Check for updates

Nordic Hydrology, 25, 1994, 79-100
No part may be reproduced by any process without complete reference

An Operational Forecasting Snowmelt Model with Objective Calibration

Paper presented at EGS XVIII General Assembly
(Wiesbaden, Germany – May 1993)

J. Y. Rodríguez
EDF-DTG, Ressources en Eau, F-38040 Grenoble, France

After a review of existing operational models for daily snowmelt forecasting, an operational oriented one has been developed in order to provide a simple tool for one-to-three-day ahead flow management. The main advantage of this lumped degree-day model lies in the algorithmic development which allows a quick and objective parameter calibration. The proposed iterative algorithm is able to furnish a reduction of the number of parameters and an error criteria plotting which allows to choose an adequate set of them. A case study – La Durance at la Clapière station (2,170 km^2) – illustrates the use of this proposed methodology. The case study is not limited to a classical fitting on calibration data and testing on a validation set, but also shows the actual day-to-day one-to-three-day ahead forecast made during spring 1993. The forecasting model capabilities as well as its limits are then discussed.

Introduction

Ever since its earliest stages of existence, the science of hydrology has always developed forecasting models. Linsley (1943), on the subject of snowmelt, observed that it was possible to forecast day-to-day runoff with a simple "degree-days" index. Nevertheless, although the first attempts on hydrological modelling had as main objective flow forecasting, modelling research is at present more geared towards the description, understanding and simulation of one or more internal hydrological subprocesses. Furthermore, when an operational forecasting

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

model is required by a user or a customer, the generally adopted solution consists in adapting an existing simulation model which is able to partially answer the query, even if the operational goal was not the main objective of the model. Yet, Bergström (1991) reminds us that the optimal complexity of a model is the point we should reach for each specific problem, and adds that in operational problems, the success or lack of success of a model is often judged differently by the modeller or the user of the model. In fact, experience shows that, many times, the user is unfortunately disconnected from the modeller, and the former must have sufficient understanding and knowledge of the model in order to be able to make proper use of it.

This paper presents the methodology adopted to provide an operational snowmelt forecasting model. A review of existing models justifies the development of a very simple model, with as few parameters as possible. Its originality lies in the algorithmic development which allows a quick and objective parameter calibration, and in the selected criterion of optimisation, based on operational day-to-day forecasting. The model will be summarized herein, following which, the objective algorithm of parameter calibration will be detailed. Finally, a case study on the Durance at la Clapière basin (2,170 km^2) will illustrate the operationability of the model, with a detailed discussion on the results obtained from the 1993 snowmelt period.

Selecting An Operational Forecasting Snowmelt Model

There are plenty of models on snowmelt runoff. Braun and Lang (1986) classified them according to 5 levels of complexity : Temperature index, Temperature and Wind index, the combination or extended combination methods, and finally, the energy balance method. They reported that in terms of the Nash and Sutcliffe (1970) criterion, simulations carried out in 5 Swiss basins ranging from 3.2 km^2 to 1,696 km^2 showed little difference between models, independently of their complexity degree, except for the smallest one and the maximal snowpack year of the 12 investigated. Only in this latter case, the more complex models (the extended combination or the energy balance models) gave slightly improved results. Similar results were found by Scheider *et al.* (1983) who compared a very simple temperature index model with a more complex energy balance one, taking into consideration not only their simulation capabilities but also their simplicity. They concluded that the simple model was more readily usable in areas with limited meteorological data.

These modelling conclusions were also drawn following field observations. Schneider (1957) found that the recharge water level, as well as snowmelt, during spring in a small-sized alpine basin were strongly correlated with the air temperature above 0°C. This conclusion was also arrived at by Kinosita *et al.* (1969) on a

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

134 km^2 basin, showing that the most relevant index of snowmelt was the air temperature, recorded near the basin outlet in their case, with solar radiation and wind velocity as a secondary link to the melting runoff.

A degree-day model has been retained in this paper for an operational purpose. Martinec and Rango (1986) pointed out that this method is popular because the temperature is a reasonably good measure of heat flux, and, at the same time, it is reasonably easy to measure, extrapolate and forecast. Roughly speaking, this kind of model may be written as

$$Qs = k\,(T-T_0)\,D \tag{1}$$

where Qs is the daily snowmelt, k is the degree-day factor, $(T-T_0)$ is the difference between an air temperature (daily average, maximum, minimum or other) and a threshold parameter below which the snowmelt is not supposed to occur. D is an index of the snowpack depletion.

The degree-day factor has been considered by Martinec (1960), at the point-scale, linearly dependent on the density of the snow. Roche and Slivitzky (1969) assumed, for simplicity, this term to be constant. Bergström (1975) initially assessed this factor increasing with the accumulated melt, but concluded that there were no improvements using a variable degree-day factor. Yet, different field measurements (Martinec 1960; 1963) and results from degree-day optimization (Bergström 1975; Martinec *et al.* 1983; Peña and Nazarala 1983) suggest that in many cases this factor may be considered as linearly dependent on snow density, cumulative melting or the day in the snowmelt season.

The threshold temperature T_0 is supposed to be close to the 0°C value, but adjustments may be carried out in an effort to correct the representativeness of the temperature station (Bergström 1975) or to include its location in the basin (Martinec *et al.* 1983). The temperature index commonly used is the average daily temperature, because this is the most available data and no systematic improvements have been found when using maximal or minimal values.

The depletion of the snowpack index D was derived by Roche and Slivitzky (1969) and Martinec *et al.* (1983) on the basis of the percentage of surface basin covered by snow, considered as an input of the model. Bergström (1975) divided the basin into altitude bands, and each band was supposed to be able to provide snowmelt until its snowpack disappeared. Nevertheless, if the basin or the altitude band is completely covered by the snow, the melt runoff provided generally does not depend on the amount of available water equivalent.

The two widely used degree-day models – SRM model (Martinec *et al.* 1983) and HBV model (Bergström 1975) – have been and are currently being used for operational purposes. Nevertheless, in the SRM case, the depletion curve, commonly obtained by observing the level of the snowpack limit, is not forecastable (Martinec *et al.* 1983). Furthermore, in order to obtain quite good results in simulation, the variability of some snowmelt and runoff coefficients of the SRM model, which

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

sometimes vary not only from month to month, but also from year to year, may be great (Martinec and Rango 1986). It is evident that, for operational purposes, it is preferable to keep the model parameters constant (Quick and Pipes 1972), or derived externally. Some specific research studies were carried out by Martinec (1985) and Rango (1988) in order to adapt the SRM model to operational forecasting problems, which show how difficult it is to transform a simulation model into one used for operational forecasting.

The case of the HBV model is slightly different. Even if it has been essentially used as a simulation model (Braun and Renner 1992), it also was, and is still, used for operational purposes (Anderson 1992). However, this model has about 20 parameters, even if most of them are less critical than the others, because it is a complete hydrological model which may be used for purposes other than snowmelt runoff simulation. Furthermore, some methodological efforts have been made in order to develop a process-oriented calibration scheme (Harlin 1991). Nevertheless, Braun and Renner (1992), who used a manual optimization although rather labour-intensive, reported that one cannot directly relate basin characteristics to parameter values, implying that an important calibration effort has to be made for each new case study.

Finally, as indicated by Anderson (1992), large improvements can be achieved by increasing model complexity at the early stages of model development, but, quite soon, model gives results that are difficult to overrun with more sophisticated sub-routines. In the same way, the experience of the Electricité de France operational forecasting center shows that simpler models are, independently of all operational problems of data transmission and acceptability of information, more robust and reliable than ones of greater complexity. Furthermore, in operational practices, as pointed out by Quick (1972), it is important to bear in mind that the major source of error lies in the inherent error of the forecast of the input variables. All these points have contributed towards the building of an operational snowmelt model that employs only few parameters.

The Operational Snowmelt Model

The snowmelt model retained here is part of degree-day family. It will be, deliberately, only applicable to the pure snowmelt phenomenon. Rodriguez and Saulnier (1992) pointed out that in small and medium sized basins (ranging from hundreds to thousands of square kilometres), the time lag differences between the snowmelt runoff and the direct rainfall-runoff justifies the use of different models, each for its own purpose. Both models may be combined when certain rainfall events occur during the snowmelt period, using in this case, the lowest time step of both.

In order to reduce the number of parameters, the model is supposed to be lumped. The cost of an operational network quickly limits the number of teleme-

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

tered points, and even if a raingauge is available for each 200-300 km^2, a more distributed model will not necessarily give better results. All parameters are therefore calibrated and then kept constant. The total outflow during a recession or a runoff snowmelt day is defined by

$$Q_T(d) = Q_R(d) + Q_S(d) \tag{2}$$

where $Q_T(d)$ is the total runoff, $Q_R(d)$ the recession flow and $Q_S(d)$ the snowmelt component at day d.

Data required to fit the model is limited to the total daily flow, the daily gross precipitation (commonly obtained by lumping a group of individual raingauges located inside or around the basin) and the daily air temperature. Certain characteristics, such as the hypsometric curve of the basin or the temperature lapse rate are also needed. Generally, ΔT is computed monthly using stations located at different altitudes, but a value of approximately 0.6°C / 100 m also gives results almost as accurate as those obtained with more detailed lapse rates.

The Baseflow Model

The baseflow recession model is fitted with daily data. Days without snowmelt and quick rainfall-runoff are selected from the total recorded data. The melting is supposed to occur only during the "snowmelt period", determined by a flow regime curve analysis. In Middle and South Europe, and elevations between 2,000 and 3,000 metres, this period commonly encompasses April to July, but some partial snowmelt can occur between December and August. In order to avoid possible bias produced by early or late melting, recession data does not include outflows occurring weeks before the snowmelt season. The data set obtained by this selection is used to fit a two-parameter recession law

$$Q_R(d) = \rho\{Q_T(d-1)\}^{\varepsilon} \tag{3}$$

where ϱ is a kind of recession coefficient and ε an exponent, which is preferred to the classical simple recession curve

$$Q_R(d) = \rho'\{Q_T(d-1)\} \tag{4}$$

because it has been observed in many case studies that depletion is accentuated by flow magnitude. Furthermore, it is possible to demonstrate that this formulation is close to the one proposed by Martinec (1970). If the exponent ε in Fig. (3) is less than one, as commonly obtained, the higher the value of $Q(d\text{-}1)$, the bigger is the depletion.

The Snowmelt Model

As indicated in the previous section, the retained model is a degree-day one. The basic equation is

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

$$Q_S(d) = (\alpha d' + \beta)\,(T-T_0)\,\frac{\text{Stock}(d)}{\text{Average Stock}} \tag{5}$$

where $Q_S(d)$ is the snowmelt of the day d (mm/d), $(\alpha d' + \beta)$ is the degree-day factor, (mm/d°C), which increases with d', the number of days from the start of the snowmelt period. T is an air temperature index, generally daily, while T_0 is a threshold air temperature below which no snowmelt occurs (°C) considered as parameter. Finally, Stock(d)/Average-Stock is a lumped standardized water equivalent of the snowpack at day d (mm).

This variant of the degree day model aims to include two improvements: firstly, an average linear increase of the degree-day factor, as has been proposed before by Peña and Nazarala (1983) and Martinec and Rango (1986); secondly, a direct relationship between the amount of total snowpack and the melting runoff. Some field results (Flerchinger *et al.* 1992) pointed out that in a small alpine catchment, the response between snowmelt, groundwater and streamflow was drastically different from year to year, with the years in which normal or high snowpack yielding a faster time response than those with little snow accumulation. In this way, the model attempts to produce more or less snowmelt, and therefore it has a greater daily variation of melting, under identical conditions of temperature and snowpack areal extent, depending on the amount of the equivalent snowpack. In particular, high gradients during the starting time for the spring flow, a crucial point in determining an acceptable model, as pointed out by Anderson (1992), would be better modelled when melt inputs are high.

The Equivalent Snowpack Evolution

The equivalent snowpack evolution Stock(d) is always computed from gross rainfall and air temperature, but some differences exist during, as well as, outside the snowmelt season. Before the snowmelt season, only increases are supposed to occur by accumulating snow from the end of the last snowmelt period to the present day. Snowpack residuals vanish the first day after the last snowmelt period. When pricipitations occur, they pass through a solid/liquid filter, governed by a simple relation which includes temperature and hypsometric curve.

The lumped temperature series are held at a fixed altitude z_0 (for example, the altitude of thermogauge if only one measurement point is used). If the temperature lapse rate ΔT in °C per 100 metres is known, it is possible to estimate at any altitude z the temperature $T(z)$ by

$$T(z) = T(z_0) + (z-z_0)\,\Delta T \tag{6}$$

and therefore, the level of isotherm 0°C, I_0. If the hypsometric curve is expressed *versus* the catchment percentage located below the altitude (see an example in Fig. 3), the knowledge the day d of I_0 will directly provide the ratio $R(d)$, and the solid precipitation $PS(d)$, which increases the water equivalent of the snowpack

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

$$PS(d) = R(d)\,PG(d) \tag{7}$$

where $PG(d)$ is the gross or lumped precipitation. Although this is a very crude approach, it is worth to note that the availability of complementary data, and in particular snow courses on some local points in the basin, may be used, as suggested by Braun (1991), as verification criteria in order to validate this snow accumulation sub-model. Some attempts can also be made to calibrate this kind of operational model, avoiding the estimation of the snowpack equivalent, by using directly measured values obtained from some representative snow courses in the basin (Saule 1992).

During the snowmelt season, the equivalent snowpack is modelled by a mass balance relation

$$\mathrm{Stock}(d+1) = \mathrm{Stock}(d) - Q_S(d)\,K + PS(d) \tag{8}$$

where Stock(d) is the lumped snow-water equivalent at day d (in mm), $Q_S(d)$ is the daily snowmelt (in mm), $PS(d)$ is the daily snowfall, and K is a snow depletion parameter. This will be described in the following section.

An Objective Algorithm to Fit The Operational Snowmelt Model

The snowmelt model, governed directly by Eqs. (5) and (8), and indirectly by Eqs. (2) and (3), is an implicit and non-linear model. Even if it has only 4 parameters (α, β, K and T_0), the calibration of this kind of model is generally done by a time consuming trial-and-error method, which does not ensure convergence to a satisfactory enough optimum point. Furthermore, the high time-cost of this calibration commonly stops modellers in their research, preventing a more detailed analysis of other inputs or combinations of inputs, which may be helpful in terms of model explanation. The purpose of this section is to propose an automatic algorithm, even though some simplification hypothesis must be made, which allows a more satisfactory solution. The basic ideas are:

– *First*, if an estimation $S(d)$ of the equivalent standardized snowpack is known at each day d, and the threshold temperature T_0 is also supposed to be known, the relation Eq. (7) may be written as

$$Qs\;(d) = \alpha(T-T_0)\,d\,S(d) + \beta\,(T-T_0)\,S(d) \tag{9}$$

if $T > T_0$ and nil elsewhere.

– *Secondly*, once the baseflow model has been calibrated, using Eqs. (2) and (3), the daily snowmelt $Qs^*(d)$ can be estimated by

$$Qs^*(d) = Q_T(d) - \{\rho\, Q_T(d-1)^{\varepsilon}\} \tag{10}$$

however, if a computed $Qs^*(d)$ is negative, it automatically vanishes. The snow-

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

melt is thus considered as the increment produced by the melting over the recession state of the basin. Therefore, when the melting stops, the outflow will follow its own recession curve.

Under these assumptions, it is possible to solve Eq. (9) using Eq. (10) by the classical optimization methods. For instance, only the least squares method has been used to determine α and β, but other methods may be employed in this context.

In practice, the estimation of $S(d)$ is performed by

$$S(d) = \frac{\overline{\mathrm{Stock}(d')}}{\overline{\mathrm{Stock}(0)}} \; \frac{\sum^{d} PS(i)}{\overline{\mathrm{Stock}(0)}} \tag{11}$$

The first term – the average snowpack at a day d' *versus* the average snowpack at the start of the melting period – translates the average depletion of the water equivalent during the snowmelt season over the calibration set. The second one may be considered as a correction factor of the average depletion curve according to the amount of available water equivalent at a day d.

– *Thirdly*, if the fourth parameter K is also supposed known, it is possible, once parameters α and β have been estimated based on Eq. (9), to determine year by year the resulting Stock (d), by using Eqs. (5) and (8). In fact, K must ensure the correct depletion of the equivalent snowpack and, for balancing reasons, has to be fitted around the value

$$K_0 = \frac{\sum PS}{\sum Q{*}s} \tag{12}$$

where the sum of PS is calculated over the hydrological period, while the sum of Q_S is performed only during the snowmelt period.

– *Finally*, if each Stock (d) is computed year by year, it is possible to reiterate the process by using a new estimate of $S(d)$ with Eq. (11). For initialization, some studies (Saulnier 1991) have shown that convergence does not depend on the initial shape of the snowpack depletion curve, providing that it is not too far from a realistic one. A simple linear snowpack depletion may be used at this stage.

In summary, the proposed algorithm is able to furnish, by an iterative algorithm, two parameters (α and β of the degree-day factor) if the other two (K and T_0) are fixed (Fig. 1). The identical framework can be used if the degree-day factor is assumed to be constant or derived externally (for example, with the average density on a telemetered snowgauge). The other advantage of this approach lies in the possibility of plotting the error criteria on a two-dimensional space T_0 and K, making it easier to choose an adequate set of parameters. In practice, two criteria are commonly used in operational context to select the parameters:

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

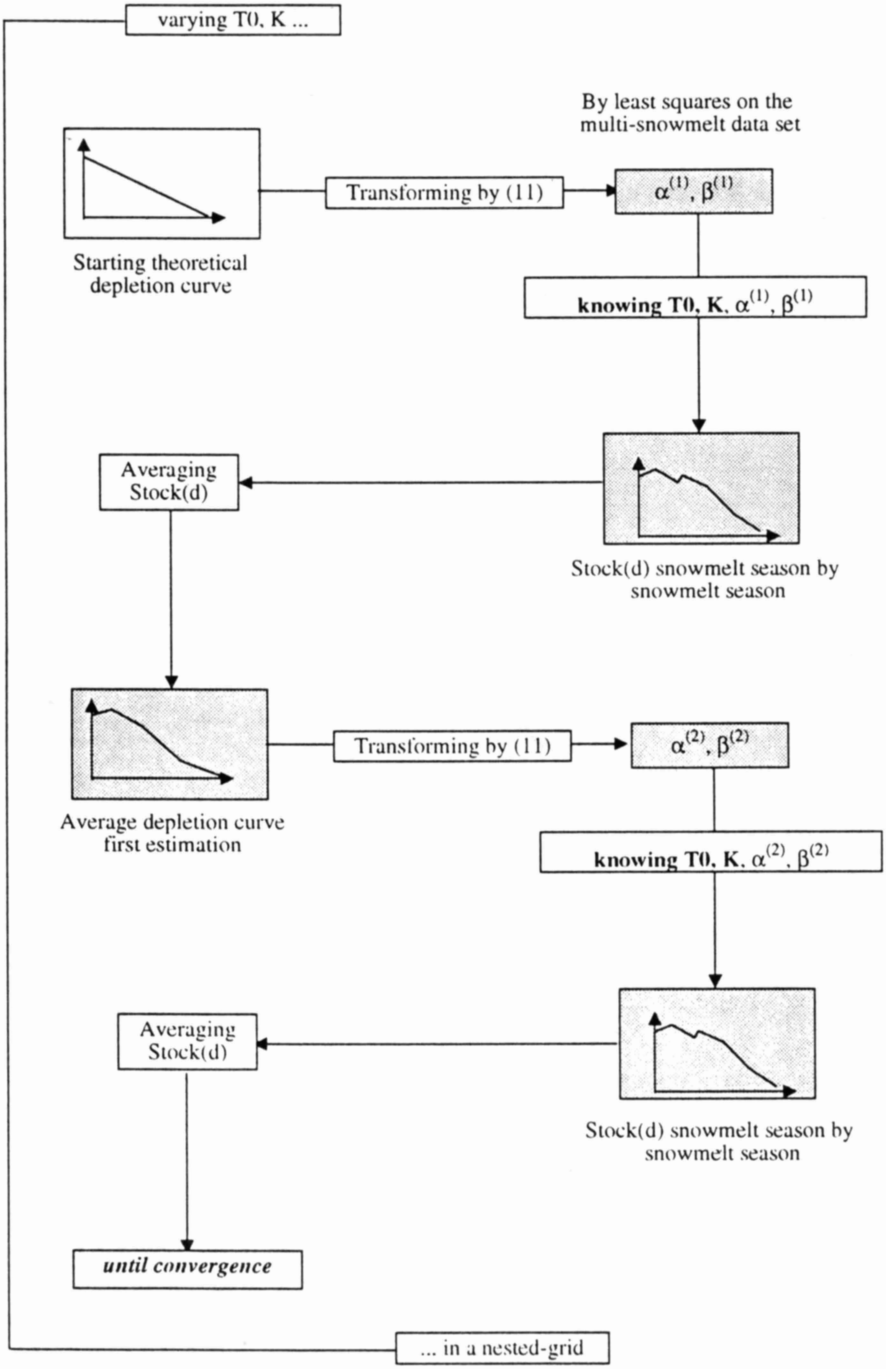

Fig. 1. Iterative algorithm scheme for the operational snowmelt model fitting.

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

- The correlation, during the snowmelt period, between first differences of outflows *RDQ* – which is the most useful information on operational requirements (see for example in rainfall runoff models Duband *et al.* 1993) –. This choice helps the selected model to give the best possible high variations of flows forecasts.
- The ratio $\bar{\omega}$ between modelled snowmelt by Eqs. (5) and (8) and those obtained by Eq. (10). As these values are not exactly the "true" values, this criterion is secondary. However, it prevents that we obtain a set of parameters which is optimum in terms of *RDQ*, though giving results in term of snowmelt balance which are too far from reality.

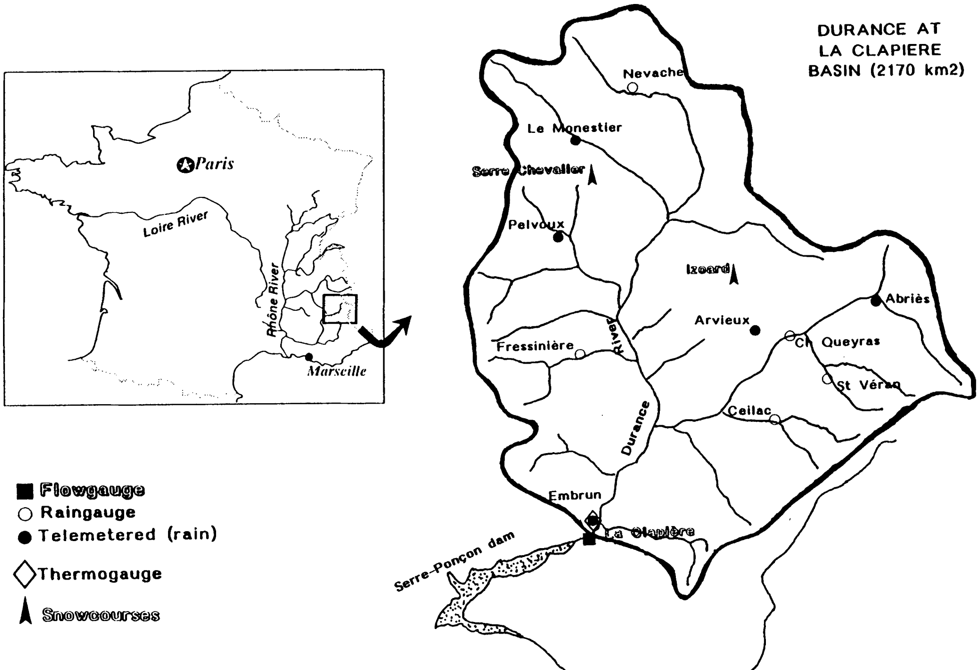

Fig. 2. Durance at la Clapière basin location.

The Durance River At la Clapière Station (2,170 km^2)

The Durance watershed at la Clapière Station is located in the South-Eastern part of France (see Fig. 2). Downstream is the Serre-Ponçon dam, the biggest reservoir in France (1,272 Hm3), filled by the Durance River, and to a lesser extent, by the Ubaye River. The dam is managed with a multi-purpose objective : Hydropower, agricultural supply, and even recently touristic needs require that the level of the dam remains as close as possible to the maximum operating level between June and

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

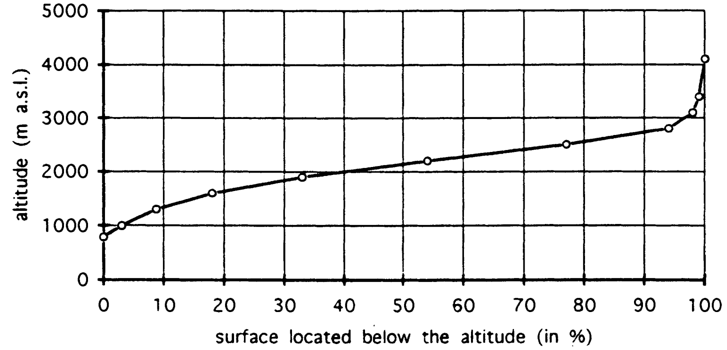

Fig. 3. Durance at la Clapière hypsometric curve.

August. These requirements demand the highest possible degree of accuracy in the medium short streamflow forecast, over a period of one to three days, during melting.

Because of the importance of the hydropower dam, the basin has been well monitored since 1955 by Electricité de France (see Fig. 2). Complementary information may be provided by other French authorities. In particular, daily air temperatures are available from the National Weather Center Météo-France. The basin rises from 780 m.a.s.l. at the outlet to 4,103 m. About 60% of the total surface is located above 2,000 m (Fig. 3). Snow accumulation commonly starts by November, but, during particular years, it may begin as early as October. Some partial snowmelt can be detected in March, although the main snowmelt contribution occurs between April and July.

Data Used

Flows at La Clapière station (2,170 km^2) have been measured since 1960. The data have been split into two sets : the calibration set from 1961 to 1979; and the validation set, 1980-1991. The period from August 1969 to July 1970 has been removed because there were no flow data during January 1970.

The raingauges selected for this study were those located near the mountainous areas, with altitude locations ranging from 1,490 m to 2,010 m. All these raingauges, except for the one at Fressinières, are automatic, hourly recording types equipped with an integrated heating system. Daily temperatures were measured at Embrun station, near the outlet. The temperature lapse rate ΔT was obtained monthly by analysis of air temperatures at different points. Values ranging from 0.64°C/100 m in September to 0.77°C/100 m in March were found. The accumulation model gives an average value of the lumped water equivalent of the snowpack on April 1st as 341 mm. Values obtained at this date are compared with the average snowpack measured at the Izoard and Serre-Chevalier snow courses in Fig. 4.

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

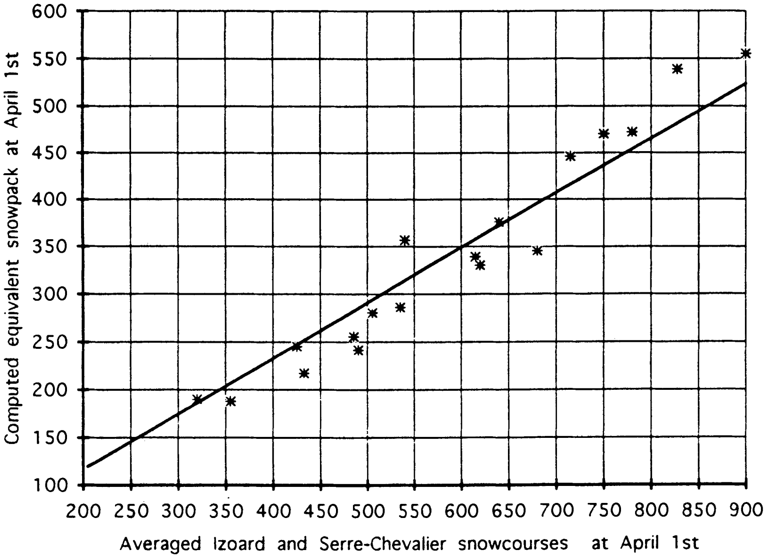

Fig. 4. Computed and measured snowpack water equivalent on April 1^{st}.

These snow courses are well-known in the Durance basin to have a strong correlation with the total flow volume during the snowmelt period. The good agreement between this modelled and measured intermediate variables validates the accumulation model in the Durance River.

Fitting The Operational Snowmelt Model

Once the recession baseflow model Eq. (3) was calibrated, the iterative algorithm has been implemented to fit the snowmelt model. T_0 and K were varied according to a nested-grid. The central point of K, K_0, was computed by Eq. (12), resulting $K_0 = 12.8$, which means that, on the average, 12.8 mm of equivalent snowpack provides 1 mm of snowmelt. This amount may seem excessively high, but, as the snowmelt has been defined as an increment over the recession flow, it also includes the groundwater layer recharge.

The starting point of T_0 may be estimated by computing the temperature at the thermogauge station when the mean hypsometric elevation is supposed to be at the freezing point. In this case study, taking ΔT around 0.7, T_0 = 8,5°C. Some attempts have been made to explore the air temperature index performances (see for more details Rodriguez 1993). Without counting the data criticism and conditioning, each trial took about 1 hour CPU on a VAX 6310 computer for about 50 sets of nested parameters K and T_0. The retained one was performed by averaging the air temperature at Embrun station for 2 days, including the day of forecast.

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

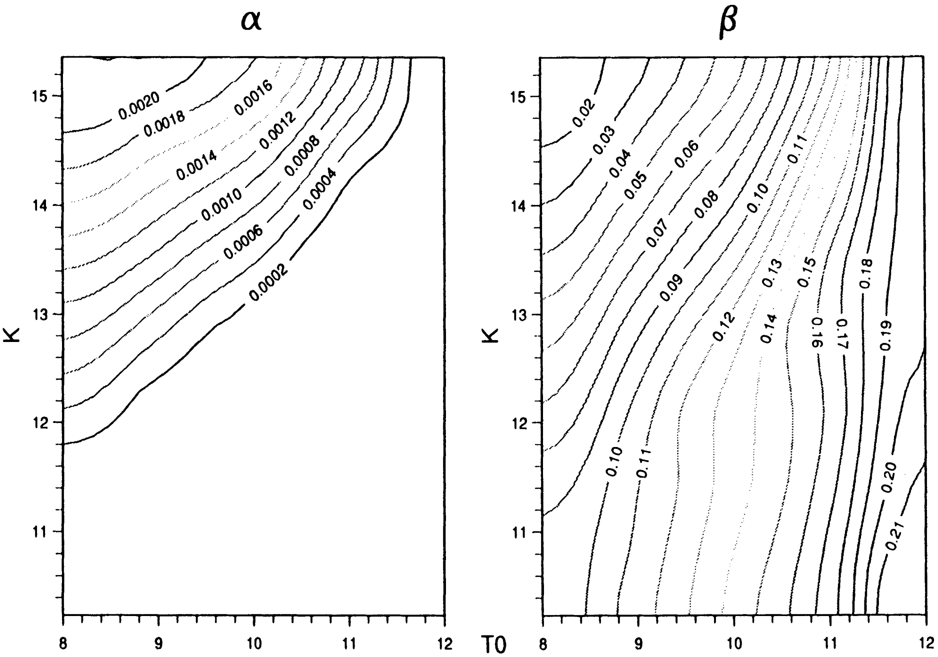

Fig. 5. (α, β) parameters functions *versus* (K, T_0) grid.

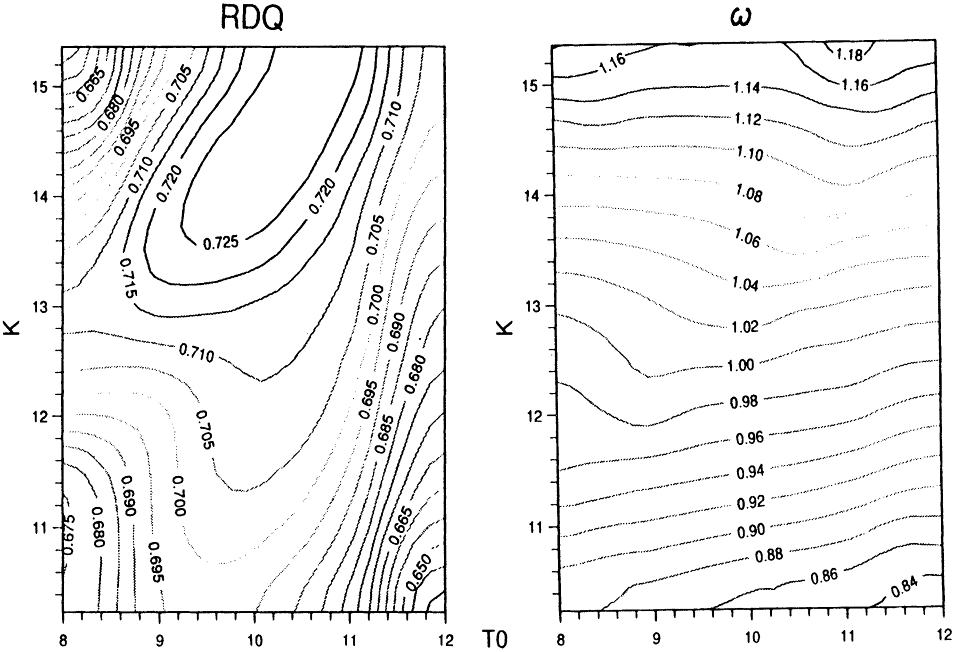

Fig. 6. Criteria plot functions.

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

The parameters α and β are plotted *versus* the nested-grid K and T_0 in Fig. 5. When one of them was found to be less than zero, it was automatically deleted. Fig. 5 shows that the slope of the degree-day factor is positive only in the left-superior part of the (K, T_0) grid. When α is set to zero, the intercept coefficient β of the degree-day factor is not strongly dependent on K. It might be translated as an overparametrisation of the snowmelt model, even if it is governed by only four parameters. Nevertheless, when the error-functions are plotted on the same (K, T_0) grid (Fig. 6), it appears that performances in term of the correlation coefficient of first differences of flows (RDQ) decreases strongly when the slope of the degree-day factor α is set to zero.

Since the optimum in terms of RDQ is not heavily pronounced, the second criterion $\bar{\omega}$ is also useful in selecting the set of parameters (see also Fig. 6). When $\bar{\omega}$ is greater than one, it means that the model is overestimating the whole snowmelt volume. However, it must be kept in mind that error-functions must be used with caution, as pointed out by Bergström (1975), and have to be completed by chronological graphics.

The selected operational model is therefore defined by parameters given in Table 1. The convergence of the algorithm is illustrated by the evolution of the average water equivalent of the snowpack, deduced from the 18-year data set calibration. Fig. 7 shows the linear depletion curve of the standard snowpack used to initate the algorithm, and the quick convergence (5 iterations in this case study) to the final depletion curve.

Fig. 8 shows an example of the model one day ahead computing capacities. Days with a rainfall-runoff superimposed component over the snowmelt are not computed, even if the model is able to provide an estimation of the snowmelt part of the total runoff. During the 1961 snowmelt calibration period (Fig. 8a.), the computed flows were close to the measured ones. Nevertheless, although the model is being updated daily, the results are not always excellent, as shown during the

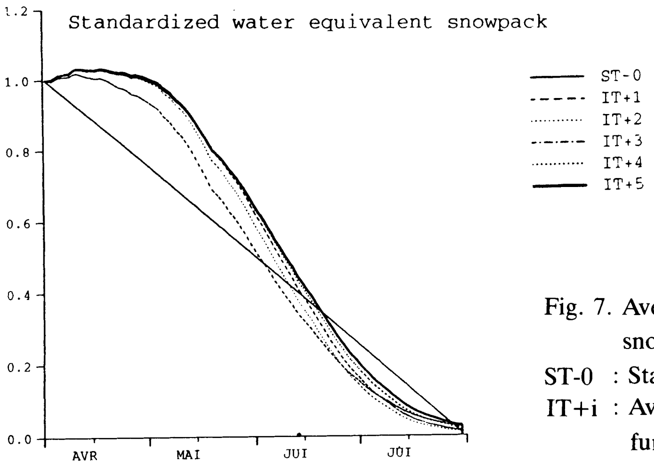

Fig. 7. Average standardized equivalent snowpack convergence.

ST-0 : Starting function.

IT+i : Average snowpack depletion function at i^{th} iteration.

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

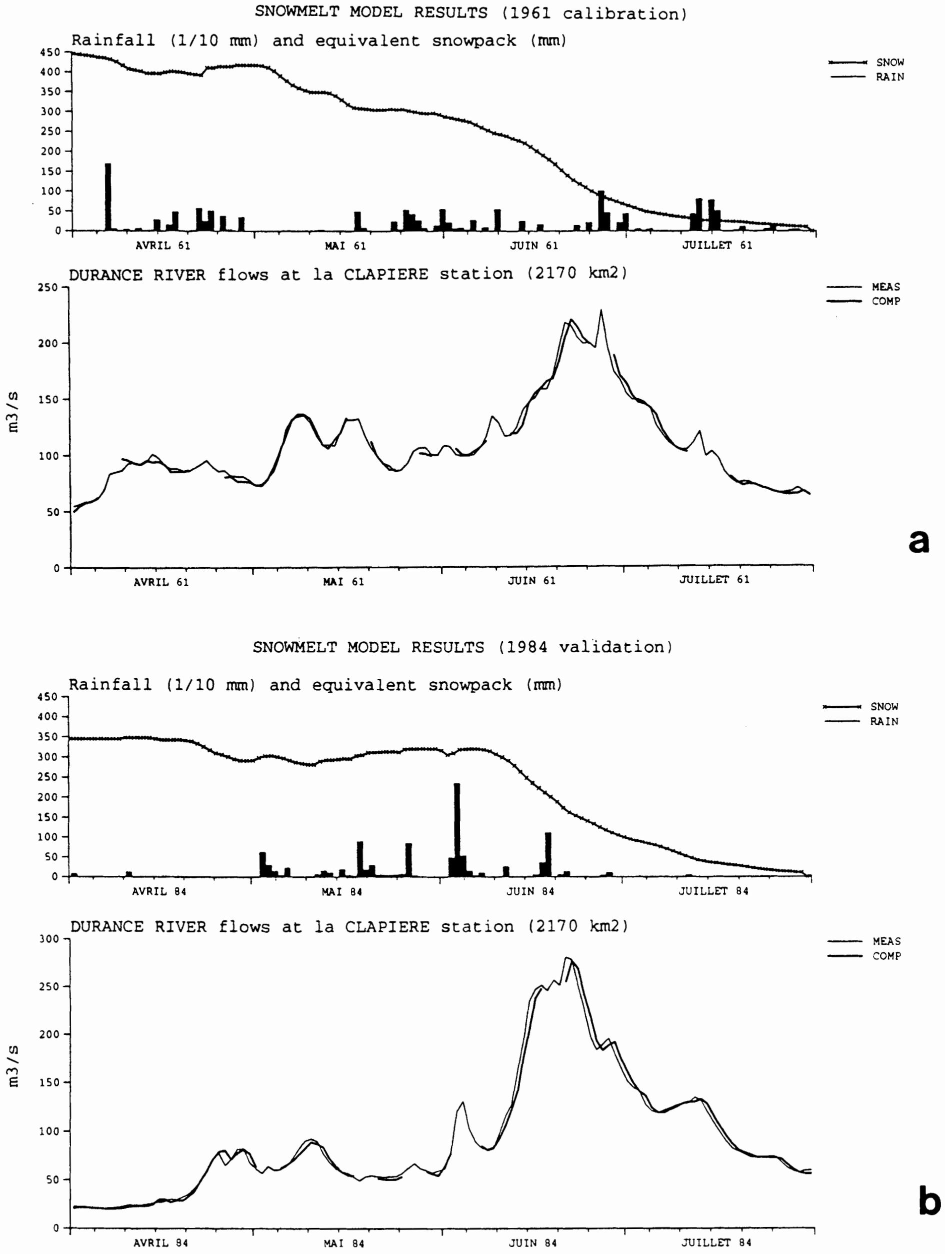

Fig. 8. Model snowmelt results (a: calibration, b: validation)

MEAS : Measured flow Durance at la Clapière River (in m^3/s).
COMP : Computed flows one-day-ahead with up-dating (in m^3/s).
SNOW : Equivalent snowpack evolution (in mm)
RAIN : Liquid precipitation (in 1/10 mm).

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

Table 1 – Parameter values for the Durance at la Clapière snowmelt model

ϱ	1.038	K	12.8
ε	0.977	T_0	10 °C
α	9×10^{-4}	Temperature index	$(T(d)+T(d\text{-}1))/2$
β	0.88		

second part of the snowmelt period, where the model seems to produce a systematic error. It can be explained both by the internal definition of the snowmelt component, as an additional contribution over the baseflow recession, and the criteria used to select the model, the RDQ coefficient, which tends to deliberately reproduce as closely as possible the higher variations of flow. Fig. 8 also shows the snowpack water equivalent evolution during the snowmelt season. The model reproduces some increments in the snowpack equivalent due to snowfall, and depletes correctly at the end of July.

Table 2 – Criteria coefficients

	Calibration set (1961-1979)	Validation set (1980-1991)
RDQ	0.73	0.77
$\bar{\omega}$	1.08	1.05
RQ	0.99	0.99

In Table 2, the two criteria retained in this study, both in the calibration and the validation periods are given, as well as the correlation coefficient RQ between measured and calculated discharge. It is worth noting that RQ must not be used for the assessment of operational forecasts because of the highly inherent autocorrelation of flows. Certain tests can be carried out with autocorrelation coefficients; in the snowmelt period, the natural flow autocorrelation coefficient may take on a value of about 0.95, while the autocorrelation on its first differences is commonly close to zero. Furthermore, a model which is able to climb up to RDQ=0.7 is likely to be successful in operational work.

The model proposed in this case study seems to be quite a robust one. Criteria remain in the same range during the calibration and the validation set. Fig. 8b shows the 1984 snowmelt validation period, where the higher meltings were found after the middle of June. The snowmelt model correctly reproduces this later snowmelt, by keeping the snowpack almost invariant during May.

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

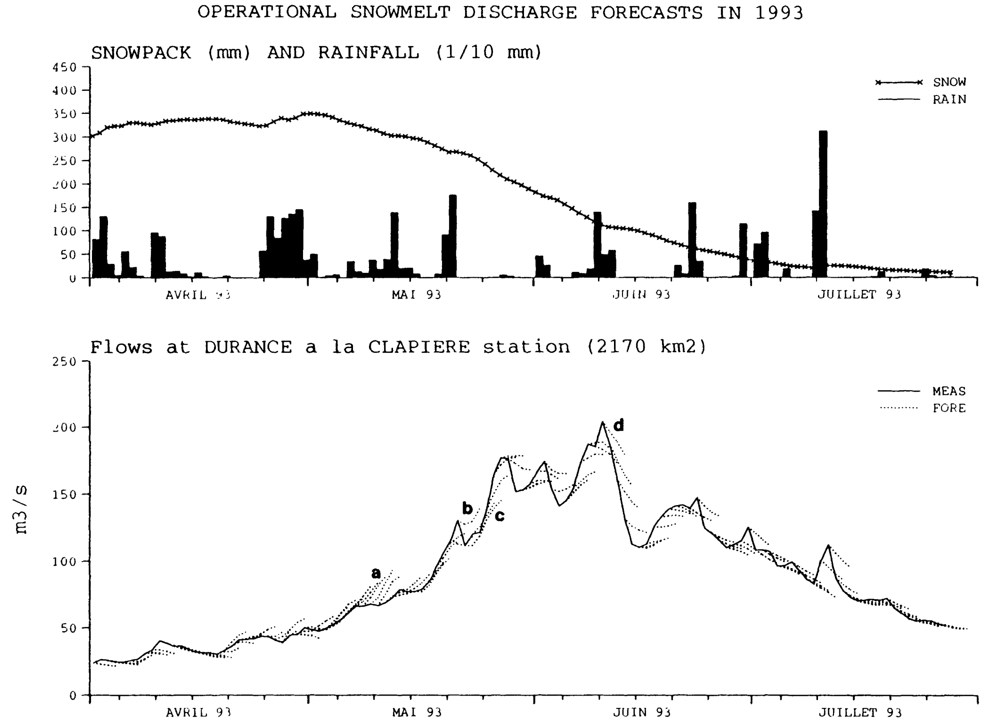

Fig. 9. Operational snowmelt results (1993 Spring daily forecasting):
MEAS : Measured flow Durance at la Clapière River (in m^3/s).
FORE : Forecasted flows three-days-ahead with up-dating (in m^3/s).

Implementing The Operational Model

After calibrating and validating the model, the final step consists in implementing it for operational purposes. A very simple daily management of the snow-water equivalent program was built, with automatic data collection of flows, precipitation and temperature. The telemetered raingauges used were different from those employed in the calibration stage, but a statistical treatment over 30 years of daily precipitation from April to July shows that very little correction was required to estimate the gross precipitation over the Durance at la Clapière watershed with the reduced telemetered network.

Each day, at about 8 a.m., the model user entered into the model the forecasted minimum and maximum temperatures at Embrun station, provided by the PERIDOT model of Météo-France (Pottier 1990). The minimum of the current day was assumed to have occured the night before. Thus, the forecast temperature index at current day *d* uses only one real forecasted value – the maximum on day *d* –

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

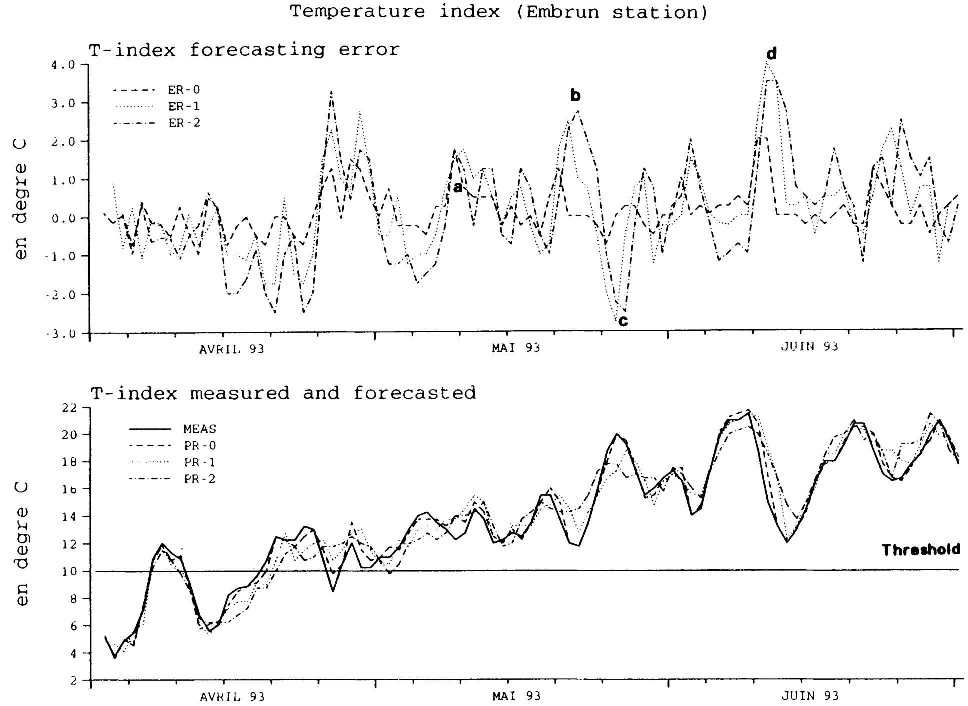

Fig. 10. Air temperature Index. Measured and forecasted values during 1993 spring.
MEAS : Measured temperature index from Embrun station (in °C).
PR-i : Predicted temperature index i days before (in °C).
ERR-i : Temperature index error forecasting i days before (in °C)
Threshold : T_0 parameter used in the Durance at la Clapière snowmelt model (in °C).

whereas the forecast air *T*-index on one or two days ahead are essentially based on minimum and maximum assessed air temperatures.

Fig. 9 shows the results of the daily three-days-ahead forecast 1993 snowmelt season. This season has been more rainy than others, and cooler during April. There was a tentative start to the snowmelt at the end of April, but high variations of melting were registred only between May 15th and June 15th. Operational forecasting values were not always close to reality, but the major trends of flows were always correctly given. Fig. 10 shows the time series of air temperature index measured during this snowmelt season, and those forecasted on day *d*, *d*-1 and *d*-2. The forecast values on day *d* were close to the measured values, as expected, but sometimes errors in an absolute range of one or two °C were found. On the other hand, forecast values one or two days ahead may present errors, (Fig. 10), in a very large range from -3 to 3°C.

The forecast *T*-index errors, added to the particular model ones, were the main

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

cause of the operational model errors. It is easy to identify snowmelt errors (a) to (d) in Fig. 9 which are strongly related to air temperature index errors in Fig. 10. Furthermore, it seems, but this conclusion has to be strenghtened by other observations, that higher errors are produced with higher temperature variations. Obviously the problem of forecasting temperature has not been completely solved, particulary in mountainous areas. Nevertheless, since the operational model uses, in this case study, a temperature index averaged over two days, model errors are less pronounced than temperature ones.

Discussion

A lumped snowmelt model, based on the degree-day approach, has been elaborated for operational purposes. The proposed model is close to the HBV snowmelt routine (Bergström 1975) and the SRM model (Martinec *et al.* 1983), but it has been implemented an objective calibration algorithm. The whole model assumes that the recession baseflow model (close to Martinec 1970) is governed by two parameters, and the snowmelt model by four. The fitting algorithm provides, by using an iterative approach, two optimum parameters once the other two were fixed. Furthermore, through error function plotting, it is possible to guide the choice of a set of parameters. However, the operational snowmelt model deliberately avoids the rainfall-runoff component, because the time responses of a medium-sized watershed (from 100 to some 1,000 km^2) are commonly less than the day. In these cases, the snowmelt model has to be combined with a rainfall-runoff one (Rodriguez and Saulnier 1992).

The suggested methodology is not reduced to the proposed operational model, and other similar models might be fitted by this approach. For example, the model proposed herein supposed that the degree-day factor is linear depending on the day of the snowmelt season, but some attempts may also be made at changing the degree-day relation (a parabola or more complex law), or at using relations between the degree-day factor and other inputs, as daily average density on a telemetered snowgauge, in order to take into account the snowpack transformation with fresh snowfalls.

Although the model has a low level of complexity, some intermediate results, such as the lumped water equivalent of the snowpack, can be validated with observed data. A case study (the Durance River at la Clapière station, 2,170 km^2) illustrates the use of this proposed methodology. By replacing the labour-intensive manual optimization of this kind of model (as reported by Braun and Renner 1992) by a fast automatic one, it has been possible to investigate temperature indices, resulting in the average value over two days as the most significant one for this case study. The retained model was also validated with a validation set. The results, in terms of the two retained criteria (correlation of first variation of flows RDQ, and

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

ratio $\bar{\omega}$ between modelled snowmelt and those estimated by filtering the baseflow) were robust.

Finally, the daily one-to-three-days-ahead operational forecast during the 1993 snowmelt season have been presented. The forecasts gave the major trends of flows but, even if the air temperature index is computed from an average value over two days, the results show, as expected and pointed out by Rango (1988), that the correspondence of forecast and observed streamflow is heavily dependent on the accuracy of a temperature forecast. Possibly, the most surprising result is that temperature is not as easy to forecast as pointed out by Martinec and Rango (1986). While the temperature forecast remains an unsolved problem, the best snowmelt model will still be strongly dependent on the accuracy of forecast local temperature. However, further research studies on error treatment should be helpful to improve operational short term daily forecasting.

Acknowledgements

The last section of this paper would never have been written without the help of J. M. Tessier, who made daily use of the model and carefully collected the data needed to analyze the forecast errors of the operational snowmelt model.

References

Anderson, L. (1992) Improvements of Runoff Models, What way to go? *Nordic Hydrology, Vol. 23*, pp. 315-332.

Bergström, S. (1975) The development of a snow routine for the HBV-2 model, *Nordic Hydrology, Vol. 6*, pp. 73-92.

Bergström, S. (1991) Principles and confidence in hydrological modelling, *Nordic Hydrology, Vol. 22*, pp. 123-136.

Braun, L.N. (1991) Modelling of the snow-water equivalent in the mountain environment, Proceed. of the Vienna Symposium, August 1991, IAHS Publ. No. 205, pp. 3-17.

Braun, L.N., and Lang, H. (1986) Simulation of snowmelt runoff in lowland and lower Alpine regions in Switzerland, in Modelling Snowmelt-Induced Processes (Proceed. of the Budapest Symposium), IAHS Publ. No. 155, pp. 125-140.

Braun, L.N., and Renner, C.B. (1992) Application of a conceptual runoff model in different physiographic regions of Switzerland, *Hydrological Sciences Journal, Vol. 37, No. 3*, pp. 217-231.

Duband, D., Obled, Ch., and Rodriguez, J.Y. (1993) Unit hydrograph revisited: an alternate iterative approach to UH and effective precipitation identification, *Journal of Hydrology, Vol. 150*, pp. 115-149.

Flerchinger, G.N., Cooley, K.R., and Ralston, D.R. (1992) Groundwater response to snowmelt in a mountainous watershed, *Journal of Hydrology, Vol. 133*, pp. 293-311.

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

Harlin, J. (1991) Development of a Process Oriented Calibration Scheme for the HBV Hydrological Model, *Nordic Hydrology, Vol. 22*, pp. 15-36.

Kinosita, T., Aoki, S., and Ishizuka, K. (1969) Analysis of snow melt floods, *in* Floods and their computation, IAHS Publ. No. 84-85, pp. 645-655.

Linsey, R.K. (1943) A simple procedure for the Day-to-Day Forecasting runoff from snowmelt, Trans. Amer. Geophys. Union. Part III, pp. 62-67.

Martinec, J. (1960) The degree-day factor for snowmelt forecasting, in Proceed. of Symposium General Assembly of IAHS. Helsinki. Finland, IAHS Publ. No. 51, pp. 127-134.

Martinec, J. (1963) Forecasting streamflow from snow stage in an experimental watershed, in Proceed. of Symposium General Assembly of IAHS, Berkeley, USA, IAHS Publ. No. 63, pp. 127-124.

Martinec, J. (1970) Study of snowmelt runoff process in two representative watersheds with different elevation range, Proceed of Symposium on the results on representative basins, Wellington, New-Zealand, IAHS Publ. No. 96, pp. 29-39.

Martinec, J. (1985) Snowmelt runoff models for operational forecasts, *Nordic Hydrology, Vol. 16*, pp. 129-136.

Martinec, J., Rango, A., and Major, E. (1983) The snowmelt-Runoff Model (SRM). User's manual. NASA Reference Publication 1100, NASA/Goddard Space Flight Center, Maryland, USA (110 pp.).

Martinec, J., and Rango, A. (1986) Parameter values for snowmelt runoff modelling, *Journal of Hydrology, Vol. 84*, pp. 197-219.

Nash, J.E., and Sutcliffe, J.V. (1970) River flow forecasting through conceptual models. Part-I A discussion of principles, *Journal of Hydrology, Vol. 10*, pp. 282-290.

Peña, H., and Nazarala, B. (1983) Pronóstico de caudales de deshielo a corto plazo, Proceed. of Vlth Congreso nacional de la Sociedad Chilena de Ingeniería Hidráulica. pp. 393-407, Santiago, Chile.

Pottier, P. (1990) Prévision de température par adaptation statistique du modèle Péridot, *La Météorologie, Vol. 32*, pp. 29-32.

Quick, M.C. (1972) Forecasting runoff; operational practices, in The role of snow and ice in hydrology, Proceed. of the Banff Symposia. Edited by Unesco-WMO-IAHS, pp. 943-955.

Quick, M.C., and Pipes, A. (1972) Daily and seasonal runoff forecasting with a water budget model, in The role of snow and ice in hydrology, Proceed. of the Banff Symposia. Edited by Ynesco-WMO-IAHS, pp. 1017-1034.

Roche, M., and Slivitzky, M. (1969) Modèle mathématique pour une crue de fonte de neige, in Floods and their computation, IAHS Publ. n° 84-85, pp. 688-699.

Rango, A. (1988) Progress in developing an operational snowmelt-runoff forecast model with remote sensing input, *Nordic Hydrology, Vol. 19*, pp. 65-76.

Rodriguez, J.Y. (1993) Mise au point d'un algorithme de calage de modèles du fusion de type degré-jours: Application au BV de la Durance à la Clapière. Internal Report n° ID/mod-93-05. Electricité de France, Division Technique Générale, Sce. Ressources en Eau. Grenoble, France, 24 pp.

Rodriguez, J.Y., and Saulnier, G.M. (1992) An operational combined model for flow forecasting, in *Fluid Flow modelling*, Proceed. of Hydraulic Engineering Software IV, Valencia, Spain. Editors: W.R. Blain and E. Cabrera. Computational mechanics Publications, Elsevier Applied Science, pp. 61-72.

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest

Saule, Th. (1992) Modèle degré-jour de fusion de la neige. Application aux bassins de la Durance à la Clapière, l'Ubaye à Roche Rousse et la Romanche aux Chambons. Student Report. ENSHMG/EDF - DTG Sce. Ressources en Eau, Grenoble, France, 51 pp.

Saulnier, G.M. (1991) Modélisation de la fusion de la neige par une méthode »Degré-jour«. Utilisation des données provenant d'un télénivomètre. Identification des paramètres du modèle non linéaire par un algorithme itératif. Student Report. ENSHMG/EDF - DTG Sce. Ressources en Eau, Grenoble, France, 60 pp.

Schneider, R. (1957) Correlation of ground-water levels and air temperatures in the winter and spring in Minesota, in Proceed. of Symposium General Assembly of IAHS, Toronto, Canada, Publ. IAHS No. 44, pp. 219-228.

Scheider, W.A., Logan, L.A., and Goebel, M.G. (1983) A comparison of two models to predict snowmelt in Musoka-Haliburton, Ontario, in Proceed. of the 41th Annual Meeting – Eastern Snow Conference, pp. 157-168.

First received: August 1993
Revised version received: 25 November, 1993
Accepted: 4 January, 1994

Address:
EDF-Division Technique Générale,
Sce. Ressources en Eau,
37, rue Diderot, B.P. 41,
38040 Grenoble,
France.

Downloaded from http://iwaponline.com/hr/article-pdf/25/1-2/79/4354/79.pdf
by guest