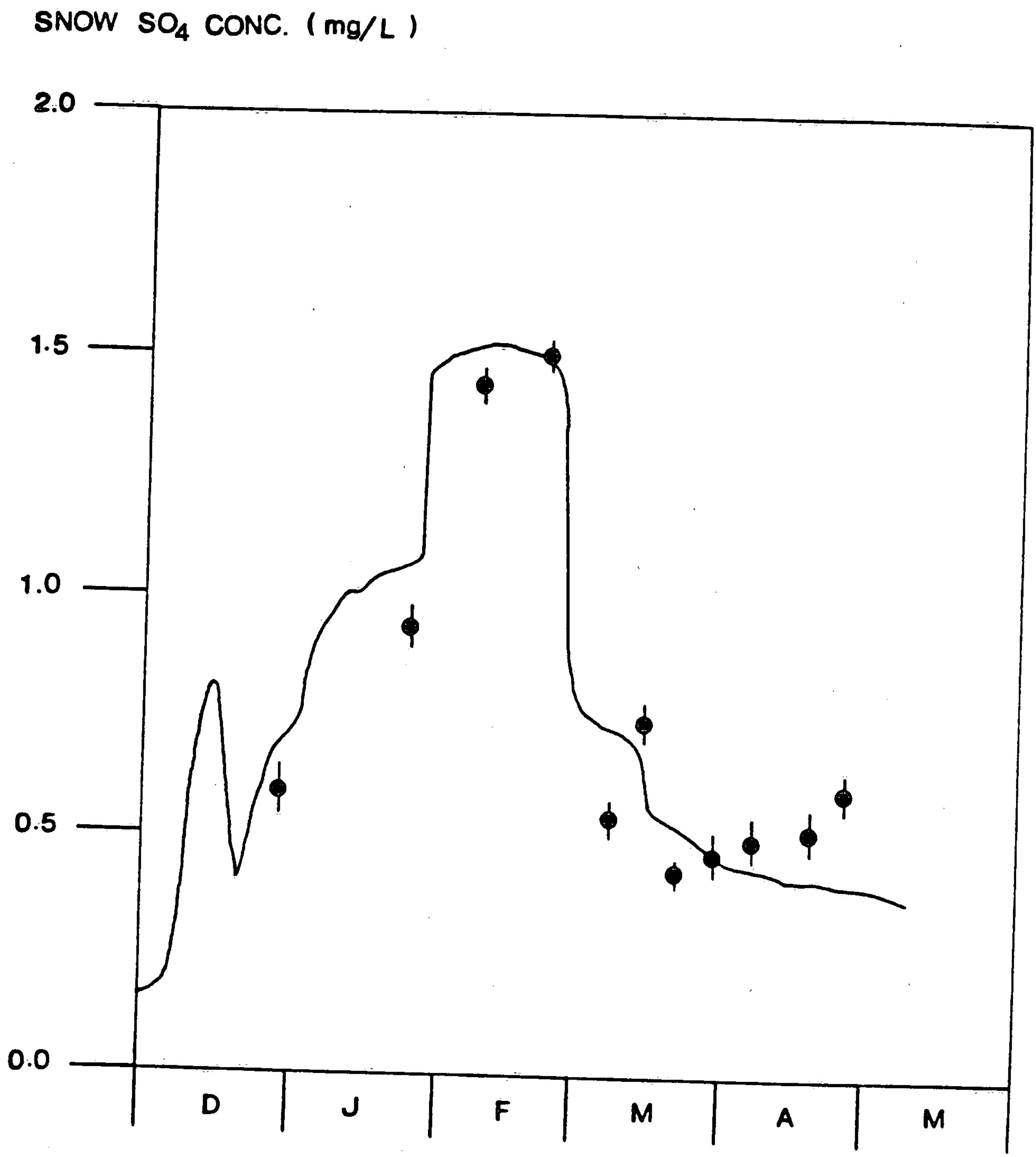


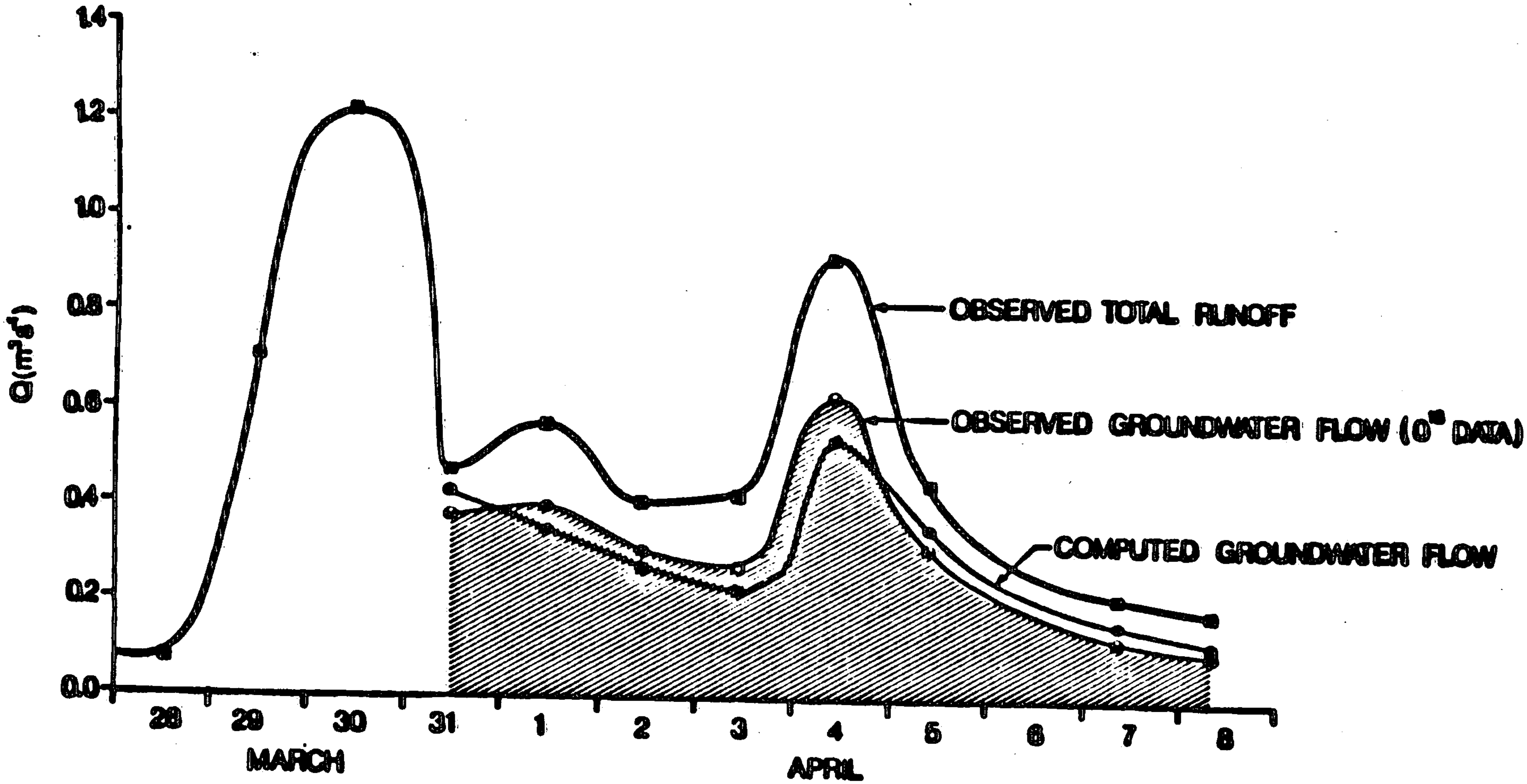
S5
L1
L2
S0
S1
S4
L3
L5
S3
S2
L4
Hudson Bay
Manitoba
Ontario
Quebec
Turkey Lakes Watershed
USA
0
1 km
N
Watershed Boundary



(a)
(b)
TURKEY LAKE STA1
TURKEY LAKE STA2
TURKEY LAKE STA3
TURKEY LAKE STA4
OBSERVED DATA
SIMULATED DATA
RUNOFF CM/DAY
PRECIPITATION CM/DAY
1981
1982
1983
1984
TURKEY LAKE STA 1
TURKEY LAKE STA 2
TURKEY LAKE STA 3
TURKEY LAKE STA 4
% TOTAL RUNOFF


SNOW WATER EQUIVALENT (cm)
20
15
10
5
0
D
J
F
M
A
M


SNOW SO4 CONC. (mg/L)
2.0
1.5
1.0
0.5
0.0
D
J
F
M
A
M


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Q(m³s⁻¹)
OBSERVED TOTAL RUNOFF
OBSERVED GROUNDWATER FLOW (0¹⁸ DATA)
COMPUTED GROUNDWATER FLOW
28
29
30
31
1
2
3
4
5
6
7
8
MARCH
APRIL