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Application of a Snowmelt-Runoff Model Using Landsat Data

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The snowmelt-runoff model developed by Martinec (1975) has been used to simulate daily streamflow on the 228 km^2 Dinwoody Creek basin in Wyoming, U.S.A. using snowcover extent from Landsat and conventionally measured temperature and precipitation. For the six-month snowmelt seasons of 1976 and 1974 the simulated seasonal runoff volumes were within 5 and 1%, respectively, of the measured runoff. Also the daily fluctuations of discharge were simulated to a high degree by the model. Thus far the limiting basin size for applying the model has not been reached, and improvements can be expected if the hydrometeorological data can be obtained from a station inside the basin. Landsat provides an efficient way to obtain the critical snowcover input parameter required by the model.

Introduction

A snowmelt-runoff model has been developed on the basis of experimental measurements in two small mountain watersheds of central Europe (Martinec 1975). In the present study, the model was applied to simulate the snowmelt-runoff in a basin significantly larger than those on which it was developed. The changing areal extent of the seasonal snowcover is an essential variable in this procedure. Progress in satellite remote sensing (Rango and Itten 1976) has enabled aircraft photographs to be replaced by a more efficient monitoring of snowcover by Landsat. Another aim of this study was to test the use of the snowmelt-runoff model under conditions of a normal hydrometeorological network, i.e., a low density of measurement points usually at low elevation stations, in contrast to a well-equipped experimental or representative basin. The model seems particularly amenable to these kinds of data because it is relatively simple and requires as input data only the extent of snowcover, temperature (degree days), and precipitation.

Related Research

Earth resources and environmental satellites have provided a means for the timely, efficient and accurate monitoring of watershed snowcovered area. Rango and Itten (1976) describe several techniques available for analysing the data ranging from simple photointerpretation to automated digital methods. The most appropriate method should be selected based on required accuracy, turn-around time, existing remote sensing expertise, and facilities available. Rango and Itten (1976) indicate that snowcovered area measurements from Landsat are as accurate as aircraft surveys, less expensive and hazardous, and can be used to cover much more extensive areas.

The satellite-derived snow extent data have shown significant promise for use in seasonal streamflow estimation. Rango, Salomonson, and Foster (1977) used meteorological satellite snow extent data to derive a regression relationship between early April snowcovered area and April-June seasonal yield on the Indus River in Pakistan. In large data sparse areas such as these, the snowcovered area data may be the only available hydrologic information. Thompson (1975) in Wyoming found that the snowcovered area on a particular date was better related to the runoff accumulated up to the date of the Landsat pass expressed as a percentage of the seasonal runoff than to just the seasonal runoff. Such relationships are not only useful for volumetric flow forecasts but also for short term estimates of time distribution of seasonal runoff. Long-term snowcovered area data from aircraft and, subsequently, from Landsat have been found to be useful in reducing seasonal runoff forecast error when incorporated into procedures to update water supply forecasts as the melt season progresses (Rango, et al. 1979). This study found that snowcovered area will be most effective in reducing forecast error on watersheds with substantial area in a limited elevation range, erratic precipitation or snowpack accumulation patterns, and poor coverage by precipitation stations or snow courses.

Regarding the use of snowmelt runoff models for daily flow simulation Viessman (1968) states that the areal extent of the snowpack must be known as this relates to the potential snowmelt contribution from a basin and to initial ground conditions which materially affect the disposition of melt water or rainfall. Models such as by Martinec (1975) or the Streamflow Synthesis and Reservoir Regulation (SSARR) model (U.S. Army Corps of Engineers 1975) recognize this and call for direct input of snowcovered area. The effects of elevation in relation to snowcovered area have been considered by various investigators. Martinec (1970) provides the option of treating snowcover in 500 m elevation zones, whereas the SSARR model has been modified by Speers, Kuehl, and Schermerhorn (1979) for snowmelt runoff simulation utilizing up to 20 elevation bands. The Swedish HBV model also has the capability of handling snowcover in 10 different elevation zones in a basin, assuming uniform snow conditions within each band (Bergström 1979). Several hydrologic models, although not originally requiring snowcover input, have been modified to accept satellite snow extent data for the generation of daily discharge values (Leaf 1975; Hannaford 1977).

Characteristics of the Test Site

Previous applications of the snowmelt-runoff model have occurred on a variety of small experimental watersheds in Europe. They are shown in Fig. 1 in comparison with the watershed used in this study, the Dinwoody Creek basin in west central Wyoming, U.S.A. Dinwoody Creek is in the Rocky Mountains, whereas Modrý Důl is in the Krkonoše Mountains, Lago Mar in the Pyrenees, Lainbachtal in the Bavarian Alps, and the Dischma basin in the Swiss Alps.

Dinwoody Creek is located in the portion of the Rocky Mountains referred to as the Wind River Mountains where the range of elevation is from about 2,000 m to 5,000 m. Two major rivers rise out of the Wind River Range, namely, the

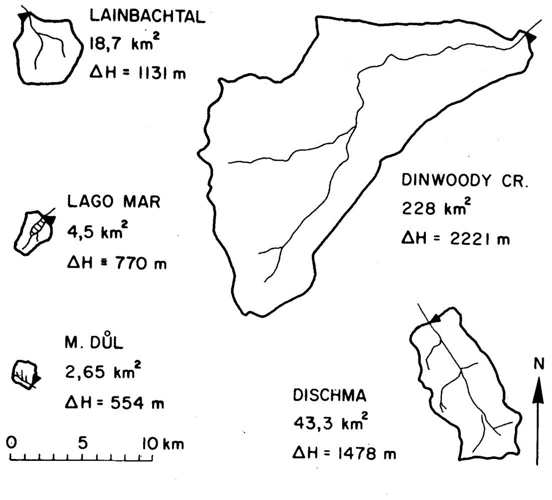
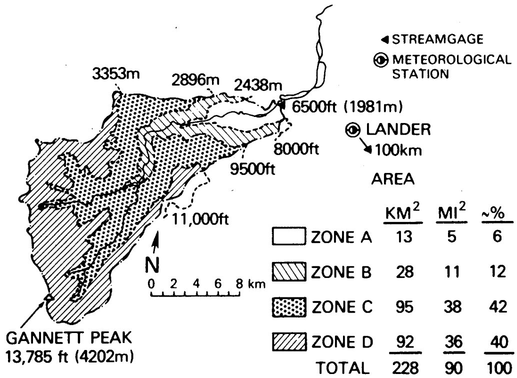


Fig. 1. Area and elevation range (ΔH) of basins in which the snowmelt-runoff model (Martinec 1975) has been applied.



	KM^2	MI^2	~%
☐ ZONE A	13	5	6
▧ ZONE B	28	11	12
▒ ZONE C	95	38	42
▨ ZONE D	92	36	40
TOTAL	228	90	100

Fig. 2. Elevation zones and areas of the Dinwoody Creek basin.

Green and Wind Rivers, and flow diversions for irrigation are numerous; only in the extreme headwaters or on small tributary streams do relatively unimpaired records exist. Dinwoody Creek is a tributary to the Wind River and flows from southwest to northeast. As shown in Fig. 2 the streamgage is at 1,981 m, and the highest point is 4,202 m.

The Dinwoody Creek basin is typical of many in the western United States in that although it has a high water yield from melting snow no conventional hydrometeorological measurements are made inside the basin. Hourly temperature and precipitation are measured by the National Weather Service in the valley at Lander, Wyoming at an elevation of 1,696 m and 100 km from Dinwoody Creek, and these data were used for input to the snowmelt-runoff model. The U.S. Soil Conservation Service measures snow depth and density at 3,100 m inside the basin on the 1st of each month from February to May. Streamflow is measured year-round at the streamgage by the U.S. Geological Survey. The areal extent of snowcover used in the study was extracted from all available 0.6-0.7 μm band

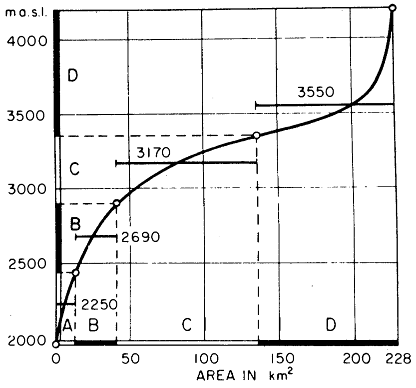


Fig. 3. Area-elevation curve of the Dinwoody Creek basin with the hypsometric mean altitude of each zone shown.

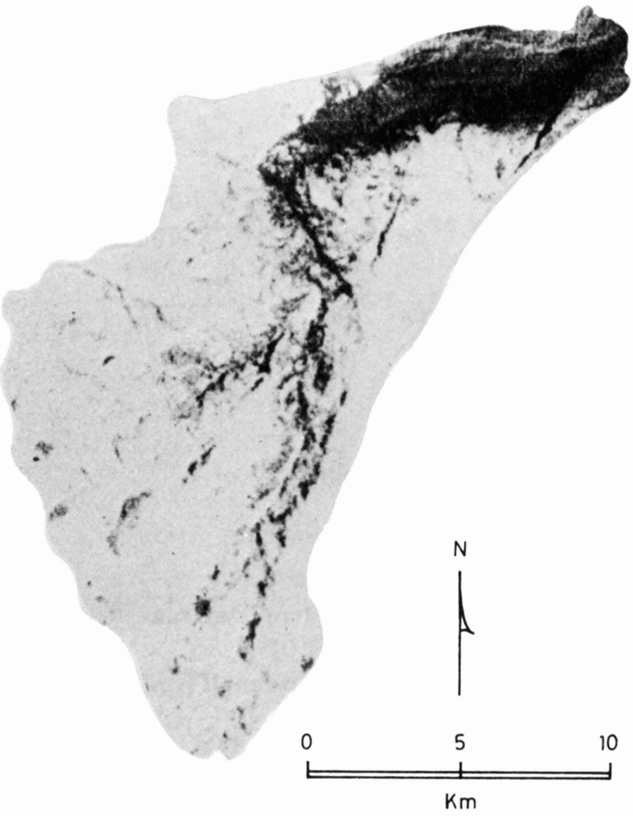


Fig. 4. Landsat image of the Dinwoody Creek basin on 14 May 1976.

images from Landsat and evaluated separately for the elevation zones shown in Fig. 2. Fig. 3 shows the area-elevation curve for Dinwoody Creek with the hypsometric mean elevation of each zone indicated. Fig. 4 is a Landsat image of the Dinwoody Creek basin that was used for snow mapping as viewed through a mask of the watershed boundary.

Application of the Model in the Dinwoody Creek Basin

The deterministic approach used in the development of the model facilitates its application in new conditions. For the Dinwoody Creek basin, it was merely found necessary to increase the number of elevation bands to four as shown in Fig. 2 and to take into account a longer time lag in comparison with the Dischma basin. The model equation (Martinec 1975) was thus rearranged as follows:

$$
\begin{aligned}
Q_{n+1} \equiv c_n \Big\{ & [a_{An}(T_n + \Delta T_{An})\, S_{An} + P_{An}] \frac{A_A \cdot 10^{-2}}{86400} \\
+ & [a_{Bn}(T_n + \Delta T_{Bn})\, S_{Bn} + P_{Bn}] \frac{A_B \cdot 10^{-2}}{86400} \\
+ & [a_{Cn}(T_n + \Delta T_{Cn})\, S_{Cn} + P_{Cn}] \frac{A_C \cdot 10^{-2}}{86400} \\
+ & [a_{Dn}(T_n + \Delta T_{Dn})\, S_{Dn} + P_{Dn}] \frac{A_D \cdot 10^{-2}}{86400} \Big\} \\
& (1 - k_{n+1}) + Q_n\, k_{n+1} \qquad (1)
\end{aligned}
$$

where

Q is the average daily discharge [m^3s^{-1}]
c_n is the runoff coefficient
a_n is the degree-day factor [cm · °C^{-1} · d^{-1}]
T_n is the measured number of degree-days
ΔT_n is the correction by the temperature lapse rate [°C·d]
S_n is the snow coverage (100% = 1.0)
P_n is the precipitation contributing to runoff [cm]
A is the area [m^2]
k_n is the recession coefficient
n is an index referring to the sequence of days
A, B, C, D as subscripts refer to the four elevation zones
$\frac{10^{-2}}{86400}$ converts cm·m^2 per day to m^3s^{-1}

Values determined for certain model parameters are pertinent throughout the entire snowmelt season. The watershed area of Dinwoody Creek as obtained from topographic maps was 228 km^2 with 13 km^2 for zone A, 28 km^2 for zone B, 95 km^2 for zone C, and 92 km^2 for zone D. The recession coefficient is determined from the equation

$$k = 0.884\, Q^{-0.0677} \qquad (2)$$

where Q is discharge in m^3sec^{-1}.

The equation was derived by plotting Q_n against Q_{n+1} for recession flow cases for 1973-1976. From the envelope of points defined it is possible to determine k for any desired Q. By plotting k versus Q on log paper, a straight line can be defined and its equation determined (Fig. 5). It is evident that k increases with decreasing Q. The result for Dinwoody Creek confirms the experience of k generally being greater in larger basins. From analysis of the hydrographs, the time lag for Dinwoody Creek is approximately 18 hours, i.e., snowmelt runoff

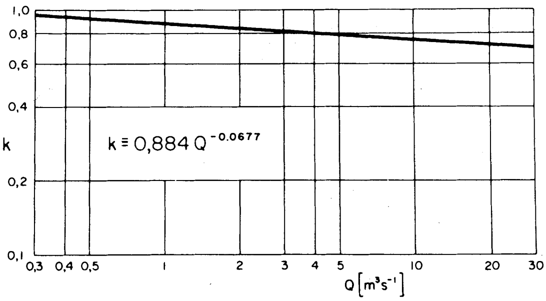


Fig. 5. Relation between the recession coefficient k and the discharge Q for Dinwoody Creek.

from the basin starts rising at about midnight so that temperatures from 0600 to 0600 hours correspond to discharge from 2400 to 2400 hours.

Other model parameters logically change throughout the snowmelt season and can be adjusted every 15 days, if necessary. The degree day factor, a was shown by Martinec (1960) to be related to the relative snow density, ρ, by the equation $a = 1.1\rho$. Thus the general seasonal increase in ρ could be used as an index for the increase in a. The Dinwoody Creek basin a was gradually increased from 0.35 on 1 April to 0.60 on 30 September in zone D. In view of the length of the snowmelt season, seasonal variations of other parameters have to be evaluated. Based on sparse information on climate (Barry and Chorley 1970), the temperature lapse rate was estimated to be higher in the Wind River Mountains than in the Alps and to vary from 0.85°C per 100 m in April to 0.95°C per 100 m in July to 0.80°C per 100 m in September. A lack of direct measurements prohibits the actual determination of the lapse rate. Regional differences between the meteorological station at Lander airport and the mountainous basin were accounted for by subtracting up to 2°C from the Lander data. The runoff coefficient was also assumed to vary during the season; it was estimated in the range from 0.85 in April to 0.75 in July to 0.90 in September.

Three variables need to be currently assessed for model calculations of daily snowmelt runoff, namely, snowcovered area, temperature (degree days), and precipitation. Landsat 0.6-0.7 μm images are used at a scale of 1:1,000,000 with a zoom transfer scope which allows registration and interpretation of the snowcover on Dinwoody Creek at 1:250,000 scale. The snowline is traced across the entire watershed and then the snowcovered area is planimetered manually in each of the four elevation zones. The points for each Landsat pass are used to construct a temporal snowcover depletion curve for each zone. Once the depletion curves for the April-September period are drawn, the daily snowcover values are read off and substituted into Eq. (1).

Air temperature expressed in degree days is used in this simple model as an index of snowmelt. For the Dinwoody Creek basin the Lander airport temperature data were used. The number of degree days for each 24 hour period is determined by summing the hourly temperatures and dividing by 24 and using 0°C as the base temperature. Temperatures below the freezing point are regarded as 0°C. Maximum and minimum temperatures could also be used in this degree day determination. The degree day figures refer to the 24 hour periods starting at 0600 hours. These temperature data are extrapolated to the hypsometric mean elevation of the respective elevation zone by the previously discussed temperature lapse rate. The resulting degree days are used for calculating snowmelt. Extrapolation errors would be minimized if the temperature was measured in the basin and near the mean elevation.

Daily precipitation amounts at Lander were employed to satisfy the model input requirements. Lacking an acceptable method for extrapolating the precipitation data both horizontally and vertically, the Lander data were used as zonal inputs as recorded. Again, measurement of precipitation in the basin would greatly aid in the application of the model for snowmelt runoff simulation. For the final snowcovered area determinations, the sequence of precipitation events at Lander was used for identification of late season transient snowfall temporarily causing an increase in snowcovered area but not contributing to the snowmelt hydrograph.

Once all the necessary input data were prepared on a daily basis, Eq. (1) was used to calculate snowmelt depths by zones and to transform these values to runoff by the previously mentioned recession techniques. In the Dinwoody Creek basin snowmelt starts about 1 April and continues well into September. The model was used to simulate daily streamflow from 1 April-30 September for 1976 and 1974. Specific parameter values decided on before running the model were used throughout. An optimization of these values with the aim to improve the agreement of the computed and measured runoff did not appear necessary. Model runs both with no updates through the entire period and with runoff updates every two months were performed. This updating provided certain improvements in simulations, but because possible application on ungaged watersheds is of considerable interest, only simulations with no updating will be discussed. Simulated flow was compared with discharge measured at the U.S. Geological Survey streamgage both on a seasonal and daily basis. Total volume differences for the six month period were compared on a percentage basis. To facilitate comparison of the daily discharge amounts a nondimensional «goodness of fit» function was used as proposed by Nash and Sutcliffe (1970) in the following equation:

$$R^2 = \frac{\frac{1}{n}\sum_{i=1}^{n}(q_i - \bar{q})^2 - \frac{1}{n}\sum_{i=1}^{n}(q_i - q_i')^2}{\frac{1}{n}\sum_{i=1}^{n}(q_i - \bar{q})^2} \qquad (3)$$

where

R^2 is a measure of model efficiency
q_i = observed discharge
q_i' = simulated discharge
$\bar{q}$ = mean of observed discharge
n = number of discharge values

The measure of model efficiency that they propose (R^2) is analogous to the coefficient of determination and is a direct measure of the proportion of the variance of the recorded flows explained by the model (Kite 1975).

Results

The changing areal extent of the seasonal snowcover monitored by Landsat is important information for the snowmelt-runoff model. Fig. 6 shows the zonal depletion curves of the snow coverage in 1976. In plotting these curves it is advisable to bear in mind their characteristic shape (Leaf 1967) and to disregard short term deviations which may be caused by occasional snow storms in the summer. This new snow is taken into account as precipitation contributing to runoff on the first melting day after the snowstorm.

With parameters and variables determined on each day as desribed in the previous section, a day-to-day simulation of the runoff was carried out. A temporal comparison with the discharge measured by the U.S. Geological Survey at the outlet of the basin is illustrated in Figs. 7 and 8. Since the simulation was

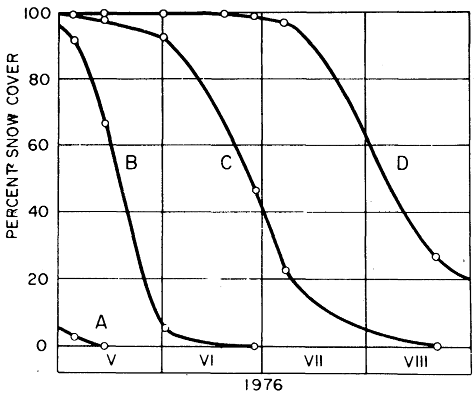


Fig. 6. Depletion curves of snow coverage in the Dinwoody Creek basin in elevation zones A, B, C, and D for May – August 1976.

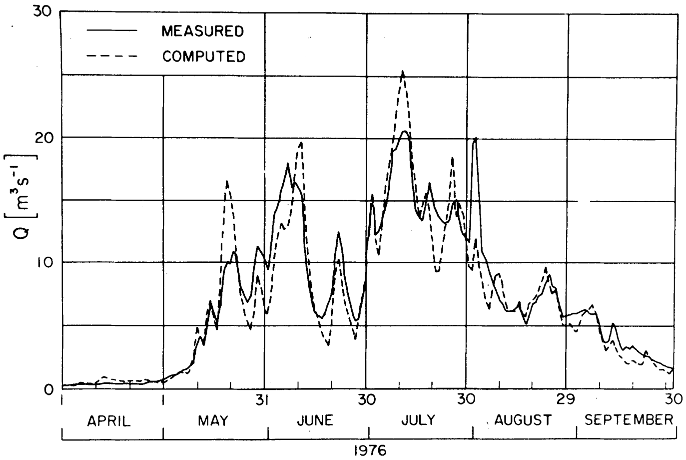


Fig. 7. Simulated and actual streamflow for Dinwoody Creek for April – September 1976.

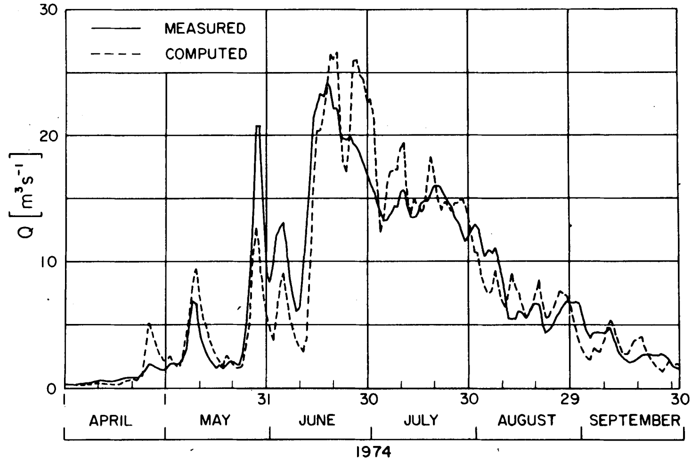


Fig. 8. Simulated and actual streamflow for Dinwoody Creek for April – September 1974.

continued for 6 months without any updating by the actual discharge, these examples indicate possibilities of the runoff simulation in ungaged basins by using Landsat data and temperature measurements.

Comparison on a seasonal basis for 1976 indicates a 5% difference between the 6 month volumes for the computed and measured flows. For 1974 this volumetric difference is only about 1%. Such differences are quite reasonable when compared to conventional simulation procedures. The daily differences in simulated and actual discharge were evaluated using R^2 Eq. (3). For 1976 R^2 was

0.86 and for 1974 it was 0.83. This indicates that about 85% of the variation in the actual daily runoff values is explained by this modeling approach.

The agreement between the simulated and measured runoff could be improved if temperature and precipitation were measured inside the basin. Although there is a procedure for extrapolating the Lander temperature data to the Dinwoody Creek basin it does not take into account the inherent climatic differences between the valley and mountain locations. The uncertainties of temperature extrapolations can be reduced by installing inexpensive automatic meteorological stations (Strangeways and McCulloch 1965) in the areas of interest. The precipitation values assumed for Dinwoody are probably in even greater error because of the same climatic differences. As an example, Johanson (1971) showed that as the precipitation gage density increased from a single gage for a 2,500 mi^2 (6,475 km^2) watershed to one per 250 mi^2 (648 km^2) the calibration error between simulated and recorded flows improved from 19% to almost zero.

An important application of runoff models is, of course, for use in discharge forecasting. Fig. 9 shows different runoff patterns in the two years which have been simulated with a reasonable accuracy. By replacing a simulation based on data from a past season with an operational forecast, the operation of a reservoir for water power generation or for water supply could be improved.

To enhance this prospect, the processing of the Landsat data should be accelerated in order to update the depletion curves of the snow coverage within several days after each satellite overflight. The behavior of the depletion curves in relation to the initial snow accumulation and to subsequent temperatures should be studied enabling extrapolations to be made. The range of short-term discharge forecasts depends on possibilities of temperature forecasts. Statistical temperature

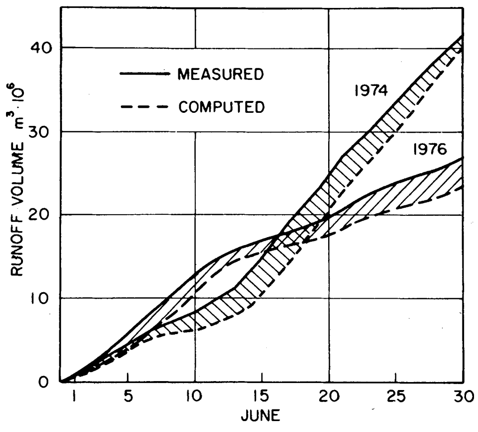


Fig. 9. Cumulative curves of computed and measured runoff volumes for June 1976 and 1974 for Dinwoody Creek.

data can also be used to predict the runoff to be expected with a given probability. In these cases the model does not require information on the water equivalent of the snowcover at the start of the melting season. This value is naturally important for seasonal forecasts of runoff volume, but it can hardly be measured on an areal basis in a large mountain basin. It remains to be seen whether water equivalent can be measured in the future by remote sensing or at least approximately estimated by frequent snowcover monitoring.

Conclusions

The snowmelt runoff model developed by Martinec (1975) was designed to operate under conditions where snowmelt is the major contributor to runoff and in mountain basins with a great elevation range. Originally the model was developed in small basins, but it appears to be applicable in watersheds of several hundred km^2, based on results from the Dinwoody Creek basin in Wyoming. The limiting upper size apparently has not yet been reached. Improved simulation accuracy would most likely result from the location of a hydrometeorological station in the basin at or near the hypsometric mean elevation. In fact, it seems that the quality of the hydrometeorological data has had a more significant effect on simulation accuracy than the increase in basin size from 43 km^2 to 228 km^2. Conversely, snowmelt runoff computations in the Dinwoody Creek basin were facilitated by the relatively low summer precipitation in the area.

Landsat provides the means for obtaining the critical snowcover input parameter required by the snowmelt model on the Dinwoody Creek basin. The satellite platform is the most efficient way to obtain snow extent on a basin of this size. It must be considered, however, that certain locations such as the Swiss Alps or the northwestern United States have a high frequency of cloudiness which severely hampers the effectiveness of Landsat. In such conditions geosynchronous satellites or the use of cloud-penetrating sensors operating in the microwave region must be considered.

The determination of model parameters and variables on a rational basis such as in this model with little or no optimization facilitates its application in new basins. Although only streamflow simulation was attempted in this study, the use of this model for discharge forecasts has great potential. A means of extrapolating the snowcover depletion curves based on more commonly observed parameters, such as temperature and snow water equivalent, would be required. Coupling this with either forecasts of temperature or statistical temperature data would permit use of the model as a water management tool. The fact that the model can provide reasonable flow simulations for a 6 month period without any updating by actual discharge measurements further indicates the possible application to ungaged watersheds.

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References

Barry, R. G., and Chorley, R. J. (1970) *Atmosphere, Weather, and Climate.* Holt, Rinehart, and Winston, Inc., New York, 320 pp.

Bergström, S. (1979) Spring flood forecasting by conceptual models in Sweden, Proceedings of the Workshop on Modeling of Snow Cover Runoff, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, pp. 397-405.

Hannaford, J.F. (1977) Investigation application of satellite imagery to hydrologic modeling snowmelt runoff in the southern Sierra Nevada, Phase 1 Final Report, NAS 5-22957, Goddard Space Flight Center, Greenbelt, Maryland, 48 pp.

Johanson, R.C. (1971) Precipitation network requirements for streamflow estimation, Technical Report 147, Department of Civil Engineering, Stanford University, Stanford, California.

Kite, G.W. (1975) Performance of two deterministic hydrological models, Proceedings of the Symposium on Application of Mathematical Models in Hydrology and Water Resources Systems, IAHS – AISH Publication No. 115, Bratislava, pp. 136-142.

Leaf, C. F. (1967) Aerial extent of snow cover in relation to streamflow in central Colorado, International Hydrology Symposium Proceedings, Fort Collins, Colorado, pp. 157-164.

Leaf, C. F. (1975) Applications of satellite snow cover in computerized short-term streamflow forecasting, in Operational Applications of Satellite Snowcover Observations, NASA SP-391, Washington, D.C., pp. 175-186.

Martinec, J. (1960) The degree-day factor for snowmelt-runoff forecasting, IAHS Publication No. 51, Surface Waters, pp. 468-477.

Martinec, J. (1970) Study of snowmelt runoff process in two representative watersheds with different elevation range, IAHS Publication No. 96, Symposium of Wellington, pp. 29-39.

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

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 Itten, K.I. (1976) Satellite potentials in snowcover monitoring and runoff prediction, *Nordic Hydrology, 7,* pp. 209-230.

Rango, A., Salomonson, V. V., and Foster, J. L. (1977) Seasonal streamflow estimation in the Himalayan region employing meteorological satellite snow cover observations, *Water Resources Research, 14,* No. 2, pp. 359-373.

Rango, A., Hannaford, J.F., Hall, R. L., Rosenzweig, M., and Brown, A. J. (1979) Snow-covered area utilization in runoff forecasts, *Journal of the Hydraulics Divison,* ASCE, Vol. 105, No. HY1, pp. 53-66.

Speers, D., Kuehl, D., and Schermerhorn, V. (1979) Development of the operational snow band SSARR model, Proceedings of the Workshop on Modeling of Snow Cover Runoff, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, pp. 369-378.

Strangeways, C., and McCulloch, J. S. G. (1965) A low priced automatic hydrometeorological station, *Bulletin IAHS,* Vol. X, No. 4, pp. 57-62.

Thompson, A. G. (1975) Utilization of Landsat monitoring capabilities for snowcover depletion analysis, in Operational Applications of Satellite Snowcover Observations, NASA SP-391, Washington, D.C., pp. 113-127.

U.S. Army Corps of Engineers (1975) Program description and user manual for SSARR model – streamflow synthesis and reservoir regulation, Program 724-K5-G0010, North Pacific Division, Portland, Oregon, 188 pp.

Viessman, W. (1968) The synthesis of snowmelt hydrographs, in Snow Hydrology, Proceedings of the National Workshop Seminar, Canadian National Committee, International Hydrological Decade, Frederickton, New Brunswick, pp. 66-79.

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