Hydrological Sciences Journal

ISSN: 0303-6936 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/thsj19

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Hydrological Sciences–Bulletin–des Sciences Hydrologiques, 26, 4, 12/1981

Problems of modelling a high mountainous drainage basin with predominant snow yields

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ABSTRACT This paper describes and compares various approaches to modelling a high mountain basin with dominant snow yields. Three different conceptual models were thus applied to the same test basin over the same test periods, and with identical calibration: (a) one specially developed for the given basin, using a refined description of the physiographic features and including a snowmelt routine based on energy budgets at 12 h intervals; (b) a general purpose hydrological model (HSP model), partially standardized and applied to the basin considered following the users' manual; (c) an intermediate model, much like the HSP model except for the snowmelt routine. Conclusions have been drawn about the structure of models such as the usefulness of introducing some routines far more sophisticated than those of the average model, but mostly about estimations of missing input data required by the model. Some variables such as thermometric gradients or spatial distribution of precipitation are much more crucial than the possible choices between different approaches for modelling evapotranspiration and even snowmelt.

<u>Problèmes de la mise en modèle d'un bassin versant de haute montagne avec prédominance de la fonte des neiges</u>

RESUME Cet article décrit et compare diverses variantes dans la modélisation déterministe d'un bassin versant de haute montagne où l'apport nival est dominant. Pour cela, trois modèles conceptuels ont été employés: (a) un modèle spécialement mis au point pour ce bassin, utilisant une description détaillée et une procédure de fonte de neige par bilans énergétiques sur 12 h; (b) un modèle à vocation générale (modèle HSP), relativement standardisé et appliqué au bassin considéré en suivant le manuel de l'utilisateur; (c) un modèle intermédiaire, reprenant l'essentiel du précédent (HSP) sauf pour la partie neige. Les conclusions portent sur la structure des modèles, en particulier l'inutilité d'introduire dans certaines parties un degré de sophistication par trop supérieur au raffinement moyen du modèle et surtout sur les

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estimations des données nécessaires aux modèles. Ainsi, des variables comme les gradients thermométriques ou la distribution spatiale des précipitations apparaissent bien plus critiques que le choix entre les différentes formules d'évapotranspiration ou de fonte de neige.

INTRODUCTION

In a previous paper, Obled & Rossé (1977) described the development of various snowpack formation and snowmelt models. The concern for maximum control of all the input and output of this hydrological cycle subsystem had then limited the application of these models to well-equipped experimental lysimetric sites. The conclusions were as follows:

(a) It is useful to simulate, even in a simplified way, the thermal state of the snowpack and particularly the surface temperature.

(b) Simulations which can use time intervals of 1-3 h and space intervals of 10-30 cm inside the snowpack with the upper 5-10 cm layer being treated separately are satisfactory.

(c) A simplified model, which uses 12 h time intervals (i.e. daytime and night-time) and which separates only the surface layer from the snowpack considered as a whole, still provides reasonably good results.

The next step was to extend this simplified model to a high mountain drainage basin for the entire hydrological cycle. At that time, the main purpose was to determine whether this energy balance approach was worthwhile.

Two possible alternatives, i.e. formulating a complete drainage basin model or using an existing one, were tried and compared. Charbonneau (1974), therefore, built a mathematical model (Durance model) adapted to high mountain basins, capable of taking into account a rough topography and simulating snow thermal exchanges properly; while the latter course was taken by Lardeau (1977) who chose the well known HSP model of Hydrocomp (Crawford *et al.*, 1975), enjoying a long experience with snow covered basins.

These models were built on different snowmelt hypotheses as well as on different hypotheses covering the remainder of the hydrological cycle: the different results could not be assigned to either of those hypotheses without some degree of uncertainty.

To explain these different results and to understand the particular role of the snowmelt routine, the original HSP was considered as a reference and a third model was introduced, the modified HSP, the characteristics of which were that it shared the same snowmelt hypotheses as the Durance model, but the same ones covering the remainder of the hydrological cycle as the original HSP model.

DESCRIPTION OF THE DRAINAGE BASIN

Physical characteristics

The drainage basin chosen was on the Durance River in the French Alps (Fig. 1). The outlet of the basin is located at La Clapière

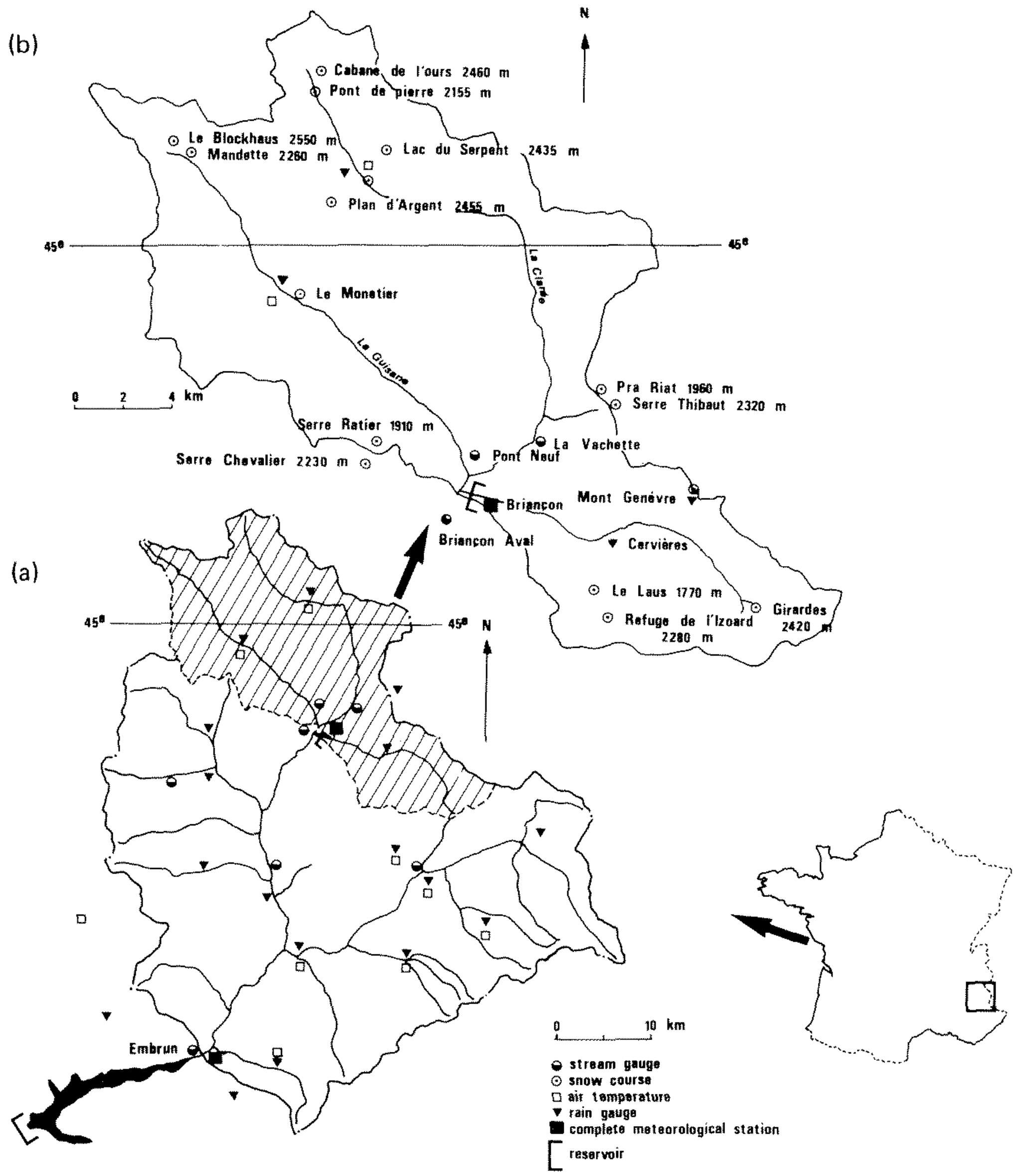

Fig. 1 Maps of the basins considered with the available network of measuring stations: (a) complete basin; (b) test basin.

(elevation 786 m, area 2170 km^2), just at the entrance of the Serre Ponçon Reservoir. This basin is referred to as "the complete basin" throughout this paper.

However, to reduce computer time and preparation of meteorological data, the basin used for comparisons was limited to the Briançon Aval flow measuring station (elevation 1187 m, basin area 548 km^2) and is called the test basin.

The test basin reaches an elevation of 3663 m, and glaciers cover some 12 km^2 of it. The dominant hydrological phenomenon is snowmelt which usually starts in March in the lower part of the basin, but starts later at higher altitudes. In addition, the Mediterranean climate is responsible for high insolation and relatively sparse vegetation (Fig. 2).

The three deep valleys running through this mountainous region are oriented northwest-southeast; the steep mountain slopes are not very permeable. The valley floors rest on thick layers of sediment and

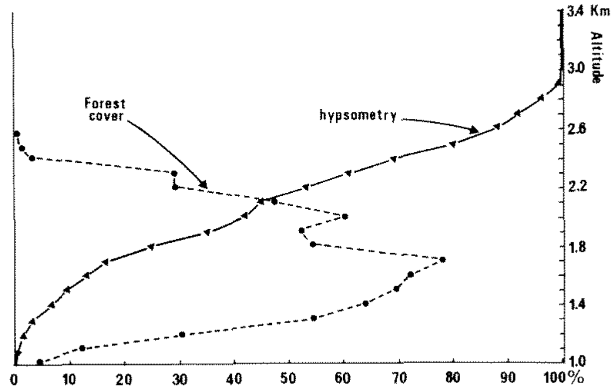

Fig. 2 Hypsometric curve and distribution of forest with elevation for the complete basin.

huge accumulations of moraine allow the surface runoff to reach groundwater levels.

Although the rivers experience their greatest flows during the snowmelt period and relatively low flows during winter, it is not unusual to have a few floods caused by rainstorms in autumn. These are difficult to predict, since a slight decrease in temperature transforms rain into snow on most of the basin, so calibration efforts were mainly devoted to the snowmelt period.

Measuring sites

Of the 21 precipitation stations available on or within the immediate vicinity of the complete basin, 19 give daily recordings and 2 record hourly. It should be noted, however, that the stations are generally located on the valley floors. The highest (St Veran, elevation 2040 m) sits just above the mean elevation of the basin which accounts for the fact that meteorological conditions in the higher part of this basin are not well known. There are also 14 temperature stations available, but none of these are located in the higher half of the basin. A number of snow surveys are carried out every winter until the end of the accumulation period and were used only to check the snow amounts according to the models. As the Briançon recording station rests on a fairly well protected site, wind measurement data from the Embrun station (located outside the test basin) were the only ones used. These readings, however, were somewhat unrepresentative of the wind over the basin due to the fact that wind velocity generally increases with altitude, also during calm weather local phenomena such as valley winds can upset the standard pattern.

The test basin has three flow measuring points:

	Drainage basin area (km^2)	*Outlet altitude (m)*
La Vachette	210	1351
Pont Neuf	201	1206
Briançon Aval	548	1187

Discharge at the Briançon Aval station is subject to human interference. A reservoir on the Cerveyrette tributary is filled once a week to supply the town of Briançon; this explains the pattern breaks in the hydrographs presented later.

COMPARISON OF MODELS

Snowmelt models may be compared at three levels: the first involves the description of the physiographic features of the area (square grid system or sub-basin) and their nature (topography, vegetation, soil types, hydrographic network, etc.); the second level is the choice of an algorithm to represent the snowmelt process (degree-days or a more sophisticated snowmelt routine); the third level deals with estimating missing data and spatial extrapolation of point-measured variables.

Description of the physiographic features

The Durance model was developed especially for the Durance basin where precipitation occurs mostly in the form of snow. Each sub-basin was divided into segments of nearly uniform exposure and slope, and each segment was further divided into three elevation bands corresponding to the farming, forest, pasture or rock zones (Fig. 3(a)). The wooded part of each band was submitted to a heat budget

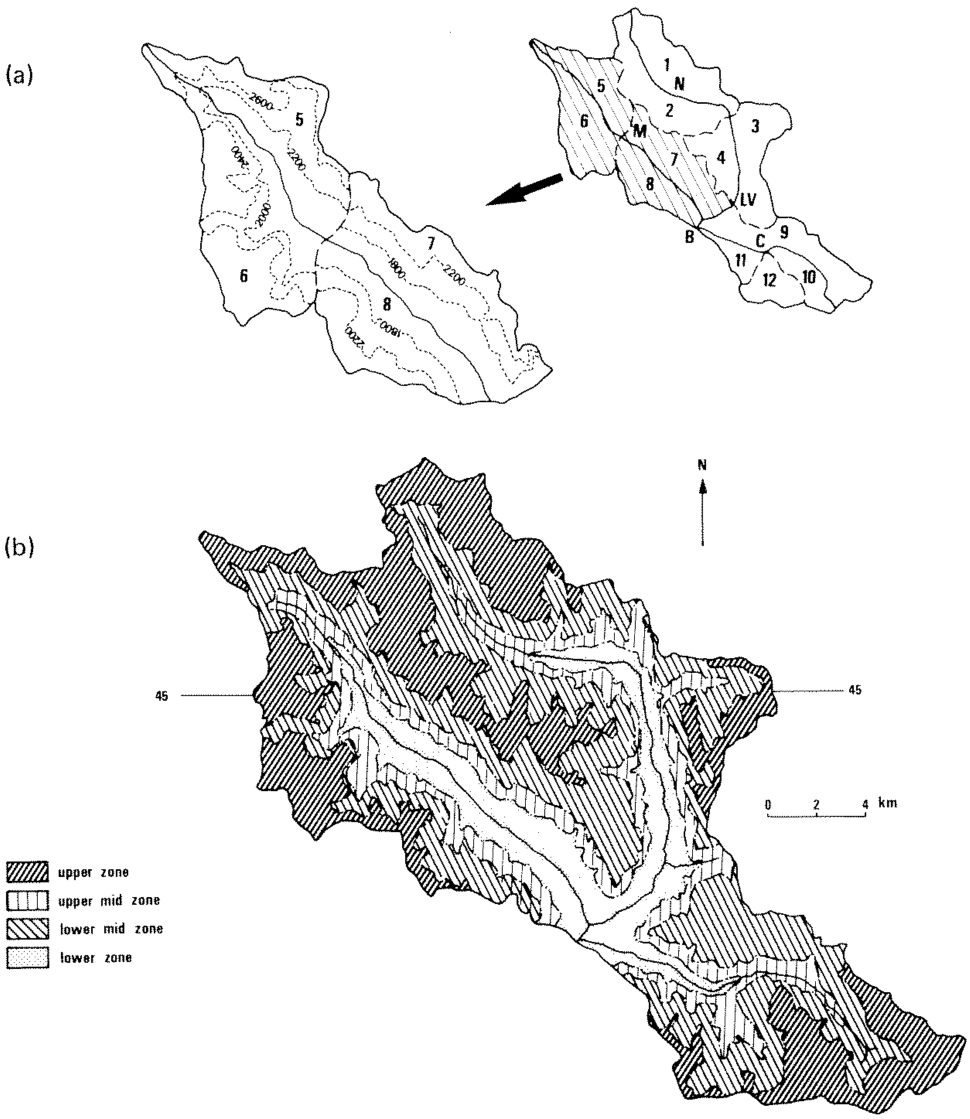

Fig. 3 Subdivision of the test basin: (a) for the Durance model (12 segments divided into three altitude zones as shown for the segments 5-8); (b) for the HSP model (four segments).

different from the one used for the treeless part.

For each segment, the depth of water available per unit of time was calculated by combining the depths provided by the three elevation bands; this water was assigned directly to the hydrographic system, without considering possible lateral water exchange between bands.

The segments of the HSP model were chosen as areas sharing the same hydrological characteristics but not necessarily coinciding with a sub-basin. The computed water available for routing was then distributed among the sub-basins according to their surface within the segment. The variety of slope and exposure, therefore, is not represented here in order to reduce computer time due to complexity of HSP's production phase (Fig. 3(b)).

It should also be noted that the connection to the hydrographic network is slightly artificial. In particular, a portion of surface or delayed runoff actually moves first towards the segment immediately below (Stephenson & Freeze, 1974) and not directly to the river as HSP assumes.

Choice of algorithm to represent the snowmelt process

The Durance model The flowchart of the hydrological cycle was inspired by the CEQUEAU model (Girard *et al.*, 1972; Charbonneau *et al.*, 1977). It was run on a 3 h basis while the snowmelt computations were processed on a 12 h time interval. A first approach was based on a melt factor method, although it was difficult to adjust deterministically because global radiation decreases with altitude much less than air temperature. It will not be discussed here. For the second one, Charbonneau adapted Obled & Rossé's (1977) simplified snowmelt version. The thermodynamic budget of the snowpack over an interval of 12 h requires the evaluation of the following five components: transfer of heat from rain, radiation, latent heat, convection heat transfer and heat conduction in snowpack, of which the last four terms are governed by the snow surface temperature. The 12 h computed snowmelt was then divided into four parts with consideration given to current weather conditions, i.e. fair, cloudy or rainy weather (Fig. 4). Before reaching the river network, meltwater experienced two lag times: (a) the first delay represents the flow through the snowpack, and three basic distributions were chosen (Table 1) according to snowpack thickness; (b) the second delay represents the overland flow and was assumed to be constant (3 h).

The HSP model The "lands" part of the hydrological cycle having been fully described by Crawford *et al.* (1975) we will limit ourselves to recalling his comment that the HSP model's concern for generality must not prevent it from being applicable to small, highly-urbanized basins. Therefore, the time interval can be as low as 5 min for surface runoff, while riverflow and infiltration are dealt with at fixed intervals of 15 min. The snowmelt, calculated at hourly intervals, is brought down to 15 min by simple division.

As for the Durance model, the snowmelt hypotheses are based on the Corps of Engineers (1956) *Snow Hydrology Report*, but may be subject to certain criticisms:

(a) In the calculation of the infrared radiation budget, air temperature is assumed to be around 0°C, and consequently a simplified

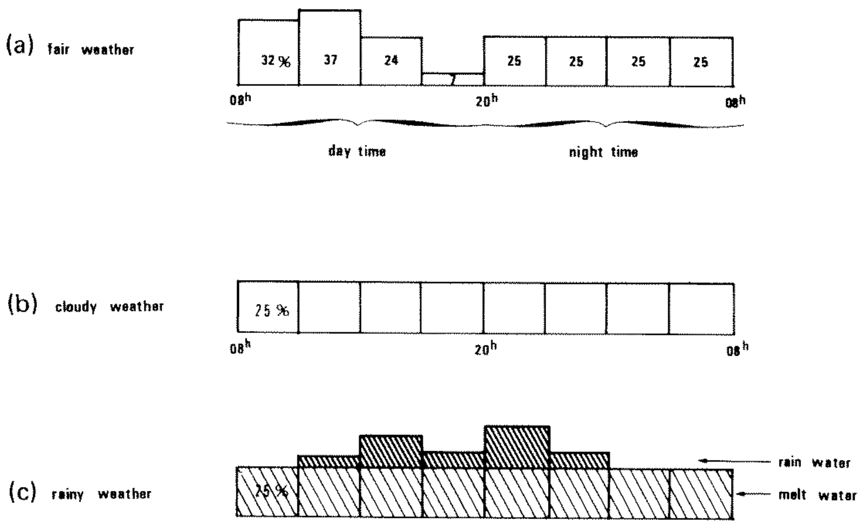

Fig. 4 Standard timing of surface melt for different weather situations (in % of the computed 12-h melt layer).

linear equation is used when estimating this component. Snow surface temperature, which governs the backradiation, does not appear explicitly since it is also assumed to be close to 0°C. Both assumptions are very often incorrect, especially at night, even in temperate climates. In addition to this, air temperature in a dense forest being slightly lower and fluctuating less than in treeless zones, each one of these should be given a separate heat budget evaluation (this was introduced in the modified HSP version).

(b) The *Snow Hydrology Report* formula for melt by convection-condensation has been modified so that snow temperature is equal to 0°C and vapour pressure to 6.1 mbars. In fact, vapour pressure e_{sat} is quite sensitive to snow surface temperatures t_s as can be seen:

t_s = 0°C e_{sat} = 6.11 mbars
-5°C 4.02 mbars
-10°C 2.60 mbars

so that the assumption is often in error.

(c) Snow evaporation is computed regardless of the snow surface temperature.

(d) In the computation of the cold content, the mean snowpack temperature is obtained by assuming a linear profile from air temperature at the top of the snowpack to 0°C at the base. In fact, cold content is determined by previous events and by the current surface temperature; it is not a simple function of the air temperature in the time interval.

Table 1 Percentage of surface melt delivered at the bottom of the snowpack during the next time interval of 3 h

	Time interval						
Snow depth	1	2	3	4	5	6	7
H < 500 mm	0.22	0.33	0.28	0.13	0.04		
500 < H < 1000 mm	0.19	0.30	0.26	0.16	0.06	0.03	
H > 1000 mm	0.16	0.26	0.25	0.16	0.10	0.06	0.01

Data estimation and extrapolation

Radiation In the Durance model, the division into segments was made according to slope and orientation, thus allowing a refined evaluation of the potential incoming radiation. A correcting factor was further introduced for shading effects due to the surrounding relief (which, at Briançon, can represent an average of 2 h less insolation per day over the year). In the HSP model, spatial extension is much less refined. The segments cover several types of orientation and slope, and the combined effects of these physical characteristics were taken into account by a single parameter. Thus, HSP requires for each 15 day period, an estimate of the potential radiation on the horizontal surface. This value is modulated on an hourly basis according to the cloud cover. The modified version of the HSP model used a statistical relationship to estimate total incident radiation from the duration of insolation and the daily amplitude of air temperature variation. The relationship was used to reconstruct the global radiation at Briançon for the simulation period (from 1965 to 1968).

Cloud cover For all the models, the areal cloud cover distribution over the basin was assumed to be uniform whereas, in fact, clouds are usually concentrated near the mountain peaks. However, when cloud cover data were not available as such, HSP reconstructed them from hourly precipitation to modulate the longwave atmospheric radiation.

Air temperatures Air temperatures are measured at a certain number of stations, so the problem is to extrapolate these values spatially. To do this, HSP utilizes a thermometric gradient that can vary from 0.6 to 0.9°C per 100 m, but cannot be modified by the user. This gradient changes during the day and reaches a maximum at about 3 p.m. These average gradient values are usually derived from the radio-sondage curves obtained in a free atmosphere with a clear horizon. The use of average gradient values in mountain basins is widespread in hydrological modelling, but may often be unrealistic. Another approach is used in the Durance model: each day a regression between temperatures (minimum and maximum separately) and station altitudes is determined from the readings at 14 stations in or near the basin. If the relationship is non-significant, an average gradient, usually small, is used instead of the regression equation. The correlation coefficients, averaged for each month, are given for the year 1965 (Fig. 5). It should be noted, however, that the statistical approach is still affected by the location of the stations (valley floor), and their variable exposure.

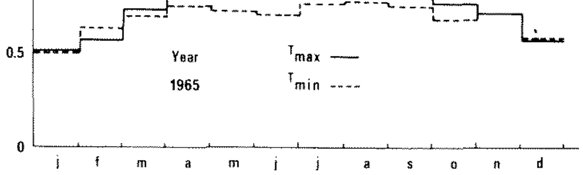

Fig. 5 Monthly averages of daily correlations between temperature and elevation.

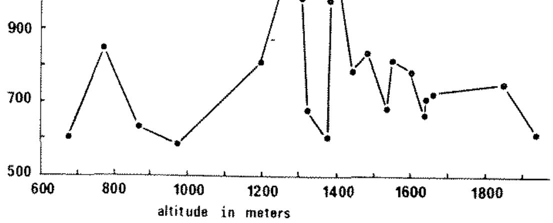

Fig. 6 Mean annual precipitation *vs.* elevation at 21 measurement sites in the complete basin.

Precipitation

(a) Effect of elevation and regional effects. An initial study (Charbonneau, 1974) showed that the relationship to altitude was not a simple one (cf. Fig. 6). Climatological analysis shows three distinct pluviometric regions in the Haute Durance basin with different means and the same precipitation lapse rate of about 1 mm m^{-1} $year^{-1}$. Orographic influences are considerable and are a function of the direction of the disturbance (see Fig. 7). For example, in 1967, the water equivalent during mid spring ranged from about 300 mm at Lac du Serpent, to 600 mm at Cabane de l'Ours, and up to 900 mm at Blockhaus, although these stations share similar altitudes and exposures. However in 1968 the differences were much lower. In the HSP model, those points belong to the same land surface segment, and therefore the parameters cannot be modified because they apply to the entire segment. In the more refined spatial division of the Durance model, each segment is associated with the nearest recording station, but this more expensive method does not always provide an adequate snow cover pattern which, in any case, is highly variable from year to year.

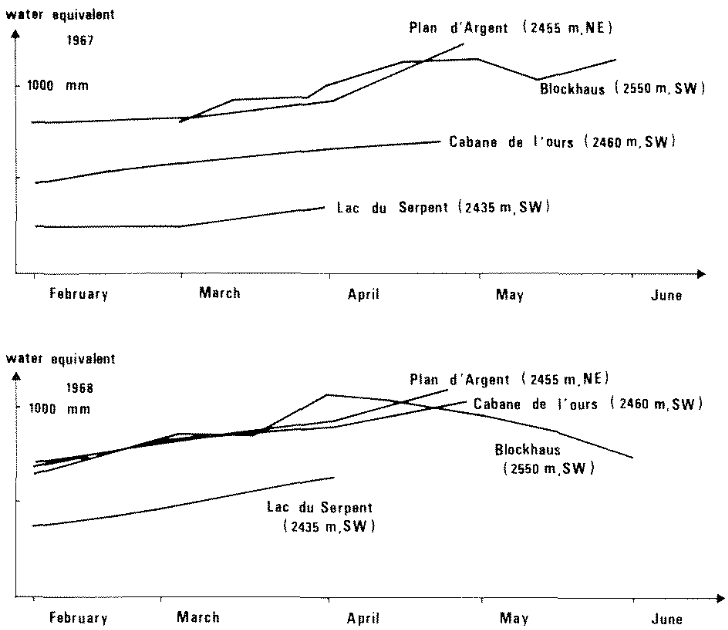

Fig. 7 Evolution of the seasonal snowpack in water equivalent at four locations with similar elevations.

(b) Nature of precipitation. The transition between rain and snow generally occurs between 0 and 2°C. The altitude of the 0°C isotherm is determined by air temperature gradient alone (Durance model) or combined with dew point temperature gradient (HSP) which are both of consequence mainly during spring and fall. If these gradients are erroneous (usually too large), liquid precipitation will be considered as snow and increased by the HSP's *snow correction factor* for raingauges when it snows, thus causing a water equivalent overestimation. Precipitation erroneously considered as snow also causes important secondary thermal effects: sudden increase of albedo, large amount of energy required to melt this precipitation, etc.

CALIBRATION OF MODELS AND RESULTS

It is not possible to describe in detail all the tests involved in order to adjust the models. With four years of data available, it was decided to use the last two years (1967 and 1968) to adjust the models and to test them during the other two years (1965 and 1966). The aim was to select two years which would be sufficiently different (the lean year 1967 and the surplus year 1968) for adjusting models under varied conditions. The simulation was begun on 1 October 1966, to avoid the problem of the initial values.

The quality of each simulation run was measured by four coefficients: the correlation coefficient between daily observed and

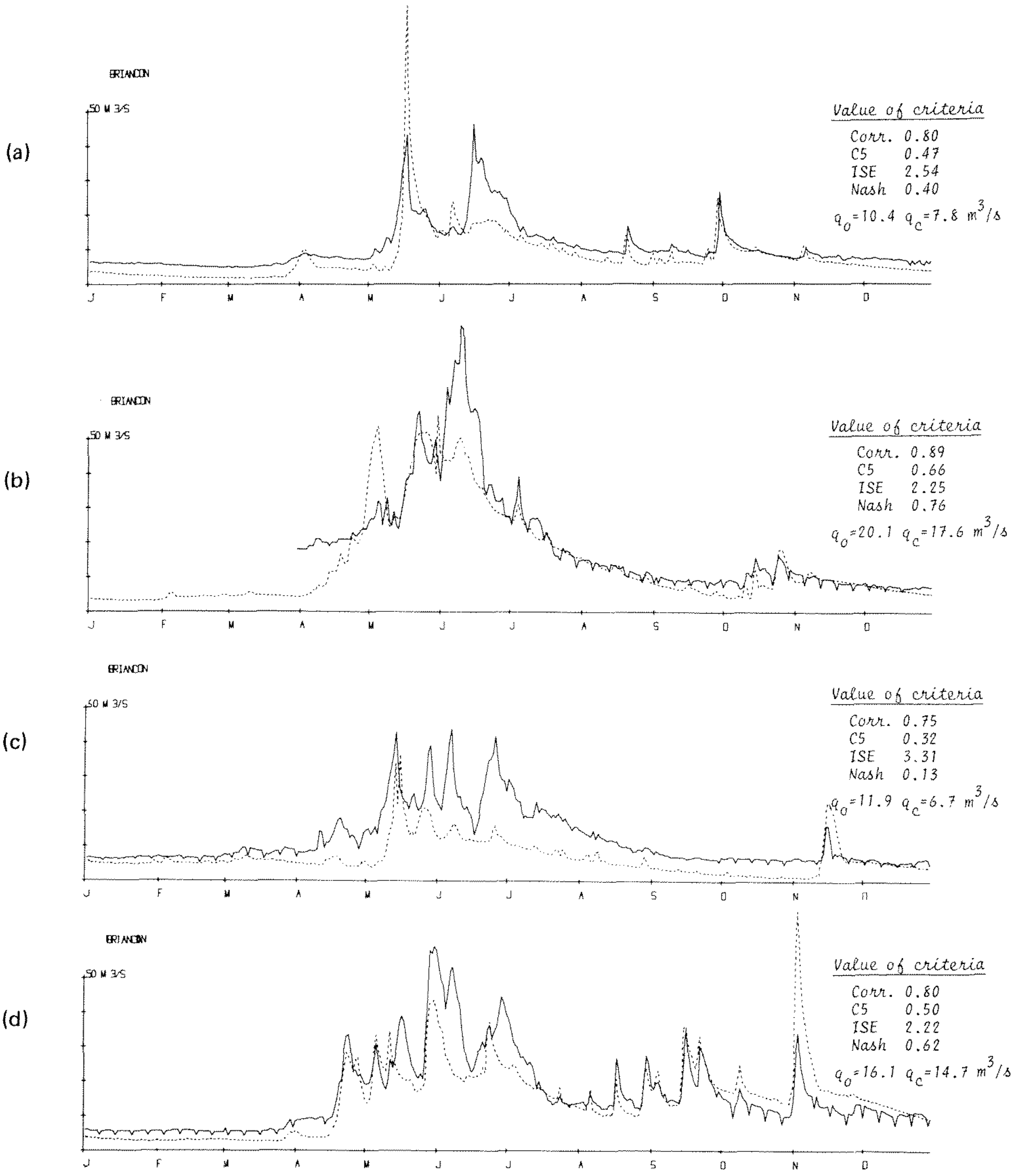

Fig. 8 Durance model: test periods (a) 1965, (b) 1966, calibration periods (c) 1967, (d) 1968.

computed flows, the relative error weighted for the departure from the mean (C5), the integral square error (ISE), and the Nash coefficient, as discussed by Fortin *et al.* (1971). The mean annual observed and computed flows $\bar{q}_O$ and $\bar{q}_C$ are also given in Figs 8-11.

The Durance model was initially adjusted on the complete basin using all the streamflow information such as the Briançon Aval data for example. So, the parameters were not modified when the simulations were restricted to the upper test basin only (Fig. 8). The original HSP model was the most carefully adjusted, using data from the test basin only (Fig. 10). Finally, the modified HSP was used with the same parameters used for the original HSP, except for the snowmelt component (Fig. 9).

In fact, it became obvious that the parameters Kl (ratio of average segment rainfall to average station rainfall) and SCF (snow

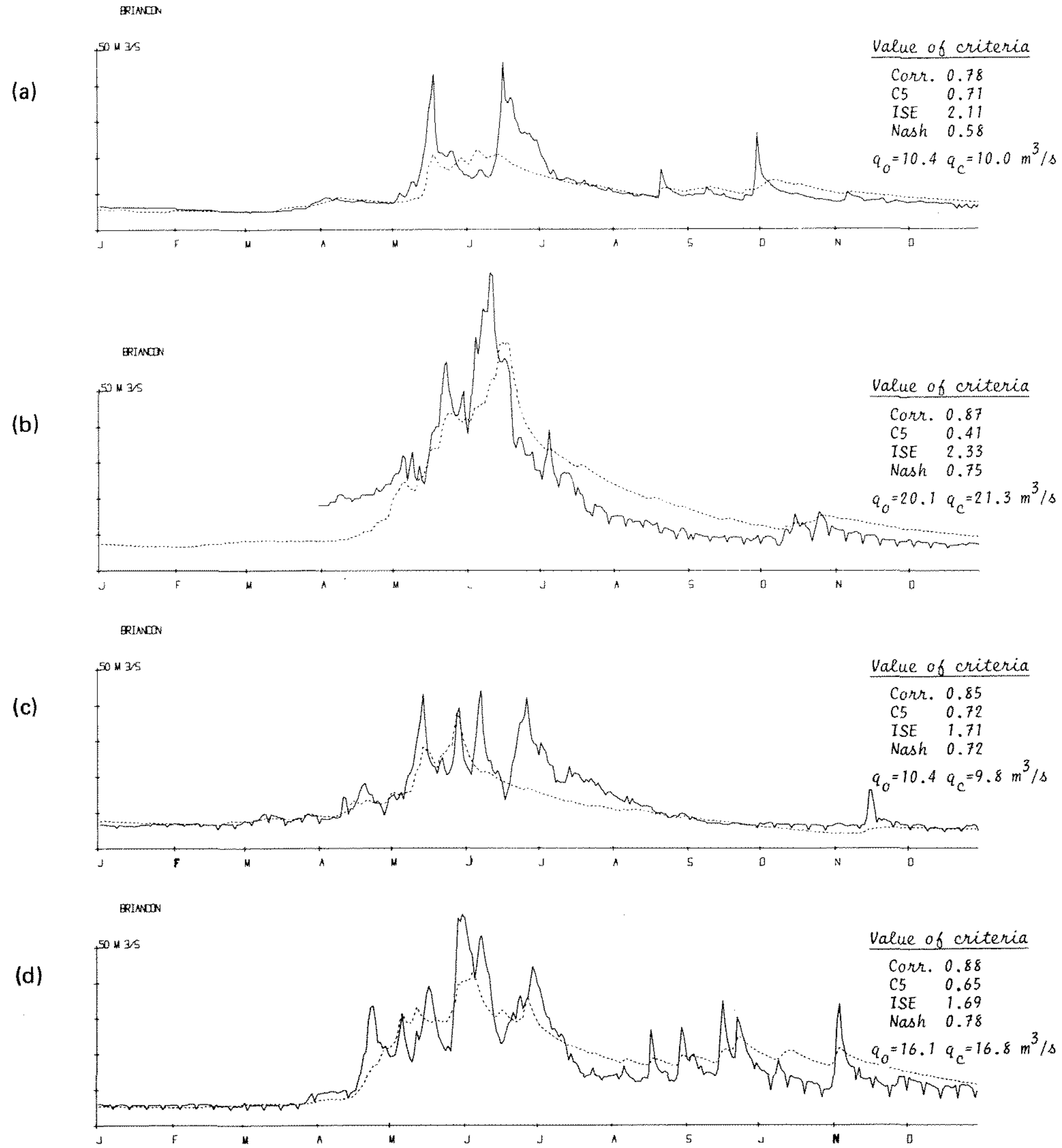

Fig. 9 Modified HSP model: test periods (a) 1965, (b) 1966; calibration periods (c) 1967, (d) 1968. (Same parameters as in Figs 10 and 11 except for the snowmelt routine).

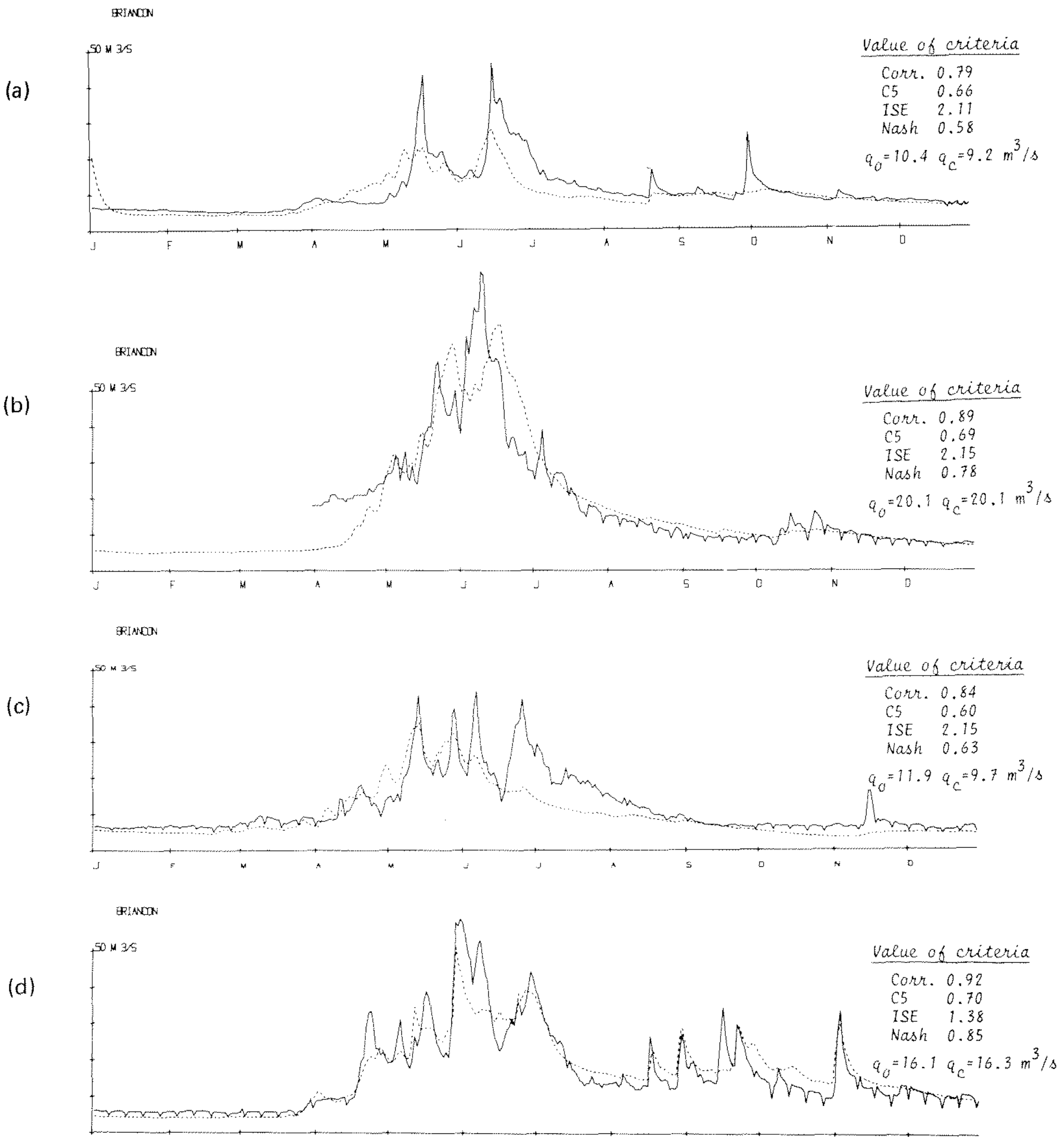

Fig. 10 Original HSP model: test periods (a) 1965, (b) 1966; calibration periods (c) 1967, (d) 1968 (*test 1*: parameters adjusted to fit the 1968 annual volume).

correction factor) were not stable from year to year, either for the Durance model or for HSP. This is illustrated in Figs 10 and 11: if one adjusts the original HSP to the 1968 data (Fig. 10(d)), 1966 is quite well simulated (Fig. 10(b)), while 1965 is deficient (Fig. 10(a)), and the 1967 forecast volume is strongly deficient (Fig. 10(c)). The opposite happens if the simulation run is adjusted to 1967 (HSP model, Fig. 11(a) to (d)).

The results from both the Durance model and the original HSP model show fairly rapid responses. The relatively delayed response produced by the modified HSP model could be due to the interpolation method which tends to calculate lower temperature data but assumes systematically higher (i.e. 0°C) surface temperatures. The original HSP model corrects this effect by assuming a systematically minimized

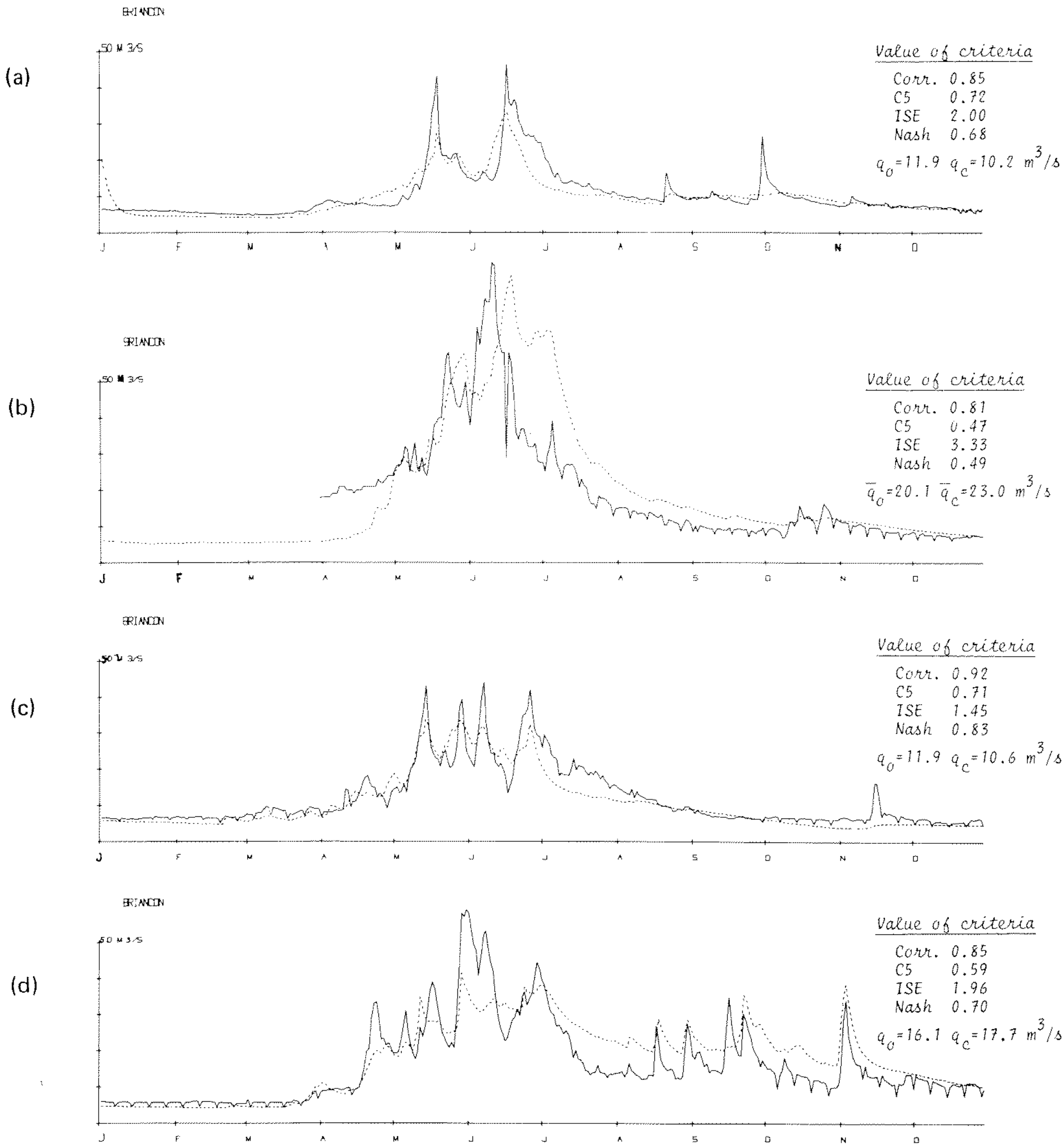

Fig. 11 Original HSP model: test periods (a) 1965, (b) 1966; calibration periods (c) 1967, (d) 1968 (*test 2*: parameters adjusted to fit the 1967 annual volume).

cold content factor, which the modified version could not.

Certain unrealistic assumptions of the HSP model do, however, occasionally alter some values of the parameters. For instance, snow evaporation is assumed proportional to the (e_a - e_{asat}) difference where e_a is vapour pressure of the air and e_{asat} is saturated vapour of the air, instead of the (e_a - e_s) difference used in energy budget models such as Anderson's (1976) where e_s is the vapour pressure at the snow temperature. It follows that in order to get realistic evaporation losses of about 10 to 30 mm per snow season, the value of the multiplier parameter EVAPSNOW expected to be close to 1.0 when following the instruction manual must be taken as 0.1.

Another major difficulty was the reconstruction of correct air temperatures with altitude since their great spatial variability is hard to handle in the models. Tables 2 and 3 show that for similar altitude ranges, the gradient of the maximum temperatures is much larger between Briançon and Névache than between Briançon and Le Monetier, the latter pair being in the same valley. Furthermore, the gradient computed by the HSP model (see example given in Table 4) is larger than any of those actually observed for maximum temperature values.

CONCLUSIONS

Model adjustments and comparisons based on data from a well-equipped mountain basin led us to the following conclusions regarding the data and model structures.

Basic data requirements

(a) The main shortcoming of the deterministic models tested was the conservation of the quantity of water entering the basin. It is essential that this volume be estimated accurately, but this is nearly impossible because the two usual parameters (pluviometer correction factor and snow correction factor) are completely inadequate and highly variable from one snowstorm to another. To counter this, we suggest a truly "objective analysis" of each important event. This would allow the use of all the information including any irregularly conducted snow surveys. However, the introduction of this operation in a model requires too much standardization of the data and prevents adaptation to overall

Table 2 Average thermometric gradients between Briançon (1324 m) and Le Monetier (1590 m)

Year	Average maximum: Briançon (°C)	Average maximum: Le Monetier (°C)	Gradient (°C/100 m)	Average minimum: Briançon	Average minimum: Le Monetier	Gradient (°C/100 m)
1965	12.295	12.140	0.09	0.720	−1.634	1.418
1966	12.987	12.504	0.29	1.827	−0.338	1.304
1967	13.896	13.626	0.16	2.201	−0.95	1.240
1968	12.738	12.586	0.09	1.785	−0.458	1.120

Table 3 Thermometric gradients between Briançon (1324 m) and Névache (1660 m)

Year	Average maximum: Briançon (°C)	Average maximum: Névache (°C)	Gradient (°C/100 m)	Average minimum: Briançon (°C)	Average minimum: Névache (°C)	Gradient (°C/100 m)
1965	12.295	9.950	0.640	0.720	−3.269	1.089
1966	12.987	10.401	0.706	1.827	−2.830	1.272
1967	13.896	11.473	0.662	2.201	−2.808	1.368
1968	12.738	10.060	0.731	1.785	−3.160	1.351

Table 4 Example of temperature extrapolation by the HSP model

Date in April 1968	Maximum temperature observed at Le Monetier (1490 m) (°C)	Temperature at 3 p.m. extrapolated by HSP for the upper segment no. 1 (average altitude 2600 m) (°C)
20	21	10.9
21	22	11.9
22	21	10.9
23	21	10.9
24	15	4.9
25	15	4.9

climatic conditions. It should be separate from the model itself and can be carried out deterministically (Rhea, 1977) or statistically (Chemerenko, 1974; Bras & Rodríguez-Iturbe, 1976), as currently done for initializing meteorological forecasting models.

(b) It is essential to have knowledge of the temperature profile above the basin for heat budget computations and for determination of the nature of precipitation. This curve varies with the type of weather and the time of day. Utilization of a "standard" synoptic curve is usually inconsistent with real mountain conditions.

(c) Local values of shortwave radiation are the easiest to reconstruct. Furthermore, theoretical derivations show that the effects of shade and orientation could locally modify the instantaneous heat budget for snowmelt by more than 100%. But to account for it in a model, a considerable computational effort and a fairly small subdivision of the basin are required. Although this has been achieved in the Durance model, results do not differ substantially from those of the HSP model which uses a much coarser subdivision. This unexpected conclusion is due to the smoothing effects when integrating over a varied topography and a sufficiently large time interval, and to the interaction between the different radiation components.

(d) The variation between values of potential radiation over a basin computed from different methods has less importance than the climatological changeableness of actual radiation caused by the presence of clouds. Even if local topographical effects may probably never be well represented, the cloud cover must be observed nevertheless because the longwave radiation budget is very sensitive to the presence of clouds.

(e) Wind data are important for snowmelt calculations; they have considerable effect during wet and unstable weather conditions. During calm weather, the situation is quite different and local phenomena may dominate. For example, when the wind velocity readings were multiplied by two, the simulation obtained showed a pronounced influence on flows: melting occurred earlier and weather phenomena such as condensation and convection were easily observable while annual volume diminished slightly, i.e. more evaporation. All these problems have been examined in more detail by Obled & Harder (1979).

Model structure evaluation

(a) Choosing between different models for a given part of the hydrological cycle is in itself questionable. For example, there is no point in using a sophisticated model for surface flow, seepage or evapotranspiration if this refinement will be upset by the uncertainty about temperature and humidity data. Similarly different approaches to modelling the channel flows had no marked effect on the daily values. These interactions between model components were particularly obvious when using a new snowmelt routine with the original HSP model.

(b) A greater refinement in describing the basin's topography multiplies the necessary subdivisions and becomes expensive later.

(c) With snowmelt models, the comparisons have shown the failure of degree-day methods when the weather is very variable and the topography rough.

(d) Due to uncertainties about the snow cover distribution and its water equivalent, the latter part of the snowmelt period may sometimes be omitted. Furthermore, there is no usefulness in employing a detailed model of the water's progress in the snow cover, over ground surface and even in the small river tributaries when concentration times are all less than a day.

This leads to the conclusion that it is difficult and costly to compare models. Moreover, an overall comparison does not indicate the relative validity of model components, as far as the snowmelt routine was concerned. Comparison between model components should preferably be done on experimental basins or basin segments where there is maximum control of input and output data (Obled & Rossé, 1977).

Results

(a) The Durance model responds quite well, which is a reason in favour of energy balance computations even if this model was calibrated for the complete basin.

(b) The original HSP model was subjected to the greatest number of tests and has the best four-year adjustment. This is partly explained by its large number of degrees of freedom.

(c) The modified HSP model kept all the parameter values used to run the HSP model, except for the snowmelt routine, and it did not seem to benefit as much as expected from the heat budget component. Nevertheless, this could be explained by the fact that this routine receives the air temperature values from the main program which has been shown to underestimate systematically the maximum temperature which influences the snowmelt.

As far as adaptability of ready-made models goes, they do avoid the formulation of a complete basin model, but whenever they are unsuited either because they are too sophisticated for certain parts, and not enough for others, adjusting them may be overly time-consuming. For example, it took almost as much time to set up and adjust the HSP model as to formulate and set up the Durance model.

The main errors are not caused by the modelling of the hydrological cycle but rather by its peripheral parts dealing with data estimation or extrapolation. Standardized procedures for the estimation of missing data included as part of the models should be avoided and replaced by careful objective analyses of precipitation, snow cover, and temperature fields which are made outside the model itself taking into account all the relevant information about the basin.

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Received 4 March 1981; accepted 5 June 1981.