Nordic Hydrology, 12, 1981, 265-274

Accuracy of Snowmelt Runoff Simulation

A. Rango and J. Martinec

Goddard Space Flight Ctr., Greenbelt, MD, U.S.A., and
Fed Inst. for Snow and Avalanche Res.,
Weissfluhjoch/Davos, Switzerland.

Results of runoff simulations from various basins using a snowmelt runoff model were analyzed in order to predict the accuracy of simulations in future applications of the model. It was found that the model can be applied to nearly any mountainous basin where snowmelt runoff is an important factor if input data on temperature, precipitation, and snow cover are available. The simulation accuracy will depend on the quality of the input data as well as on the density of observations, size of the basin, care in determination of the recession coefficient, and amount of precipitation during snowmelt. Most accurate simulations will result when: 1) temperature and precipitation are recorded at the basin mean elevation; 2) snow cover observations are available once per week; 3) several climatic stations are available for large basins; and 4) a few years of runoff records exist for determination of the recession coefficient. Decreases in simulation accuracy will be expected as these optimum conditions are compromised, however, acceptable simulations will result with the following minimum conditions: 1) temperature and precipitation data are available in the general vicinity of the basin; and 2) snow cover observations are available 2-3 times during the snowmelt season. The availability of satellite observations of snow cover extent has permitted successful application of the model to large basins.

Introduction

A snowmelt runoff model described earlier (e.g., Martinec 1975a) uses air temperature, snow coverage, and precipitation during the snowmelt period as essential input data. A good quality of measurements was ensured in the well-equipped small representative basins where this procedure was developed. Less favorable conditions for measuring temperature and precipitation have been encountered in the subsequent applications of the model in larger basins in which only data from the normal hydrometeorological network were available. Although the model appears to be adaptable to an increased size and elevation range of a basin, its performance is likely to deteriorate with the decreasing quality of basic data.

Results from various basins are analyzed with the aim to predict the accuracy of the runoff simulation in future applications of the model.

Computing Procedure and Selected Basins

The previously mentioned variables appear in a simplified recapitulation of the model as follows

$$R_n = c_n(a_n T_n S_n + P_n)(1-k_n) + R_{n-1} k_n \tag{1}$$

where

R_n – The daily runoff depth [cm]
c_n – the runoff coefficient
a_n – degree-day factor [cm x °C^{-1} x d^{-1}]
T_n – the number of degree-days [°C x d]
S_n – the snow coverage (100% = 1.0)
P_n – the precipitation contributing to runoff [cm]
k_n – the recession coefficient
n – an index referring to the sequence of days

In larger basins, the runoff is obtained by adding inputs from several elevation zones. The runoff depth is usually converted into discharge in m^{3}s^{-1}. Various parameters of the selected basins are listed in Table 1.

Modry Dul (Dincer et al. 1970) and Dischma (Martinec 1975b) are situated in Central Europe, and Dinwoody (Rango and Martinec 1979) and Bull Lake (Rango 1980) in the Rocky Mountains (U.S.A.). They are all mountain basins with a runoff regime significantly influenced by snowmelt. The size and shape of these watersheds are illustrated in Fig. 1.

Table 1 – Characteristics of basins used for model testing

Basin	Area (km^2)	Elevation Range (m.a.s.l.)	Number of Elevation Zones	Average Yearly Runoff Depth	Approx. Duration of Snowmelt Period (months)
Modry Dul	2.65	1,000 - 1,554	1	1,797 mm	1.5
Dischma	43.3	1,668 - 3,146	3	1,202 mm	3
Dinwoody	228	1,981 - 4,202	4	525 mm	6
Bull Lake	484	1,790 - 4,185	4	486 mm	6

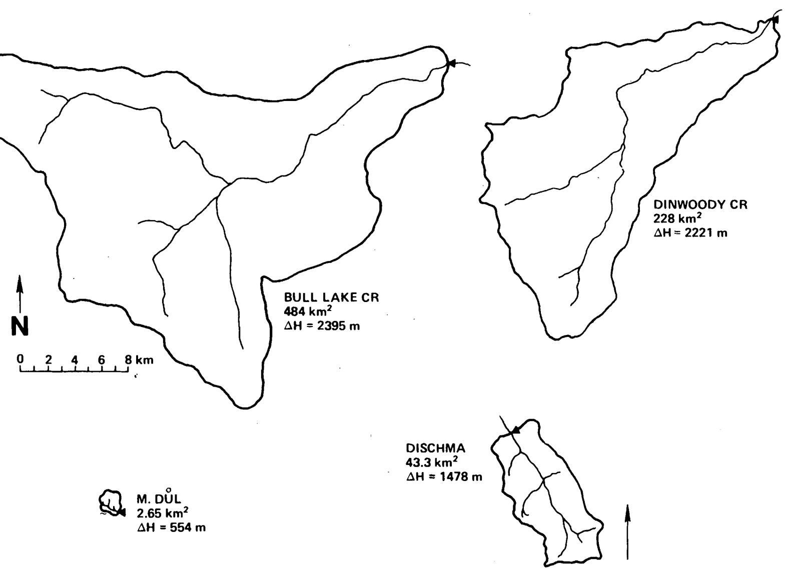

Fig. 1. Area, shape, and elevation range ($\triangle H$) comparison of basins tested.

Results of Runoff Simulations

The variables and parameters of the model are either measured or determined beforehand. This approach is preferred to optimization techniques aiming at the best possible agreement between the simulated and measured values. Thus, an application of the model in a new basin requires a specific assessment of certain factors, particularly the recession coefficient and runoff coefficent, but not a calibration by data sets from the past. Day-by-day computations of discharge are carried out throughout the snowmelt period without an updating by the measured discharge values.

The following criteria are used to evaluate the accuracy of simulation

$$D_v = \frac{V_c - V_m}{V_m} \tag{2}$$

where

D_v – a volumetric difference for the whole snowmelt period [%]
V_m – the measured runoff volume [m^3]
V_c – the computed runoff volume [m^3]

and

$$R^2 = 1 - \frac{\sum(Q_m - Q_c)^2}{\sum(Q_m - \bar{Q})^2} \tag{3}$$

where

R^2 – a measure of model efficiency (Nash and Sutcliffe 1970)
Q_m – the measured runoff on consecutive days of the snowmelt period [m^3s^{-1}]
Q_c – the computed runoff on consecutive days of the snowmelt period [m^3s^{-1}]
Q – the average runoff from the snowmelt period [m^3s^{-1}]

Results are listed in Tables 2 and 3 together with some indicators of the quality of temperature and precipitation measurements. The snow coverage as a further variable is assessed in the subsequent paragraph, followed by the recession coefficient and the time lag as model parameters to be determined. The remaining parameters of Eq. (1), *c* and *a*, also influence the accuracy of the runoff simulation, but an evaluation of this effect exceeds the scope of this paper.

Table 2 – Quality of temperature input data and model performance

Basin	Area per one station (km^2)	Distance of Extrapolation Vertical (m)	Distance of Extrapolation Horizontal (km)	Frequency of Measurements (hr^{-1})	D_v(%)
Modry Dul	2.65	280	1	continuous record	+ 1.7
Dischma	43.3	0	0	1	– 0.65
Dinwoody	228	1,860	85	1	+ 3.3
Bull Lake	484	1,850	60	1	+ 4.8

Table 3 – Quality of precipitation input data and model performance

Basin	Area per one station (km^2)	Distance of Extrapolation Vertical (m)	Distance of Extrapolation Horizontal (km)	Snowmelt Period Precipitation/ Measured Runoff	R^2
Modry Dul	1.32	90	0.7	0.12	0.95
Dischma	43.3	170	14	0.60	0.83
Dinwoody	228	1,860	85	0.30	0.85
Bull Lake	484	1,850	60	0.38	0.82

Effect of Temperature Data

Point measurements of the air temperature must be extrapolated to the average hypsometric elevation of the basin in order to determine the number of degree-days in Eq. (1). If the basin is divided into several elevation zones, the temperature is extrapolated to the respective zonal average hypsometric elevations using the hypsometric curve of the basin (Fig. 2).

The degree-day numbers thus determined directly influence the computed snowmelt-runoff volume. In Modry Dul, the deviation, D_v, listed in Table 2 is probably due to the eccentric position of the temperature station and to the

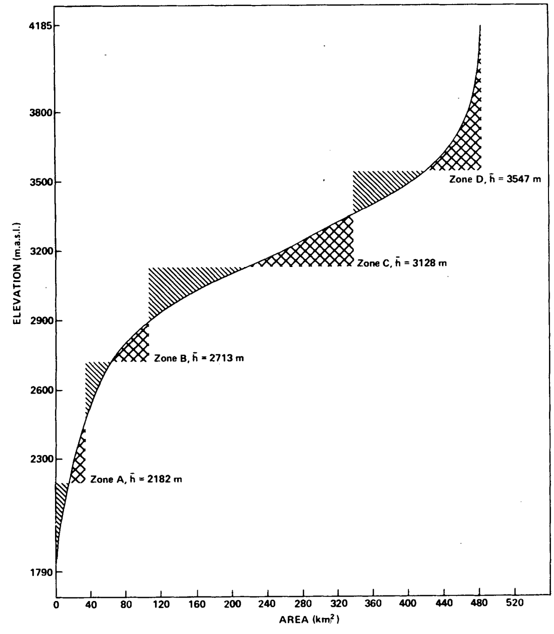

Fig. 2. Determination of zonal mean hypsometric elevations ($\bar{h}$) using an area-elevation curve for Bull Lake Creek.

vertical extrapolation by a lapse rate. In Dischma, this deviation is smaller because the temperature is measured in the representative point of the basin at the average hypsometric altitude. In the larger basins of Dinwoody and Bull Lake, deviations become more significant due to the considerable vertical distance of extrapolation, as well as to the distance between the basins and the temperature station. In addition, the snowmelt season is longer, as indicated in Table 1, causing more uncertainties in estimating the lapse rate.

The size alone of the Dinwoody and Bull Lake basins is not responsible for the increase of D_v. Runoff simulations in the South Fork basin (559 km^2) and in the Conejos basin (730 km^2) achieve an average volume accuracy of $D_v = +1.4\%$ and $+0.5\%$, respectively (Shafer et al. 1981). However, they have two well-placed temperature stations so that the uncertainties in temperature extrapolations are greatly reduced.

Effect of Precipitation During the Snowmelt Period

Point measurements of precipitation must be interpreted for the basin or, if necessary, separately for the partial areas. The model performance is influenced by the representativeness of precipitation gaging stations for the given basin. As seen in Table 3, the basin Modry Dul has the highest density of precipitation stations and the best measure of model efficiency R^2. The density in the Dinwoody and Bull Lake basins is much smaller than that in Dischma. In addition, the station is situated too low and at a great distance from the Dinwoody and Bull Lake basins. However, these disadvantages are compensated by the small amount of precipitation in the snowmelt period as compared with that in the Dischma basin. Therefore, there is no further deterioration of R^2 in the two bigger basins. A dry climate in the snowmelt period also reduces the uncertainties of determining whether a precipitation event was snow or rain.

Effect of Snow Coverage Data

Errors in determining the snow-covered areas are directly proportional to the resulting errors in the calculated snowmelt thus affecting the volume error D_v. A deterioration of the model efficiency R^2 must also be expected with inadequate data on the snow coverage. In the Modry Dul basin, only terrestrial observations of the snow coverage were available. This was sufficient due to the small size of the basin and a smooth relief of the terrain. In Dischma, the snow coverage was evaluated from orthophotographs. In the Dinwoody and Bull Lake basins, excel-

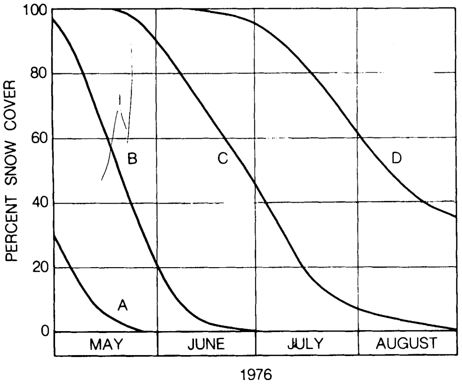

Fig. 3. Landsat-derived snow-cover depletion curves for Bull Lake Creek in elevation zones A, B, C, and D.

lent Landsat data were available which allowed construction of snow-cover depletion curves as shown in Fig. 3. Thus, the data on the snow coverage were good in all cases, and no effect on the values of D_v and R^2 could be evaluated.

Effect of the Recession Coefficient

In all basins investigated so far, the recession coefficient appeared to be related to the discharge as follows

$$k \equiv a\,Q^{-b} \qquad (4)$$

where a, b are constants to be derived for each basin.

Thanks to this characteristic pattern of the recession flow, the snowmelt model automatically eliminates discrepancies between the computed and measured discharges in the process of day-to-day computation, wherever the recession sets in.

Fig. 4a shows a runoff simulation starting with a measured discharge twice as high as the computed value. In about 12 days, this discrepancy is automatically reduced to a minimal level. A similar agreement is reached in Fig. 4b which corresponds to a simulation with an up-dating (substituting the measured value instead of the computed one) on the first day. If the computed discharge is lower than the measured one, a higher value of k results from Eq. (4). Consequently, the computed recession is slower than the actual one, and the deficit is diminishing. If the computed value of discharge is higher than the measured one, Eq. (4) gives a lower value of k than the real one. A more rapid recession results, and the computed values approach the measured runoff from the other side. The necessary condition for this self-adjusting mechanism is a careful assessment of Eq. (4) in the basin in which the model is applied.

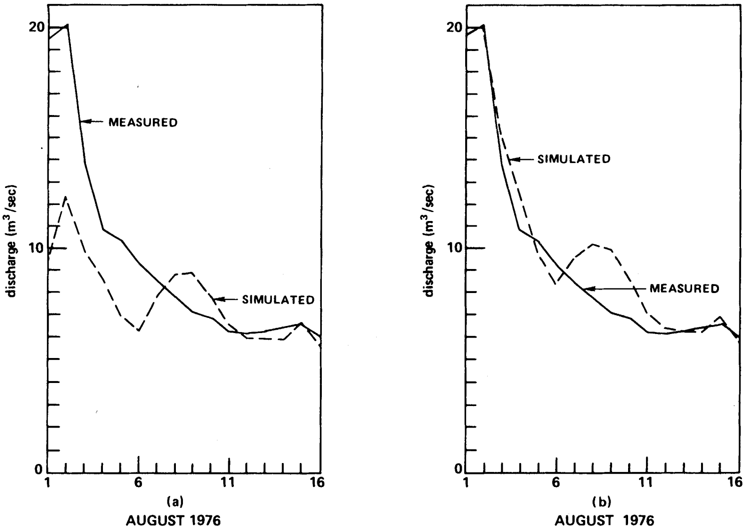

Fig. 4. Discharge simulation in the Dinwoody Creek basin starting with: (a) a large deviation from actual discharge and (b) an updated correct discharge.

Effect of the Time Lag

The time shift between the daily cycles of temperature and discharge is generally short in small mountain basins and becomes longer in bigger mountain basins. In Modry Dul, the time lag is about 4 hours so that the simulated 24-hour periods of discharge always begin at 10:00 hours, assuming the temperature minimum occurring at 6:00 hours.

In the Dischma basin, the simulated 24-hour periods of discharge always begin at 12:00 hours and, in Dinwoody and Bull Lake, at 0:00 hours the next day. Uniform time lags have been used, with no apparent adverse effect on the timing of discharge peaks. This simplified procedure is no longer possible in still bigger basins where different time lags should be evaluated and taken into account in the consecutive stages of the snowmelt season.

Application to New Basins

The model can be applied to nearly any mountainous basin where snowmelt runoff is an important factor if data on temperature, precipitation, and snow cover are available, and reasonable runoff simulations can be expected. The accuracy of these simulations will depend on the quality of the temperature, precipitation, and snow-cover data, as well as on the density of observations, size of the basin, care in determination of the recession coefficient, and amount of precipitation during snowmelt. It can be envisioned that the optimum conditions for accurate runoff simulations will result when: 1) temperature and precipitation are recorded at the hypsometric mean elevation of the basin inside the basin boundaries (or at the zonal mean elevation for large basins); 2) snow cover is available reliably once per week to detect short-term variations in zonal areal extent; 3) several climatological stations are available for large basins, especially in areas with frequent summer precipitation events; and 4) several years of daily runoff records have been acquired for the determination of k. Decreases in accuracy will be expected as these optimum conditions are compromised. However, acceptable simulations will result even under the following minimum conditions: 1) temperature and precipitation data are observed at a base station considerably removed from the basin in both horizontal and vertical distance; 2) snow-cover observations are only available two to three times during the snowmelt season; 3) climatological observations are not possible at multiple stations; and 4) no runoff records are available so that the recession coefficient must be estimated on the basis of a comparison of basin size with previously analyzed basins.

References

Dincer, T., Payne, B.R., Florkowski, T., Martinec, J., and Tongiorgi, E. (1970) Snowmelt runoff from measurements of Tritium and Oxygen-18, *Water Resources Research, 6,* No. 1, pp. 110-124.

Martinec, J. (1975a) Snowmelt- runoff model for stream flow forecasts, *Nordic Hydrology, 6,* No. 3, pp. 145-154.

Martinec, J. (1975b) New methods in snowmelt-runoff studies in representative basins, IAHS Publication No. 117, Symposium of Tokyo, pp. 99-107.

Nash, J.E., and Sutcliffe, J. V. (1970) River flow forecasting through conceptual models; Part I – A discussion of principles, *Journal of Hydrology, 10,* No. 3, pp. 282-290.

Rango, A., and Martinec, J. (1979) Application of a snowmelt-runoff model using Landsat data, *Nordic Hydrology, 10,* pp. 225-238.

Rango, A. (1980) Remote sensing of snow covered area for runoff modelling, Hydrological Forecasting (Proceedings of the Oxford Symposium), IAHS-AISH Publication No. 129, pp. 291-297.

Shafer, B.A., Jones, E.B., and Frick, D.M. (1981) Snowmelt runoff simulation using the Martinec-Rango model on the South Fork Rio Grande and Conejos River in Colorado, NASA AgRISTARS Report CP-G1-04072, Goddard Space Flight Center, Greenbelt, Maryland, 48 pp.

Received: 21 September, 1981

Address:

A. Rango,
Code 924,
Goddard Space Flight Center,
Greenbelt, Maryland 20771,
U.S.A.

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