SPATIAL AND TEMPORAL VARIATIONS IN SNOWMELT DEGREE-DAY FACTORS COMPUTED FROM SNOTEL DATA IN THE UPPER RIO GRANDE BASIN

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ABSTRACT

The spatial and temporal variation of degree-day melt factors (DDF's) computed from SNOTEL data were evaluated for the Upper Rio Grande Basin to improve modeling and forecasting of snowmelt runoff. Data from seven SNOTEL sites in the Upper Rio Grande Basin were analyzed for the 1996-2000 melt seasons. Average degree-day factors varied among sites with varying density of forest cover. DDF's also varied among years due to incidence of cloudy weather and timing of melt during the season. Degree-day factors for each year at each site generally increased linearly with Julian Date during the melt season, but the rate of change increased with site exposure. Best predictions of daily melt using SNOTEL data were obtained using daily degree days, Julian Date, and an indicator variable for presence/absence of precipitation. Overall, SNOTEL data produced estimates of daily DDF's that were in good agreement with data from previous studies.

INTRODUCTION

Snowmelt runoff modeling using the Snowmelt Runoff Model (SRM) (Martinec et al. 1998) makes use of degree-day melt factors (DDF's). With this model DDF's are used to predict melt within several elevation zones across large watersheds. Typically DDF's are increased during each melt season. Since DDF's can range between about 0.1 to 0.8 cm of melt per degree C day (Gray and Male 1981, U. S. Army, Corps of Engineers 1956), choice of appropriate values are useful during snowmelt runoff modeling application. The first objective of the analysis reported in this paper was to provide realistic DDF's for model applications within the Upper Rio Grande Basin of Colorado.

Computation of degree-day melt factors requires melt and air temperature data that can be obtained from SNOTEL sites within the Upper Rio Grande Basin. SNOTEL sites generally consist of a snow pillow, air temperature sensor and shielded precipitation storage gage located in a small forest opening at high elevation, remote sites with data telemetered to base stations at least daily. SNOTEL sites have been in operation for two decades within this basin and are primarily used to obtain peak snowmelt accumulations each winter for use in seasonal statistical forecasts of spring runoff volumes. SNOTEL data are used less frequently for derivation of DDF's in part because of concern with data reliability caused by bridging of snow over the snow pillows. However, SNOTEL sites can potentially provide an abundant source of daily melt and temperature data over a range of annual melt conditions and sites in large basins such as the Upper Rio Grande. A second objective of this study was to determine the usefulness of SNOTEL data for derivation of daily DDF's.

The two major approaches to melt prediction in common use are the degree-day or temperature index method and the energy budget method. Degree-day factors avoid need for meteorological data other than air temperature and are generally effective in predicting longer-term or average melt rates over a period of days. The energy budget approach requires more complete meteorological data and generally is thought to be more accurate and useful for predicting and understanding shorter-term variations in melt rates. Unfortunately, meteorological data needed for energy budget computations are not available at SNOTEL sites.

The assumption implicit in the degree-day approach is that melt rates are a linear function of the excess of mean air temperature above a base or reference temperature. Using this approach, daily melt rates are commonly predicted as:

$$\text{melt rate (cm d}^{-1}\text{)} = \text{DDF}\ (T_m - T_b)$$

where DDF is the degree day factor in cm °C^{-1} d^{-1}, T_m is average air temperature during a day (°C), and T_b is a base temperature at which no melt occurs, often taken to be 0°C. Bengtsson (1976), among others, has theoretically

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equated energy budget and degree-day approaches for melt prediction. He showed how melt prediction using the degree-day approach varied with meteorological conditions, especially with variations in incoming solar radiation and snowpack albedo. For this reason, DDF's are commonly adjusted upwards during the melt season in modeling snowmelt runoff to account for changing radiation absorption by the snowpack (Anderson 1973). Others, (for example Yoshida 1962) have shown that degree-day factors decline during cloudy weather. SNOTEL data in this study were also used to help determine adjustments needed for DDF's for seasonal radiation changes and cloudy weather.

METHODS

SNOTEL data for 1996-2000 from seven selected sites within the Upper Rio Grande Basin (Table 1, Figure 1) were employed in the analysis. Data were taken from the USDA, Natural Resources Conservation Service, National Water and Climate Center website at http://www.wcc.nrcs.usda.gov/water/w_data.html. Five of the seven SNOTEL sites are located in the western portion of the upper basin, while two sites, Culebra #2 and Trinchera, are located in the eastern portion of the upper basin. Data from several other SNOTEL sites located in or just outside the basin were not employed in this analysis, but could be added in future analyses. Descriptive data about SNOTEL site features such as surrounding forest cover density, slope, aspect and wind exposure are given in Table 1. Although all SNOTEL sites were located in forest openings, Beartown and Lily Pond sites appear to have the lowest forest cover percentage and protection from winds, while Wolf Creek Summit and Cumbres Trestle have the greatest forest cover density.

Degree-day melt factors (DDF) were computed from SNOTEL data as the ratio of daily melt to the daily degree days above a base temperature ($T_b = 0°C$ in this study) where mean daily air temperature (°C) was computed as $T_m = (T_{max} + T_{min})/2$. Daily melt (cm) was computed from snow pillow data as:

$$\text{Melt} = (WE_1 - WE_2) + P_{snow}.$$

where WE_1 and WE_2 are snowpack water equivalents (cm) on consecutive days and P_{snow} is daily snowfall in cm. This approach assumes that all rainfall occurring during each day drained completely from the snowpack and that snowpack mass changes due to vapor exchange and blowing snow were negligible. Daily snowfall was computed from measured daily precipitation (P) and mean daily air temperature as:

$$P_{snow} = P \text{ when } T_m \leq 0°C$$
$$P_{snow} = [(T_c - T_m)/T_c]\, P \text{ when } 0°C < T_m \leq T_c.$$

A critical temperature (T_c) of 2°C above which all precipitation was assumed to be rain was used.

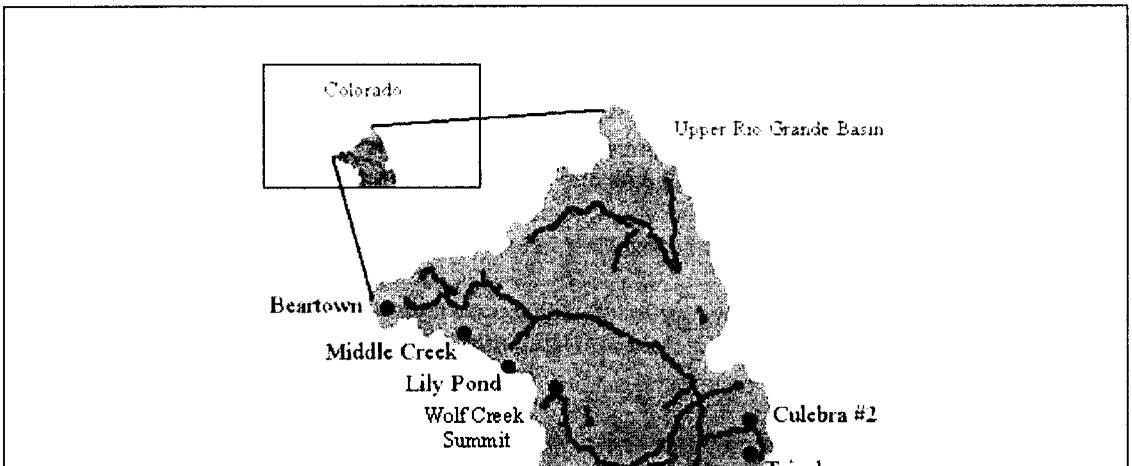

Figure 1. Map of Upper Rio Grande Basin in Colorado with locations of the SNOTEL sites used in the analysis.

TABLE 1
DESCRIPTION OF SELECTED SNOTEL SITES
UPPER RIO GRANDE BASIN

SNOTEL Site	Latitude (° N)	Longitude (° W)	Elevation (m)	Forest Cover (%)	Slope (%)	Aspect	Wind Exp.
Wolf Creek Summit	37° 29'	106° 48'	3352	80	20	W	low
Beartown	37° 43'	107° 31'	3526	20	30	S	mod-high
Cumbres Trestle	37° 01'	106° 27'	3054	70	5	S	mod
Middle Creek	37° 37'	107° 02'	3429	60	15	S	mod
Lily Pond	37° 23'	106°32'	3352	40	10	S	mod
Culebra #2	37° 13'	105° 12'	3200	50	15	SE	mod
Trinchera	37° 21'	105° 14'	3310	60	20	N	mod

[1] Approximate canopy coverage of adjacent forest cover, slope steepness, aspect and relative wind exposure based upon personal communication from Mike Gillespie, NRCS, Colorado.

Errors in the melt computation procedure can originate from field measurements and assumptions in the computations described above. Potential field measurement errors could result from measurement of water equivalent changes, daily precipitation and air temperatures. Bridging of the snowpack over the snow pillow or ice bridge collapse are possible sources of snowpack water equivalent measurement errors during snow accumulation, but these errors are expected to be smaller during the main melt season. Precipitation data are collected with shielded gages to minimize snowfall measurement errors, but some errors probably exist due to high winds at the more exposed sites. Air temperatures are measured with a shielded, but unaspirated, thermistor thermometer that could cause some measurement error.

Degree-day melt factors were computed for all melt days that met certain criteria set to avoid computational problems. Days with small amounts of melt or mean temperatures close to 0°C often produced highly variable DDF due to the precision of SNOTEL data. Snow pillow and precipitation data were measured to the nearest 0.1 inch (0.254 cm) and air temperature only to the nearest 0.1°C. To avoid these computational problems, only DDF computations for days with $T_m > 1$°C were used in the analysis of degree-day factors. In addition, DDF computations began after peak snowpack accumulation each spring and were terminated when snowpack water equivalent reached about 2.54 cm to avoid computational problems caused by suspected incomplete snowcover on the pillows.

Degree-day factors computed following these guidelines were then analyzed for differences among sites and over time each year. Average DDF's were derived by linear regression of melt rate against degree days using regression analysis through the origin for all qualifying melt days in each year and site. To study the nature of temporal variations of degree-day melt factors during each melt season at each site, computed daily DDF's at each site were linearly related to Julian Date or potential solar irradiation. Finally, daily melt data for all years at each SNOTEL site were used to predict melt using degree-days, Julian Date, potential solar irradiation, estimated global radiation, and presence/absence of precipitation. Global radiation was estimated using the diurnal variation in air temperatures at each site (Bristow and Campbell 1984) using the RadEst program (http://www.cahe.wsu.edu/~soilsim/research/RD_index.htm)

RESULTS AND DISCUSSION

Average SNOTEL Site Degree-Day Factors

Relationships between melt and degree days are illustrated in Figure 2 for Wolf Creek Summit and Lily Pond SNOTEL sites for all 1996-2000 data combined. The best relationship between SNOTEL melt and degree days was found at Wolf Creek Summit (R^2=0.61, standard deviation=0.68 cm) that has dense surrounding forest cover.

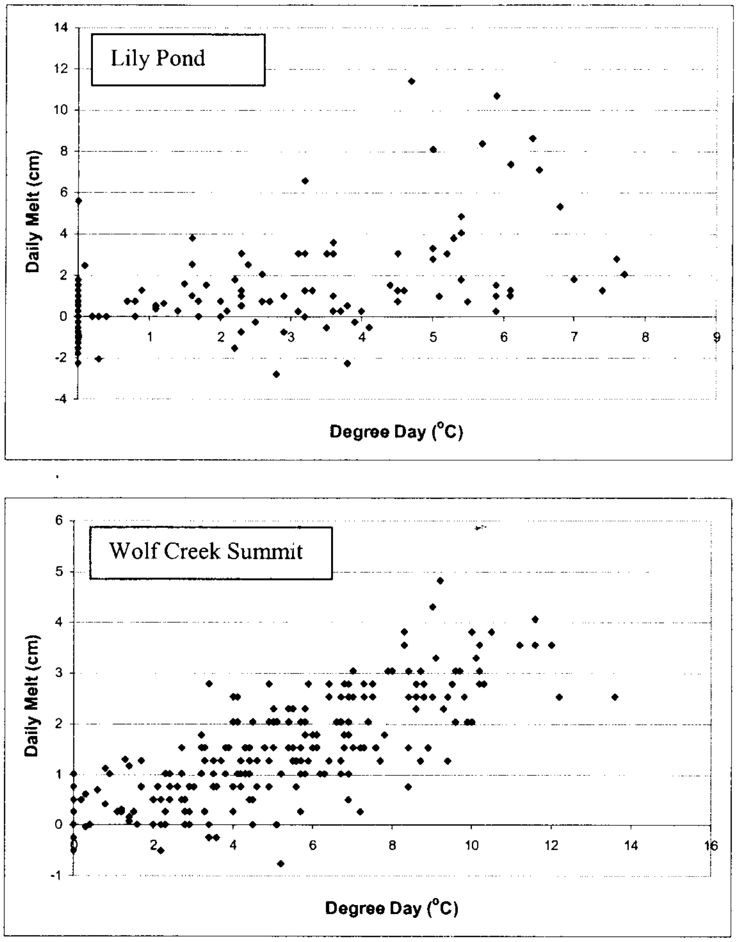

Figure 2. Daily melt plotted against degree days for Lily Pond and Wolf Creek Summit SNOTEL sites for 1996-2000.

The poorest fit between melt and degree days was found at Lily Pond (R^2=0.26, standard deviation=2.1 cm) a site with the second lowest estimated forest cover. These data confirm the long-established observations that degree-days make better melt predictors in forested or sheltered environments (U. S. Army, Corps of Engineers 1956). Data further support the commonly assumed linear relationship between melt and degree-days above a base temperature of 0°C.

Average degree-day factors for the entire 1996-2000 period varied among the seven SNOTEL sites (Figure 3). Lowest average values were found at Wolf Creek Summit (0.29 cm $°C^{-1}day^{-1}$) and Trinchera (0.33 cm $°C^{-1}day^{-1}$). Higher average degree-day factors occurred at Beartown and Lily Pond, 0.54 and 0.59 cm $°C^{-1}day^{-1}$, respectively.

Middle Creek, Cumbres Trestle and Culebra were intermediate in degree day factors. R^2 for these relationships in individual years ranged between 0.23 and 0.76, with an overall average R^2 of 0.44. The mean degree-day factor for 1996-2000 at the seven sites was 0.43 cm $°C^{-1}$ day^{-1}. These degree-day factors fall within the general range of factors found in the literature (U. S. Army, Corp of Engineers 1956). SNOTEL sites with lower DDF's were those with higher estimated forest density (Wolf Ck. and Trinchera), which again suggests that microsite characteristics at each SNOTEL site may be important to data interpretation. Lower DDF's have generally been found at forest sites in previous studies and forest cover density surrounding SNOTEL sites appears to affect melt rates.

Degree-day factors averaged across all SNOTEL sites in a given year also varied (Figure 4). The annual averages for 1996-2000 ranged between a high of 0.5 cm $°C^{-1}$ day^{-1} in 1999 to a low of 0.3 cm $°C^{-1}$ day^{-1} in 2000. Differences in the nature of weather in each melt season and amount of snowpack probably were responsible. The

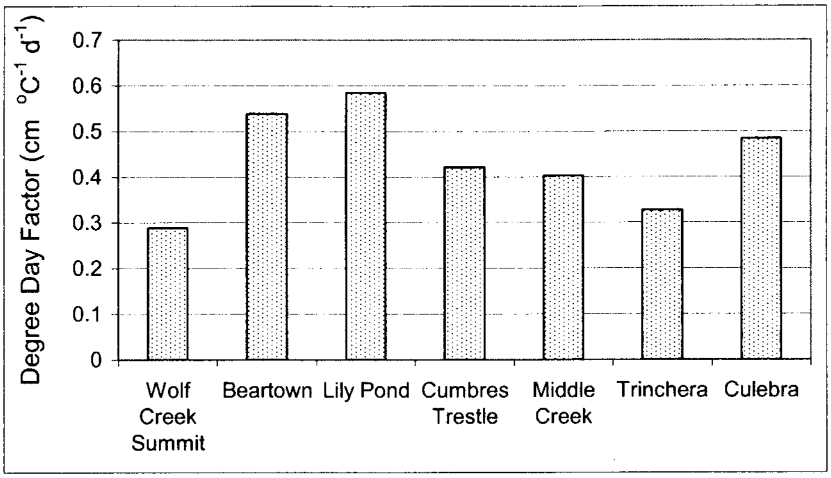

Figure 3. Average degree-day melt factor for each SNOTEL site during 1996-2000 in the Upper Rio Grande Basin.

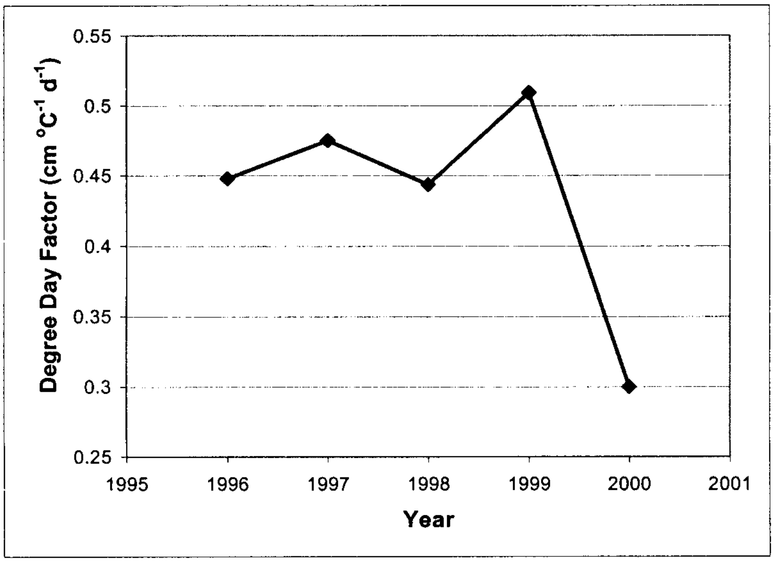

Figure 4. Average annual degree-day factors for 7 SNOTEL sites in the Upper Rio Grande Basin during 1996-2000.

year 2000 had the lowest or second lowest snowpack water equivalent, depending upon site, which caused most melt to occur earlier in the spring when lower DDF's occur. In addition, cloudy weather produces less melt for a given degree day total as explained in the final section of the paper.

Correlations of annual average DDF's between pairs of SNOTEL sites for each year during the 1996-2000 period also revealed some spatial associations. Degree-day factors from Trinchera and Culebra sites in the eastern portion of the basin were significantly and positively correlated over the five-year period (R^2=0.62), but showed lower positive or negative correlation (R^2<50%) with data from the other SNOTEL sites in the western portion of the basin. Relatively high correlation occurred in the annual average DDF's among all sites in the western portion of the basin during 1996-2000 (R^2>50%), except Beartown for which data were not well correlated with that from any of the other sites. Varying weather conditions between eastern and western portions of the Upper Rio Grande basin may cause variations in melting conditions among these groups of SNOTEL sites that should be considered when modeling runoff from the basin.

Seasonal Variations in Degree-Day Factors

Degree-day factors generally increased during the melt season at the SNOTEL sites. Trends found at Wolf Creek Summit and Lily Pond sites with varying forest cover density are shown in Figure 5. Degree-day factors were significantly related to Julian Date at the four SNOTEL sites with the highest estimated forest cover density, including Wolf Creek. At the other more exposed sites, such as Lily Pond, seasonal variations in DDF's were too large to detect trends with Julian Date. Similar relationships were derived with essentially the same R^2 using potential solar irradiation for a latitude of 37°N latitude, rather than Julian Date. The slopes of the average 5-year relationship between DDF's and Julian Date varied among sites (Table 2). Ranges of applicable Julian Dates for equations are given in Table 2. The lowest slopes occurred at Wolf Creek Summit (0.0047 (cm $°C^{-1}$ day^{-1}) day^{-1}) and Trinchera (0.0046 (cm $°C^{-1}$ day^{-1}) day^{-1}) which had the highest estimated forest cover and the highest significant slope occurred at Cumbres Trestle (0.01 (cm $°C^{-1}$ day^{-1}) day^{-1}) with a lower forest density. Clearly, the shading of the SNOTEL site by the surrounding forest and landscape affected the seasonal trends. At the most exposed sites, trends in DDF's with Julian Date probably existed but were not detectable due to wider variations in DDF's.

Seasonal progression of DDF indicated in Table 2 suggests the average rate of change of melt during the spring season at these sites. Given an average daily degree days of about 4-5 °C-day apparent in Figure 2, slopes of the relationships of DDF with Julian Day show that melt rates increase an average of 0.02 to 0.05 cm d^{-1} during the melt season at these sites.

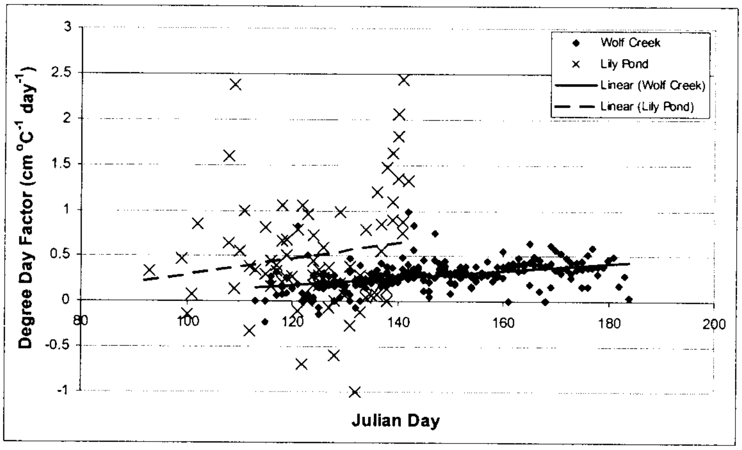

Figure 5. Seasonal variations in degree-day factors at the more exposed Lily Pond and more shaded Wolf Creek Summit SNOTEL sites during 1996-2000.

TABLE 2

DEGREE-DAY FACTOR VARIATIONS WITH JULIAN DATE
UPPER RIO GRANDE BASIN, 1996-2000

Site	n	Intercept cm $°C^{-1}$ day^{-1}	Slope (cm $°C^{-1}$ day^{-1}) day^{-1}	Julian Date Range	R^2 %	Standard Deviation
Wolf Creek Summit	207	-0.395	0.0047	115-175	21	0.14
Beartown	132	n.s.	n.s.	n.s.	n.s.	n.s.
Cumbres Trestle	125	-0.775	0.0100	95-150	24	0.25
Middle Creek	137	-0.519	0.0072	95-165	18	0.26
Lily Pond	79	n.s.	n.s.	n.s.	n.s.	n.s.
Culebra	85	n.s.	n.s.	n.s.	n.s.	n.s.
Trinchera	90	n.s.	0.0046	80-135	5	0.28

n.s. = not significant

The dependence of DDF's on time of year is generally attributed to the seasonal progression of solar energy available for melt caused by increased potential solar irradiation and declining snowpack albedo. Potential solar irradiation at this latitude and time of year increases by about 9.2×10^4 J m^{-2} day^{-1}. The equivalent rate of change in potential daily melt would be 0.0275 cm d^{-1}, given the latent heat of fusion of 0.334 MJ kg^{-1}. All of this potential daily melt rate increase would not be realized because of reductions in solar radiation received by the snowpack due to atmospheric attenuation and local shading as well as reductions in solar absorbed due to snowpack albedo. The actual rate of change in daily melt (0.02 to 0.05 cm d^{-1}) equals or exceeds this potential rate, even without reduction of the potential rate for atmospheric attenuation, local shading and albedo effects, indicating the seasonal increases in DDF's are also due to other factors, such as increasing longwave radiation and sensible heat convection.

Melt Prediction at SNOTEL Sites

Stepwise regression analysis (Table 3) was used to determine the best predictors of melt using data typically available at SNOTEL sites. In addition to degree-days, variables considered were Julian Date, potential solar irradiation, rain vs. non-rain days, precipitation amount and estimated global radiation. Degree-days were the best predictor of melt of all variables tested. Degree-day coefficients ranged from 0.22 to 0.42 cm °C^{-1} day^{-1} which are consistent with previously derived average DDF's, even though equations in Table 3 do not pass through the origin.

Julian Date was also significant at all sites, but Julian Date explained much less variation (~5-10%) than degree-days in the overall melt prediction equations. Julian Date coefficients ranged from 0.01 to 0.04 cm d^{-1}, numbers consistent with to slightly less than daily melt in previous discussion given above.

The presence/absence of rainfall, essentially a surrogate for cloudy weather, proved to be significant predictor at all but one site, but the contribution of the precipitation indicator added little (~1% R^2) to explained variation in melt rates. Days with precipitation generally had less melt. Precipitation days were accompanied by 0.2 to nearly 0.7 cm less melt for a given Julian date and degree-day total. The magnitude of the precipitation (cloudy weather) effect was generally greater at sites with low forest cover, as expected, but the relationship was not strong. Despite the possibility of condensation/convection melting during rain, snow or mixed precipitation days, the lower overall net radiation energy supply due to cloud cover prevailed and caused reduced melt.

TABLE 3
EQUATIONS RELATING DAILY SNOTEL MELT (cm) TO DEGREE-DAYS (°C day), JULIAN DATE (Jan 1=0), AND PRESENCE/ABSENCE OF PRECIPITATION
UPPER RIO GRANDE BASIN, 1996-2000

SNOTEL Site	n	Intercept	Degree-Day Coefficient	Julian Date Coefficient	Precipitation Indicator (Y=1, N=0)	R^2 (%)	Standard Deviation
Wolf Creek Summit	234	-3.40	0.218	0.0266	-0.195	74	0.559
Middle Creek.	172	-2.57	0.232	0.0247	-0.262	62	0.710
Beartown	189	-2.22	0.316	0.0249	-0.552	43	1.261
Cumbres Trestle	128	-3.58	0.243	0.0374	-0.464	64	0.877
Lily Pond	188	-4.86	0.425	0.0427	n. s.	29	2.029
Trinchera	169	-0.966	0.240	0.0129	-0.684	50	0.684
Culebra	214	-0.647	0.281	0.0118	-0.416	45	0.798
All Sites	1294	-1.12	0.245	0.0146	-0.37	42	1.104
West*	911	-1.65	0.242	0.0185	-0.37	38	1.22
East*	381	-0.70	0.253	0.0116	-0.408	45	0.760

* West =Wolf Creek Summit, Middle Creek, Beartown, Cumbres Trestle and Lily Pond sites only, East =Trinchera and Culebra sites only.

The melt prediction equations for data from all seven SNOTEL sites and east vs. west basin sites combined are also given in Table 3. All three combined equations are quite similar. Use of the equation for western basin sites would be most appropriate for prediction of daily melt for the Del Norte, CO gaging station; however, only about 40% of variations in melt rate can be explained overall. In contrast, similar equations for individual SNOTEL sites explained up to 74% of variation in daily melt.

Potential solar irradiation and estimated global radiation did not significantly add to melt prediction at these SNOTEL sites. Julian Date and presence/absence of precipitation were certainly correlated with radiant energy supply and probably were responsible for lack of significance of potential and global radiation estimates. Although solar radiation data are not generally available at SNOTEL sites, estimation of global radiation based upon daily variations in air temperature (Bristow and Campbell 1984) may help with melt prediction in other studies. The global radiation estimation procedure is based upon daily air temperature variations at open sites and may not reflect the effects of partial shading by forest and topography at SNOTEL sites. Adaptation of this approach to SNOTEL sites could be useful in other studies.

CONCLUSIONS

SNOTEL data were quite useful for derivation of daily snowmelt and degree-day melt factors (DDF's) in the Upper Rio Grande Basin. Since the DDF is a simple ratio of melt to degree days, computational problems did exist on days with low melt and low degree-day totals due to the precision of precipitation and water equivalent measurements (±0.25 cm). Days near the end of the melt season also give very low DDF's due probably to incomplete snow cover on the snow pillows. Forest and other landscape features around SNOTEL sites greatly affected derived DDF's. Better characterization of forest and landscape and microclimatic (solar and thermal radiation, wind speed, humidity) conditions at each site would improve usefulness of SNOTEL data.

Prediction of snowmelt runoff using the Snowmelt Runoff Model in the Upper Rio Grande Basin can be enhanced through use of DDF's derived from SNOTEL data. Adjustment of DDF's for effects of varying forest cover would be needed. Varying correlations of data among SNOTEL sites in the eastern and western portions of the basin also suggest that regional weather differences cause melt variations across the basin. An alternative to use of DDF's in daily snowmelt modeling would be to predict daily melt from degree-days, Julian Date and presence/absence of precipitation using multiple regression relationships.

SNOTEL data analysis showed that increases of DDF's during the melt season could be linearly related to Julian Date. Rates of change of DDF's with Julian Date were greater than increases expected due to changing potential solar irradiation alone. It was also observed that days with precipitation were associated with reduced daily snowmelt at SNOTEL sites, for a given Julian Date and degree-day total. Melt reductions due to cloudy weather on days with precipitation appeared to more than offset any melt increases caused by condensation on the snowpack due to higher humidity.

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REFERENCES

Anderson, E. A. 1973. National Weather Service River Forecast System-Snow Accumulation and Ablation Model. US Dept. Commerce, NOAA, Tech. Mem. NWS HYDRO-17.

Bengtsson, L. 1976. Snowmelt estimated from energy budget studies. Nordic Hydrol. 7: 3-18.

Bristow, R. L. and G. S. Campbell. 1984. On the relationship between incoming solar radiation and daily maximum and minimum temperature. Agr. For. Meteorol. 31:159-166.

Gray, D. M. and D. H. Male (Ed.). 1981. Handbook of Snow: Principles, Processes, Management and Use. Pergamon Press, Toronto. 776 p.

Martinec, J., A. Rango, and R. Roberts. 1998. Snowmelt Runoff Model (SRM) Users Manual. Dept. Geog., Univ. Berne, Geographica Bernensia P 35. 84 p.

U. S. Army, Corps of Engineers. 1956. Snow Hydrology. North Pacific Div., Corps of Engin., Portland, OR. 437 p.

Yoshida, S. 1962. Hydrometeorological study on snowmelt. J. Meteorol. Res. 14:879-899.