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Snowmelt–runoff forecasts based on automatic temperature measurements

J. MARTINEC Federal Institute for Snow and Avalanche Research, Weissfluhjoch/Davos, Switzerland

Abstract. Air temperature appears to be the most important factor in a snowmelt–runoff model. In an alpine representative basin, an automatic meteorological station situated at 2420 m a.s.l. greatly improves the evaluation of temperatures throughout the whole range of elevation. If temperatures must be extrapolated from a distant station, the uncertain vertical lapse rate affects the results. The range of discharge forecasts depends on a quick transmission of data and on temperature forecasts. It is also possible to assume temperatures of several months ahead, to adjust the depletion curves of the snow coverage and to simulate the resulting runoff.

Prévisions de l'écoulement provenant de la fonte des neiges fondées sur les mesures automatiques de la température

Résumé. *La température de l'air joue un rôle important dans un modèle de l'écoulement* provenant de la fonte des neiges. Dans un bassin représentatif alpin, les températures qui changent avec l'altitude peuvent mieux être évaluées grâce à une station météorologique automatique située 2420 m s.m. Si la température est extrapolée à partir d'une station eloignée, les résultats sont influencés par les variations des gradients thermiques verticaux. La période utile de la prévision dépend de la transmission rapide des données et des prévisions de la température. Il est aussi possible de modifier les courbes de la surface enneigée par des températures supposées et de simuler l'écoulement qui en résulte.

INTRODUCTION

Snowmelt–runoff computations in the mountainous regions require reliable temperature data in the whole elevation range of a basin. Uncertain extrapolations from the nearest observation point of the normal network can be avoided by placing automatic meteorological stations in locations where direct measurements are needed. A Wallingford-type station (Strangeways and McCulloch, 1965) is in operation at the average altitude of a basin in the Swiss Alps with the aim of developing and testing a snowmelt–runoff model. The access to this site, shown in Fig. 1, is limited by avalanche risks in the winter and spring months, and the station is therefore operated by batteries and solar cells so that the data can be stored on a cassette for about eight months.

EVALUATION OF TEMPERATURE DATA

Temperature data in the Dischma basin are available at 15-min intervals. Hourly average values are used to determine the number of degree-days for 24-h periods. As an example, temperatures and the corresponding snowmelt hydrograph are plotted in Fig. 2.

In view of the big elevation range of the basin, the snowmelt is computed separately for three elevation zones:

Zone A, 1668–2100 m a.s.l., average elevation 1938 m a.s.l.
Zone B, 2100–2600 m a.s.l., average elevation 2370 m a.s.l.
Zone C, 2600–3146 m a.s.l., average elevation 2750 m a.s.l.

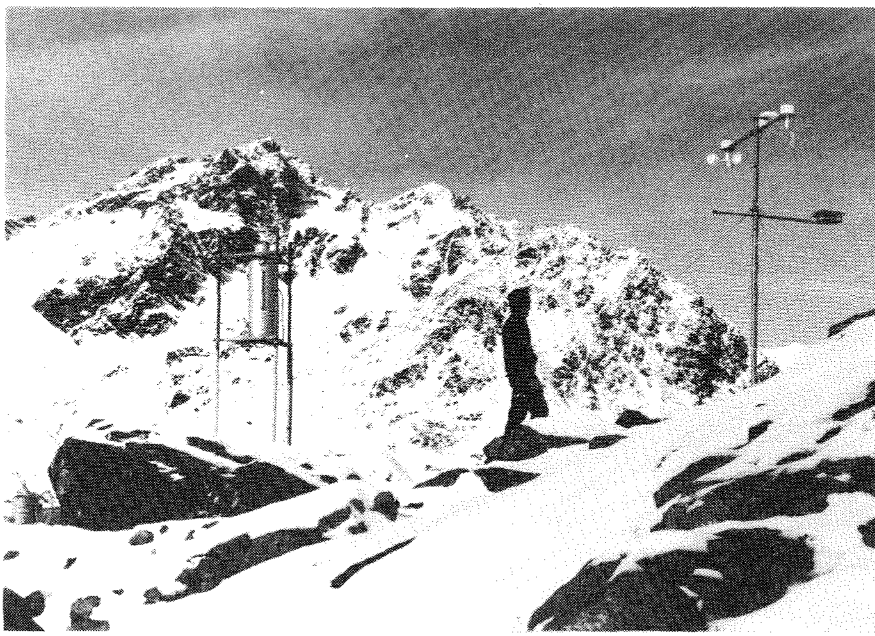

FIGURE 1. Automatic meteorological station (Wallingford-type) operated in the Dischma basin, Swiss Alps, at 2370 m a.s.l. (in 1974). (Photo E. Wengi).

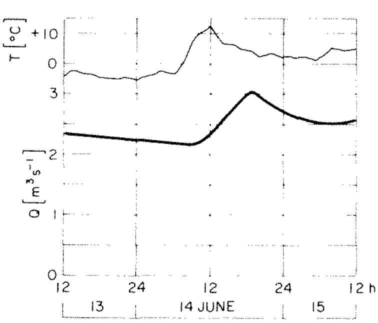

FIGURE 2. Automatically measured air temperatures compared with the snowmelt hydrograph.

Average elevations are determined by the area–elevation curve. In 1974 the station was situated at 2370 m a.s.l. so that the measurements have been directly used to determine the degree-days in zone B. This procedure consists of computing an arithmetical mean from hourly values starting with the interval 0600–0700 h and ending with the interval 0500–0600 h. Temperatures below freezing point are considered as 0°C. For other altitudes, temperatures are corrected by a vertical lapse rate. A value of 0.65°C per 100 m was used to obtain $\Delta T_A = +2.8°C$ for zone A and $\Delta T_C = -2.5°C$ for zone C.

In the snowmelt period from 8 May to 30 July 1974 a total of 263.7 degree-days has been measured at 2370 m a.s.l., corresponding to an average of 3.14°C · day per day. The greatest number of 10.57°C · day was recorded on 14 July. The cumulative

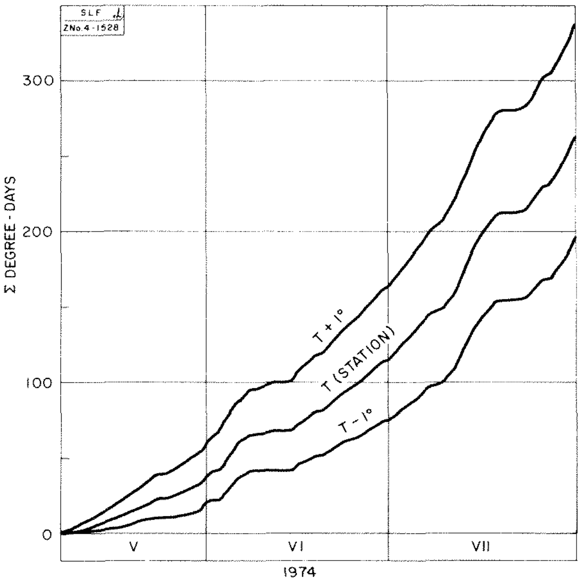

FIGURE 3. Cumulative curves of degree-days for temperatures measured in May–July 1974, for temperatures increased by 1°C and for temperatures reduced by 1°C.

curve is illustrated in Fig. 3. The other cumulative curves refer to a hypothetical change of temperature by +1°C and by –1°C each day.

DEPLETION CURVES OF THE SNOW COVERAGE

In the Dischma basin, the maximum snow accumulation is usually reached in April. From periodical observations during the ablation period, depletion curves of the areal extent of the snow cover can be constructed. Their shape differs each year according to the initial snow accumulation and to the subsequent energy input which is represented by the temperature. Since the meltwater volume is the product of the snowmelt depth and of the snow-covered area, the depletion curves are important for snowmelt–runoff computations.

If runoff patterns are simulated for hypothetical temperatures, the depletion curves of the snow coverage obtained in the given year (that is to say with a given starting accumulation of snow) must be also modified. The snow-covered area is reduced for example to 50 per cent not because a certain number of days elapsed but because a certain number of degree-days occurred. Relations between the snow coverage and accumulated degree-days in 1974 are plotted in Fig. 4. In zone A the areal extent of snow decreases more quickly than in the upper zones, since there is a smaller initial water equivalent of snow.

In 1974, depletion curves drawn in Fig. 5 result from degree-days plotted for zone B in Fig. 3. If temperatures are artificially increased or decreased as shown in Fig. 3, the resulting depletion curves plotted in Fig. 5 are obtained by using Fig. 4. For example the snow cover in zone B requires 120 degree-days to be reduced to 50 per cent of the total area. From Fig. 3, this total of degree-days is reached roughly on 19 June for the increased temperatures and on 12 July for the reduced temperatures. Therefore the modified depletion curves in Fig. 5 reach 50 per cent also on these respective dates.

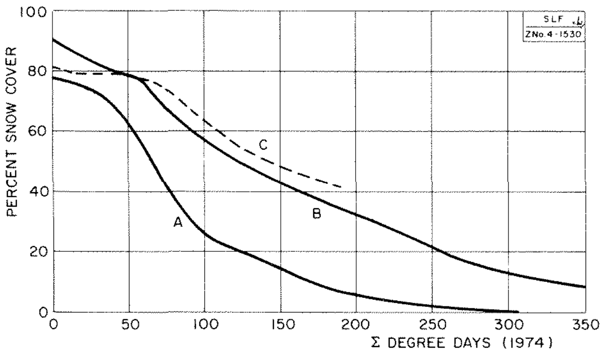

FIGURE 4. Relations between the accumulated degree-days and the areal extent of the snow cover in 1974.

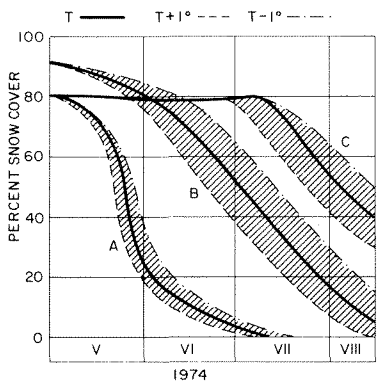

FIGURE 5. Depletion curves of the snow coverage in 1974, modified curves for hypothetical warm and cold temperatures.

SNOWMELT–RUNOFF SIMULATION

In the snowmelt–runoff model which has been described elsewhere (Martinec, 1975) the snowmelt is computed as follows:

$$M = a \cdot T \tag{1}$$

where

M is the snowmelt depth [cm];
a is the variable degree-day factor [cm °C^{-1} day^{-1}]; and
T is the number of degree-days [°C · day].

The meltwater volume is transformed into discharge on a daily basis:

$$Q_n = c_n (M_n \cdot S_n + P_n)(1 - k_n) + Q_{n-1} \cdot k_n \tag{2}$$

where

Q is the daily runoff depth [cm];
c is the runoff coefficient expressing the losses;
S is the snow coverage as a decimal number;
P is the precipitation contributing to runoff [cm];

$k = Q_{m+1}/Q_m$ is the recession coefficient;
n refers to the sequence of days; and
m refers to the sequence of days in a period of recession.

It should be noted that k is related to Q:

$$k = u \cdot Q^{-v} \tag{3}$$

where the values of u and v must be determined for the given basin. Figure 6 shows that the precipitation, too, should be measured in the basin. Rainfalls recorded by the automatic station coincide with discharge peaks at the outlet of the basin. In a distance of only 17 km from the station, no rain was measured which would correspond to the sharp discharge peak.

Figure 7 gives an example of a snowmelt–runoff simulation compared with the actual runoff in the Dischma basin. The degree-days were measured by the automatic meteorological station, the degree-day ratios ranged from 0.4 to 0.55 cm $°C^{-1}$ day^{-1}, c was in the range 0.7–1.0, k was computed by equation (3) with u, v determined

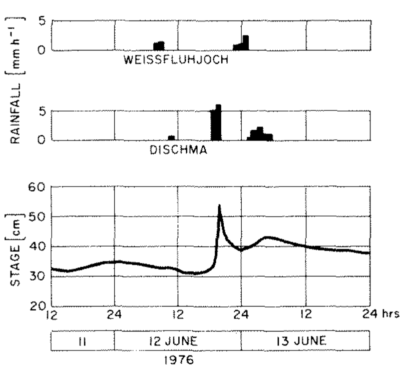

FIGURE 6. Coincidence between rainfalls measured directly in the Dischma basin and discharge peaks in comparison with rainfall measurements 17 km away.

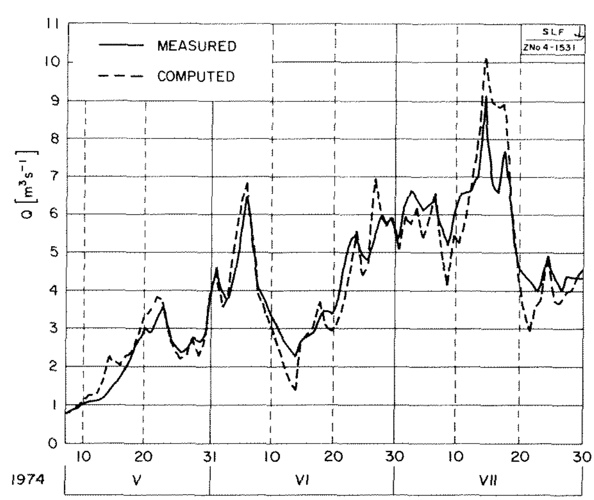

FIGURE 7. Comparison between the computed and measured runoff in the Dischma basin.

for the Dischma basin. The snow coverage was evaluated from air photographs for the previously defined zones A, B, and C. The recent progress in remote sensing (Rango and Itten, 1976; Haefner, 1979) offers new possibilities to monitor the snow cover.

RUNOFF FORECASTS

For operational forecasts, an automatic meteorological station must transmit the data each day in order to update the model computations. The areal extent of the snow cover should be known within a few days from each observation date. The range of short term forecasts of the snowmelt runoff depends on temperature forecasts.

If a long term assessment of runoff patterns is required, statistical temperature data can be used which characterize for example a warm or a cold season. To illustrate this effect, the runoff from the Dischma basin in 1974 has been computed for temperatures indicated in Fig. 3. The corresponding modified depletion curves of the snow coverage (Fig. 5) have been used. The interpretation of precipitation either as new snow or as rainfall has been also adapted to the new conditions. The snowmelt runoff for a cold and warm season is illustrated in Fig. 8. In the early stages a higher

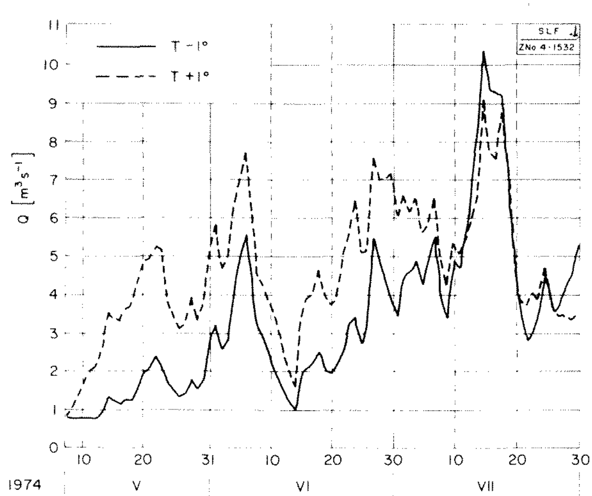

FIGURE 8. Hypothetical runoff simulated for an artificial increase and decrease of temperatures measured in the snowmelt season 1974.

runoff results from higher temperatures. At the same time the areal extent of the snow cover is reduced more quickly. This leads later to a reversed effect: in the middle of July, low temperatures produce a higher discharge peak than high temperatures. Since the initial water equivalent of snow and the subsequent precipitation amount remain the same, the hypothetical changes of temperatures can only redistribute the runoff. When the last snow disappears, approximately the same total runoff volume is reached as with the real temperatures. Certain differences might result if the amount of losses is affected by the new runoff pattern.

The situation is different if temperature deviations result from a false temperature lapse rate which is used for the extrapolation. In this case the original depletion curves of the snow coverage together with false temperatures produce false runoff volumes. Serious errors can occur, especially if the temperature is measured outside the elevation range of the basin.

For example, the average elevation of the Dinwoody Creek basin in the Rocky Mountains is about 1500 m higher than the nearest temperature measuring station. Consequently a change of the lapse rate of 0.1°C per 100 m causes a change of temperature of 1.5°C. Lapse rates of 0.9°C per 100 m in June and 0.95°C per 100 m in July have been assessed for this semiarid region and used for a satisfactory runoff simulation (Martinec and Rango, 1979). If a lapse rate of 0.8°C per 100 m is used instead, an exaggerated runoff is computed as shown in Fig. 9.

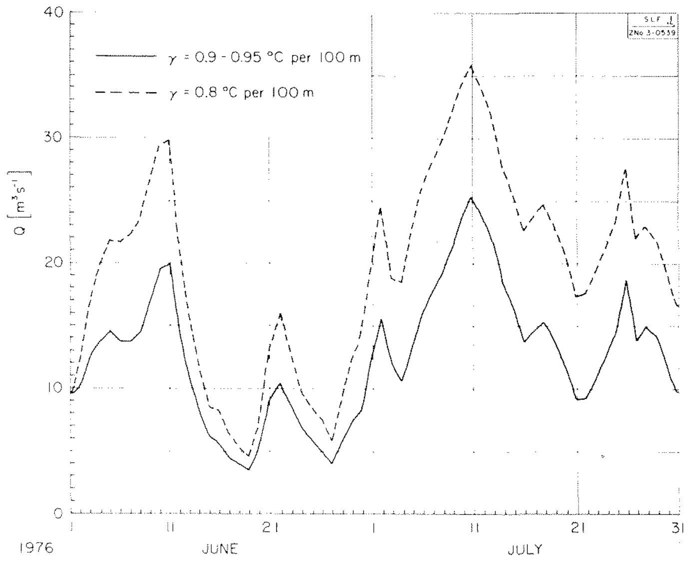

FIGURE 9. The effect of a false temperature lapse rate on the computed runoff in the Dinwoody Creek basin (Rocky Mountains). The temperature is extrapolated from a low station situated outside the basin.

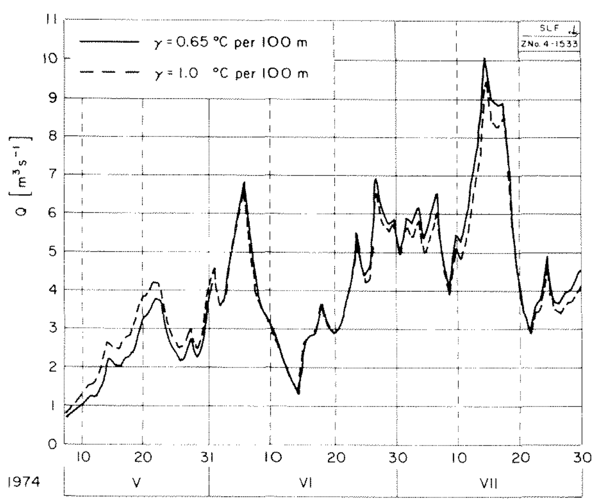

FIGURE 10. The effect of different temperature lapse rates on the computed runoff in the Dischma basin minimized by measuring the temperature at the average altitude of the basin.

In the Dischma basin, the sensibility of model computations to a false assessment of the temperature lapse rate is reduced by measuring temperatures at the average altitude. Figure 10 shows that even a change of the lapse rate from 0.65 to 1.0°C per 100 m has very little effect on the simulation of runoff.

CONCLUSION

The outlined deterministic approach to snowmelt–runoff forecasting requires data on air temperatures representative for the given basin and an efficient monitoring of the areal extent of the seasonal snow cover. Automatic meteorological stations and remote sensing techniques improve the possibilities to obtain these data not only for research projects, but also for operational purposes.

REFERENCES

Haefner, H. (1979) Digital mapping of the mountain snowcover under European conditions. In *Operational Applications of Satellite Snowcover Observations* (NASA Final Workshop in Sparks, Nevada) (in press).

Martinec, J. (1975) New methods in snowmelt–runoff studies in representative basins. In *The Hydrological Characteristics of River Basins* (Proceedings of the Tokyo Symposium, December 1975), pp. 99–107: IAHS Publ. no. 117.

Martinec, J. and Rango, A. (1979) Discharge forecasts in mountain basins based on satellite snow cover mapping. In *Operational Applications of Satellite Snowcover Observations* (NASA Final Workshop in Sparks, Nevada) (in press).

Rango, A. and Itten, K. I. (1976) Satellite potentials in snowcover monitoring and runoff prediction. *Nordic Hydrol.* 7, 209–230.

Strangeways, I. C. and McCulloch, J. S. G. (1965) A low priced automatic hydrometeorological station. *Bull. Int. Ass. Hydrol. Sci.* X, no. 4, 57–62.