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REVISITING THE DEGREE-DAY METHOD FOR SNOWMELT COMPUTATIONS[1]

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ABSTRACT: The simple, empirical degree-day approach for calculating snowmelt and runoff from mountain basins has been in use for more than 60 years. It is frequently suggested that the degree-day method be replaced by the more physically-based energy balance approach. The degree-day approach, however, maintains its popularity, applicability, and effectiveness. It is shown that the degree-day method is reliable for computing total snowmelt depths for periods of a week to the entire snowmelt season. It can also be used for daily snowmelt depths when utilized in connection with an adequate snowmelt runoff model for computing the basin runoff. The degree-day ratio is shown to vary seasonally as opposed to being constant as is often assumed. Additionally, in order to evaluate the degree-day ratio correctly, the changing snow cover extent in a basin during the snowmelt season must be taken into account. It is also possible to combine the degree-day approach with a radiation component so that short time interval (<24 hours) computations of snowmelt depth can be made. When snowmelt input is transformed to basin output (runoff) by a snowmelt runoff model, there is little difference between the degree-day approach and a radiation-based approach. This is fortuitous because the physically-based energy balance models will not soon displace the degree-day methods because of their excessive data requirements.

(KEY TERMS: degree-day method; snowmelt; hydrograph analysis and modeling; snow and ice hydrology.)

INTRODUCTION

Snowmelt in the spring of the year is an especially important process in many parts of the world because of its direct link to water supply and other water resource applications. This is particularly true of mountain regions where snowmelt runoff generally makes up at least 50 percent of the total flow and sometimes exceeds a 95 percent contribution (Shafer *et al.,* 1982). In order to estimate this resource better, different types of models are used for forecasting snowmelt runoff, including energy balance and temperature-index or degree-day models. Fully distributed energy balance models working on a basinwide basis are rare, with those developed by Leavesley and Stannard (1990) and Bloschl *et al.* (1991) as examples. Degree-day models operating on a basinwide basis are much more common. Rodriguez (1994) points out that the two most widely used degree-day models were developed by Martinec *et al.* (1983) and Bergstrom (1975).

The degree-day method for snowmelt runoff computations has been used in different ways for more than 60 years (Clyde, 1931; Collins, 1934). It has been repeatedly suggested that degree-day models be replaced by the more detailed energy balance models to improve the accuracy of snowmelt calculations. However, as recently demonstrated in an international comparison of snowmelt runoff models (WMO, 1986), the degree-day method is a standard tool, a favorite with snowmelt runoff modelers and operational hydrologists, and has an accuracy comparable to more complex energy budget formulations. This apparent discrepancy between an assumed improved accuracy with energy balance snowmelt calculations and a continued preference for the degree-day approach results to a large extent from some misconceptions about the degree-day approach that will be the focus of this paper.

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APPLICATIONS OF THE DEGREE-DAY METHOD

The degree-day method calculates the daily snowmelt depth, M (cm), by multiplying the number of degree days, T (°C d), by the degree-day ratio, a (cm $°C^{-1}$ d^{-1}):

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

Linsley *et al.* (1958) defined a degree day as a departure of one degree per day in the daily mean temperature from an adopted reference temperature (in Equation 1 the reference temperature is 0°C and therefore is omitted). Garstka *et al.* (1958) reported that degree days could be calculated not only by using the average of the daily maximum and minimum temperatures, but also by using the daily maximum temperature and the average of the maximum and effective minimum temperatures (where the effective minimum temperature is the actual minimum value unless less than 0°C when the effective minimum is then considered to be 0°C). Most users of the degree-day approach currently use the average of the daily maximum and minimum temperatures in Equation (1), although the average temperature can also be calculated from hourly values.

Although Equation (1) is simple, when it is applied to a basin without considering the difference between the snowmelt (input) and runoff (output) as well as the changing snow cover, some erroneous calculations can result. As shown in Figure 1 for the Coeur D'Alene River basin (3,144 km^2) in Idaho, the first cumulative 500 degree days are "responsible" for 85 percent of the annual runoff and the following 2000 degree days only 15 percent (Collins, 1934). But this does not mean that the degree-day ratio in the first period was 20 times higher than in the second period. Both runoff losses and a declining snow covered area have to be considered.

In another early application of the method, Linsley (1943) found it difficult to determine the actual volumes of snowmelt, so he determined the degree-day ratios (plotted in Figure 2) from temperatures and the basin runoff. The low average ratio for March of 0.1 cm $°C^{-1}$ d^{-1} contrasts with the high ratio by the end of June of 0.7 cm $°C^{-1}$ d^{-1} for two reasons: (1) the runoff in the early part of the snowmelt season does not contain all the meltwater (the remaining meltwater follows later as recession flow and increases the runoff in the latter part of the snowmelt season; and (2) the degree-day ratio from Equation (1) gradually increases as the snow becomes wet, and the decreasing albedo enhances the heat gain from the increasing solar radiation.

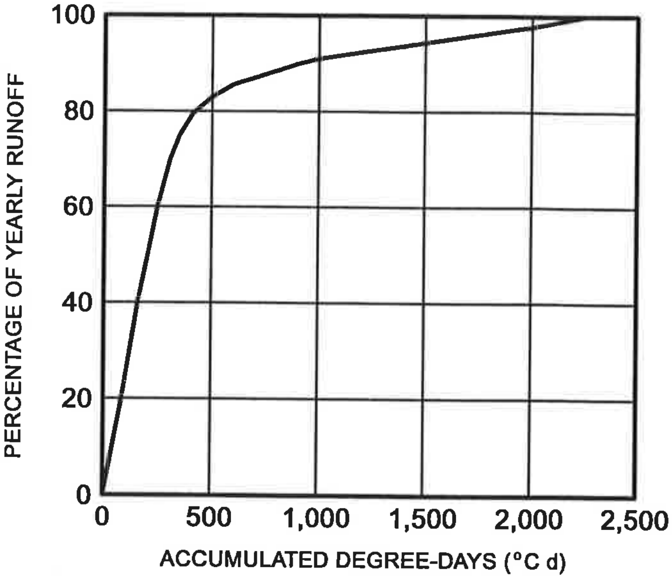

Figure 1. Relation Between Accumulated Degree-Days and Accumulated Runoff Depths in the Coeur D'Alene River Basin, Idaho (after Collins, 1934).

In addition, losses are not taken into account in this evaluation. In order to realistically evaluate the degree-day ratios (factors), it is thus necessary to measure the snowmelt depths. Two different methods have been used:

1. Snow Lysimeter: Zingg (1951) evaluated an overall value of a = 0.45 cm $°C^{-1}$ d^{-1} for the whole snowmelt season at a horizontal test plot at Weissfluhjoch, 2540 m a.s.l.
2. Radioactive Snow Gauge: Martinec (1960) evaluated variable degree-day ratios from differences of the water equivalent of the snowpack on consecutive days.

In both cases the daily values may be distorted by the overlapping of meltwater from a 24-hour period to the next one. This problem is eliminated when the residual meltwater in the snowpack remains about the same by the end of the consecutive 24-hour periods. The results by the two methods are not quite identical because the decrease of the water equivalent results not only from the meltwater which has left the snowpack (Method 1), but also from evaporation at the snow surface (Method 2). Consequently, degree-day ratios from Method 1 might be slightly lower than the ratios obtained by Method 2.

If the degree-day ratios can be assessed for the given conditions, the computed snowmelt can be transformed into the basin runoff by a hydrological model.

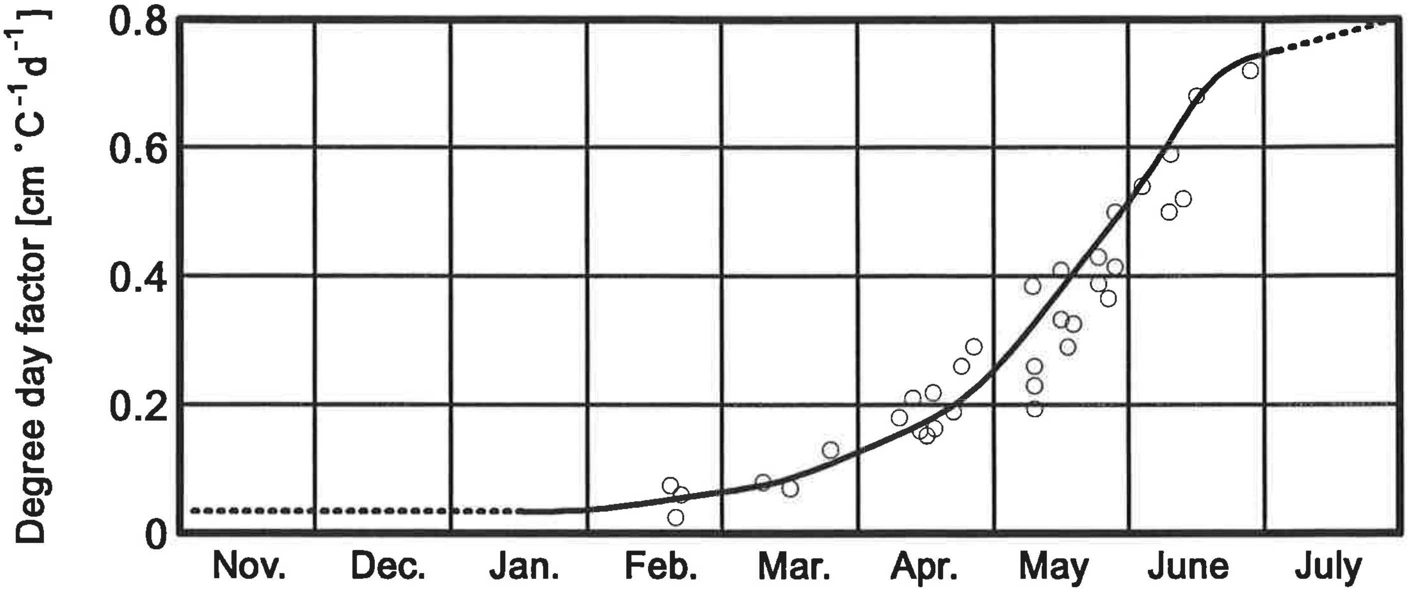

Figure 2. Degree-Day Factors Derived from Basin Runoff During Snowmelt in the San Joaquin River Basin, California (after Linsley, 1943).

VARIABILITY OF THE DEGREE-DAY FACTOR

It has become a common topic of dissertations and papers to compare the accuracy of the degree-day method with the energy balance method. It is to be expected that a complete energy balance is more accurate. The issue is, however, whether the difference is big enough to justify additional installations of measuring instruments and whether the additional variables needed can be extrapolated from point measurements to areal values and forecasted ahead as easily as air temperatures. Through misunderstanding of the degree-day method, the difference in accuracy is often artificially increased so that the desired point can be made with even more emphasis. For example, if a constant, relatively low degree-day ratio is used throughout the entire snowmelt season, the degree-day method starts falling below the measured discharge after about two months (Pipes and Quick, 1987) and its accuracy deteriorates. There are other studies which use a single value of the degree-day factor and, as a result, seem to prove the inaccuracy of the method. Although it is frequently assumed that the degree-day factor is a constant, there is no excuse for this because the variability of the degree-day factor is already well documented. By using appropriate degree-day factors which should gradually increase during the course of the snowmelt season, the accuracy of the degree-day method can be greatly improved.

To apply the degree-day method effectively, guidance must be given to the user on how to evaluate the variable degree-day ratios. The seasonal changes and the influence of the forest are illustrated by the recommended values of Weiss and Wilson (1958):

Beginning April:

Forest	0.185 cm °C^{-1} d^{-1}
Open Area	0.37 cm °C^{-1} d^{-1}

Beginning June:

Forest	0.37 cm °C^{-1} d^{-1}
Open Area	0.74 cm °C^{-1} d^{-1}

Similar values are recommended by the World Meteorological Organization (WMO, 1964) and shown in Table 1.

TABLE 1. Degree-Day Ratios (cm °C^{-1} d^{-1}) as Proposed by the World Meteorological Organization (WMO, 1964).

	Moderate Forest Cover	Partial Forest Cover	No Forest
April	0.2	0.3	0.4
May	0.3	0.4	0.6
June	0.4	0.6	0.7

Seasonal increases of degree-day ratios were also later reported by Bengtsson (1980): "On sites in Sweden at northern latitudes from 57° to 67°N, degree-day factors increased from 0.3 cm $^{\circ}C^{-1}$ d^{-1} in March to 0.5 and 0.6 cm $^{\circ}C^{-1}$ d^{-1} in May."

An early study (Martinec, 1960) showed great variations of degree-day ratios evaluated continuously for 35 days. When the daily ratios were averaged for several days (mostly six-day periods), the values became more consistent and a relationship to the relative density of snow could be established:

$$a\left[cm^{\circ}C^{-1}d^{-1}\right] = 1.1\frac{\rho_s}{\rho_w} \tag{2}$$

where a = the degree-day factor, ρ_s = density of snow; and ρ_w = density of water.

Snow density appears to be a convenient index for evaluating the variable degree-day ratios because it represents snow properties which affect the snowmelt. Apart from temperature itself, snow density is the easiest additional variable to obtain because it is measured operationally once a month and sometimes twice a month. The snow density can also be estimated from the age of the snow cover and settling curves for each snow layer (Martinec and Rango, 1991). Older wet snow with higher density has a lower albedo (Anderson, 1973) (Figure 3) and a high liquid water content, so each degree day (which also represents the radiation component) becomes more melt-efficient. In addition, the solar radiation increases from March to June. These views are also supported by Kuusisto (1980), who derived further relations between the snow density and the degree-day factor:

$$\text{Forest:}\quad a\left[cm^{\circ}C^{-1}d^{-1}\right] = 1.04\frac{\rho_s}{\rho_w} - 0.07 \tag{3}$$

$$\text{Open:}\quad a\left[cm^{\circ}C^{-1}d^{-1}\right] = 1.96\frac{\rho_s}{\rho_w} - 0.239 \tag{4}$$

Equations (3) and (4) are compared with Equation (2) in Figure 4.

The previously mentioned erratic nature of daily values were caused by different variables that affect the degree-day factor like wind speed (Martinec, 1960). Martinec's (1960) results proved that the daily snowmelt depths cannot be accurately computed by the degree-day method. However, as will be explained later, as long as the short-term average factors (for example, biweekly values) are properly selected, the daily errors do not significantly propagate to the computed runoff if a good model for the basin response is used.

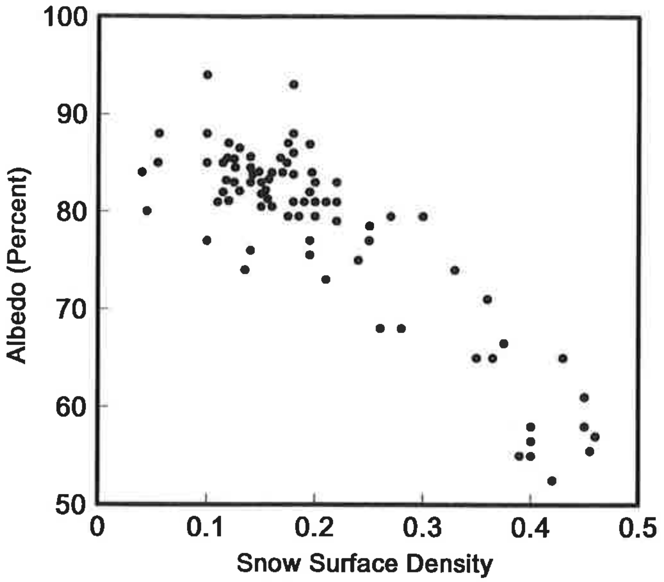

Figure 3. Relation Between Snow Density and Albedo (after Anderson, 1973).

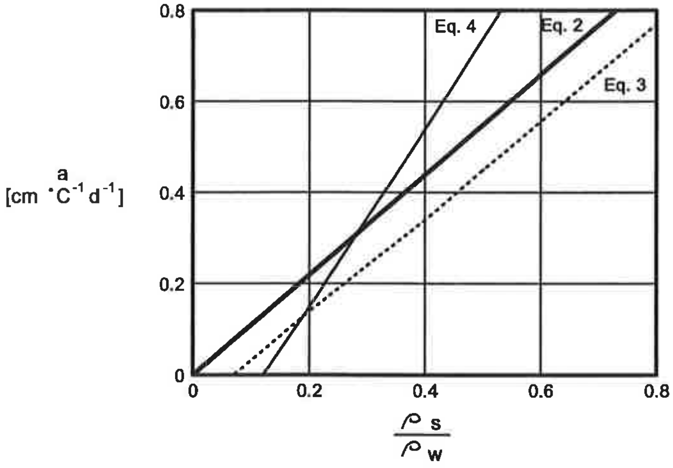

Figure 4. Relationships Between the Degree-Day Factor and the Relative Density of Snow [from Martinec (1960) (Equation 2) and Kuusisto (1980) (Equation 3 – Forest; Equation 4 – Open].

DEGREE-DAY FACTOR FROM LYSIMETER MEASUREMENTS

As already mentioned, one possibility to measure degree-day ratios consists in comparing the outflow from a snow lysimeter with the number of degree days. As also mentioned, the daily values must be expected to scatter considerably. It is possible, however, to evaluate average degree-day factors for monthly intervals and to compare the results with values obtained from Equation (2). The data listed in Table 2 are for runoff periods starting at 0800 hours on the first day and ending at 0800 hours on the next day. The number of degree days refers to the period starting at 0445 hours on the first day and ending at 0445 hours on the next day. The total is composed of daily degree-day numbers which were computed from positive as well as (if applicable) negative hourly mean temperatures. If a negative temperature resulted for a particular day, it was considered as 0°C.

DEGREE-DAY FACTORS IN UNUSUAL CONDITIONS

Investigations and applications of degree-day ratios reported above took place mostly in the zone between 35° and 55°N. With snow densities during the snowmelt season ranging from 0.3 to 0.5 g cm^{-3}, corresponding degree-day ratios in the range of 0.35 to 0.55 cm $^{\circ}C^{-1}$ d^{-1} can be expected. Lower values should be used for fresh snow. Indications are that to the south of the 35°-55°N zone (for example, in the Himalayas), these values are slightly higher, probably due to the increased solar radiation. Conversely, to the north of the zone, they are lower, probably due to a decrease in solar radiation.

In glacierized basins, it was noticed that runoff simulations at the end of the snowmelt season required an increase of the degree-day factor to 0.6 cm $^{\circ}C^{-1}$ d^{-1}, probably because ice with a low albedo became exposed. Actually, even higher degree-day factors can be derived from an empirical formula for glacier ablation (Kotlyakov and Krenke, 1982):

$$A = 1.33\,(\bar{T}_{6\text{-}8} + 9.66)^{2.85} \qquad (5)$$

where A = total glacier ablation [mm] and $\bar{T}_{6\text{-}8}$ = average temperature in degree days for June, July, and August.

For $\bar{T}_{6\text{-}8}$ = +4°, Equation (5) gives A = 2290 mm and the number of degree days in June-August is 368 °C d. Thus,

$$a = \frac{229}{368} = 0.62 \text{ cm } ^{\circ}C^{-1}\, d^{-1}\,.$$

Similarly, a = 0.79 cm $^{\circ}C^{-1}$ d^{-1} for $\bar{T}_{6\text{-}8}$ = 2° and 0.61 cm $^{\circ}C^{-1}$ d^{-1} for $\bar{T}_{6\text{-}8}$ = 6°.

Another empirical formula for glacier melt (Young, 1982) reads

$$M = 1.56 + 5.338 \cdot T \qquad (6)$$

where M = icemelt depth [mm d^{-1}] and T = temperature [°C]. For T = +4°, Equation (6) gives

$$a = 0.1\frac{M}{T} = 0.57 \text{ cm } ^{\circ}C^{-1}\, d^{-1}\,,$$

for T = +2°, a = 0.61 cm $^{\circ}C^{-1}$ d^{-1}, and

for T = +6°, a = 0.56 cm $^{\circ}C^{-1}$ d^{-1}.

Higher than normal degree-day ratios are also encountered with avalanche deposits, especially if the snow surface is dirty. A low albedo of 0.2 was measured and a degree-day factor of 0.85 cm $^{\circ}C^{-1}$ d^{-1} was evaluated for an avalanche deposit near Davos (Martinec and de Quervain, 1975). If snowmelt is accompanied by rainfall, it can be computed that only small amounts of snow are melted by the rain itself. Nevertheless, snowmelt rates are high so that degree-day ratios higher than usual are indicated. As Anderson (1970) notes, the high snowmelt rates in a rain on snow event are caused by the latent heat of condensation.

TABLE 2. Degree-Day Factors from Lysimeter and Snow Density Measurements.

Period 1985	Lysimeter Runoff Depth (cm)	Lysimeter Runoff Depth Without Rain (cm)	Number of Degree Days	Degree-Day Factor From Lysimeter	Degree-Day Factor From Snow Density
May 9-31	22.636	20.048	47.721	0.423	0.44
June 1-30	34.080	30.220	59.529	0.509	0.48
July 1-12	41.932	34.058	67.993	0.501	0.516

AREAL DEGREE-DAY FACTOR

The meltwater volume from a basin or from a partial area of a basin results from the equation

$$V = A \cdot S \cdot a \cdot T \cdot 0.01 \qquad (7)$$

where V = meltwater volume [m^3], A = area [m^2], S = portion of A covered with snow (decimal number), a = degree-day factor [cm $°C^{-1}$ d^{-1}), T = number of degree days [C° d], and 0.01 = conversion of m to cm. The areal degree-day factors should correspond to the values from point measurements if the degree days are extrapolated correctly by the lapse rate from the meteorological station to the mean hypsometric elevation of the given area.

Figure 5 shows degree-day ratios from point measurements as well as areal values compared with the line defined by Equation (2) which was derived from earlier point measurements. The areal values were computed from the decrease of the measured average water equivalent of the snow cover in the Czech Republic basin Modry Dul (2.65 km^2, 1000-1560 m a.s.l.) for several weeks and from the total numbers of degree days for these periods (Martinec, 1963). The good agreement between point and areal degree-day factors is due to the following favorable circumstances:

1. The terrain is not rugged, the accumulation of snow is relatively large, and the ablation period is short. As a result, the basin was nearly completely snow covered in the examined periods.
2. There was very little snowfall during the ablation periods in proportion to the measured differences of the areal water equivalents of the snow cover.

In less favorable conditions, computations of the areal degree-day factor may be distorted in particular by the changing snow coverage. This may lead to assumptions that the areal degree-day factor is something different than a value derived from point measurements. The misunderstanding can be illustrated by the following example:

> A calibrated snowmelt runoff model is used in an alpine basin. In an early stage of the snowmelt season, a value of a = 0.25 cm $°C^{-1}$ d^{-1}

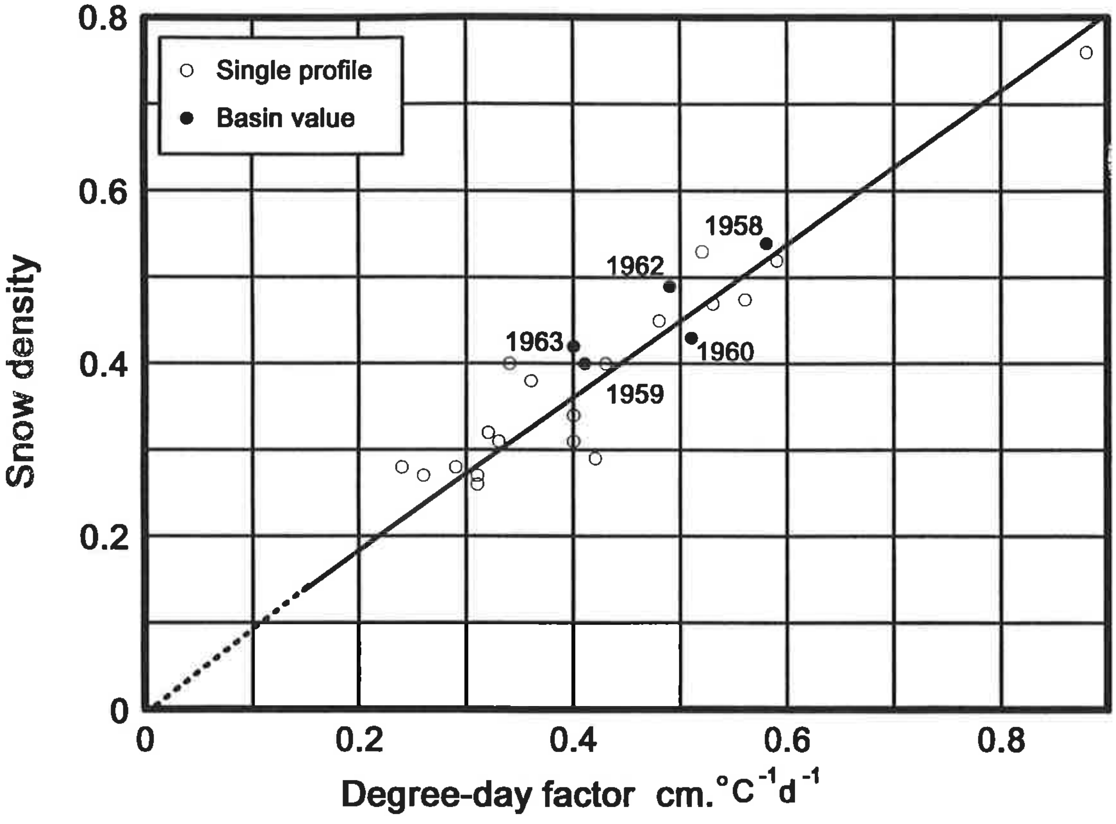

Figure 5. Relation Between the Point and Areal Values of the Degree-Day Factor and the Relative Density of Snow on the Modry Dul Basin, Czech Republic.

is optimized to give the best agreement with the measured runoff. In a later stage of the snowmelt season, the optimization brings the same result.

Conclusion:

1. The areal degree-day factor is lower than the generally recommended point values in Table 1.
2. Although point degree-day ratios are said to increase during the snowmelt season, the areal degree-day factor remains constant.

Both conclusions are false because the changing snow coverage was disregarded. Most calibration models simulate the accumulation and subsequent ablation of the seasonal snow cover from precipitation and temperatures extrapolated to a number of elevation zones in a basin. Consequently the zones below a simulated snow line become snow-free and the zones above this snow line appear as completely snow covered. But what if, as could be expected in rugged alpine terrain, the snow coverage was only 70 percent, and what if it decreased, as always happens, to 50 percent in the later stage? Then the same optimum performance of the model would have been achieved with $a = 0.35$ cm $^{\circ}C^{-1}$ d^{-1} and, in the later stage of the snowmelt season, with $a = 0.5$ cm $^{\circ}C^{-1}$ d^{-1}. In other words, the low value of $a = 0.25$ cm $^{\circ}C^{-1}$ d^{-1} is a mixture of a normally expected higher value and a zero-value for the snow-free parts of the elevation zone.

SNOWMELT COMPUTATION FOR SHORT INTERVALS

If hourly computations of snowmelt depths are needed, the degree-day method (converted to degree-hour method) cannot be used because it is the radiation component which is mainly responsible for the hour-to-hour variations. Also, the nightly refreezing of meltwater and its detention in the snowpack are not taken into account. For the same reason, daily and even weekly snowmelt depths computed by degree days may be very inaccurate in the early stage of the snowmelt season. It is fortunate that for runoff computations these errors are reduced by the basin response, mainly because only a small part of the snowmelt flows off immediately.

In the absence of complete data for an energy balance, the degree-day method can be complemented at least by the radiation component (Martinec and de Quervain, 1975).

$$M = a_T \cdot T + M_R (1 - r) - G \tag{8}$$

where M = hourly snowmelt depth [cm]; a_T = coefficient [cm $^{\circ}C^{-1}$ h^{-1}], not to be confused with the overall degree-day factor from Equation (1); T = temperature integrated over time in degree hours (°C h); M_R = global radiation converted to hourly meltwater depth [cm]; r = albedo as a decimal fraction; and G = net outgoing longwave radiation converted to hourly meltwater depth [cm].

With this equation, hourly snowmelt depths were computed for an entire snowmelt season and compared with the outflow from a snow lysimeter (Martinec, 1989). Even at the well-equipped test site at Weissfluhjoch in Switzerland, not all data for this simple formula were available, so the albedo and the net longwave radiation had to be estimated. An example of these evaluations is shown in Figures 6a and 6b.

In the first days with a positive energy input, no lysimeter outflow takes place because meltwater percolating from the top layer is being detained in the snowpack and partially refrozen during the night. As the liquid water content in the snow cover increases (in the given example to 2 percent by volume), meltwater starts being released but the lysimeter outflow is smaller than the meltwater production (Figure 6a). Gradually, an equilibrium between input and output is reached as illustrated by Figure 6b. At this stage, the lysimeter outflow can be used to verify snowmelt computations.

While the temperature and global radiation were continuously measured, the coefficient a_T (converted to a daily value a_{T24h}) had to be assessed with regard to the measured lysimeter outflow. It appeared to be fluctuating in a narrow range of 0.2-0.25 cm $^{\circ}C^{-1}$ d^{-1}. Lower values were evaluated on days with little wind and low air humidity. On a day with the average wind speed of only 3.1 m s^{-1} and a humidity of 46 percent, a_{T24h} went as low as 0.12 cm $^{\circ}C^{-1}$ d^{-1}.

In Figure 7, daily snowmelt depths summarized from hourly values computed by Equation (8) are compared with the lysimeter outflow. In Figure 8 the lysimeter outflows are compared with daily snowmelt depths computed from the average daily temperature (number of degree days per day) and degree day ratios evaluated by Equation (2). Rainfalls are excluded from lysimeter data in order to avoid distortion of these comparisons.

Neither method is able to simulate the lysimeter outflow at the beginning: it takes several days before the snowpack responds to the influx of energy by releasing meltwater while both methods are already computing a snowmelt input. In the following weeks, the lysimeter outflow is better simulated by Equation (8) than by the degree-day method because its components were actually verified and sometimes adjusted by the measured outflow.

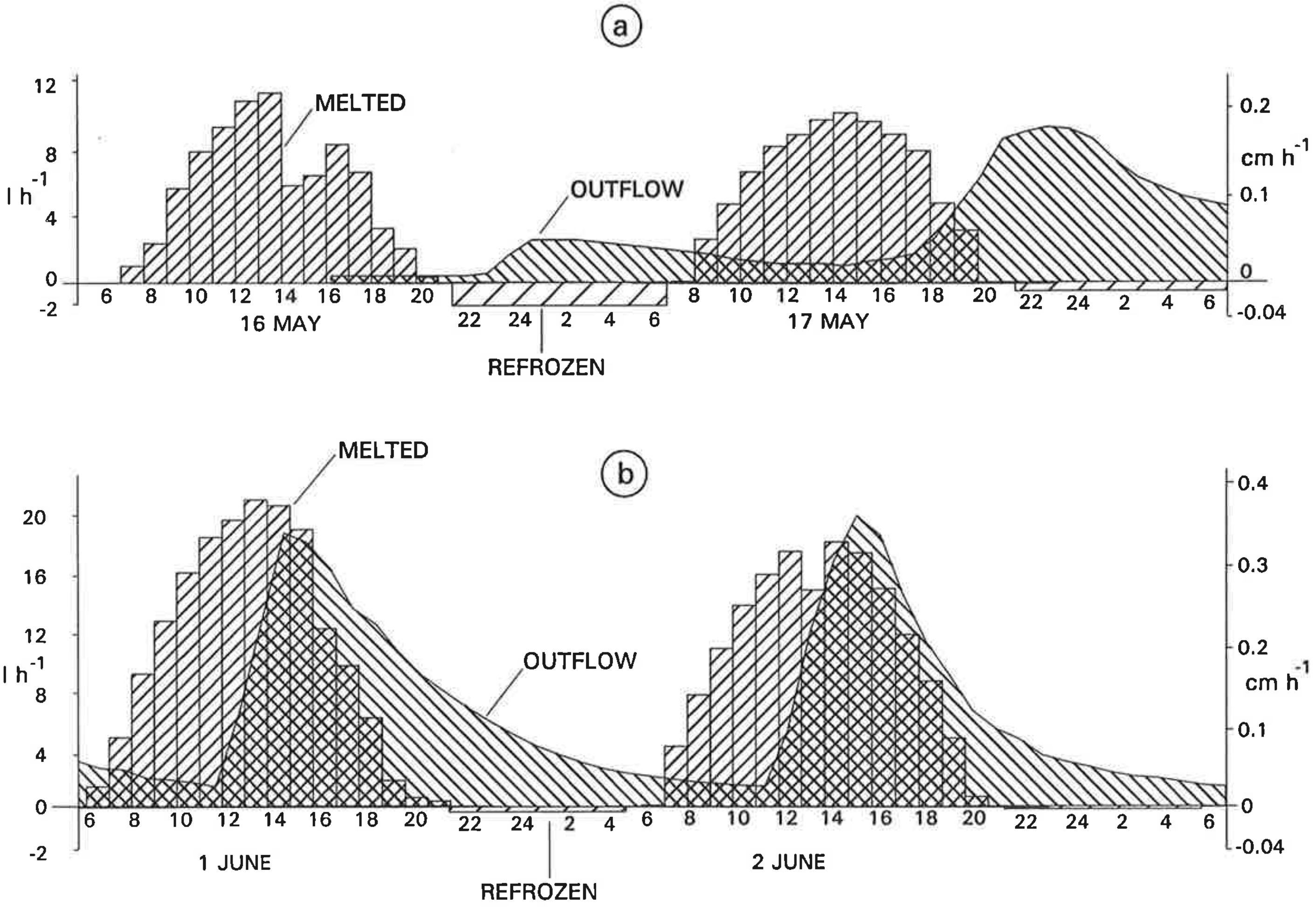

Figure 6. Computed Hourly Snowmelt Depths (cm/hour), Measured Hourly Lysimeter Outflow Depths [liters (l)/hour], and Amounts of Refreezing During the 1985 Snowmelt Season at Weissfluhjoch, Switzerland. Figure 6a is early in the snowmelt season and Figure 6b is during maximum snowmelt.

In particular, on May 29, 1985, the measured lysimeter outflow is 2.83 cm while the meltwater depth by the degree-day method amounts only to 0.56 cm. A reversed discrepancy occurs on June 14, 1985: the lysimeter outflow is only 0.88 cm and the meltwater depth by the degree-day method is 2.52 cm. Figure 9 confirms considerable differences of daily snowmelt depths computed either way.

APPLICATION IN HYDROLOGICAL BASINS

The discrepancy between degree-day calculations of snowmelt and lysimeter outflow changes when the computed input is used for runoff simulations in hydrological basins. The basin response can be better understood by examining the recession flow concept of the SRM model (Martinec *et al.,* 1983):

$$Q_n = I_n (1 - k_n) + k_n \cdot Q_{n-1} \qquad (9)$$

where Q = daily runoff [cm d^{-1}], $I_n (1 - k_n)$ = daily contribution of computed snowmelt input to basin runoff; $k_n \cdot Q_{n-1}$ = recession flow from the previous day; $k_n = 1.07\ Q_{n-1}^{-0.029}$ = recession coefficient; and n = index referring to the sequence of days.

The constants for determining k have been derived for a relatively large basin (Rhine at Felsberg, 3250 km^2). When the daily input is transformed by Equation (9), differences between the degree-day method and Equation (8) presented in Figure 9 are reduced as illustrated in Figure 10. In Figures 9 and 10, the degree-day method seems to predict less than the radiation method. This may be due to the fact that snowmelt by radiation can take place at temperatures slightly below 0°C and that there may be a few hours of melt taking place on days when the average temperature is ≤0°C even though the degree-day method would indicate no melt.

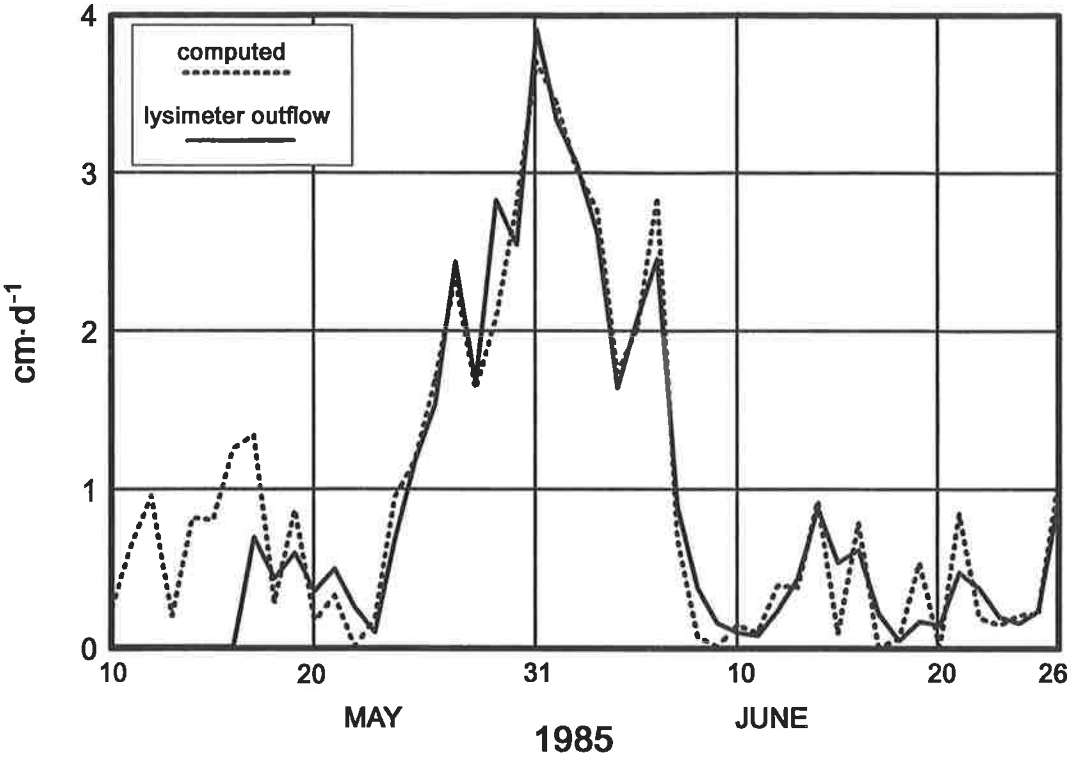

Figure 7. Daily Snowmelt Depths Computed by Equation (8) and the Measured Lysimeter Outflow, Snowmelt Season 1985.

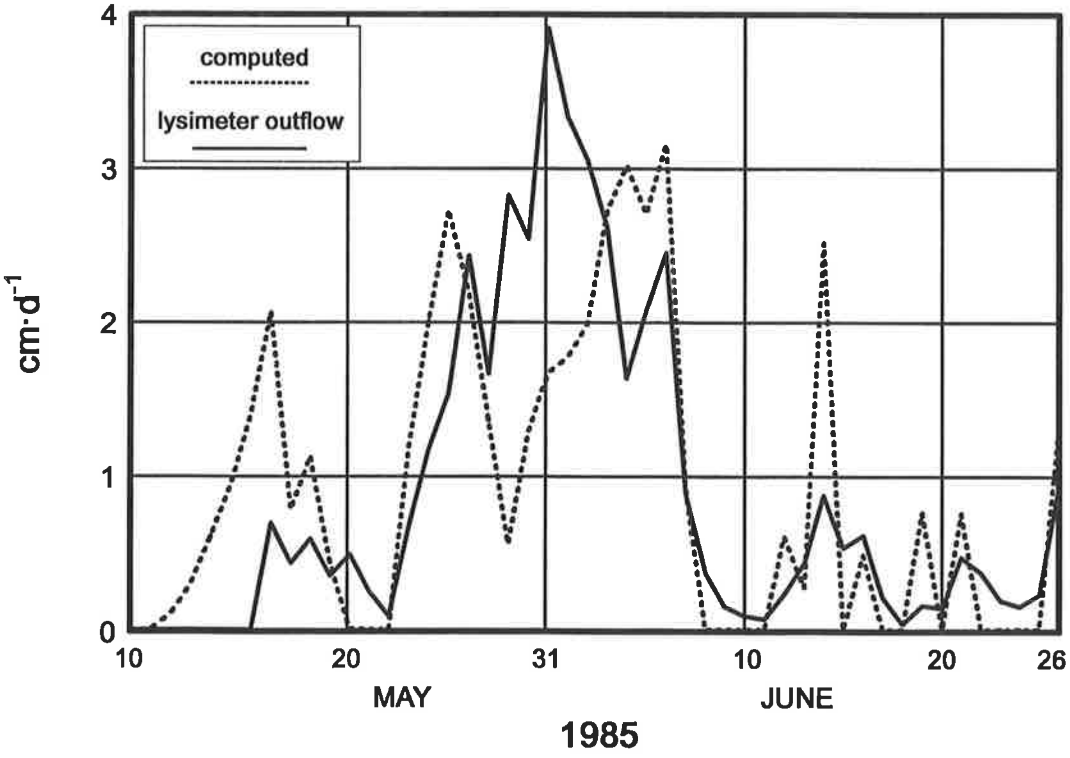

Figure 8. Daily Snowmelt Depths Computed by Measured Temperatures and Degree-Day Ratios from Equation (2), Snowmelt Season 1985.

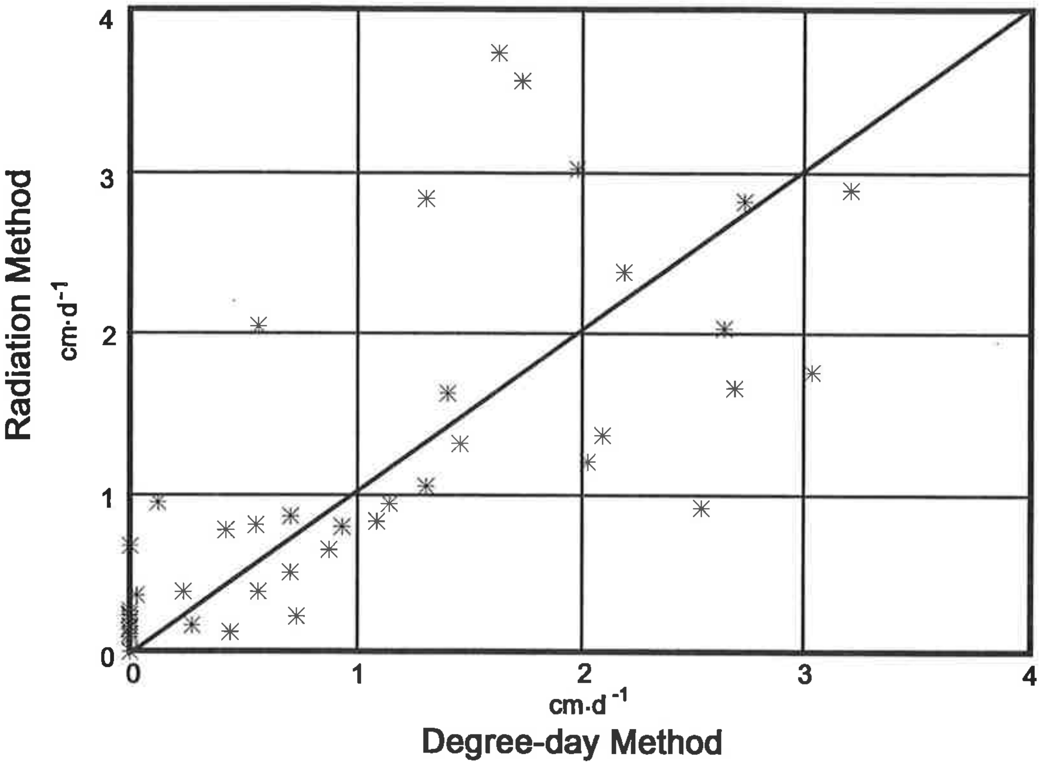

Figure 9. Relation Between Daily Snowmelt Depths Computed by Equation (8) and by the Degree-Day Method.

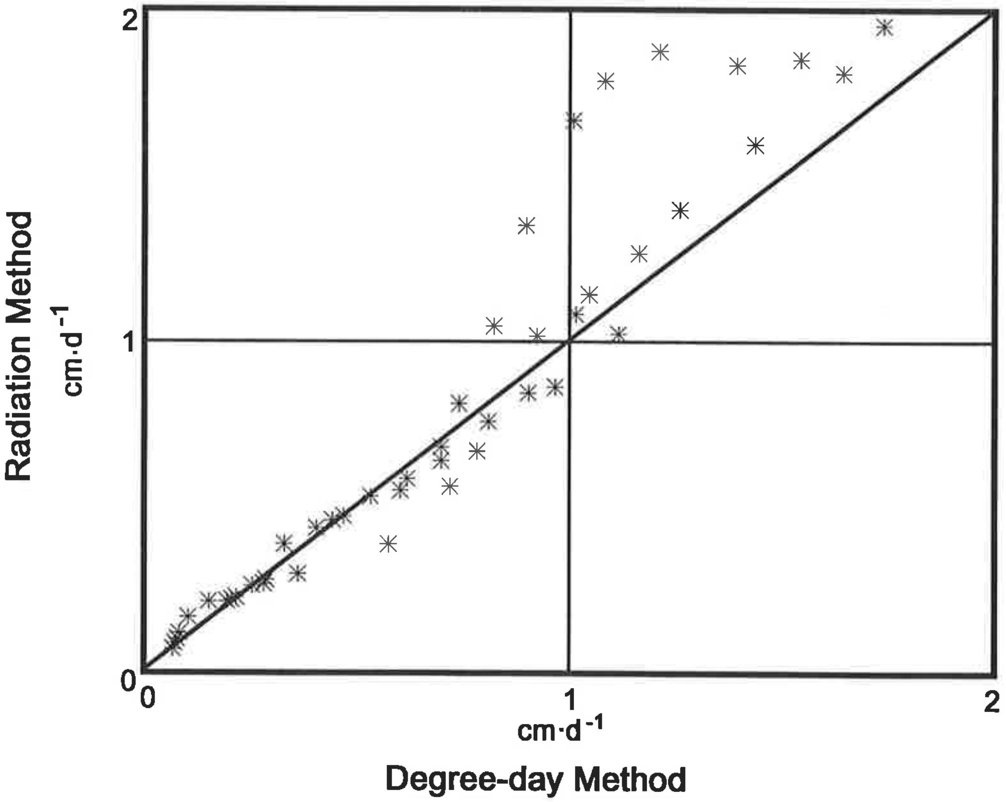

Figure 10. Relation Between Daily Snowmelt Depths Transformed Into Basin Runoff Contributions (recession coefficients corresponding to a basin size of 3250 km^2) Computed Either by Equation (8) or by the Degree-Day Method.

The two methods can also be compared by hypothetical runoff simulations as shown in Figure 11 for a basin the size of Felsberg on the Upper Rhine. As a result of the method used for the basin transformation of input, the differences are far less significant than in the case of the snow lysimeter (5 m^2), where such effect practically does not exist. While the model input computed by the degree-day method is nearly four times lower than by Equation (8) on May 28, 1985, and nearly three times higher on June 14, 1985, the hypothetical simulated basin runoff is nearly the same by both methods on these days when using the respective model inputs. It should be noted that Figure 11 does not illustrate a completely realistic runoff simulation in the Felsberg basin because the snowmelt depths were computed uniquely for the altitude of 2540 m a.s.l. and the reduction of the areal extent of the snow cover was not taken into account. This simplified comparison indicates that even when considerable errors are introduced into the calculation of daily snowmelt rates, an acceptable accuracy of simulation of the basin runoff can be achieved. This is confirmed by applications of SRM in over 60 basins (Rango, 1992).

The error in daily computed snowmelt rates is reduced in the SRM model by the input-output transformation using the recession coefficient shown in Equation (9). Increasing basin size favors this reduction of error because the recession coefficients are usually higher in large basins. In a lysimeter, the recession coefficient approaches zero and, consequently, the error of input is transferred to the output.

Another basin application consists in reconstituting the distribution of snow in terms of water equivalent at the start of the snowmelt season by monitoring the gradual disappearance of the seasonal snow cover from satellites. As has been shown in the section on "Degree-Day Factors from Lysimeter Measurements," long-term degree-day ratios are fairly consistent, so the water equivalent can be computed as follows:

$$H_w = a \cdot \Sigma T - P_s \tag{10}$$

where H_w = water equivalent of the snow cover at the start of the melting period [cm]; a = degree-day factor [cm $^{\circ}C^{-1}$ d^{-1}]; and ΣT = number of degree-days extrapolated for each partial area of the basin and totalized until the day of disappearance of snow; and P_s = precipitation in the form of snow in the melting period [cm].

The degree-day ratios listed in Table 2 actually include the effect of evaporation so that no special adjustment of Equation (10) seems to be necessary.

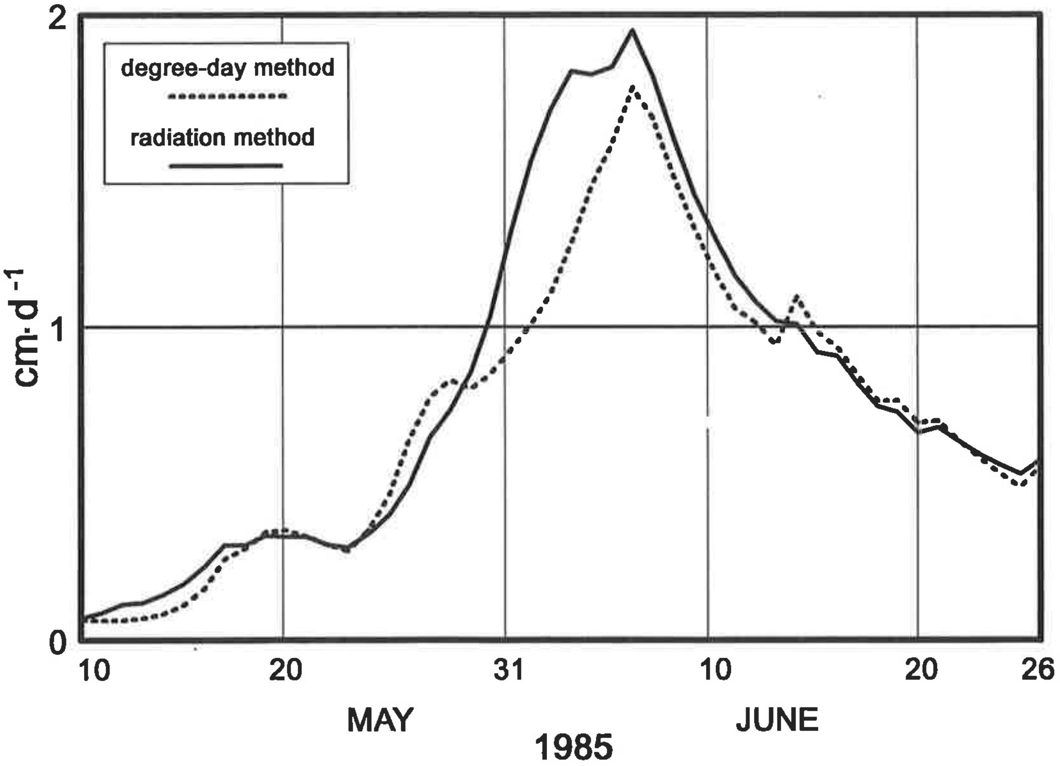

Figure 11. Hypothetical Basin Runoff (recession coefficients corresponding to a basin size of 3250 km^2) Evaluated by a Runoff Model with Snowmelt Input Computed Either by Equation (8) or by the Degree-Day Method.

As explained elsewhere (Martinec and Rango, 1981), the water equivalent of snow can be evaluated – for example, in a 1 x 1 km grid enabling isolines of equal water equivalents to be drawn. However, the degree-day factor does not take into account different exposures of grid units. This problem could be at least partially overcome by establishing a digital terrain model of the basin and by using Equation (8) for snowmelt computations.

The problem of different exposures of small grid units is greatly reduced if the water equivalent is evaluated as an areal average for an entire elevation zone of a basin. As explained elsewhere (Martinec and Rango, 1987), the so-called modified depletion curves of the snow coverage are used for this purpose.

The degree-day method using Equation (2) and Equation (10) was also applied to estimate the snow accumulation in three small basins in Wyoming (2.87 km^2, 0.29 km^2, 0.61 km^2, 330-3450 m a.s.l.) (Sommerfeld *et al.,* 1991). The degree-day approach estimated the snow accumulation in these basins to within ±6 percent of that obtained with an intensive snow core-probe survey (Sommerfeld *et al.,* 1991).

CONCLUSIONS

The simple, empirical degree-day method for calculating snowmelt runoff will not be easily replaced by more physically-based theoretical methods. If misinterpretations and inappropriate applications of the method are avoided, it can be concluded that the degree-day method is quite reliable for computing total snowmelt depth for periods ranging from one week to the entire snowmelt season.

Use of the degree-day method should not be avoided because of the sometimes erratic values of degree-day ratios. These discrepancies really occur only over short time intervals (e.g., 24-hour intervals) and put limits on the use of the method. In other cases, discrepancies and uncertainties are caused by trying to compute the degree-day factor directly from the runoff or as an areal value optimized by a runoff model without considering the variable snow coverage throughout the melt season.

Although not appropriate for calculating daily snowmelt, the degree-day method is still applicable for computing weekly snowmelt depths when the degree-day ratios are carefully assessed. For daily snowmelt depths, it is suitable for use only in connection with an adequate snowmelt runoff model for computing the basin runoff. In this case, possible daily deviations are smoothed by the basin response. The degree-day method cannot be used for shorter time intervals (hours) nor in very small areas (for example, pixels in satellite images) with different exposures to solar radiation. In such cases, however, the degree-day method may be refined by including the radiation component if pertinent data are available.

With computers ready to perform complex computations, there is seemingly no obstacle to replace a simple method of computing snowmelt by a sophisticated one. However, because measurements of the necessary variables for physically-based, energy budget methods are not available in hydrological basins, the degree-day method is likely to retain its usefulness not so much because of its simplicity but because of its modest data requirements. At the same time, users of the degree-day method (with the aforementioned limitations) can rest assured that the results they obtain are comparable to those from more complex methods.

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