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APPLICATION OF HYDROLOGICAL MODEL TO ACIDIFIED WATERSHEDS: A STUDY ON HARP LAKE CATCHMENTS

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ABSTRACT

The hydrological model by Bobba and Lam (1984) has been applied to Harp Lake watershed as part of a verification package to test its accuracy and portability. The computed hydrograph and snow water equivalent is in reasonably good agreement with observed data. The model results are consistent with the observed pH and with many of the episodic events that have occurred in these acidified catchments. Contrasts have also been made on the calibrated model coefficients for the different catchments. An attempt to relate them to the geology and soil characteristics at the site has led to realistic estimation of the soil contact times.

Le modèle hydrologique de Bobba et Lamb (1984) a été mis en oeuvre dans le bassin hydrographique du lac Harp dans le cadre d'un programme de vérification de son exactitude et de sa transportabilité. L'hydrogramme et l'équivalent en eau de la neige calculés concordent assez bien avec les résultats observés. Les résultats du modèle concordent avec le pH observé et avec de nombreux événements épisodiques qui se sont produits dans les bassins versants acidifiés. On a également fait contraster les coefficients du modèle étalonné pour les divers bassins versants. En essayant de les associer aux caractéristiques géologiques et à celles du sol sur les lieux, on a établi une estimation réaliste des temps de contact du sol.

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The hydrological model by Bobba and Lam (1984) has been applied to Harp Lake watershed as part of a verification package to test its accuracy and portability. The computed hydrograph and snow water equivalent is in reasonably good agreement with observed data. The model results are consistent with the observed pH and with many of the episodic events that have occurred in these acidified catchments. Contrasts have also been made on the calibrated model coefficients for the different catchments. 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). These models are specially developed for short-term simulation and predicting the total runoff only. Several major difficulties may arise if they are to be interfaced with hydrochemical models (e.g. Christophersen et al., 1984; Seip et al., 1985) 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 streamflow. However, since there is no one best model and since the requirement of a hydrological model for investigating long-term acification effects (e.g. Christophersen et al., 1982) differs from those for short-term flood forecasting, we have developed a model (Bobba and Lam, 1984) with a special linkage on the soil and water chemistry. The model has been applied successfully at several Canadian watersheds (Bobba et al., 1985).

The objective of this paper is to present the results of the application of this hydrological model to the Harp Lake watershed in Ontario, Canada, as part of the model verification procedure.

HYDROLOGICAL MODEL

The description of hydrological model has been described in Bobba and Lam (1984) and Lam and Bobba (1985). The primary elements considered in our model are precipitation (rainfall and snow), evapotranspiration, surface runoff, upper soil zone water storage, depletion in lower soil zone storage, interflow and

base flow. The vertical zones include a surface/snow storage reservoir, an upper soil reservoir, lower soil reservoir and groundwater reservoir (Fig. 1). The model consists of mass balance calculations for snow accumulation and snowmelting, soil moisture budgeting, runoff generation and hydrological routing.

The surface reservoir represents the volume of water content in snow, just above the soil surface. The upper soil reservoir is the top few centimeters of soil that is highly responsive to changes in weather conditions. The lower soil reservoir is less active and includes the root zones of the perennial vegetation. The bottom layer is the groundwter reservoir which is characterized by being sealed against vertical flow at the bottom by the bedrock. These four zones also coincide with the chemical acidification processes generally characterized by snow chemistry, humus formation, cation exchange and soil weathering, respectively from top to bottom layer.

APPLICATION OF THE HYDROLOGICAL MODEL

The Study Area

The Harp Lake watershed is located 10 km northeast of Huntsville, Ontario, Canada. The watershed is almost completely covered with deciduous forest. The bedrock underlying most of the subwatersheds is biotite hornblende gneisses, amphibolite and schist. The overburden consists of a till plain (Sandy loam to sand deposits >1 m thick) with thin deposits (<1 m) and rock ridges covering the remainder of the watershed (Table 1). Detailed description of the watershed was given by Jeffries and Snyder (1983).

TABLE 1
Geomorphological Parameters: Harp Lake Watershed

Catchments	Area $10^4 m^2$	Surfacial Geology Percentage			Land Use Percentage		
		Organic	Shallow	Deep	Exposed	Wetland	Forest
3	22.6	9.3	11.2	79.5	20	11	69
3A	22.4	2.9	0.0	97.1	20	1	79
4	139.0	2.7	33.7	63.5	22	9	69
5	204.8	13.3	48.6	38.1	18	9	73
6	21.5	0.0	54.8	45.2	0	2	98
6A	18.9	8.5	84.9	6.6	0	11	89

Percent Areal Extent of Surficial and Bedrock Geological Type: Harp Lake

Catchment	Surficial Deposit Type						Bedrock Geological Type		
	Minor Till	Thin Till & rock-ridges	Peat	Bedrock	Sand	Pond	Biotite-Horn-blende gneiss	Diorite	Amphi-bolite Schist
3	79.5	11.2	9.3	-	-	-	93.0	-	7.0
3A	97.1	-	2.9	-	-	-	42.6	-	57.4
4	56.1	32.8	-	0.9	7.5	2.7	13.2	-	86.8
5	34.5	48.6	13.3	-	3.6	-	100	-	-
6	45.2	54.8	-	-	-	-	100	-	-
6A	6.6	84.9	8.5	-	-	-	33.3	66.7	-

RESULTS

The hydrological model was calibrated first with data observed in 1977 for each catchment. The calibrated coefficients are then fixed for subsequent years (January 1978 to June 1982). Statistical summaries of the results calcualted with mean values during the entire 5-1/2 year period are presented in Table 2. The correlation coefficients between computed and observed total flow range between 0.73 to 0.80 indicating a reasonable agreement. As examples, Figure 3 shows the daily results of catchment 4 and Figure 4 shows the results of catchment 5. Seip et al. (1985) applied their hydrologicalmodel to the catchment 4 by considering two-layer soil model with the piston flow concept. However, in our hydrological model, we have managed to produce essentially similar results using a three-layer model without applying the piston flow. The timing of the episodes is properly simulated, but at times (e.g. March - April 1979 and March - April 1980), the magnitudes show some departure (underestimated by about 40% to 60%) from observed hydrograph. When we rerun the model for other catchments in the same watershed, similar results were observed (Figs. 3 and 4). Since the same kind of mismatching is reported in Seip et al. (1985), it is possible the meteorological data may be inadequate. Otherwise, our simulated results agree satisfactorily with observed data and in particular, the predicted snowmelt peaks coincide well with the observed pH depressions (Figs. 3 and 4).

TABLE 2
Harp Lake Catchments: Statistical Summary of Mean Model Results

Catchment	Mean Flow (cm)	Mean Model Flow (cm)	Relative Difference in Mean	Standard Deviation of Flows (cm)	Root Mean Square Error (cm)	Correlation Coefficient
3	0.154	0.164	+0.010	0.258	0.176	0.73
3A	0.145	0.131	-0.014	0.281	0.177	0.78
4	0.138	0.118	-0.020	0.215	0.133	0.80
5	0.139	0.127	-0.012	0.237	0.155	0.80
6	0.094	0.088	-0.006	0.188	0.116	0.80
6A	0.107	0.091	-0.016	0.214	0.139	0.78

The model also calculates the water equivalent in the snow pack. Table 3 shows the observed water equivalent in the snow and computed water equivalent for catchment 4 for 1982. In general, the differences between the computed and observed values are well within one standard deviation of the observational errors.

DISCUSSION

Earlier, this hydrological model has been successfully applied to different Canadian watersheds (Bobba and Lam, 1984; Bobba et al., 1985) and examined the different calibrated values of the model coefficients. During the calibration, the parameter determination was computed by a systematic search of the parameter space to minimize the sum of squared errors between observed runoff and simulated outflow volumes since parameter error compensation is probably present in calibrations, an order-of-magnitude agreement between the models is considered very good. Agreement would probably be better if more than two digit

TABLE 3
Observed and Computed Water Equivalent (mm) in Snow for Catchment 4

Date	Observed Snow Water Equivalent	Standard Deviation	Computed Snow Water Equivalent
12/1/82	132.1	16.53	98.64
15/1/82	136.7	17.26	101.14
22/1/82	149.0	17.34	113.23
29/1/82	181.2	16.52	141.49
5/2/82	202.4	26.36	176.58
11/2/82	227.3	19.92	209.53
19/2/82	206.6	29.51	217.38
26/2/82	239.6	26.81	229.99
5/3/82	261.2	22.41	250.68
11/3/82	275.2	35.79	268.33
15/3/82	266.7	33.72	259.11
19/3/82	269.7	43.53	261.07
22/3/82	276.4	39.74	265.46
26/3/82	266.7	38.78	259.40
31/3/82	271.4	35.75	239.61
2/4/82	250.6	39.04	244.31
7/4/82	248.1	35.68	247.23
13/4/82	260.8	53.19	237.94
16/4/82	201.9	58.22	206.99
19/4/82	157.9	54.48	181.06
23/4/82	130.4	68.86	157.56
26/4/82	58.8	67.98	105.55

convergence were used in the parameter optimizations. Individual parameter values may reflect only local optimums in the calibration objective function (minimization of root-mean-square error of model outflows). The physical relevance of the linear reservoir parameter permits verification as empirical techniques are developed. Admittedly, errors in individual parameters may compensate for one another in the calibration because of the synergistic relationship among all parameters.

Table 4 shows the calibrated hydrological coefficients for the various catchments of Harp Lake watershed. For example, the infiltration coefficient which regulates the flow from the upper soil zone to the lower soil zone ranges 0.8 to 2.0 cm/day. However, the deep infiltration coefficient which regulates the flow from the lower soil zone to the groundwater zone varies substantially from 0.0045 to 0.1 cm/day. These values conform to the values reported in the literature (Freeze and Cherry, 1979) for the type of geology concerned (Table 1). For example, catchment 3A which is covered with mainly minor till is less permeable than catchment 6A whose till texture is of a thinner type.

The computed lateral flow coefficients have been used to calculate the half life water residence times of the three soil reservoirs. In all cases, as expected, the groundwater reservoir has a longer residence time. Again, catchments 6 and 6A have a longer groundwater residence time than the other catchments because of the thinner till composition. These estimated residence times therefore reasonably reflect the geology of the catchments.

TABLE 4
Hydrological Model Parameters - Harp Lake Watershed

Catchments	Infiltration (cm/day)	Surface Runoff (1/day)	Deep Infiltration (cm/day)	Inter Flow (1/day)	Groundwater Flow (1/day)
3	0.80	0.700	0.040	0.600	0.080
3A	1.20	0.850	0.0045	0.500	0.062
4	2.00	0.693	0.030	0.030	0.008
5	0.80	0.800	0.030	0.032	0.008
6	0.90	0.500	0.100	0.060	0.005
6A	0.85	0.850	0.085	0.065	0.005

Half-Life Residence Time (Day) of Reservoirs

Catchments	Upper Soil Reservoir	Lower Soil Reservoir	Groundwater Reservoir
3	0.99	1.55	8.66
3A	0.82	1.39	11.18
4	1.00	23.10	86.64
5	0.87	21.66	86.64
6	1.39	11.55	138.63
6A	0.82	10.66	138.63

CONCLUSION

The hydrological model has been applied successfully to the catchments of the Harp Lake Watershed, with reasonably good predictions of the total runoff and snowwater equivalent. The relationship between the hydrology and the observed pH is also indicated, particularly during snowmelt episodes. At other times, the variations in the observed pH are the results of interactions between hydrology and hydrogeochemistry. A notable example is the relatively lower pH observed in catchment 5 compared to catchment 4. This basin processes essentially similar hydrological parameters (Table 4) except for slower surfacial infiltration and faster residence time in the upper soil reservoir, thus encouraging higher lateral flows. Thus water passing through catchment 5 has lesser contact with buffering materials in the soil and enters the stream with higher acidity. Of course, the detailed changes also depend on the buffering capacity, the weathering rate and other geochemical attributes. In general, with the hydrological components verified by the flow data, the stage is now set for linking this hydrological model with the hydrogeochemical models as outlined in Lam et al. (1985).

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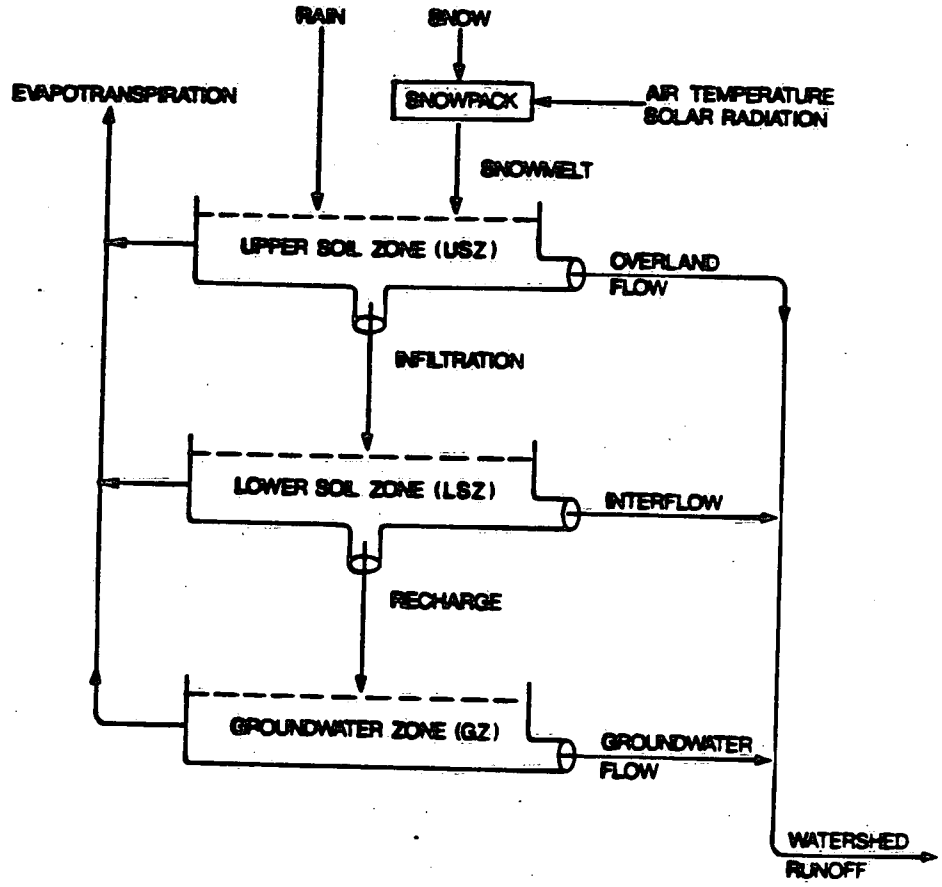

Figure 1 Conceptualized water quantity model (Bobba and Lam, 1984)

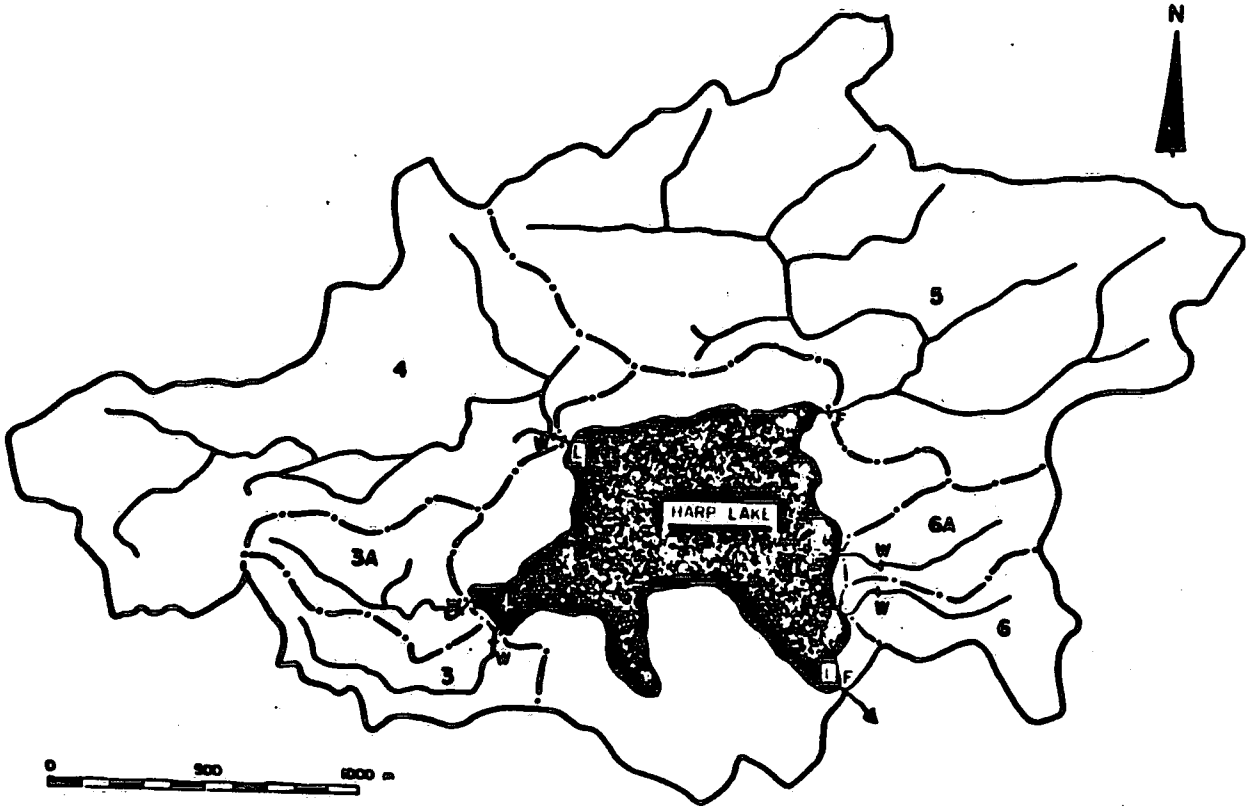

Figure 2 Location of Harp lake catchments

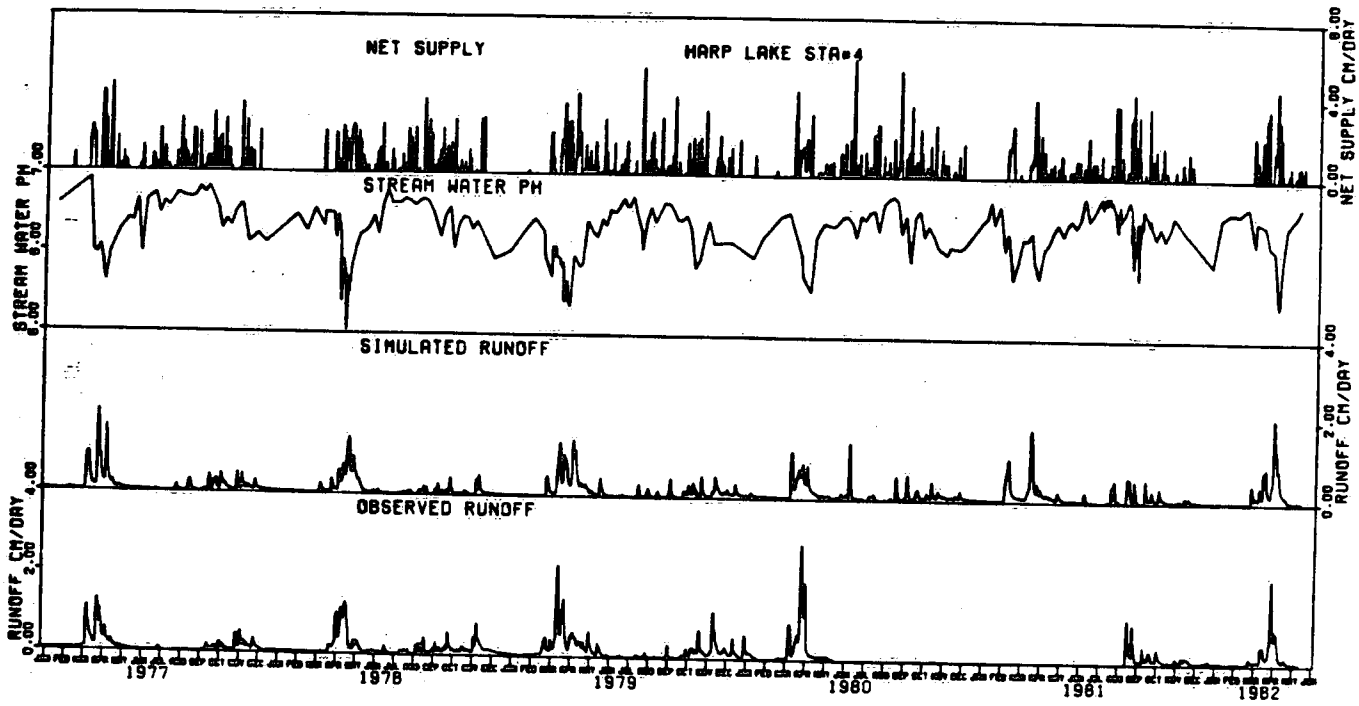

Figure 3 Observed and simulated runoff with pH at catchment 4

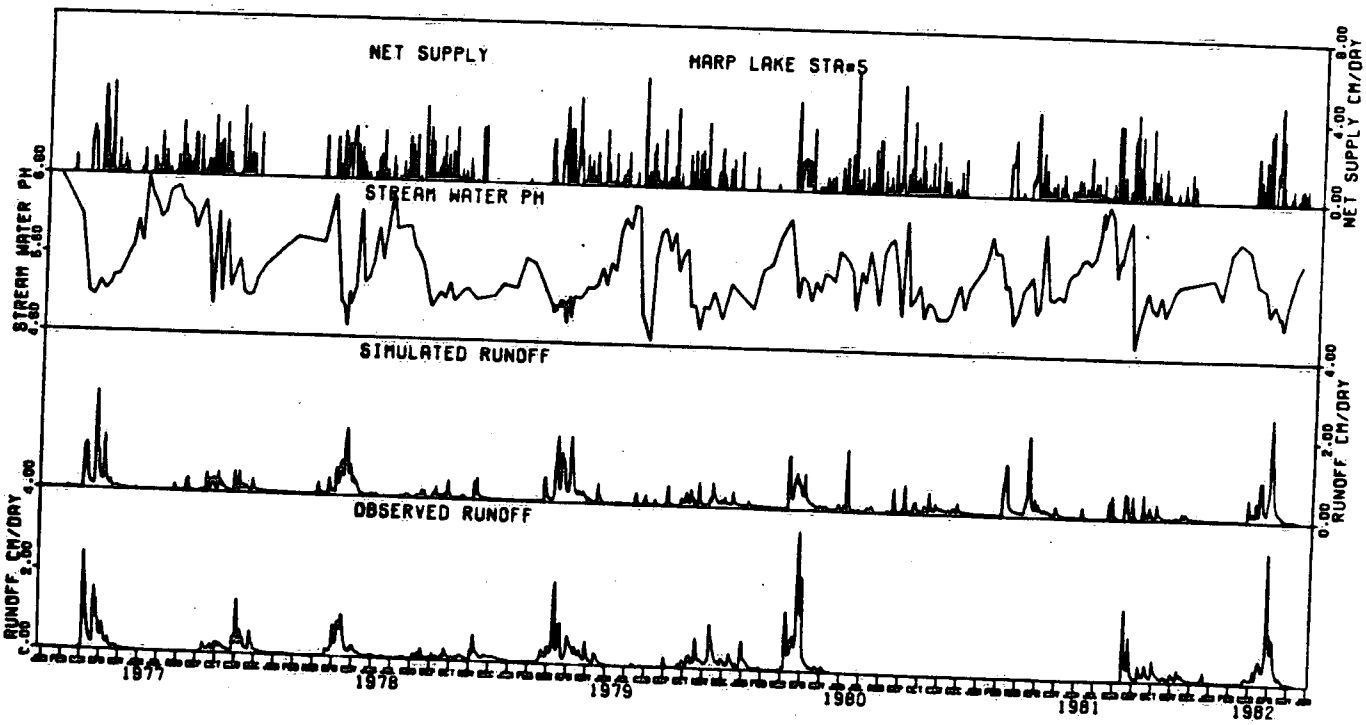

Figure 4 Observed and simulated runoff with pH at catchment 5