GENERATION OF A SNOW DEPLETION CURVE FOR AN ALPINE BASIN

by

Lisa Buchanan

INTRODUCTION

Water resource management is increasingly important in the semiarid western United States where water supplies are obtained primarily from spring snowmelt runoff from mountainous watersheds. As the spring runoff occurs over 2 to 3 months only, estimates of the timing and quantity of runoff are necessary for water planning and flood control. Basic research in snow hydrology, especially since 1956 (U.S.A.C.E.,1956), lead to development of several snowmelt runoff models to aid in water management.

Most previous work in snow hydrology has been done in forested areas with little field data collected from the alpine regions. The alpine is characterized by its heterogeneity including large abrupt elevational changes, high winds, cold temperatures and terrain ranging from alpine meadows to rocky talus slopes. Wind and topography govern snow deposition which results in formation of deep drifts interspersed with areas of thin to zero snowcover (Martinelli,1975). Snowmelt begins in May and is prolonged by melt from deeper drifts which contributes to midsummer water supply.

Snow Covered Area (SCA), the percent of a watershed area that is snow covered, has been used in runoff forecasting as an index to residual water volume in a basin (Leaf,1969,Gupta,1982), as an independant variable in regression models (Rango,1979) and as a parameter in physically based conceptual models(Anderson,1973). Incorporation of snow depletion curves, curves which describe the recession of SCA over the snowmelt season, has resulted in increased prediction accuracy for several snowmelt models (Rango,1979, Saelthun,1978, Leavesley,pers. comm.).

The objective of this study is to generate a snow depletion curve for an alpine area to be implemented into the physically based Precipitation Runoff Modeling System (PRMS). Both alpine hydrology and runoff modeling are part of the research interests of the University of Colorado Long Term Ecological Research (CULTER) program.

Study Area

The Boulder watershed is located in the Colorado Front Range northwest of Boulder, Colorado (see Figure 1). This study concentrated on the alpine basin which makes up the northern arm of the watershed, the Green Lakes Valley. The smaller basin is 7.1 km^2 and ranges in elevation from 3250 meters at the Albion townsite to 4088 meters at Navajo Peak on the Continental Divide.

Streamflow from the Upper Green Lakes Valley(2.1 km^2) the area above Green Lake 4 (GL4), is monitored by a stream gage located at the outlet from GL4 at 3550 meters elevation. Streamflow for the whole Green Lakes Valley is gaged at the Albion townsite below Lake Albion and is affected by reservoir operations at Green Lakes 1 through 3 and Albion. Gages are maintained through the LTER program at the Institute for Arctic and Alpine Research (INSTAAR).

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Department of Civil, Environmental, and Architectural Engineering Institute for Arctic and Alpine Research both at University of Colorado, Boulder Colorado

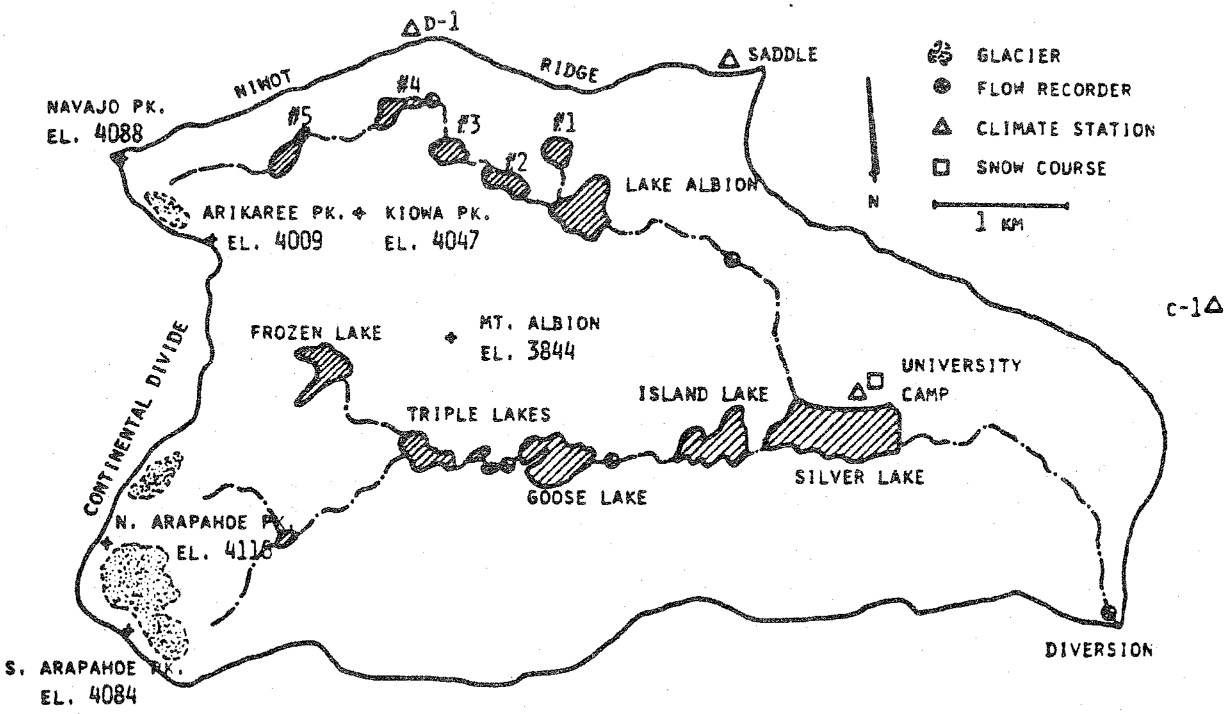


Figure 1. Boulder Municipal Watershed

Climatological stations, maintained by INSTAAR, located on Niwot Ridge, the northern boundary of the watershed, include D1, 3743 meters, C1, 3018 meters, and Saddle, 3536 meters. Continuous records of temperature, relative humidity, solar radiation and precipitation are recorded at these stations. The University Camp snow course, run by the Soil Conservation Service, also lies within the watershed at 3139 meters. In combination, the Boulder watershed and particularly the Green Lakes Valley are intensively studied compared to other similar watersheds in the United States.

Precipitation accumulated in September through May in water year 1985 was 100 percent of the 1971 to 1982 average at D1. Peak runoff at both GL4 and Albion occurred on June 8 following high temperatures on 5,6,7 June. An earlier warm period, 1-9 May, resulted in some streamflow at the Albion gage but, a storm lasting from 9 to 23 May slowed runoff and added 4.15 inches of water to the snowpack. In previous years, peak runoff at GL4 did not occur until 24 June, 2 July and 16 June in 1981, 1982 and 1984.

PRECIPITATION RUNOFF MODELING SYSTEM

PRMS was chosen for application to the Boulder alpine watershed through a screening process that involved 25 models (Brendecke and Sweeton,1985). PRMS is a deterministic, conceptual model that simulates runoff using the meterorologic and physical conditions of a watershed.

An important reason for choosing PRMS was its distributed nature. By dividing the basin into smaller subunits, the model can be used to simulate the effect on runoff of disturbances on or changes to only parts of the catchment. The basin is divided into areas of similar slope, aspect, elevation, soil type and snow distribution. These areas are termed Hydrologic Response Units (HRU)and are considered homogeneous with respect to the above characteristics. Data requirments for PRMS include, descriptive parameters for each HRU and daily climatological inputs of temperature, precipitation and solar radiation.

A flow chart of model operations is found in Figure 2. Water is input to the system as precipitation in the form of rain or snow. The model simulates snowpack accumulation and depletion, water infiltration to soil, surface, subsurface, and groundwater flow and water loss via evapotranspiration and sublimation. Total streamflow from the basin is the combination of surface, subsurface, and groundwater flow on all HRUs.

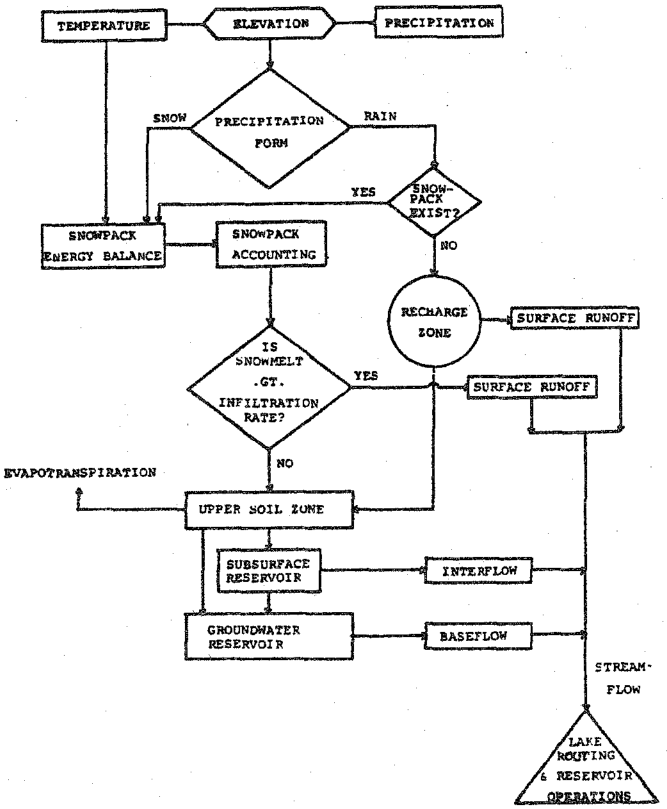


Figure 2: PRMS Flowchart Adapted from Brendecke and Sweeton, 1985.

Snow Accounting in PRMS

Of particular interest to this study is the snow accounting routines. Data from this study is used in adjusting snow accumulation, updating the snowpack water eqivalent, and creating a SCA depletion curve for the Green Lakes Valley.

During the accumulation of the snowpack, the model distributes snow evenly over each HRU in direct proportion to the amount of precipitation falling at one of five possible precipitation gages. This proportion, DSCOR, is input by the user to simulate the accumulation regimes in the basin. A mass balance is computed by the model to update HRU snow water equivalent on a daily basis. Swe obtained from snow course data can be input once per season usually at the point of maximum snow accumulation.

The snowpack is regarded as a two layer system. Heat transfer to/from the upper surface layer is governed by temperature and radiant heat fluxes. Temperature of the lower snowpack is adjusted by heat exchange with the upper layer. A point energy balance is computed two times daily on each HRU and applied to the entire HRU snow surface. Energy balance parameters include net shortwave and longwave radiation and sensible and latent heat. If the energy balance is positive, snow melts from the surface layer. Water from melt contributes to surface runoff only after the snowpack has become isothermal, the snowpack free water holding capacity is reached and the melt rate exceeds the soil infiltration rate (Leavesley,1983).

In earlier uses of PRMS, snow covered area was set to 100 percent until the entire snowpack had melted at which point snowmelt contribution to streamflow stops.

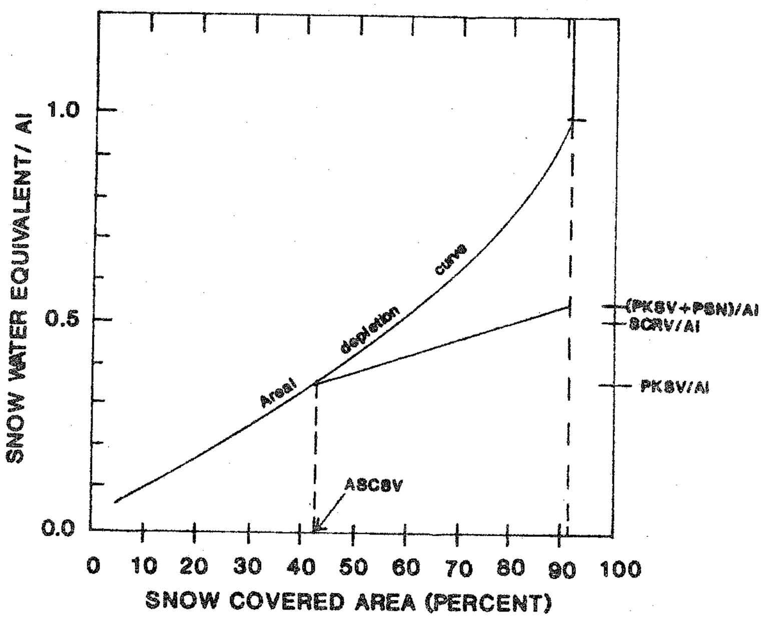
Since melt actually occurs over a portion of the HRU area, simulating melt over 100 percent of the area overestimates runoff. Late season runoff is underestimated in simulation since model SCA reaches zero before actual total snow depletion occurs. The effect of reducing the SCA with time is to reduce the area over which 1)water is generated by snowmelt, 2)water enters the soil zone and the sub surface and groundwater reservoirs, and 3) water is lost via sublimation from the snow surface. Soil evaporation also occurs on snow-free areas.

SNOW DEPLETION CURVE

Snow depletion curves were generated for each HRU similar to the curve described by Anderson (1973) for input to the National Weather Service River Forecast System (NWSRFS). The depletion curve relates swe/AI ratio to SCA where swe is the pack water equivalent at a given time and AI is the swe above which 100 percent SCA exists (Figure 3). In the alpine, the maximum SCA is generally below 100 percent due to wind redistribution of snow and the curve was adjusted so that SCA never exceeded the maximum.

Above a swe/AI ratio of 1.0, the SCA remains at the maximum value. Once the pack water equivalent melts below AI, SCA changes along the curve with respect to the swe/AI ratio. If snowmelt starts when the peak swe is below AI, AI is reset to the peak swe for that year. If snow falls (PSN) during the depletion phase, SCA is readjusted to the maximum value until 25 percent of the new snow is melted (SCRV). At this point, SCA and swe revert back to their presnowfall values (ASCSV and PKSV in Figure 3) by linear interpolation.

Figure 3:Snow Depletion Curve Adapted from Anderson(1973).



Curve values are input to the runoff model as SCA values for each tenth of the swe/AI ratio. SCA varies linearly between discrete curve points. Previously, five curve types were determined that described snow depletion in a wide variety of environments(Huber,1983). The type curve should be applicable in all years if snowcover depletes in a similar fashion each season. The heterogeneous nature of the alpine environment necessitates separate curves for each HRU in the Green Lakes Valley.

FIELD METHODS

Swe on individual HRUs was estimated from measurements taken on seven snow courses and five ablation pole lines which were run on a weekly basis. The snow courses corresponded in terms of slope, aspect and elevation to the HRUs set up for runoff simulation in the Green Lakes Valley. Location of snow and ablation courses are shown in Figure 4. Table 1 compares HRU and snow course characteristics.

Figure 4: Snow and Ablation Courses in the Green Lakes Valley 1985.

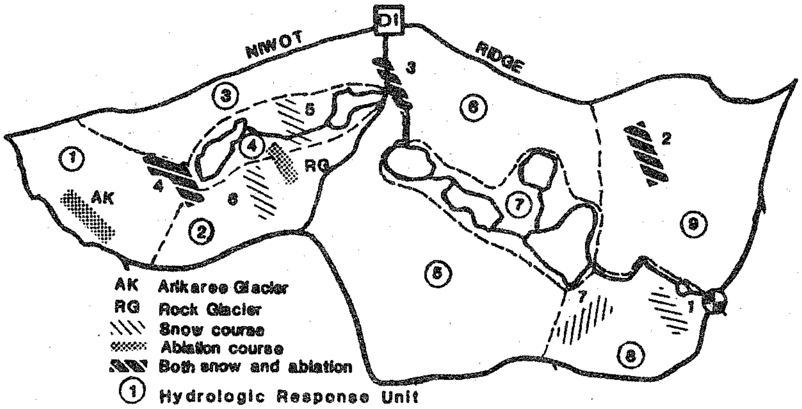


Table 1
HRU and Snow Course Comparison

HRU	elev (m)	aspect	slope	area (ha)	S.C.	elev (m)	aspect	slope
1	3854	E(90)	.16	66	4	3674	E-SE	.23
2	3807	NW(345)	.46	52	6	3689	N	.66
3	3804	SE(165)	.44	66	3	3582	F-SE	.22
4	3588	NE(75)	.03	39	5	3612	E	.03
5	3567	NE(45)	.51	161	7	3460	NE	.33
6	3549	S(180)	.31	87	2	3493	SE	.34
7	3462	SE(120)	.12	64	1	3293	F-E	.20
8	3430	NE(65)	.31	57	7			
9	3436	SE(150)	.27	150				

Table 1: Elev. is elevation in meters, aspects of F are flat, slope is ratio of rise to run. The snow course, S.C., used to describe each HRU is listed on the same line.

Snow course measurements included depth and density sampled at points spaced according to Leaf and Kovner, 1956. At each density sampling point, separate density cores were taken at three depths using a standard federal snow sampler. Depths of the cores ranged from 60 to 228 cm. Snowpack depth was monitored using a snow probe and average ablation.

Oblique aerial photographs obtained on March 25,1985 were used to estimate maximum SCA on each HRU. Vertical aerial photographs were taken on 25 May, 1 July, 9 July, and 8 August from 5182 meters m.s.l. Photo scale varied from 1:12200 to 1:9000 depending on average ground elevation for each of four flight lines. SCA was planimetered from an orthophoto of the May flight and directly from subsequent vertical photos including displacement corrections (Lillesand and Kiefer, 1979).

RESULTS AND DISCUSSION

Depth and Ablation

Average depths along each snow course and the variation in depth are shown in Table 2. These depths represent snow accumulation in 1985 only. Ice from previous years existed on snow courses 2, 3 and 4 and maximum depths including old ice layers were 810, 773 and 775 cm respectively. Average daily ablation between Jun 27 and Aug. 8, 1985 were calculated from average weekly ablation values. Ablation on snow course 2 (3493 m) averaged, 9.27cm/day while Arikaree that on Arikaree Glacier at

3805 meters was 5.24 cm/day. Ablation varied with elevation on the average according to equation 1:

$$ABL = -0.076(ELEV) + 0.009 \qquad \text{eq 1.}$$

where ABL is ablation in cm, ELEV is elevation in meters (r^2=.98).

Snow Course	Average Depth	Max Depth	Min Depth	Std.
1	300	470	133	118
2	512	714	117	182
3	496	673	265	114
4	470	675	254	139
5	322	618	130	153
6	367	586	150	138
7	477	733	118	247

Table 2: Variation in snow course depth. Std. is standard deviation. Max and Min are Maximum and Minimum depths along course.

Density

Densities were corrected by a factor of 0.91 to adjust for overestimation by the federal snow sampler(Farnes et al, 1982). Tabler's (1985) results indicate that this correction applies to melting snow as well as winter drifts.

Densities measured with the federal snow sampler did not vary consistently with depth over any of the snow courses. Figure 5 plots late season, after June 27, densities on all snow courses with depth. All regressions of density to depth were insignificant (r2<0.1). A similar uniformity of density with depth has been observed in actively melting drifts in Wyoming (Tabler,1985, Bartos and Rechard,1974). In the Green Lakes Valley, pit density profiles on Arikaree glacier (Carroll,1974) and on the Martinelli snowfield (Sarantitis,1985) suggest that density increases with depth. However, even pit data show the influence of ice lens development and melt water distribution that create denser layers at the top of the snowpack. Furthermore, when comparing two pits from Arikaree Glacier on the same date, densities at the equivalent depths varied. Such heterogeneity in the snowpack may explain the lack a consistent spatial depth/density relationship.

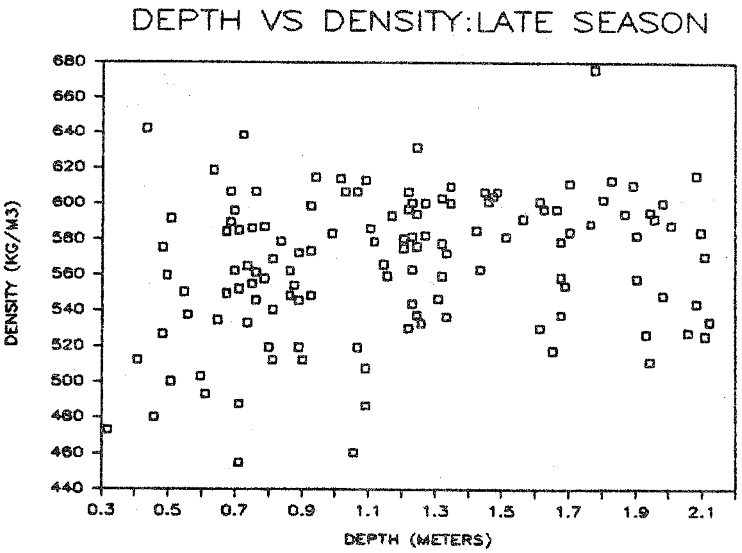


Figure 5:Density vs Depth: Late Season, June 27 to August 1, 1985.

Regression equations for average density against time, the number of days after May 9, were generated for each snow course. Snow courses 1 and 7, in the same HRU, where late and early season densities were missing, show poor correlations, though combining the two sites gives an improvement (Table 3). Maximum densities were attained near 1 July and used for all subsequent dates. Average basin density was not utilized because of differences in weekly and maximum densities between snow courses.

Maximum densities in this study ranged from 516 to 583 kg/m^3 (Table 3). Maximum density on snow course 5 is low possibly due to rapid melting caused by streamflow. By comparison, maximum densities reported by others are, 615 kg/m^3 on Arikaree Glacier (Carroll,1974), 608 kg/m^3 (Bartos and Rechard,1974) and 600 kg/m^3 (Tabler,1985).

Table 3
Regression equations for Average Density vs Time

Snow Course	slope	(May9) inter-cept	R^2	SEb	Date of Max. Den.	Max Density
1&7	3.31	411	.59	3.3	6/27	568
2	2.25	462	.91	.49	6/27	583
3	2.43	424	.95	.56	7/2	581
4	2.74	403	.92	.79	6/27	562
5	2.55	378	.96	.53	6/27	516
6	3.49	365	.86	1.4	7/9	574

Snow Covered Area

SCA was measured from photos on 25 March, 23 May, 1 and 9 July and 1 August. Intermediate SCA was estimated using linear interpolation based on accumulated degree days above 0oC and measured HRU SCA. Daily lapse rates between C1 and D1 climatological stations were used to find degree days at each snow course elevation.

The nonuniform accumulation of snow in the alpine can be seen when comparing maximum SCA and the snowmelt SCA recession on different HRUs (Table 4). Maximum SCA ranged from 58 percent on HRU 2 to 97 percent on HRUs 8 and 9. Figure 6 compares SCA recession on the upper valley HRUs, 1, 2 and 3. HRUs 1 and 2 have SCA recession curves typical of areas with primarily deep snow drifts characterized by little early SCA change but a drop in SCA in mid season. In contrast, SCA on HRU 3 decreases early in the season due to areas of shallow snow cover. Snow depth in the deeper drifts govern mid season SCA changes and are a function of the shape of the underlying terrain which is consistent between years. Previous work (Caine, 1978) showed low variability in the mid season SCA recession coefficient for 10 years of data in the Fraser Experimental Forest.

Snow Water Equivalent

Swe was estimated as the accumulated weekly swe ablation. Weekly swe ablation (ABLSWE) in cm was calculated as

$$ABLSWE(week)=ABL * DEN * SCA/SPWT \qquad \text{eq 2.}$$

where ABL equals the weekly ablation, cm, DEN is density at the beginning of the week(kg/m^3). SCA is the percent SCA at the beginning of the week and SPWT is the specific weight of water(1000kg/m^3). Swe on a given date equals the accumulated change in swe added from the date where all snow accumulated in the 1985 water year has melted. This method was chosen because 1)average densities were weighted toward the top 60 cm of snowpack, 2) knowledge of the lower snowpack densities was not required and 3) of a bias in the data toward larger snowfields. Only conditions in the upper portions of the snowpack were extrapolated to other unmonitored snowfields. This method overestimates swe (Bartos and Rechard,1978) due to areas that do not ablate the full weekly amount (Bartos and Rechard,1978) and in early season when water remains in the pack altering the density and free water content of the snowpack.

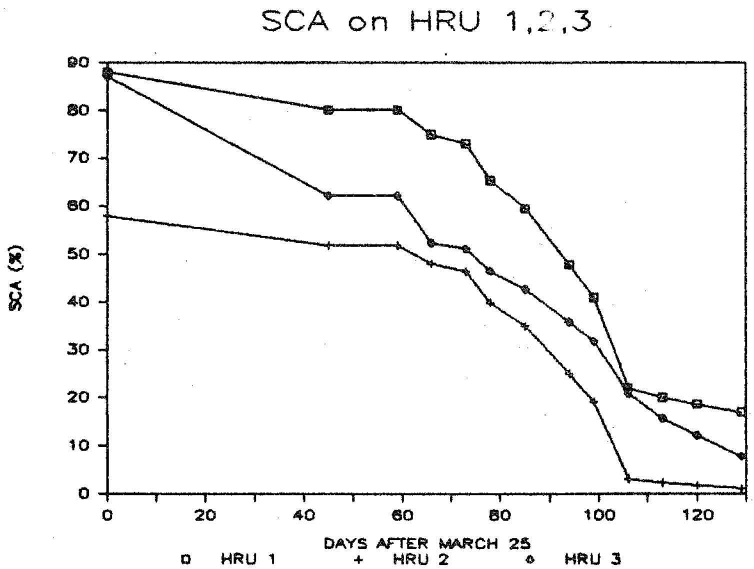


Figure 6: SCA on HRU 1,2 and 3 in the Upper Green Lakes Valley.

Table 4
Snow Covered Area for the Green Lakes Valley

HRU	3/25	5/23	5/30	6/11	6/27	7/1	7/9	8/1
1	88	80	75	65	48	-	22	17
2	58	52	48	40	25	-	3	1
3	87	62	52	47	36	-	21	8
4	91	82	75	62	37	-	2	0
U.B	81	69	62	53	37	31	14	8
6	82	51	39	28	9	3	-	0
5	78	58	43	32	14	5	-	3
7	91	73	62	44	12	3	-	0
8	97	69	56	42	17	10	-	2
9	98	74	61	43	13	3	-	1
L.B.	88	64	51	37	13	4	3	1
T.B.	86	66	54	42	20	12	7	3

SCA recession, 1985. U.B., L.B., T.B. is Upper Basin, Lower Basin, and Total Basin respectively. SCA in percent.

Maximum swe (Table 5) was calculated based on swe on May 23, 1985 and assumes that all water melted prior to May 23 remained in the snowpack and is reflected in snowpack density and depth on that date.

Though individual curves were retained for use in modeling, the snow depletion curve for HRU 6 (Figure 7) was representative of the general curve shape obtained on other HRUs. Initially, large changes in SCA are accompanied by small changes in snow storage, however in mid season, with primarily deep snow drifts, swe changes faster than SCA. Generally, the alpine curves are closest to Curve Type 4 in Anderson's classification (Huber,1978).

DSCOR Values

In PRMS, precipitation as snow accumulates on each HRU as a proportion, DSCOR, of the snow falling at a specified precipitation gage. To determine DSCOR values, a regression equation relating maximum HRU swe to HRU mean elevation was generated giving poor results (R^2=.07). Instead, the ratio of maximum HRU swe to total precipitation from September to May was used. DSCOR values for the Upper Green Lakes Valley HRUs were calculated using SCA and ablation data from 1982 and compare favorably to values obtained in 1985 (Table 6). Winter accumulation at D1 was 101 and 93 cm in 1985 and 1982 respectively. Precipitation at the Saddle gage used for HRUs 7-9, was 109 cm in 1985.

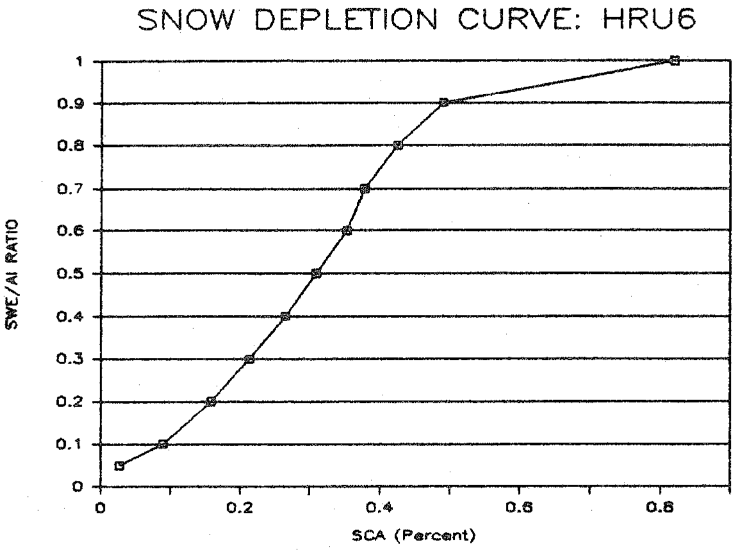


Figure 7: Snow Depletion Curve for HRU 6 in the Lower Green Lakes Valley.

Table 5
Snow Depletion Curves : Green Lakes Valley

HRU	AI (max swe,cm)	SWE/AI RATIO 1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	.05
1	137	.88	.75	.69	.62	.52	.44	.36	.27	.20	.16	.13
2	53	.58	.50	.48	.45	.41	.38	.35	.29	.22	.11	.04
3	89	.87	.55	.51	.47	.45	.41	.35	.27	.19	.13	.09
4	90	.91	.78	.75	.70	.66	.61	.56	.49	.38	.28	.12
5	65	.78	.53	.43	.40	.36	.31	.26	.20	.11	.04	.03
6	50	.82	.49	.43	.38	.35	.31	.27	.21	.16	.09	.03
7	91	.91	.76	.71	.65	.58	.50	.42	.34	.25	.13	.06
8	80	.97	.63	.55	.51	.46	.40	.34	.26	.16	.07	.05
9	71	.98	.81	.61	.58	.47	.46	.39	.31	.23	.12	.03

Table 6
DSCOR values 1985 and 1982

HRU	1	2	3	4	5	6	7	8	9
DSCOR(1985)	1.36	0.53	0.88	0.89	0.64	0.50	0.83	0.73	0.72
DSCOR(1982)	1.31	0.58	1.19	0.85					

Effect of Depletion Curves on PRMS Runoff Prediction

Subroutine SNOCOV was added to PRMS to implement the snow depletion curve. Software was supplied by the USGS in Denver, Colorado. Accuracy of runoff prediction in the Upper Green Lakes Valley increased after addition of snow depletion curves in 1985. The model was first calibrated without the depletion curves. The snow depletion curves and calculated DSCOR values were added and the HRU swe adjusted on May 20 using calculated maximum swe. Hydrographs were compared to each other and the observed hydrograph 1)graphically, Figure 8a and b, and 2) by comparison of discharge volumes, peak runoff timing and discharge and by the efficiency index, E_f (Loague and Freeze,1985) in Table 7.

Calibration of the runoff hydrograph (Figure 8a,Table 7) attempted to simulate the fast response, especially at peak runoff, in the Green Lakes Valley. A calibration which increases rapidly at the peak overestimated post peak runoff in June and drops below the observed hydrograph in July through September. The abrupt depletion of snowpack, given the assumption of 100 percent SCA, also contributes to the low late season flows. An efficiency of .157 is low considering a negative value implies that the mean observed discharge is a better indicator of runoff than predicted discharge from the model (Loague and Freeze,1985).

Addition of the snow depletion curves improves prediction of the amount of runoff over the whole snowmelt season (Figure 8b,Table 7) though the response at peak runoff decreases, a reflection of maximum SCA less than 100 percent. The efficiency index markedly improves to 0.416 with addition of the depletion curves. This efficiency, though low, compares to verification efficiencies of 0.25, for storm rainfall runoff models(Loague and Freeze). Application of the snow depletion curves and the 1985 calibration to another year would provide a better comparison.

The constant DSCOR value obtained from maximum HRU swe and snow accumulation was not sufficient to simulate snow accumulation on each HRU. On May 20, the date of snowpack adjustment, simulated swe was 84, 90, 70 and 50 percent of the calculated maximum swe on HRUs 1 to 4 respectively. Further monitoring of snow distribution during the accumulation period and allowance of a variable DSCOR value may improve estimation of this parameter.

	PEAK (CMS)	DATE PEAK	JUNE R.O. (cm)	7-9 R.O. (cm)	E_f
OBSERVED	.74	6/7	27.7	47.4	
WITHOUT SDC	.59	6/9	37.4	26.5	.157
WITH SDC	.38	6/9	31.6	37.4	.416

Table 7: Comparison of hydrographs. R.O. is runoff, E_f is efficiency index.

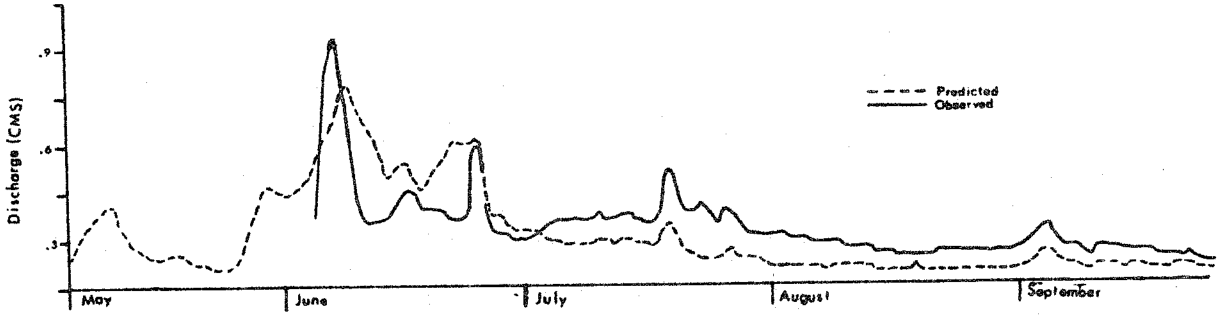


Figure 8a:Calibrated Hydrograph without the Snow Depletion Curves.

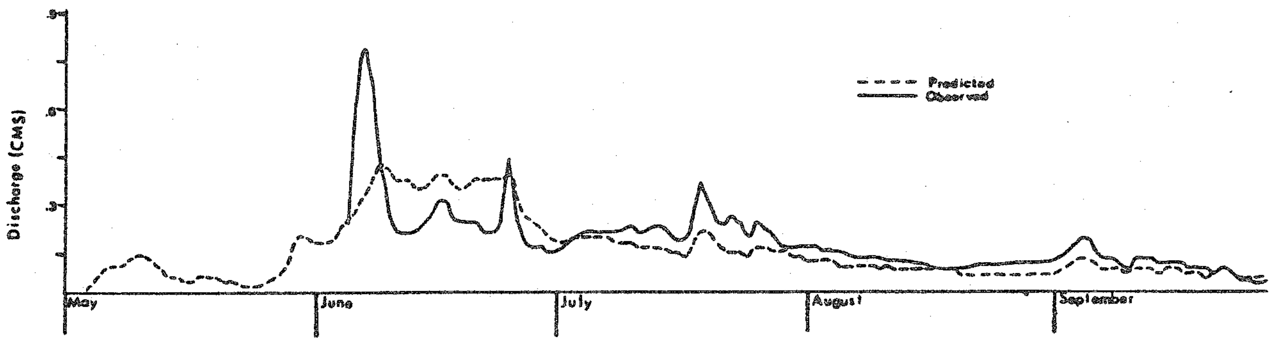


Figure 8b:Hydrograph after addition of snow depletion curves, DSCOR values and snowpack adjustment. No further calibration was done.

CONCLUSIONS

1. Decrease in ablation with elevation is confirmed
2. Lack of consistent spatial depth/density relationship
3. Mean HRU elevation/swe(max) relationship poor: possibly due to heterogeneity of the alpine
4. SCA recession variable:Dependent on topography and wind maximum SCA below 100 percent
5. Constant DSCOR value from swe(max) and max. snow accumulation not sufficient to model snow accumulation period
6. Combination of snowpack adjustment and snow depletion curves improves model prediction for 1985.
7. Further work:
    - Monitoring swe in accumulation period
    - Application of snow depletion curves and 1985 calibration to other years of record.

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