Large Scale Effects of Seasonal Snow Cover (Proceedings of the Vancouver Symposium, August 1987). IAHS Publ. no. 166

Snowmelt-runoff simulation model of a central Chile Andean basin with relevant orographic effects

HUMBERTO PEÑA & BRAHIM NAZARALA
Direccion General de Aguas
Morandé 59, 8° Piso, Santiago, Chile

ABSTRACT A snowmelt-runoff simulation model of the upper Maipo River basin, located in the Andean highlands of Central Chile, is presented. Empirical relations developed for the area are used to compute the snow and ice melt. The influence of the spatial structure of the model and the redistribution of snow falling on high slope surfaces are discussed. The role of semi-perennial snow covered areas and the runoff from the glaciers are emphasized.

Modèle de simulation de l'écoulement des eaux de fonte des neiges d'un bassin situé dans les Andes du Chili central avec des effets orographiques pertinents

RÉSUMÉ On présente un modèle de simulation de la fonte des neiges, concernant le bassin de la rivière Maipo, dans les Andes du Chili central. Le calcul de la fonte des neiges et de glace se réalise au moyen de relations empiriques développées pour cette zone. L'étude analyse l'influence de la structure spatiale du modèle et l'effet de la redistribution de la neige qui se précipite sur les surfaces qui présentent une pente élevée. Finalement on attire l'attention sur l'importance des surfaces couvertes de neige de façon semi-permanente et de l'écoulement produit par les glaciers.

INTRODUCTION

Meltwater from snow and ice in the Andes range is the most important water resource in the central area of Chile. Therefore, seasonal discharge forecasts for the high mountains are needed. For that purpose, a hydrological simulation model for the Maipo basin has been developed, which is presented in this paper.

The main difficulties in developing a simulation model for this area are:

a) the limited knowledge regarding the processes which are relevant to the snow cover behaviour at high altitudes and the meteorological conditions of the region;

b) the large elevation range, size and orographic complexity of the basins, and

c) the scarcity of hydrometeorological data in relation to the basin characteristics, particularly at high altitudes.

In order to solve these problems, a research programme was carried out and the findings were incorporated in the structure of the model. In this paper, the main characteristics of the basin and the model are summarized, particularly those aspects connected to the research programme. Also, the results of the model are analyzed.

DESCRIPTION OF THE BASIN

The Maipo basin drains the western side of the Andes range, from lat. 33° 03' to 34° 17' S, near the city of Santiago. The mountainous area of the basin covers about 5000 km^2 and the seasonal snow covered area is 4000 km^2 (Fig. 1). The elevation ranges from 800 to 6500 m a.m.s.l., with a mean of 3000 m a.m.s.l. (Fig. 2), and almost all of the basin surface is unforested.

Slopes and orientations of the basin were analyzed with a sample of 1000 points from a rectangular grid. For that purpose, only a 1:50,000 scale map was available. The results show that surfaces with slopes greater than 40° increase with elevation and those with slopes smaller than 10° decrease (Fig. 3). The exposures are, in general, regularly distributed, but western orientations predominate in some bands, due to the location of the Maipo basin on the western side of the Andes mountains.

The Maipo basin has a glacierized area of 362 km^2, including debris covered areas of 110 km^2. The mean elevation of the glaciers is 4000 m a.m.s.l. and that of bare ice surface areas is 4400 m a.m.s.l.

Precipitation originates with cold fronts. The storms usually cover large areas and last for several days. The mean annual precipitation over the basin is 1030 mm and the precipitation mean gradient has been estimated as 29 mm/100 m. The region shows a long dry period (6-7 months) and a short precipitation period in winter, so that 80% of the annual precipitation occurs in four months.

During winter, snowfall is normally observed above 1500-2000 m a.m.s.l. only, since rain on snow situations affect small areas in relation to the basin's size.

The elevation of the snow covered areas and the semiarid climatic characteristics of the region greatly influence the energy balance at the snow surface. During the melting period, radiation is predominant in the energy balance and the turbulent fluxes are small or negative due to the energy loss by evaporation. Nieves penitentes are frequently observed because of these characteristics of the energy balance. On the other hand, due to cross-correlations between the meteorological variables (air temperature, vapour

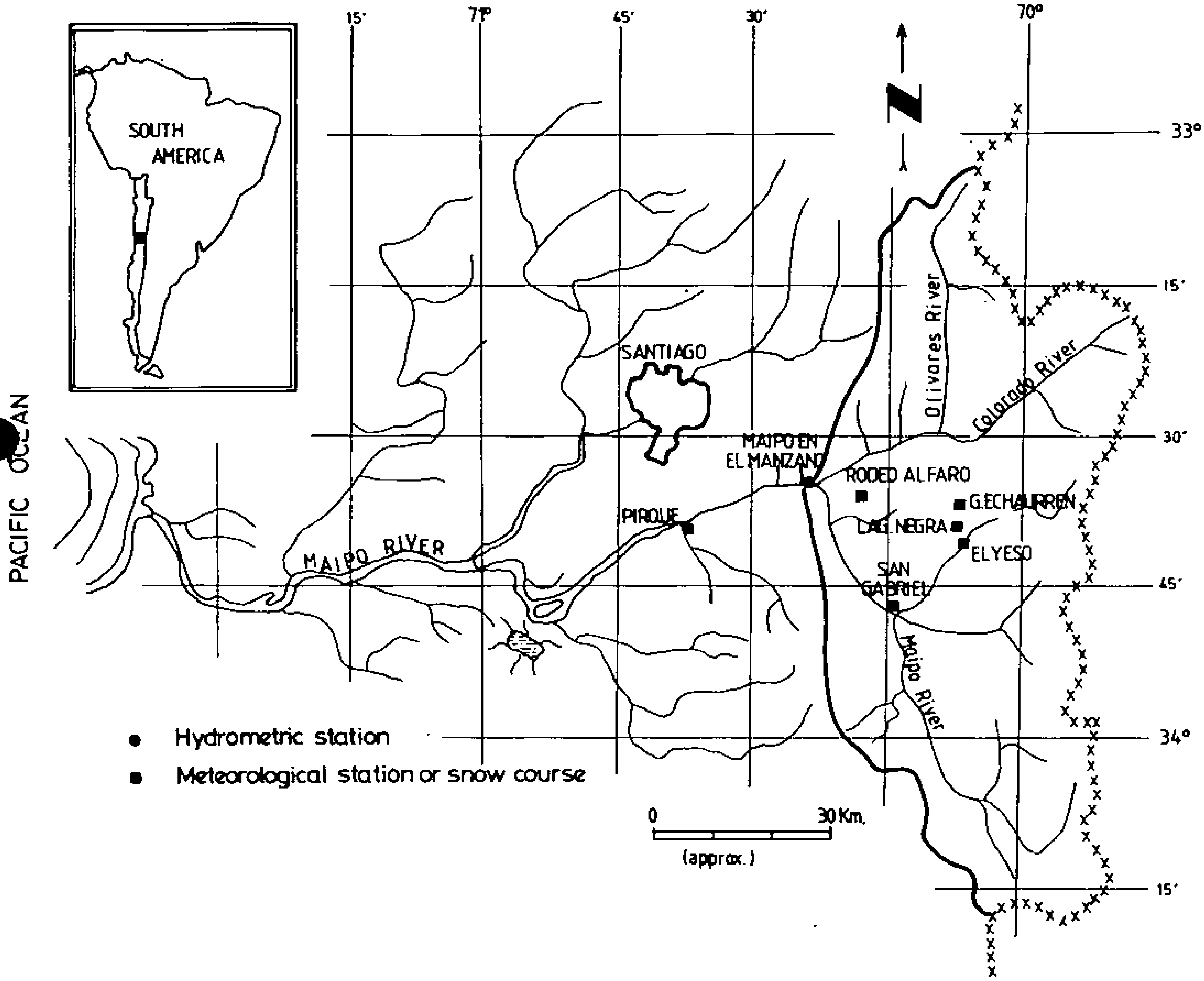

FIG. 1 Location of the Maipo Basin

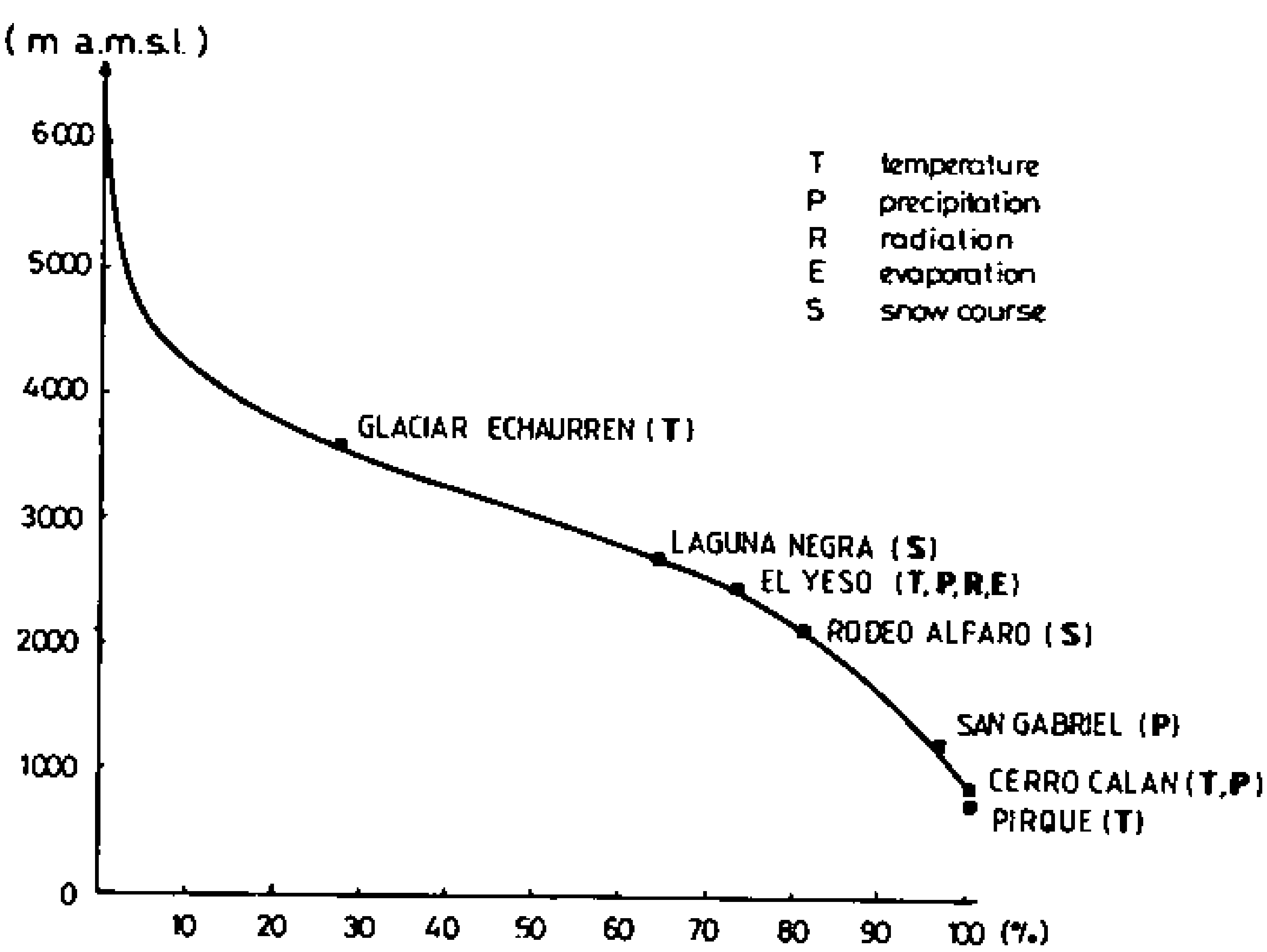

FIG. 2 Hypsometric curve of the Maipo basin and elevational distribution of the measurement stations

pressure and wind velocity), which impede an unlimited increase of the energy supply (Luna & Stowhas, 1983), a natural maxim of the snowmelt rate is observed.

Most runoff originates as seasonal snowmelt with glacial contribution being relatively unimportant at the end of the summer period and during dry years. In general, the rain contribution is negligible.

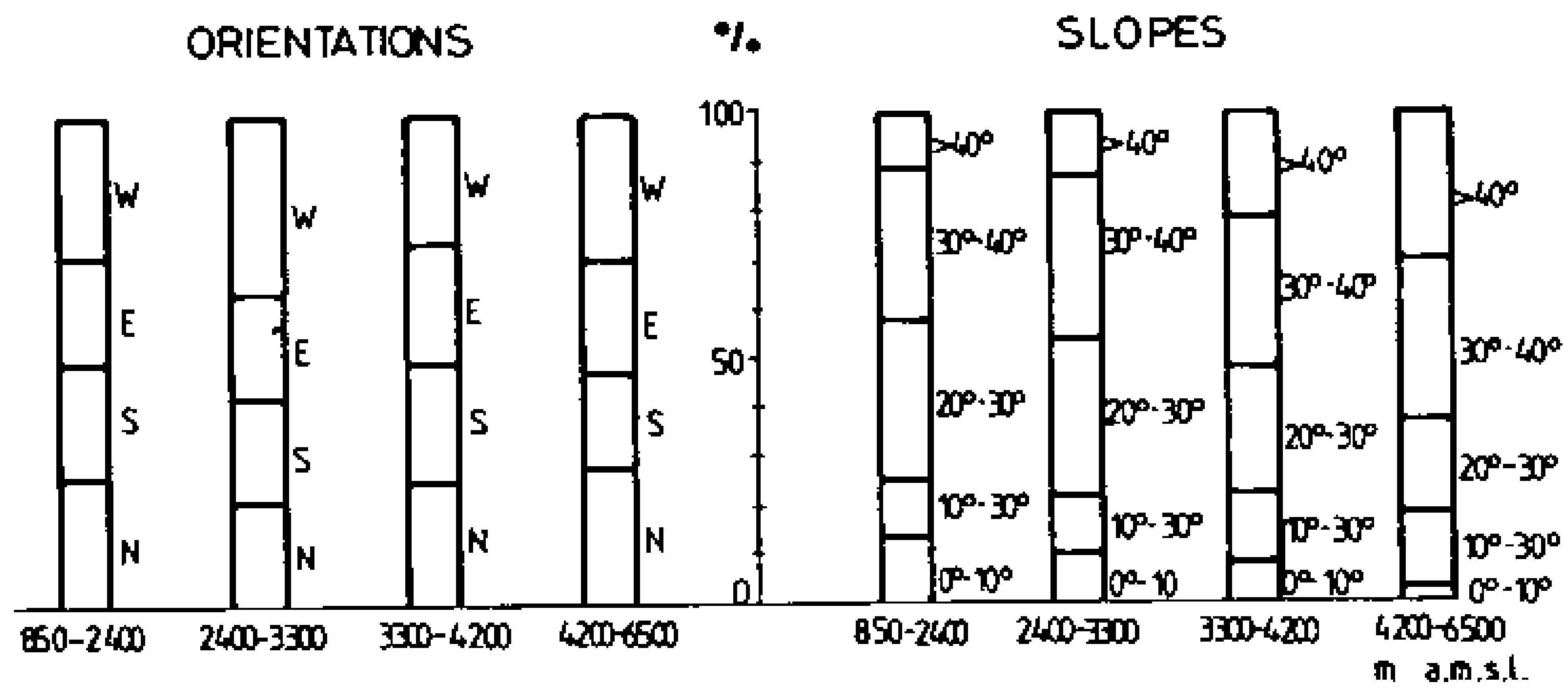

FIG. 3 Frequency distribution of orientations and slopes in the Maipo basin

SNOWMELT-RUNOFF MODEL

Model basis

The model was developed with a daily time step. Glacierized and non-glacierized areas are simulated separately. The spatial structure of the model defines elevation bands and also homogeneous surfaces in relation to orientation and slope. For that purpose, a frequency distribution of orientations and slopes is used (Fig. 3). This structure attempts to simulate the irregularities of the snow cover distribution, particularly during the summer. Accumulation, ripening and melting processes of the snowpack, ice-melting processes as well as the runoff processes up to the application of the storage functions, are simulated in each of these units.

Accumulation

The precipitation at any elevation band is calculated from the observed data at a base meteorological station through the use of an altitude distribution function. In order to derive this distribution function, a relative precipitation, p, was defined as the ratio between the precipitation of the band, or that measured from a meteorological station, at any period of time, and the mean annual precipitation for a thirty year period in the same band or meteorological station. For that purpose, a mean isohyet map, deduced from hydrological balances, was available.

In this way, the daily precipitation in the band is obtained from one of the following two methods:

a) The relative precipitation, p, at the base meteorological station and in the band are assumed to be the same.

b) The relative precipitation, p, at different meteorological stations and snow courses are used to define a relationship between p and elevation for different periods. The p in the band is calculated from these relations.

The model considers homogeneous precipitation within each elevation band, independent of the surface orientation and slope. Nevertheless, the model assumes that snow falling on high slope surfaces (>40°) is redistributed by gravity or wind over the rest of the area of that band.

Melting processes

In the model, the snowpack is represented basically as an energy and water storage unit, defined by its temperature and water equivalent which are subject to mass and heat exchanges with the environment. The energy supplies increase the snow temperature, until the mean temperature of the snowpack gets to 0°C, at which point melting occurs with any additional energy input. In temperate glaciers, on the bare-ice surfaces, ice always melts with any net energy contribution.

Daily heat exchanges over the snow or ice are represented by the following simple expressions (Pena *et al.*, 1985):

$$M = 4.89 + 0.0768\ Q_{NT} + 1.10\ T_a + 0.0125\ P\ T_a \qquad (1)$$

where: M is snowmelt (mm)

T_a is air temperature (°C)

Q_{NT} is net radiation balance (ly)

P is precipitation (mm)

During the periods that the temperature of the snowpack was below freezing, this expression was used, changing the variable T_a to $(T_a - CT_s)$, where C is a model parameter and T_s is the mean temperature of the snowpack.

Detailed measurements taken during summer field campaigns on glaciers located between 3750 and 4600 m a.m.s.l., were used to develop this expression. Also, this formula was verified on periods of several days during spring and summer, with data obtained between 2100 and 4140 m a.m.s.l. It is necessary to note that other meteorological variables, such as vapour pressure and wind velocity, do not improve the results. Besides, several formulae used in other mountainous regions of the world were tested with the same data set, resulting in great discrepancies compared to measured ablation.

The daily net radiation balance is estimated by the following expression (Pena *et al.*, 1984):

$$Q_{NT} = (1-\alpha)\ F_{t,\beta,Z,\psi}\ R_I + (0.59\ \sigma T_{Ka}^4 - \sigma T_{Ks}^4)\ (1-0.68\ N) \qquad (2)$$

where: α is albedo
R_i: incoming solar radiation (ly)
$F_{t,\beta,Z,\psi}$ is a function of the date of the year (t), slope (β), orientation (Z) and percentage of sky radiation to global radiation (ψ)
σ is the Stefan-Boltzmann constant (ly • $°K^{-4}$ day^{-1})
T_{Ka} and T_{Ks} are air and snow temperatures (°K)
N is cloud amount (tenths)

The function $F_{t,\beta,Z,\psi}$ corrects for the incoming solar radiation by geometrical relations, to take into account the surface exposure and slope.

A measured set of ablation data at Echaurren glacier was utilized to validate this procedure under different exposures and slopes. Although the results were acceptable, new validations under other conditions would be useful.

The albedo of the snow is calculated as a logarithmic function of the age of the surface snow layer, generated from the albedoes measured in the region. To apply that function, the model labels in a simple way, any snow layer corresponding to each day's precipitation. Thus, the different snow rates generate a spatial variation of the albedo. The aim of this formulation is to represent the effect of summer storms, which change the albedo while the fresh snow remains.

In order to compute the water balance of the snowpack, the sublimation of the snow was estimated multiplying by a constant value, the pan evaporation at a base station. This factor was calibrated based on daily heat balances of the snow. Changes in the pan evaporation with altitude were not considered.

Runoff model

The runoff model used in snow covered areas is based on the UBC model (Pipes & Quick, 1977), with minor changes. According to this model, four routing elements are defined, whose inputs are controlled by the soil moisture deficit. To simplify the model calibration, only single linear reservoirs were used instead of a cascade of reservoirs as in the UBC model. In glacierized areas, water originating from snow or ice melting is assumed to be divided into specifiable fractions which go to two single linear storage components.

APPLICATION TO THE MAIPO BASIN

The proposed model was applied to simulate the discharges measured at the hydrometric station El Manzano, at 850 m a.m.s.l., near the outlet of the mountainous area of the Maipo River.

Meteorological and snow course data utilized are shown in Figs. 1 and 2 and they correspond to sets of regular data measurements.

Nevertheless, it was necessary to derive some information through correlation procedures.

The model was calibrated on the basis of a continuous simulation, using elevation bands of 250 m and data obtained during the hydrological year 1984/1985, from April to March, which corresponds to an average hydrological year. Further, with the defined values of the parameters, a validation utilizing the years 1981/1982, 1982/1983 and 1985/1986, was done; 1981/1982 and 1985/1986 were dry years and 1982/1983 was an exceptionally rainy year. Data for the year 1983/1984 were not available.

RESULTS

The criterion for testing the efficiency of the model, R^2 (Nash & Sutcliffe, 1970), was used to assess the model performance. This is defined on the basis of the sum of squares of the residuals between measured and simulated discharge (F^2) compared with initial variance of the discharge ($F_o{}^2$) compared with initial variance of the discharge ($F_o{}^2$), as the expression:

$$R^2 = \frac{F_o{}^2 - F^2}{F_o{}^2} \qquad (3)$$

Table 1 shows the values of R^2 and $F_o{}^2$ over each annual and melting period (October-March). What is noteworthy is that the values from different periods cannot be compared because of the dependence of R^2 on the variance. The low value of R^2 for the melting period of 1981/1982, which had a very flat discharge, partially reflects this fact. In order to show the performance of the model, two snowmelt hydrographs, one for a dry year (1981/1982) and another for a rainy year (1982/1983), are included in Fig. 4.

Only minor changes were made in the relative precipitation computed from the base meteorological station, p, located at 1195 m a.m.s.l., to be used in the different bands. In this way, according to the performance of the model, a general spatial correlation of the precipitation is confirmed. Nevertheless, some differences associated with changes in precipitation gradients and spatial variability in a particular year, such as in 1981/1982, are observed. Thus, to improve the performance of the model, a more detailed formulation and new precipitation data from high elevations are needed.

The lack of data made validation of the intermediate variables very difficult. For that purpose, it was possible to compare sporadic observations of snow line variation and the evolution of the snowpack at snow courses with that generated by the model. In general, as can be seen in Figs. 5 and 6, the results show an acceptable agreement, although some discrepancies in snow accumulation and melting are detected in dry years.

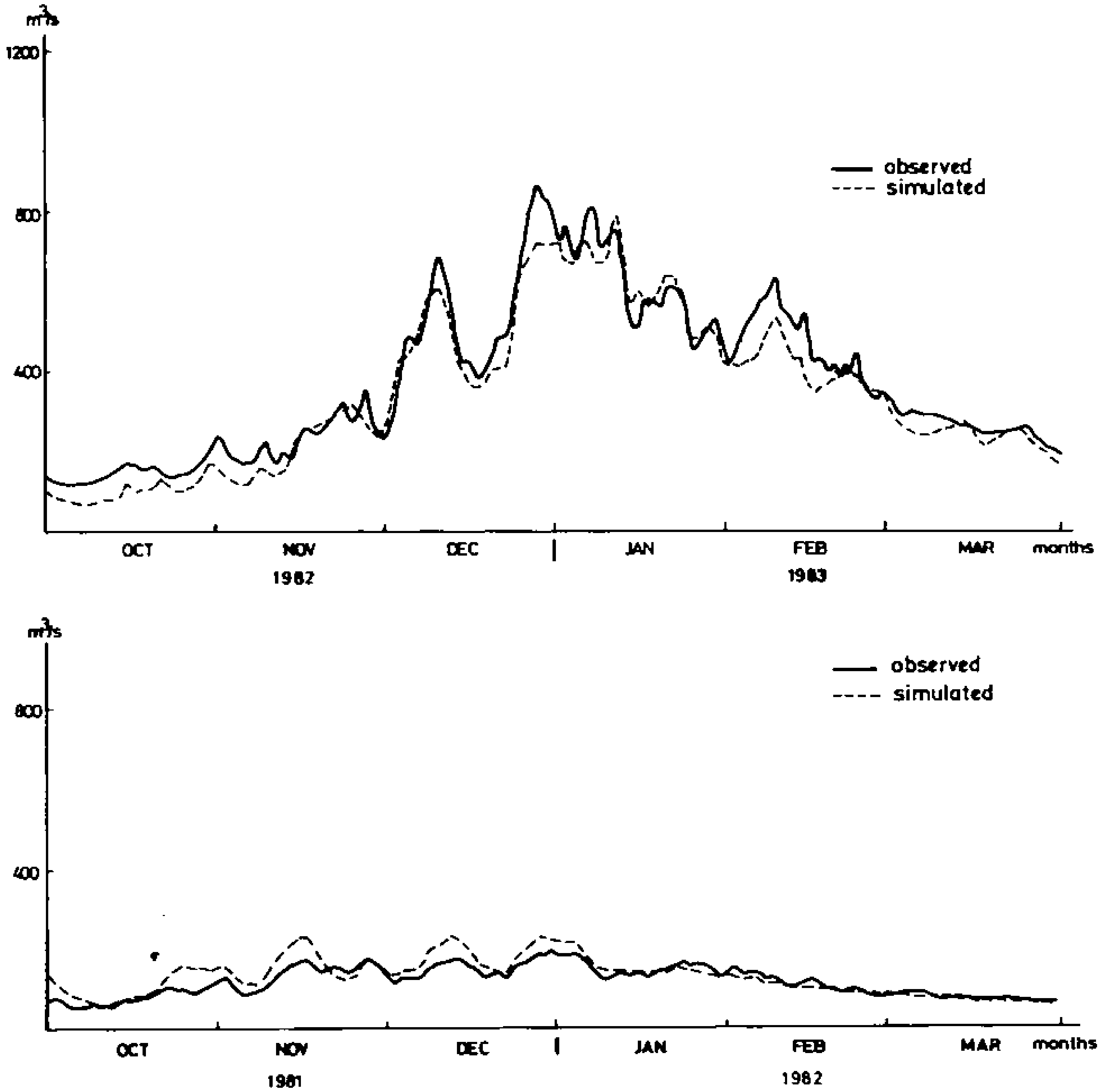

FIG. 4 Snowmelt hydrographs observed and simulated in two selected years

The influence of the spatial structure of the model has been analyzed, simulating two different situations with the same values of the parameters used in the calibration:

a) All the surfaces were assumed to be horizontal

b) Snow falling on high slope surfaces (> 40°) was not redistributed over the rest of the area of the same band.

The results of these simulations are presented in Fig. 7, based on the mean monthly discharge for the four years analyzed. These results show an increase in the runoff, particularly in late spring, due to a more efficient use of incoming solar radiation by the different snow covered runoff generation areas. During summer, the runoff may even decrease in dry years.

TABLE 1 Performance of the model (calibration and verification periods)

Period	1981/1982		1982/1983		1984/1985		1985/1986	
	F_o^2	R^2	F_o^2	R^2	F_o^2	R^2	F_o^2	R^2
Annual Period	160	0.63	4510	0.91	1139	0.93	288	0.85
Snowmelt Period	79	0.57	2154	0.93	484	0.87	147	0.73

Note: F_o^2 *expressed in* $(mm\ day^{-1})^2$

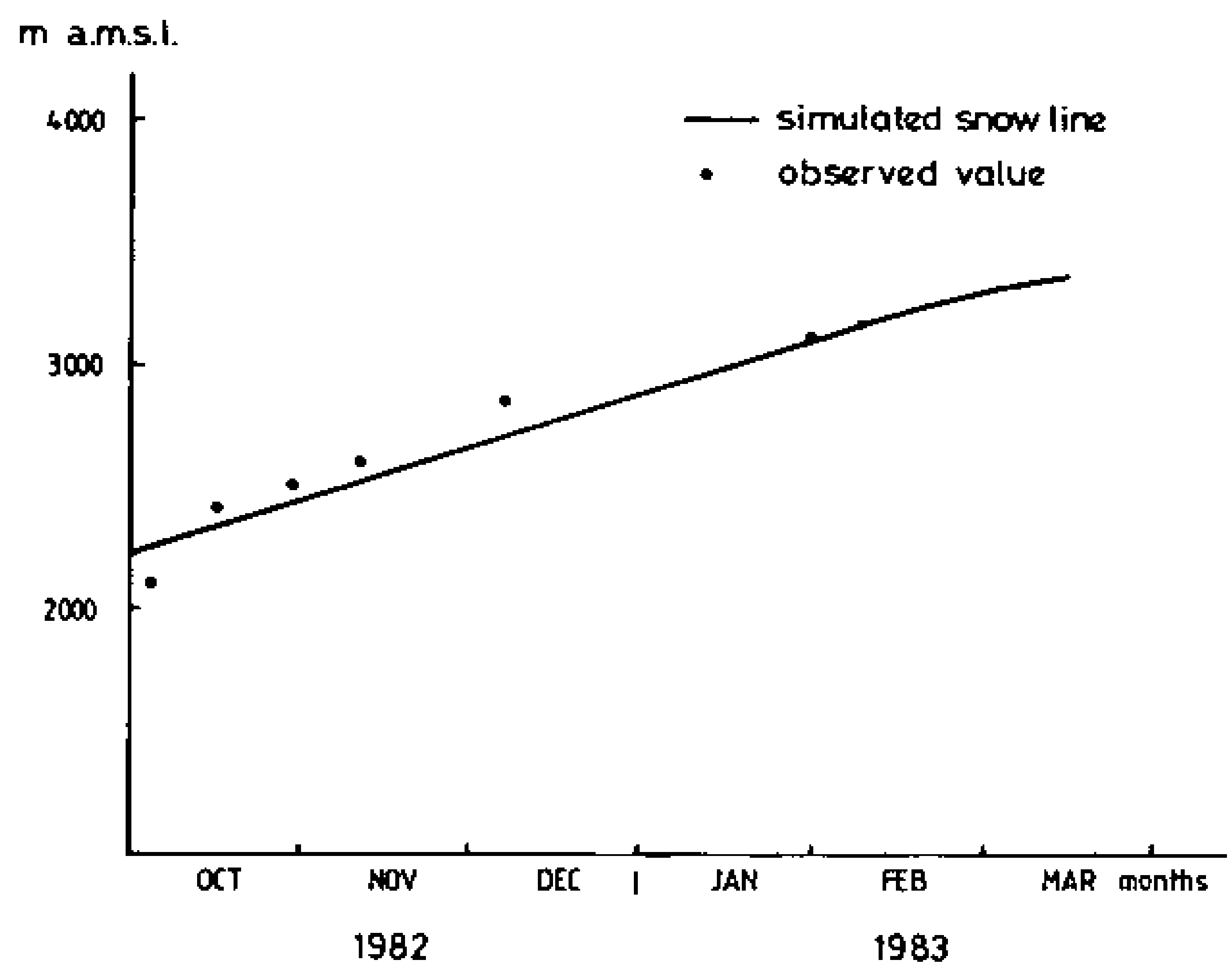

FIG. 5 Snow line variation during the snowmelt period 1982-1983

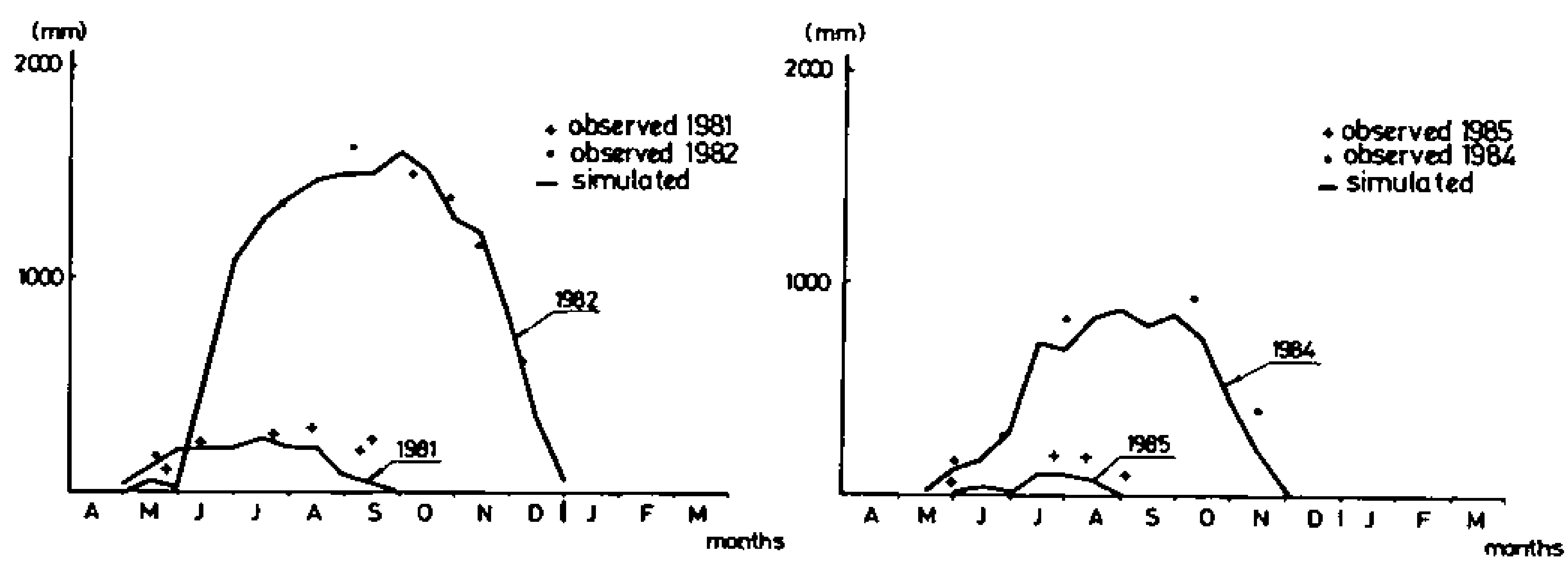

FIG. 6 Snow accumulation at the snow course of Laguna Negra (2700 m a.m.s.l.)

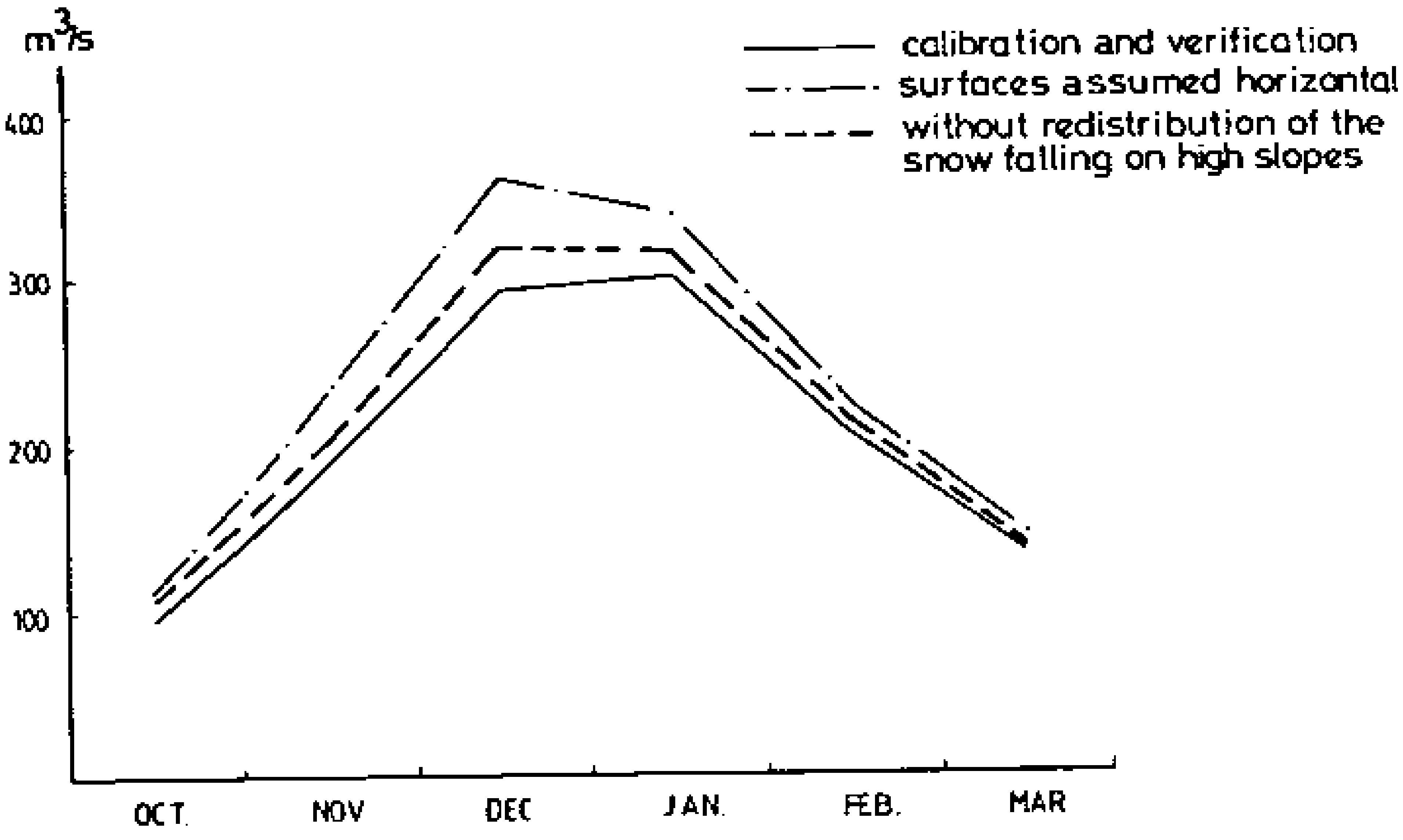

FIG. 7 Influence of the spatial structure of the model. Mean monthly discharges

The assumption of the model concerning the redistribution of the snow falling on high slope surfaces over other areas of the same band was tested by making simulations that assumed that the snow was redistributed over areas of the next lower band and, in another run, over areas of the second lower band. As is shown in Table 2, in the first case the performance of the model is marginally better in 3 years, but is worse in the other (1981/1982). In the second case, the agreement is not quite as good. According to these results, a longer period of simulation is needed to select the best assumption in this respect.

TABLE 2 Influence of the redistribution of snow falling on high slope surfaces over areas of different bands

	1981/1982 R^2	1982/1983 R^2	1984/1985 R^2	1985/1986 R^2
Calibration and verification (same band)	0.57	0.93	0.87	0.73
next lower band	0.44	0.94	0.88	0.75
second lower band	0.36	0.95	0.86	0.70

As it was assumed, the application of the model suggests that precipitation cannot increase above a certain elevation (4000 m a. m.s.l.) or an unbalanced state of the snow storage at high elevations occurs.

The role of semi-perennial snow covered areas, according to the model results, is important. As is shown in Table 3, snow remaining at the end of dry years is negligible, but in rainy years can be very significant. For example, the snow storage at the end of the 1982/1983 melting period represents 34% of the snow accumulated at the beginning of the melt period and 74% of the mean annual precipitation over the basin.

TABLE 3 Snow storage over the basin, at the beginning and the end of snowmelting periods (mm)

	1981/1982	*1982/1983*	*1984/1985*	*1985/1986*
October 1	*410*	*2300*	*1050*	*279*
March 15	*10*	*760*	*128*	*75*

In accordance with the results of the model, the role of glaciers can be appraised from Table 4. From those values it can be concluded that even though runoff from glaciers is small in relation to total discharge, their contribution is significant during dry years at the end of the summer period (34% in February 1982). It is important to emphasize that this runoff from the glaciers represents up to 67% of the monthly discharge measured during the driest summer recorded on the Maipo River (1968/1969).

TABLE 4 Monthly discharge from glaciers, as a percentage of the total discharge (%)

Year	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*
1981/1982	*5*	*9*	*17*	*28*	*34*	*30*
1982/1983	*0*	*2*	*4*	*6*	*5*	*6*
1984/1985	*1*	*2*	*4*	*7*	*12*	*15*
1985/1986	*3*	*8*	*17*	*23*	*25*	*25*

ACKNOWLEDGEMENTS This work has been carried out as part of the studies developed by the Dirección General de Aguas of Chile.

REFERENCES

Luna, R & Stowhas, L. (1983) Determinación de la tasa de derretimiento máxima probable en un manto de nieve. *Anales VI Congreso Nacional Sociedad Chilena de Ingeniería Hidráulica.* Santiago, Chile.

Nash, J.E. & Sutcliffe, J.V. (1970) River flow forecasting through conceptual models. Part I A discussion of principles. *J. Hydrol.* 10(3), 282-290.

Peña, H., Vidal, F. & Salazar, C. (1984) Balance radiativo del manto de nieve en la alta Cordillera de Santiago. *Anales Jornadas de Hidrologia de Nieves y Hielos en América del Sur.* Santiago, Chile.

Peña, H., Vidal, F. & Escobar, F. (1985) Estimación de tasas de derretimiento de nieves. *Anales VII Congreso Nacional Sociedad Chilena de Ingenieria Hidráulica.* Concepción, Chile.

Pipes, A. & Quick, M. (1977) *UBC Watershed model.* Users manual. Vancouver, Canada.