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MODELLING THE HYDROLOGICAL REGIMES IN ACIDIFIED WATERSHEDS

by
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EXECUTIVE SUMMARY

The increased levels of acidification of waters of headwater lakes and streams in watersheds having a low capacity to buffer acidic depositions have been well documented. The processes governing the levels of acidity are under intensive study in several watersheds. To provide these studies, computer simulation models that relate the rates of acidic deposition to the lake and stream acidity have been developed.

The hydrologic flow in the watershed defines the pathway upon which the chemical interactions can occur in both the soil and water phases. This paper focuses on the discussion of such pathways as computed by a hydrological model for several Canadian watersheds. Despite the differences in soil characteristics and watershed hydrology, the model is able to simulate very well the observed flow patterns in the snowpack, in the groundwater and in the streams in these watersheds. More importantly, the different values of the model coefficients derived during model calibration are shown to be realistic and agree with measured values for the various geologies manifested in these watersheds. The relationships of these flow pathways and hydrograph to the observed stream acidity are also highlighted.

RÉSUMÉ ADMINISTRATIF

Il existe une abondante documentation sur l'augmentation des niveaux d'acidité des eaux des lacs de tête et des cours supérieurs dans les bassins hydrographiques n'ayant qu'une faible capacité de neutraliser les dépôts acides. Les procédés qui déterminent les niveaux d'acidité font l'objet d'études suivies dans de nombreux bassins hydrographiques. À cette fin même, on a mis au point des modèles de simulation qui établissent le lien entre les taux de dépôts acides et l'acidité des lacs et des cours d'eau.

Le courant hydrologique dans le bassin hydrographique détermine le cheminement. Celui-ci peut entraîner des interactions chimiques tant dans la phase sol que dans la phase eau. La présente étude fait l'examen de ces cheminements tels que calculés au moyen d'un modèle hydrologique informatisé pour nombre de bassins hydrographiques canadiens. En dépit des différences dans la qualité des sols et l'hydrologie de ces bassins, le modèle est en mesure de simuler avec précision les modèles d'écoulement dans la couverture de neige, les eaux souterraines et les cours d'eau observés dans ces bassins hydrographiques. Ce qui compte encore davantage, les différentes valeurs des coefficients du modèle obtenues lors de l'étalonnage du modèle paraissent réalistes et conformes aux valeurs mesurées pour les diverses caractéristiques géologiques révélées dans ces bassins hydrographiques. On fait également ressortir le rapport entre ces cheminements de l'écoulement et l'hydrogramme, et l'acidité notée dans les cours d'eau.

ABSTRACT

Application of a hydrological model to three Canadian watersheds forms part of a verification package to test its accuracy and portability. Agreement of model results with observed data on hydrograph, groundwater flow and snowpack is reasonably good. The model results are consistent with the observed pH and with many of the episodic events that have occurred in these acidified watersheds. Contrasts have also been made on the different calibrated coefficients at several locations in these watersheds. An attempt to relate them to the geology and soil characteristics at the site has led to realistic estimation of the soil contact times.

RÉSUMÉ

L'application d'un modèle hydrologique à trois bassins hydrographiques canadiens fait partie d'un progiciel de vérification destiné à en établir l'exactitude et la transférabilité. La conformité des résultats obtenus grâce au modèle et des données observées à l'hydrogramme, dans l'écoulement des eaux souterraines et la couverture de neige, est assez bonne. Les résultats du modèle sont conformes au pH enregistré et à nombre d'événements épisodiques qui se sont produits dans ces bassins hydrographiques acidifiés. On a également comparé les différents coefficients étalonnés en divers endroits dans ces bassins hydrographiques. On a tenté de les relier à la géologie et aux caractéristiques du sol en cet emplacement, ce qui a donné une idée réaliste des temps de contact.

1. INTRODUCTION

Earlier hydrological models have been developed mainly for flood forecasting purposes (e.g. Crawford and Linsley, 1966; Dawdy and Lichty, 1968; Ayers and Balek, 1969; Jamieson and Amerman, 1969). These models are specially developed for short-term simulation and for predicting the total runoff only. 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 compartments, not just the total stream flow. Each of these layers and compartments in turn requires strict water balances which are not usually achieved in some of these early models.

As pointed 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 important 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 we have developed (Bobba and Lam, 1985) includes these new considerations. At the present stage of development, it is crucial to establish the accuracy and portability of this new model.

The purpose of this paper, therefore, 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, snowpack and streams. In addition, several Canadian watersheds 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 known 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 or 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.

2. HYDROLOGICAL MODEL

The description of the hydrological model has been given in Bobba and Lam (1985). Briefly, the model expresses the watershed as 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.

Figure 1 illustrates the structure of the hydrological model, which comprises three distinct soil regimes: upper soil zone, lower soil zone and groundwater zone, corresponding to the overland flow, interflow and groundwater flow, respectively. The sum of these three flows then constitutes the total basin runoff.

The separation of runoff into three components 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 zone, cation exchange in the upper and lower soil zone and soil weathering in the groundwater soil zone.

3. WATERSHED DESCRIPTIONS

3.1 Turkey Lakes Watershed

This watershed is located approximately 60 km north of Sault Ste. Marie, Ontario. It has an area of about 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 lowest evaluation in the watershed is 245 m and the highest elevation, 645 m. The total watershed was divided by four subwatersheds and stream gauges were installed at the mouth of each subwatershed.

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 texture of the uppermost portion of profiles is 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 soils are generally fine-grained, light-coloured and well-foliated, and mineralogically consist of quartz and felspar with a minor mafic component.

3.2 Lac Laflamme Watershed

The Lac Laflamme Watershed (Inland Waters Directorate, 1981) is located 80 km north of Quebec City in the Forêt Montmorency. It covers an area of 0.684 sq km in a region characterized by a balsam fir-white birch forest. The watershed is underlain by Precambrian, Charnokite gneiss of the Greenville geological province but there are no outcrops within the watershed. Most of the surficial deposits are till and morain composed predominantly of potassic feldspar and plagioclase.

The lake itself covers an area of 0.061 sq km has a perimeter 3.12 and a maximum depth of 5.3 m. The drainage network within the watershed is not very extensive. The outlet stream, which is gauged, is characterized by a permanent flow while inlet streams are intermittent except for the main tributary.

3.3 Harp Lake Watershed

The Harp Lake Watershed is located 10 km northeast of Huntsville, Ontario. The watershed is almost completely covered with deciduous forest. This watershed was divided as six subwatersheds. The bedrock underlying most of the subwatersheds is amphibolite, schist and hornblende gneiss (Jeffries and Snyder, 1983). The overburden consists of a minor till (sandy loam to sand deposits >1 m thick).

4. RESULTS

4.1 Turkey Lakes Watershed

Figure 2 shows the calibration (1981) and verification (1982-83) results for the total runoff at a headwater stream station, S1. These results can be contrasted with those at a downstream station, S3 (Fig. 3). In both cases, the computed hydrograph fits well with the observed, in terms of the episodic frequencies and the magnitudes of the high flows. However, the computed portions of overland, 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 originates from the top soil layers (Fig. 4), whereas only about 30% of such input occurs in the downstream station (Fig. 5).

Also shown on Figures 2 and 3 are the observed pH data. As is well known, the stream pH is clearly strongly related to the runoff, particularly at the snowmelt periods. However, the pH depression at S1 is more acute than that at S3, because of less groundwater inputs into the stream. Semkin and Jeffries (1984) have attributed this phenomenon to the fact that shallow overburden in the headwater area allows only limited interaction between precipitation and the minerals in the soil. Our hydrological model results (Figs. 4 and 5) are consistent with this explanation.

The model has been applied to several other stations in the watershed with satisfactory results. In particular, the simulated groundwater discharge has also been compared with observed groundwater data collected at yet another station (Norberg Creek). The groundwater flow data was estimated by the ^{18}O isotope method (Bottomley and Craig, 1984). Again, the computed groundwater results conform well with the estimated (Fig. 6).

4.2 Lac Laflamme Watershed

As in the case of Turkey Lakes simulation, model calibration is based on 1981 data and model verification, on 1982-83, for Lac Laflamme (Fig. 7). The model simulates quite successfully the snowmelt runoff in April and May and the rain episodes in summer and fall. In particular, the observed pH drops at snowmelt times

(Fig. 7). The timing and the shape of the computed hydrograph fits well with the observed. Note that there are more summer fluctuations in Lac Laflamme than in Turkey Lakes.

As part of the investigation on the accuracy of the submodel components, we have also compared the computed water equivalent of the snow pack with the observed (Fig. 8). The observed snow accumulation and thawing sequences are reproduced quite closely by the results of the snow accumulation and ablation submodel. Thus, both the snow portion and the stream portion are simulated correctly for Lac Laflamme.

Figure 9 shows the various computed flow components as percentages of the total runoff. In general, about 50% surface runoff contributes to the total, cf. 70% at S1 and 30% at S3 in Turkey Lakes.

4.3 Harp Lake

Simulation of the hydrograph has been carried out for Harp Lake (station 4) by Seip *et al*. (1985) using a two-soil-layer model with the piston flow concept. Here, we have managed to produce essentially similar results using our three-layer model without applying the piston flow (Fig. 10). The timing of the episodes is properly simulated, but at times (e.g. April, 1979 and April, 1980) the magnitudes show some departure (underestimated by about 40% to 60%) from the observed hydrograph. When we rerun the model for another catchment (station 3A) in the same watershed, similar shortcomings occur again (Fig. 11). Since the same kind of mismatching also occurs in Seip et al.'s model, it is possible that some unknown processes (e.g. beaver dams) have not been accounted for by both models. Otherwise, our computed results agree satisfactorily with the observed data.

5. DISCUSSIONS

Having verified the model with several sets of observed data from different Canadian watersheds, we feel that we should examine the different calibrated values of the model coefficients. During the calibration, these coefficients are set by mathematically optimizing the least-squares variance between the computed and observed results. While the procedure itself is clearly mathematical, actual observed data have been used to influence the optimization. Therefore, it is interesting to see how much realism has been instilled upon such coefficients.

Table 1 list the calibrated hydrological coefficients for the various stations in the three Canadian watersheds. For example, the infiltration coefficient which regulates the flow from the upper soil zone to the lower soil zone ranges between 1 to 2 cm/day for all locations except station S1 in Turkey Lakes. However, the deep infiltration coefficient which regulates the flow from the lower soil zone to the groundwater zone varies substantially between 4 x 10^{-5} to 0.042 cm/day. 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, station S1 in Turkey Lakes pertains to headwater glacial soil but of silt-loam texture, whereas downstream soil such as station S3 has a smaller deep infiltration coefficient because of the fine-grained till. On the other hand, the calibrated infiltration coefficients in Lac Laflamme conforms to the values reported for morain and sandy texture (Freeze and Cherry, 1979) which is more permeable than those in Turkey Lakes. In the case of Harp Lake, although both stations are covered by silty sand, the soil at station 3A is less sandy and therefore less permeable than at station 4. Thus, generally speaking, the calibrated infiltration coefficients are consistent with the soil type of these watersheds.

To discuss the features of the other coefficients in Table 1 is certainly beyond the scope of this paper. However, a simple summary of the lateral flow coefficients in Table 1 can be made by calculating the half-life water residence times of the three soil reservoirs (Table 2) using these coefficients. In all cases, as expected, the groundwater reservoir has a longer residence time. Water tends to flow laterally to the stream more in Turkey Lakes than in the other two watersheds, because of the difference in soil permeability as discussed above. Thus, the headwater area (S1) in Turkey Lakes has a faster residence time and the more sandy station 4 in Harp Lake has a slower one. These estimated residence times are therefore also consistent with the geology of these watersheds.

6. CONCLUSIONS

Verification of the hydrological model developed for acidified watersheds in Canada has produced quite encouraging results showing reasonable agreement with the observed data on stream flow, groundwater and snowpack. The model is also shown to be fairly portable for different watersheds, as long as there are sufficient and reliable observed data for model calibration. The calibrated model coefficients for various locations in three geologically different Canadian watersheds are also contrasted with one another. Preliminary results indicate that they are fairly consistent with known values for the geology of these locations.

The stream pH and chemistry are certainly affected by the hydrology, and the residence times estimated at these sites are useful for explaining the apparent differences in water chemistry and soil contact times. Most importantly, these test results have encouraged us to link the hydrological model to hydrogeochemical models (e.g. Lam et al., 1985) for studying acidification problems in Canadian watersheds.

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Table 1 Calibrated hydrological coefficients for different Canadian watersheds

Constants	Turkey Lakes		Laflamme	Harp Lake	
	Station S1	Station S3		Basin 3A	Basin 4
Infiltration (cm/d)	0.0002	1.00	1.50	1.200	2.00
Surface Runoff (day^{-1})	0.550	0.535	0.465	0.850	0.693
Deep Infiltration (cm/d)	0.00004	0.025	0.042	0.0045	0.030
Inter Flow (day^{-1})	0.350	0.300	0.080	0.500	0.030
Groundwater Flow (day^{-1})	0.250	0.200	0.062	0.062	0.008

Table 2 Half-life residence time (day) of reservoirs

	Turkey Lakes Watershed		Laflamme	Harp Lake	
	Station #1	Station #3		Basin #3A	Basin #4
Upper Soil Reservoir	1.26	1.30	1.49	0.82	1.00
Lower Soil Reservoir	1.98	2.31	8.66	1.39	23.10
Groundwater Reservoir	2.77	3.47	11.18	11.18	86.64

FIGURE LEGEND

Figure 1 Conceptualized water quantity model.

Figure 2 Simulated and observed runoff with pH at station 1, Turkey Lakes Watershed.

Figure 3 Simulated and observed runoff with pH at station 3, Turkey Lakes Watershed.

Figure 4 Surface runoff, interflow and groundwater flow as percentages of the total runoff at station 1, Turkey Lakes Watershed.

Figure 5 Surface runoff, interflow and groundwater flow as percentages of the total runoff at station 3, Turkey Lakes Watershed.

Figure 6 Observed total runoff, observed groundwater flow (O^{18} data) and computed groundwater flow.

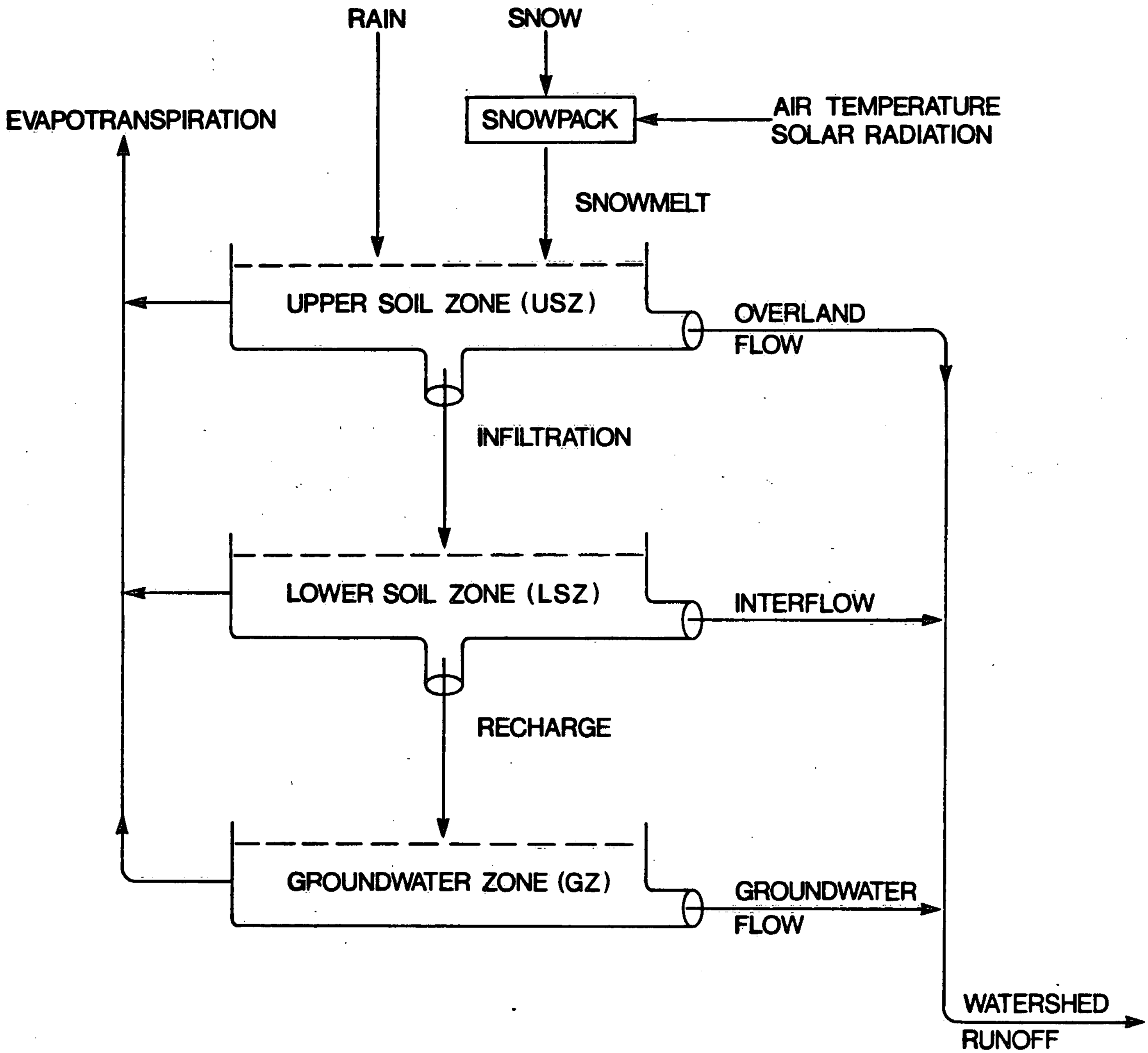
Figure 7 Simulated and observed runoff with pH at Lac Laflamme.

Figure 8 Simulated and observed water content in snowpack at Lac Laflamme Watershed.

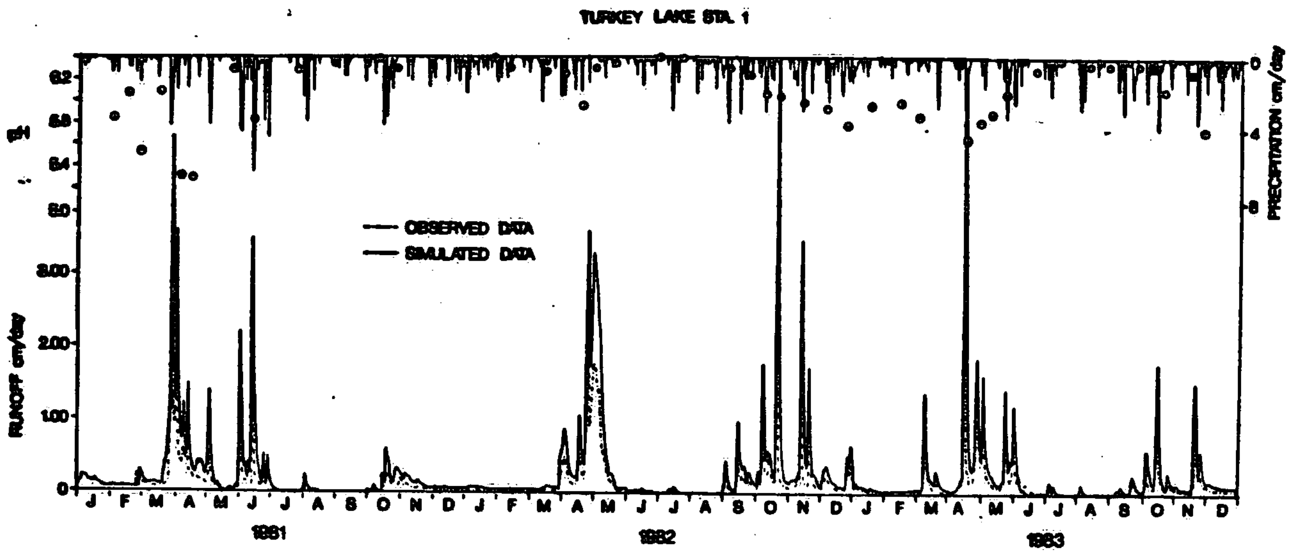
Figure 9 Surface runoff interflow and groundwater flow as percentages of the total runoff at Lac Laflamme.

Figure 10 Simulated and observed hydrograph at station 3A, Harp Lake Watershed.

Figure 11 Simulated and observed hydrograph at station 4, Harp Lake Watershed.

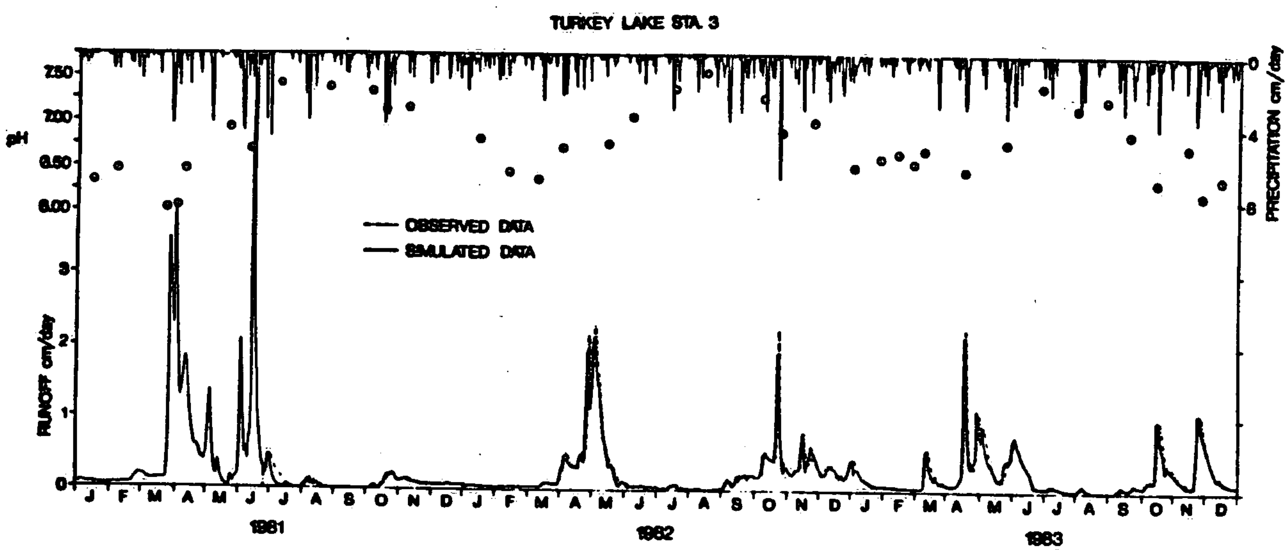


Conceptualized water quantity model (Bobba and Lam, 1984)



SIMULATED AND OBSERVED RUNOFF WITH pH.

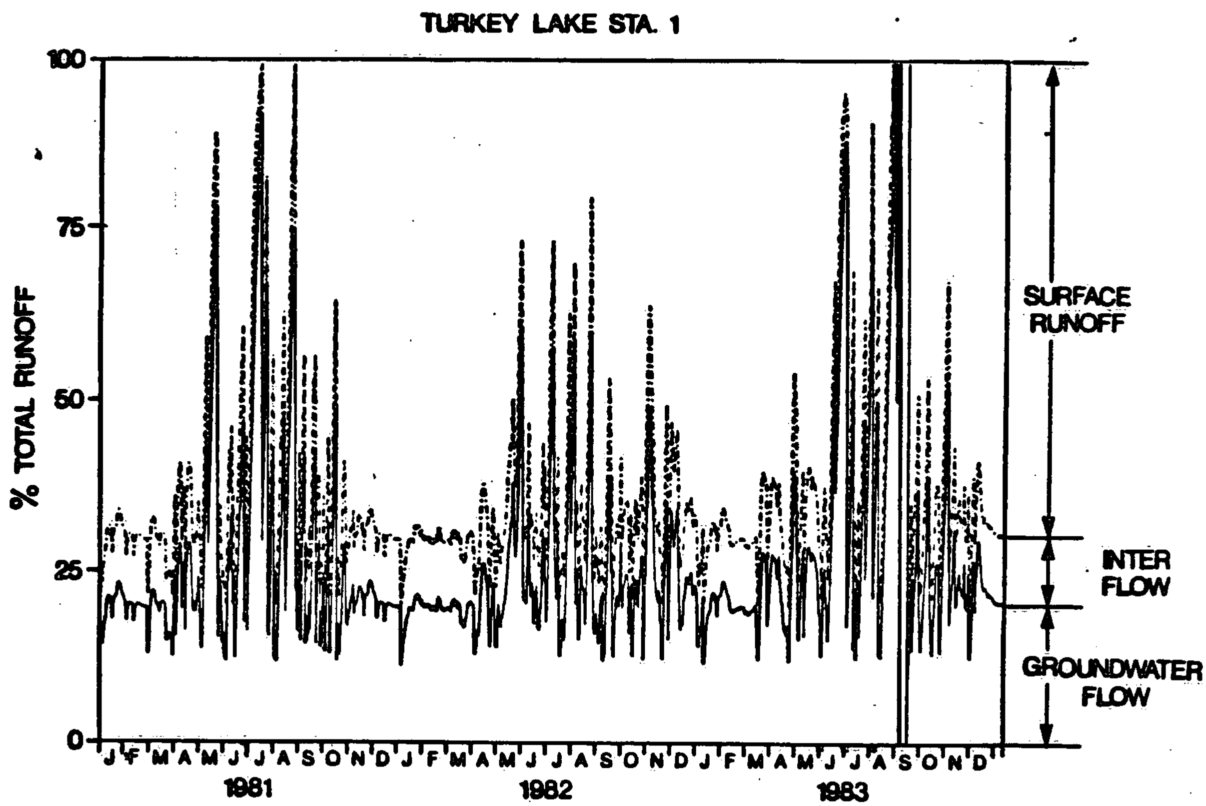
Fig.2



SIMULATED AND OBSERVED RUNOFF WITH pH.

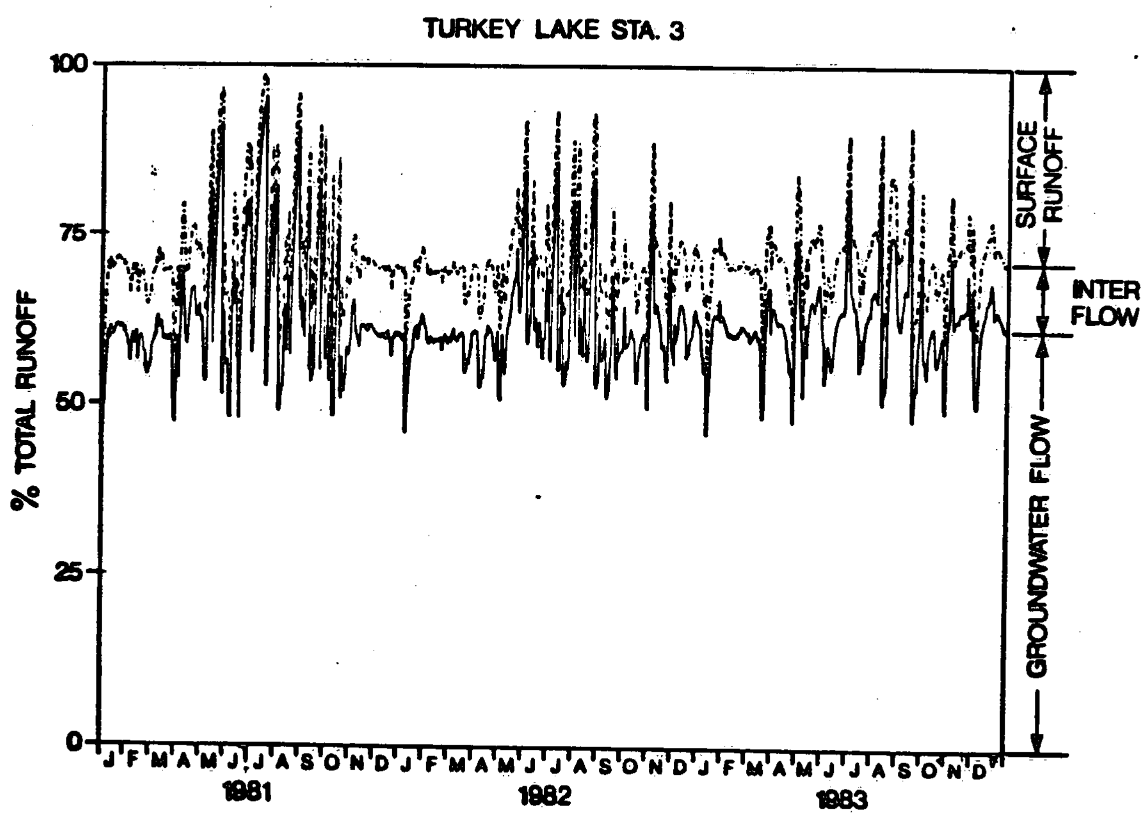
Fig.3

Fig.4



SURFACE RUNOFF, INTERFLOW AND GROUNDWATER FLOW AS PERCENTAGES OF THE TOTAL RUNOFF

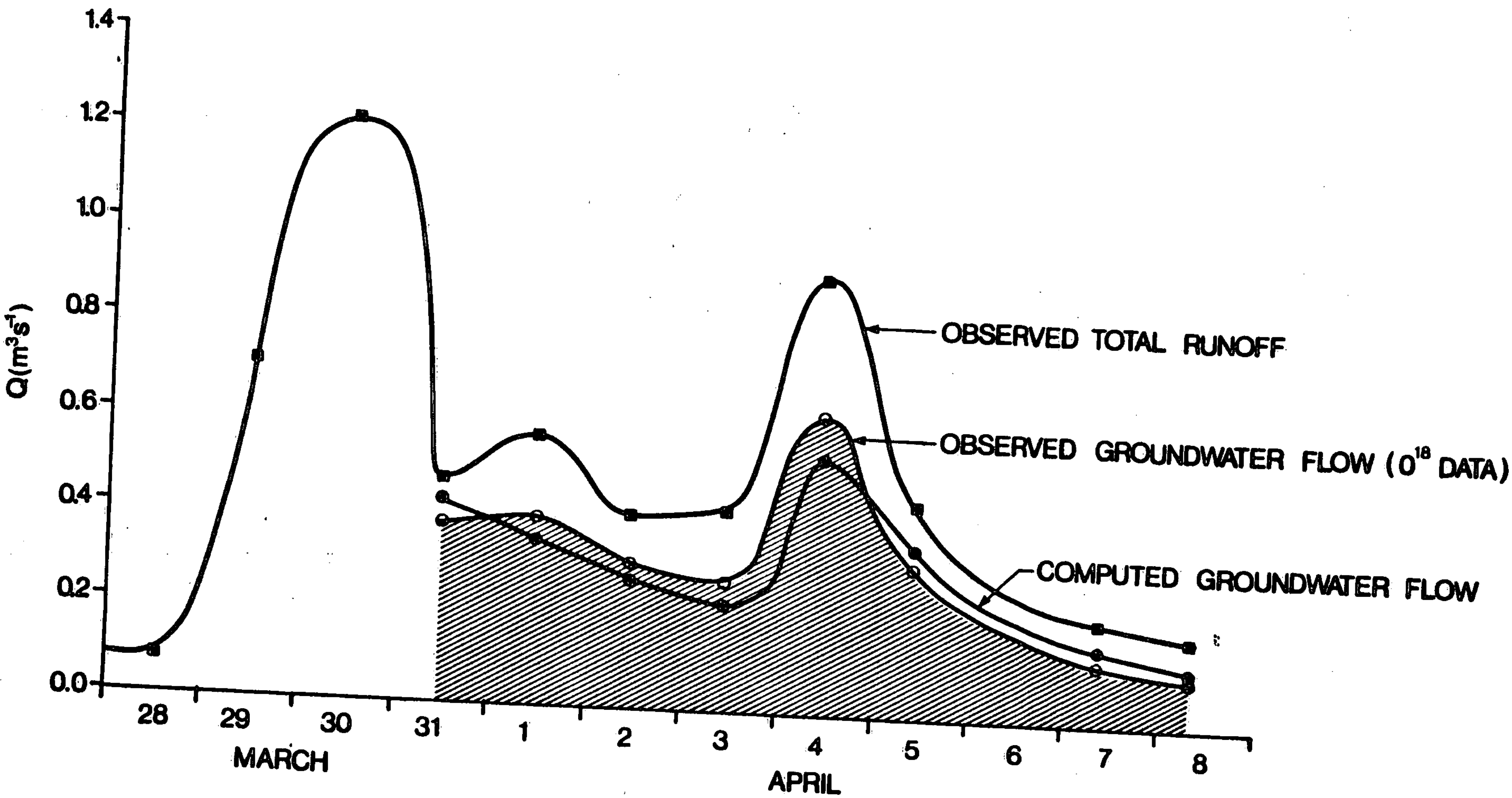
Fig.5



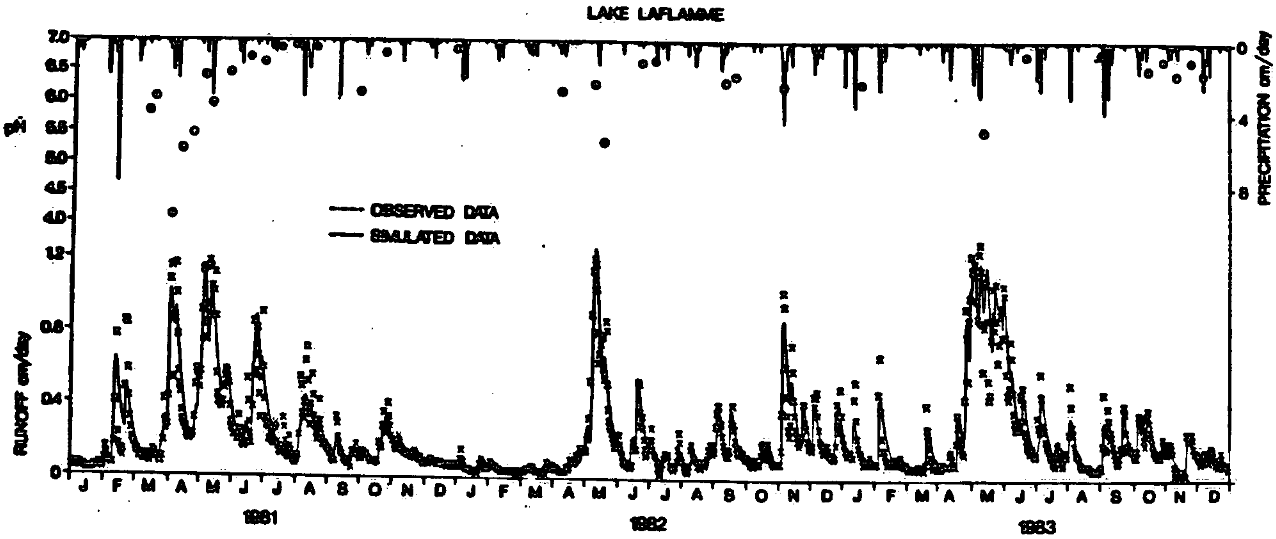
SURFACE RUNOFF, INTERFLOW AND GROUNDWATER FLOW AS PERCENTAGES OF THE TOTAL RUNOFF

Fig.6

CALIBRATION (1981), ^{18}O data
TURKEY LAKES

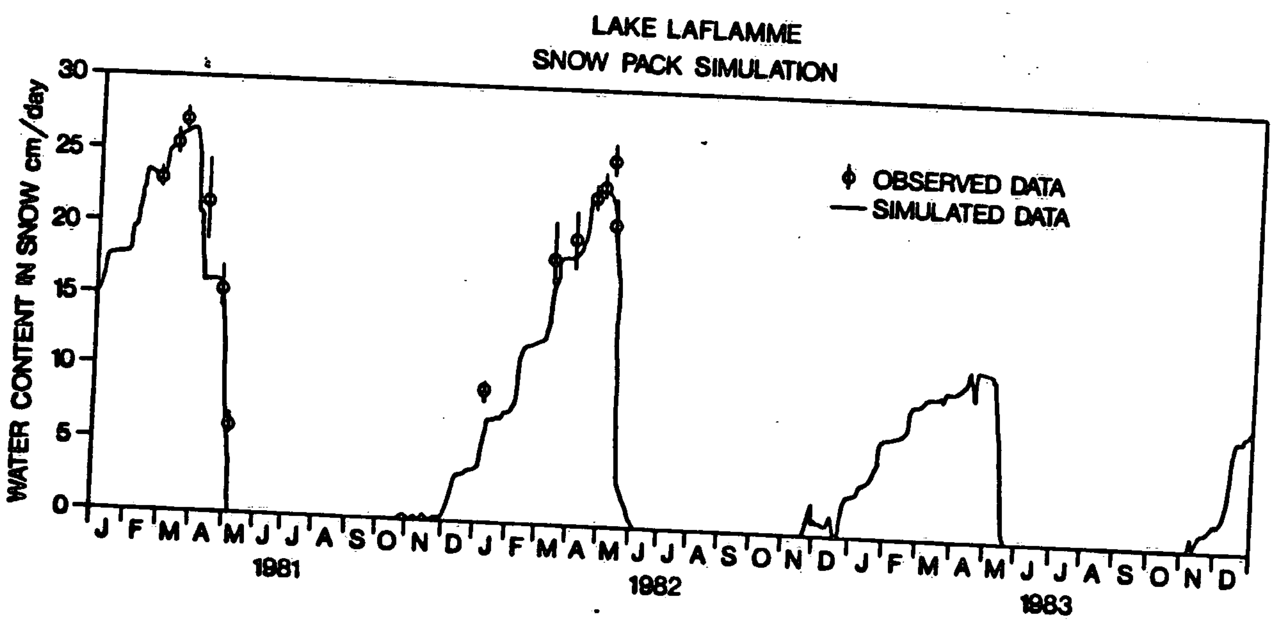


OBSERVED TOTAL RUNOFF, OBSERVED GROUND-WATER FLOW (O^{18} DATA) AND COMPUTED GROUND-WATER FLOW



SIMULATED AND OBSERVED RUNOFF WITH pH.

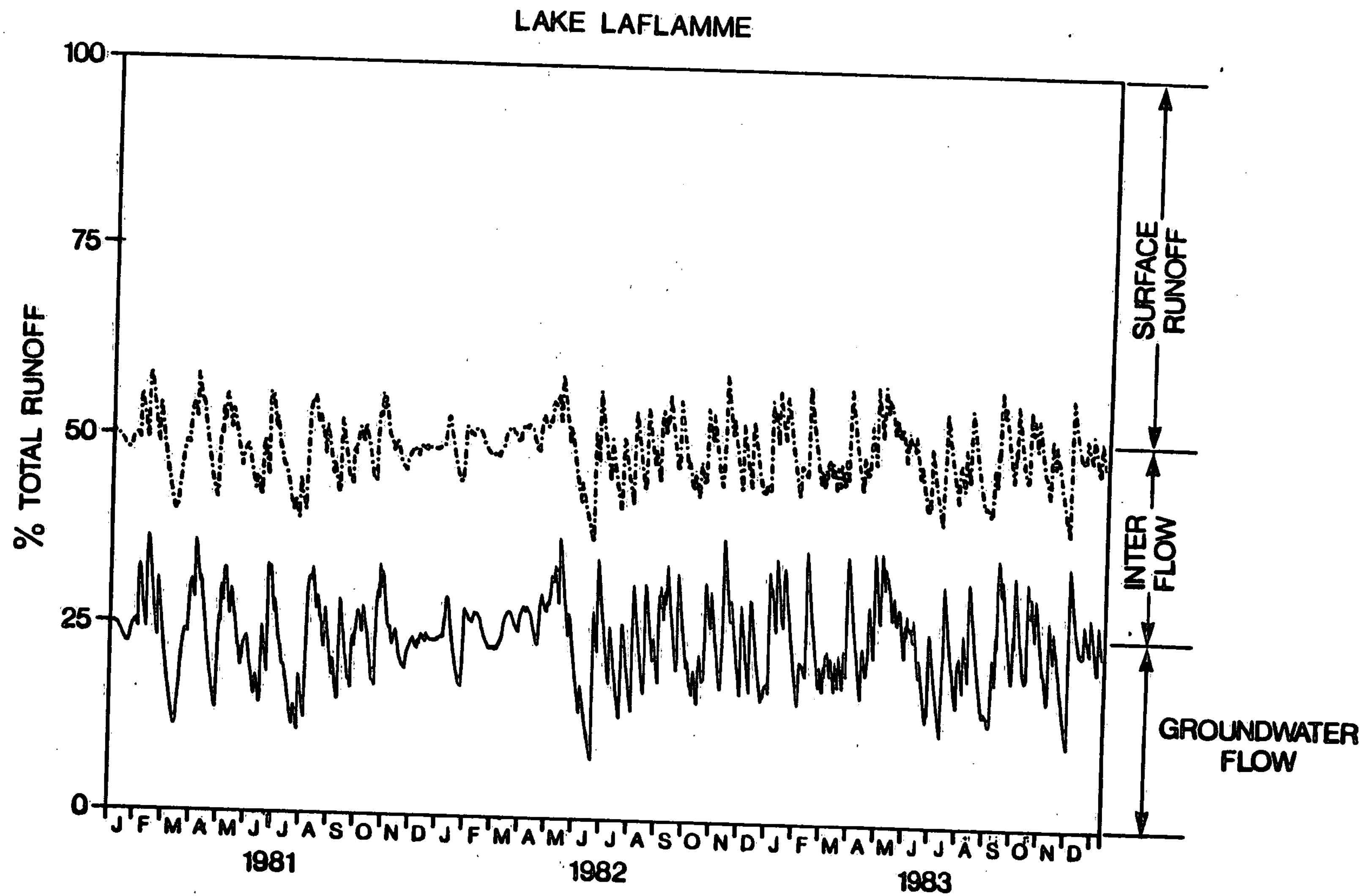
Fig.7



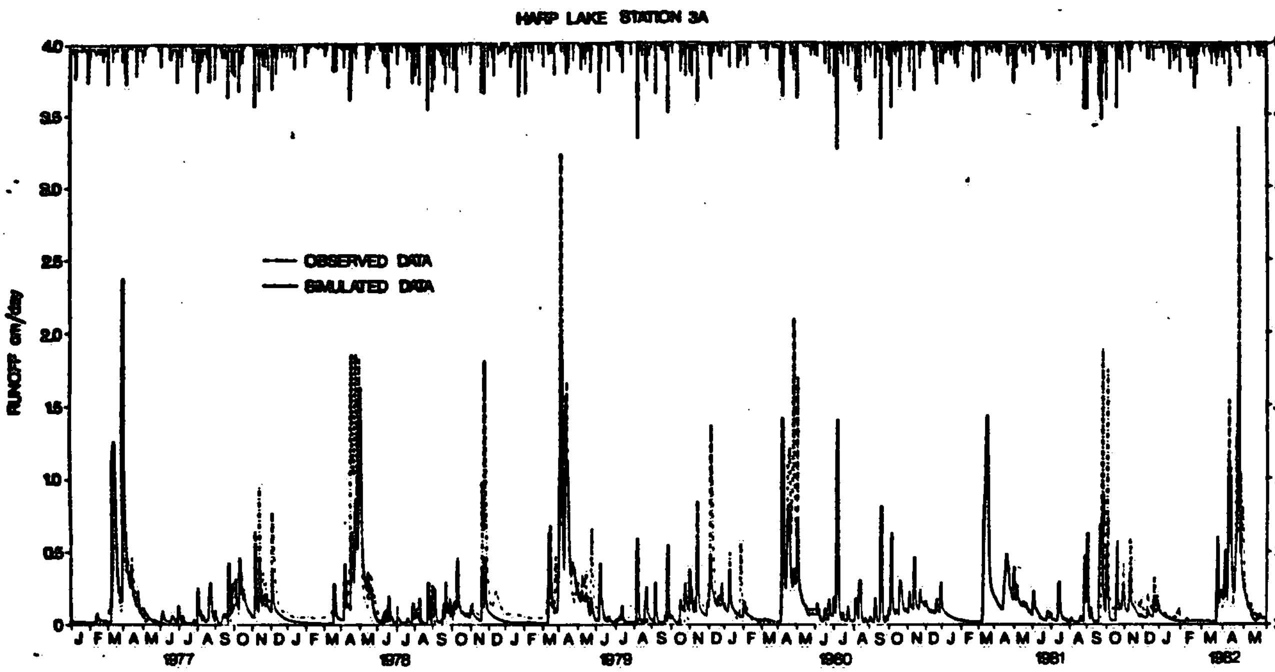
WATER CONTENT IN SNOW PACK

Fig.8

Fig.9

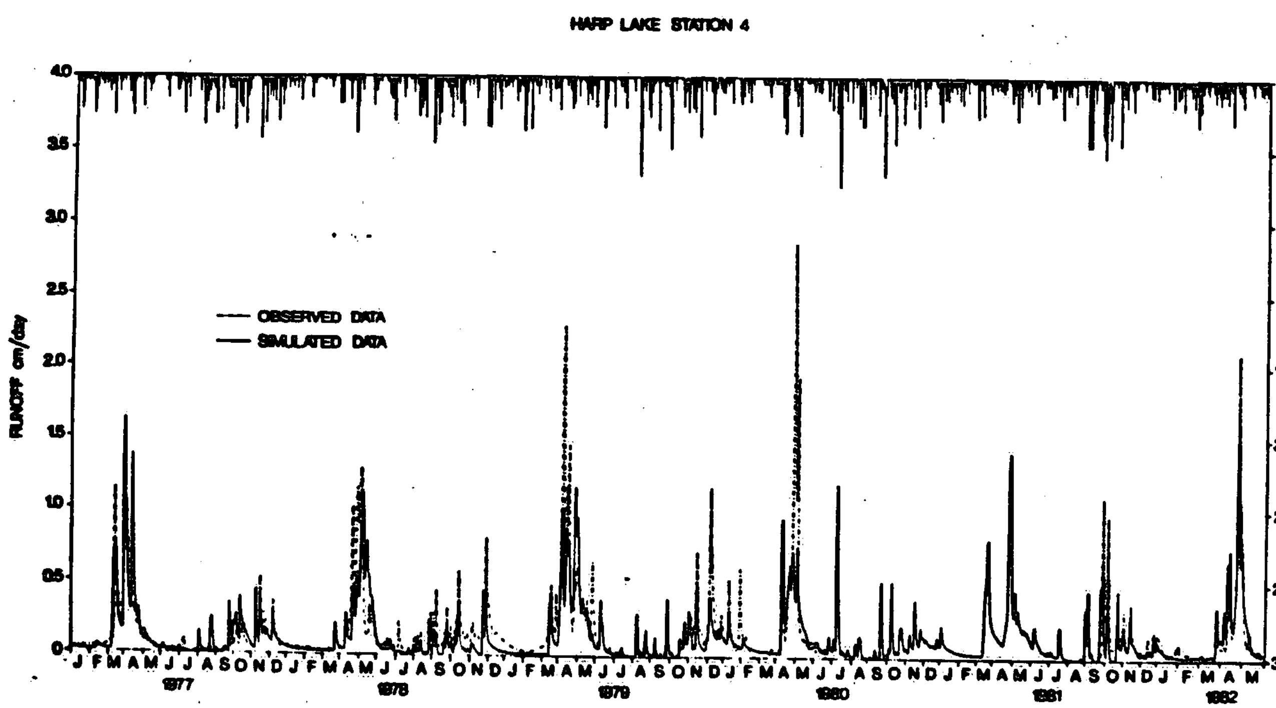


SURFACE RUNOFF, INTERFLOW AND GROUNDWATER FLOW AS PERCENTAGES OF THE TOTAL RUNOFF



SIMULATED AND OBSERVED HYDROGRAPH

Fig.10



SIMULATED AND OBSERVED HYDROGRAPH

Fig.11