A COMPARISON OF SEVERAL SNOW ACCUMULATION AND ABLATION ALGORITHMS USED IN WATERSHED MODELING

by

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INTRODUCTION

The snow water contribution to the water supply during the forage growing season is the major component of the water supply available on much of the rangeland in the Western United States. For this case, snowpack accumulation and melt are major factors in both the amount and timing of the surface runoff. A review of the literature reveals that numerous snow accumulation and melt algorithms have been developed for use in streamflow simulation models. These snow models fit into one of three types.

The first and most common is an empirical temperature driven degree-day melt factor model (ASCE, 1949 and Linsley, 1943). The second type is a more fundamental model of the processes governing the energy balance in the snowpack. This type of model requires more data than is usually available, such as solar insolation, vapor pressure, and wind (Morris and Godfrey, 1978). The third type of snow model is a combination of the other two. Empirical relationships for the energy balance processes are developed as functions of the readily available data, such as temperature and precipitation (Anderson, 1973; Riley, et al., 1972; and Leaf and Brink, 1973). Models of the first and third types were tested using data from the ARS Reynolds Creek Experimental Watershed, southwest Idaho. (Robins, et al., 1965 contains a good description of the Reynolds Creek Watershed project to which the interested reader is referred.) A brief description of each of the models tested is given in the following section.

SNOW MODELS TESTED

The Snow Algorithm from CREAMS (Knisel, et al., 1980).

The CREAMS snow accumulation and melt algorithm simply allocates and accumulates precipitation as snow when the air temperature is less than 0° Celsius. When the temperature is above 0° and snow storage exists, snowmelt occurs, and is calculated by the equation,

$$M_i = 0.18\ T_a \qquad [1]$$

where:

M_i = daily melt in inches of water and

T_a = average daily air temperature in degrees Celsius.

Mass balance is maintained by limiting the snowmelt to the amount of water in snow storage.

Generalized Temperature Melt Factor Model.

The generalized temperature melt factor model, also referred to as the degree-day method (ASCE, 1949 and Linsley, 1943), allocates the precipitation and calculates the melt on the basis of the average daily air temperature. The melt is calculated by the equation,

$$M = K_{mf}\ (T_a - T_m) \qquad [2]$$

where:

M = daily snowmelt in mm of water,

Presented at the Western Snow Conference, April 19-22, 1983, Vancouver, Washington.

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K_{mf} = melt factor coefficient in mm of water per day per degree Celsius,

T_a = average daily air temperature in degrees Celsius, and

T_m = threshold temperature for snowmelt in degrees Celsius.

The CREAMS snow model is a special case of the generalized degree-day method with K_{mf} equal to 4.572 mm per day per degree and T_m set equal to 0°. Generally, the melt factor coefficient, K_{mf}, and the melt threshold temperature are determined by calibrating the model using historical snowpack data. Figure 1 is a flow chart of the generalized temperature melt factor model.

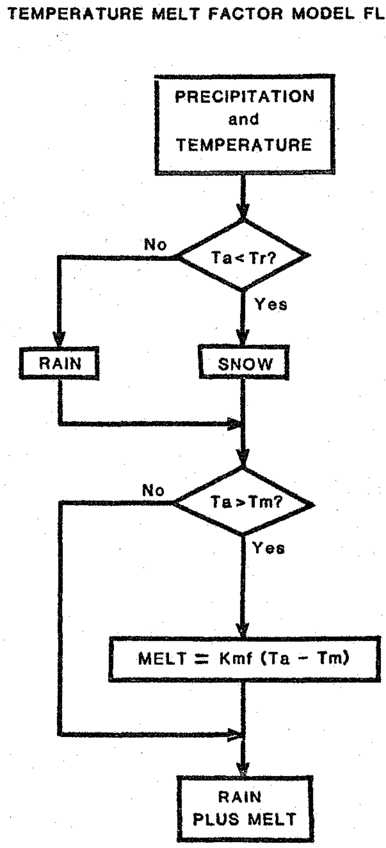


Figure 1

Flow Chart of a Generalized Temperature Melt Factor Model

Potential Solar Insolation Melt Factor Model.

A potential insolation snowmelt model was developed and tested. Daily average air temperature controlled the accumulation of the snowpack and the occurrence of snowmelt. The actual melt, however, was calculated as a function of the potential solar insolation received at the top of the atmosphere. The specific melt equation is:

$$M_i = K_{rc} \times R_p \text{ when } P_i <= 0, \text{ or}$$

$$M_i = K_{rd} \times R_p \text{ when } P_i > 0 \qquad [3]$$

where:

M_i = daily melt in mm of water,

K_{rc} = clear day radiation melt factor in mm per day per Langley,

K_{rc} = cloudy day radiation melt factor in mm per day per Langley,

R_p = daily potential radiation in Langleys, and

P_i = daily precipitation in mm of water.

The potential solar radiation values depend on the time of year and latitude of the experimental site (Lee, 1963). The radiation melt factors are obtained by calibrating the model with historical snowpack data.

Exponential Decay Temperature Melt Factor Model (Huber, et al., 1976).

Another model developed and tested was one which treats the snowpack as a linear storage reservoir with snowmelt being proportional to the amount of water in storage. The melt equation is derived as follows:

$$dS/dt = -K_s(T_a - T_m)S \qquad [4]$$

where:

dS/dt = rate of change in snow storage in mm per time period, t,

S = water equivalent of the snowpack in mm of water,

K_s = proportionality constant in inverse degrees Celsius,

T_a = average daily air temperature in degrees Celsius, and

T_m = melt threshold temperature in degrees Celsius.

Integrating equation 4 over a one day time interval yields, after some algebraic manipulation, the melt equation is:

$$M_i = S_o[1 - \exp(-K_s(T_a - T_m))] \qquad [5]$$

where:

M_i = daily snowmelt in mm of water, and

S_o = accumulated snow pack at the beginning of the day in mm of water.

The proportionality constant, K_s, and the melt threshold temperature, T_m, are determined during the calibration process using historical data.

The National Weather Service (NWS) HYDRO-17 Snow Accumulation and Ablation Model (Anderson, 1973).

The HYDRO-17 snow model was developed by Eric A. Anderson at the NWS Hydrologic Research Laboratory. It is a model of the significant physical processes governing the accumulation and melting of snow. A detailed description of the model may be found in the NWS HYDRO-17 report (Anderson, 1973). A summary of the model and modifications follows:

The accumulation process. The accumulation of snow in the NWS model is similar to that of the melt factor models described previously. If the air temperature is less than or equal to a threshold temperature, PXTEMP, the precipitation is considered to be snow and is added to the existing snowpack; otherwise, it is modeled as rain.

The melt process. The snowmelt process is divided into that occurring during rain-on-snow and that occurring during non-rain periods. This is necessary because the melt rates are generally quite different for these two conditions.

Rain-on-snow melt is assumed to occur at the snow surface and is computed from an energy balance equation. Assumptions used in applying the energy balance equation are: 1) solar radiation is zero; 2) incoming longwave radiation is equal to black body radiation at the ambient temperature; 3) the snow surface temperature is zero degrees Celsius; 4) the dew point is equal to the ambient temperature; and 5) the temperature of the rain water is equal to the ambient temperature.

The melt occurring during the non-rain periods is calculated from an empirical temperature based melt factor equation of the form:

$$Mi = M_f(T_a - MBASE) \qquad [6]$$

where:

M_i = the snow melt in mm per day,

M_f = the melt factor exhibiting a sinusoidal seasonal variation defined by the parameters MFMAX and MFMIN,

MBASE = the melt threshold temperature below which no melt occurs, and

T_a = the air temperature in degrees Celsius.

In addition to the rain-on-snow and non-rain melt, a third type of snowmelt is modeled. It is groundmelt which occurs continuously at the bottom of the snowpack. Although this melt may be small on a daily basis, it can be significant when accumulated over an entire snow season.

Modification to the NWS model. The input of the snow cover depletion curve has been modified by defining a new parameter, the areal snow cover depletion curve type (ADPT), which defines the specific curve for the site being modeled. It does this by a table lookup and interpolation procedure. Figure 2 shows the five curves covering the feasible range of types which provide the basis for the procedure. Each of the five curves is represented by eleven discrete points giving the percent snow cover corresponding to each one tenth increment in the ratio of the mean areal snow water equivalent (SWE) to the areal index (A_i). The values representing each curve are given in Table 1.

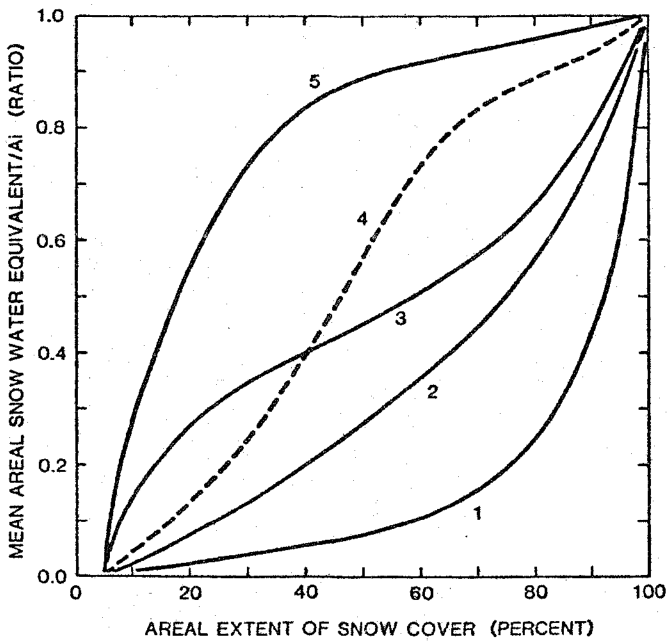


Figure 2

Five Characteristic Snow Cover Depletion Curves

The range of values for ADPT is 1.0 to 5.0. Values that have fractional parts result in depletion curves defined by linear interpolation between the two curves which bracket the specified ADPT value. For example, an ADPT value of 2.5 specifies a depletion curve half way between curve types 2 and 3. A value less than one selects curve 1 and a value greater than 5 selects curve 5.

Table 1

Snow Cover Areal Depletion Curve Values (Percent Snow Cover)

Curve Type (ADPT)	Mean Areal Water Equivalent/A_i (Ratio) 0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	5	58	76	84	89	93	95	97	98	99	100
2	5	24	40	53	65	75	82	88	93	97	100
3	5	8	14	23	40	59	73	83	90	95	100
4	5	16	26	34	40	46	52	58	66	82	100
5	5	6	8	10	14	18	22	27	35	54	100

TESTING THE MODELS

The overall objective was to test the ability of the models to simulate the snowpack at a homogeneous location represented by a surveyed snow course. The data used in testing all of the models included daily maximum and minimum temperature, precipitation, and snow course snow water equivalent at the Reynolds Mountain snow course. The procedure for testing each model was as follows:

The model was first calibrated with 1980 water year data; then, a 4-year test period including the high and low years of record, was simulated to test the validity of the calibration coefficients. The model was evaluated with an objective function and a bias function. The objective function was the accumulated absolute deviations of the simulated from the observed snow water equivalent (SWE) and the bias function was the algebraic sum of the deviations between simulated and measured snow water equivalent.

$$OBJ = \sum ABS(SWE_{com} - SWE_{obs}) \tag{7}$$

$$BIAS = \sum (SWE_{com} - SWE_{obs}) \tag{8}$$

where:

SWE_{com} = simulated snow water equivalent in mm of water, and

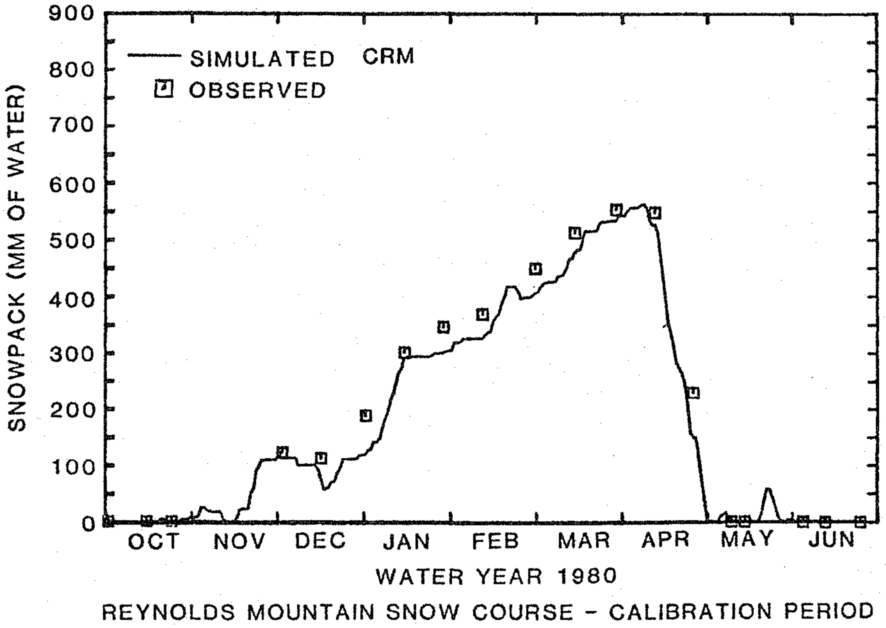
SWE_{obs} = measured snow water equivalent in mm of water.

The product moment correlation coefficient, r, between the simulated and measured SWE was also calculated. The results of the water year 1980 calibration runs and the 4-year test period runs are shown in Figures 3 through 7. Table 2 is a statistical summary of the results comparing the five models evaluated. Each of the models produced a reasonably good estimate of the snow water equivalent during the water year 1980 calibration period. All of the algorithms tested used air temperature to trigger the melt and accumulation processes. The different results must, therefore, be attributed to the way the snowmelt is calculated and routed through the snowpack.

The ARS-CREAMS model is structurally the same as the temperature melt factor model. The only difference is that the CREAMS model has a fixed melt factor of 4.572 mm per day per degree Celsius which proved to be too large for the conditions at the Reynolds Mountain snow course. The optimum values for the temperature melt factor obtained from the 1980 calibration runs were 3.8 and 4.0 mm per day per degree Celsius for clear days and cloudy days respectively. The computer output from Hydro-17 for the calibration run and the first year of the test run is shown in Figure 8.

An explanation of the major column headings and symbols used in Figure 8 is as follows:

SEQ is the accumulated days from the beginning of the simulation;
DAY is the Julian day of the year;



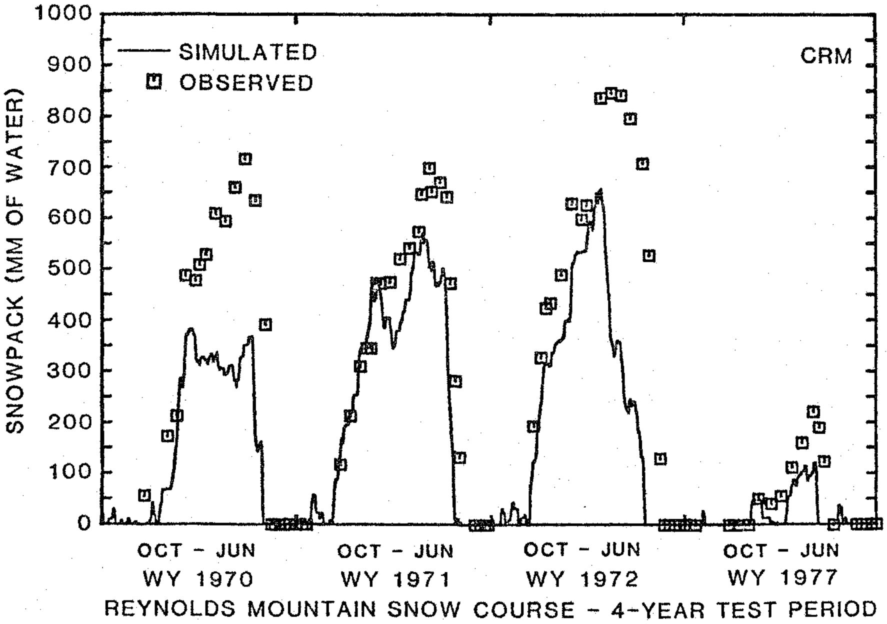
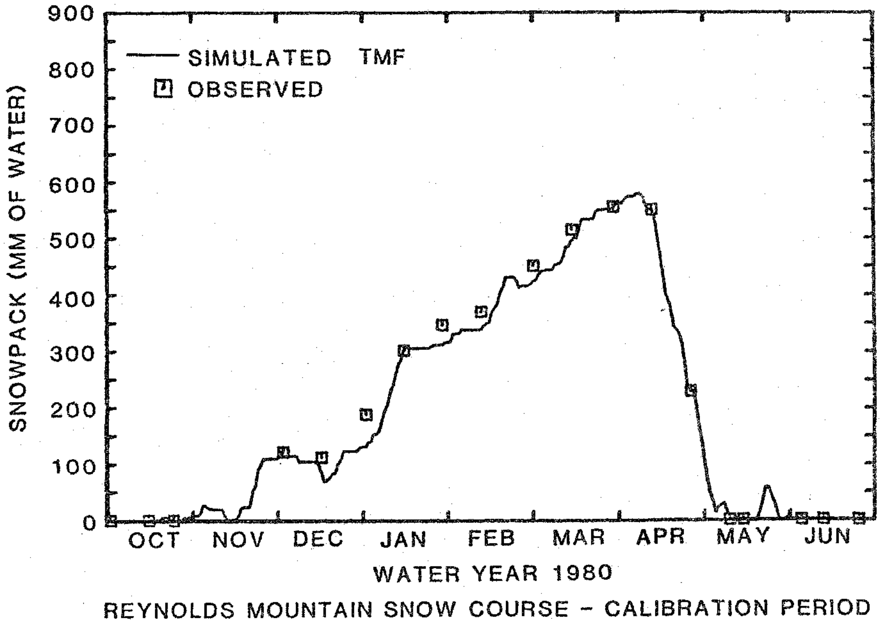


Figure 3

Snow Water Equivalent at the Reynolds Mountain Snow Course for the Calibration Water Year, 1980 (Above), and the Test 4-Years, 1970, 1971, 1972, and 1977 (Below), Snow Accumulation and Ablation Period (Simulated by the ARS-CREAMS Model)



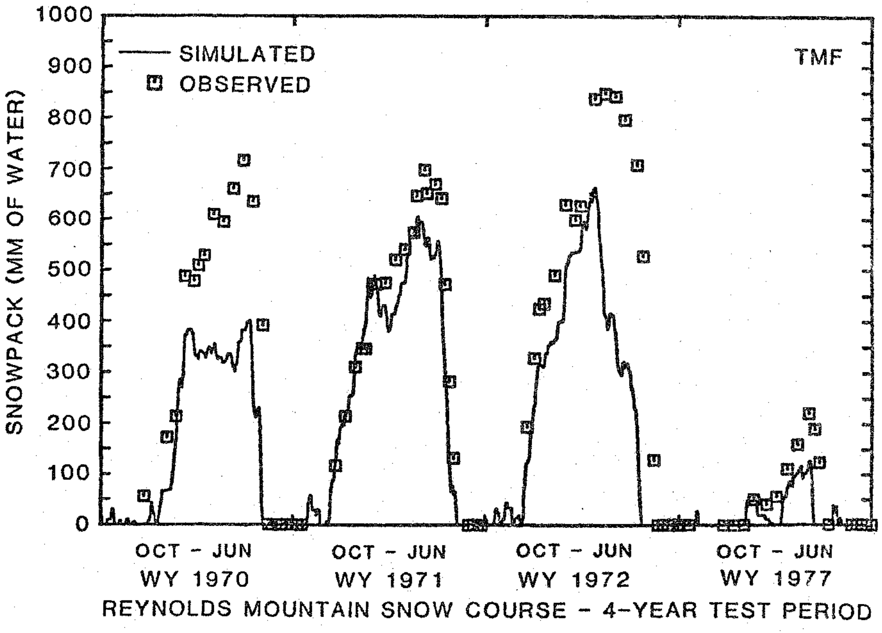
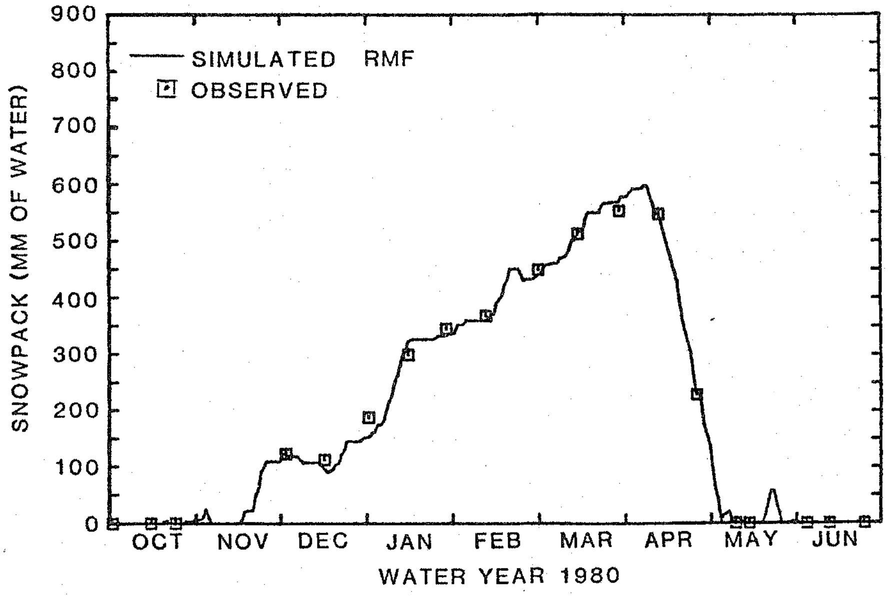
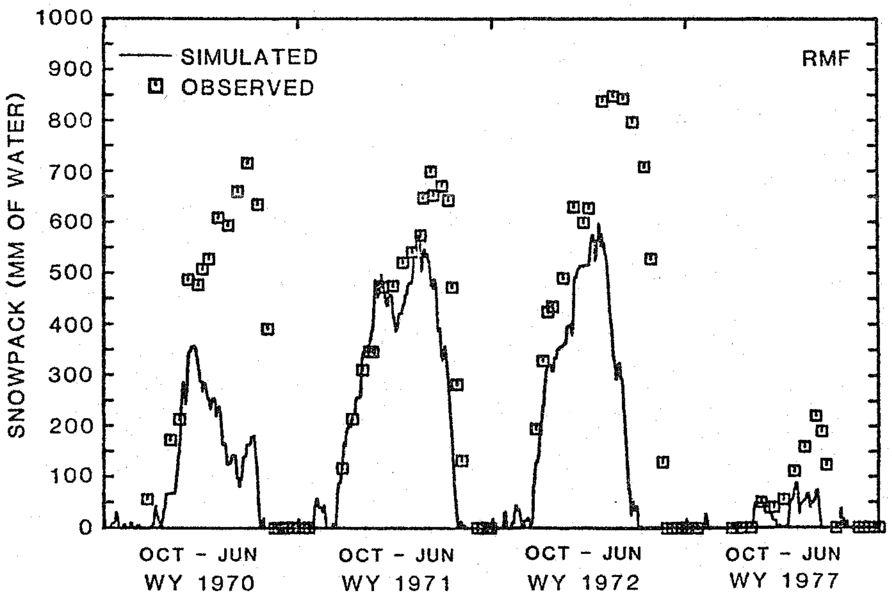


Figure 4

Snow Water Equivalent at the Reynolds Mountain Snow Course for the Calibration Water Year, 1980 (Above), and the Test 4-Years, 1970, 1971, 1972, and 1977 (Below), Snow Accumulation and Ablation Period (Simulated by the Temperature Melt Factor Model)



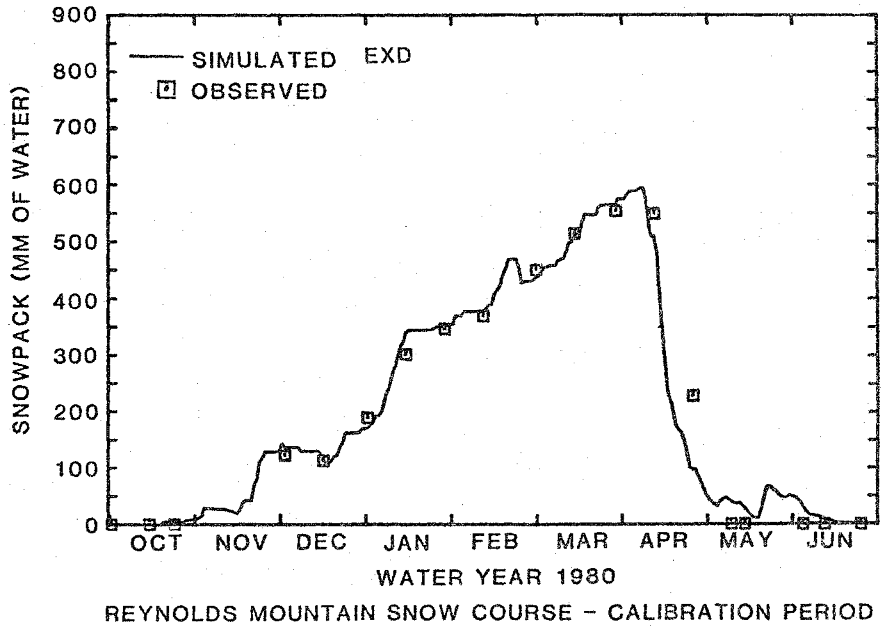
REYNOLDS MOUNTAIN SNOW COURSE - CALIBRATION PERIOD



REYNOLDS MOUNTAIN SNOW COURSE - 4-YEAR TEST PERIOD

Figure 5

Snow Water Equivalent at the Reynolds Mountain Snow Course for the Calibration Water Year, 1980 (Above), and the Test 4-Years, 1970, 1971, 1972, and 1977 (Below), Snow Accumulation and Ablation Period (Simulated by the Potential Radiation Melt Factor Model)



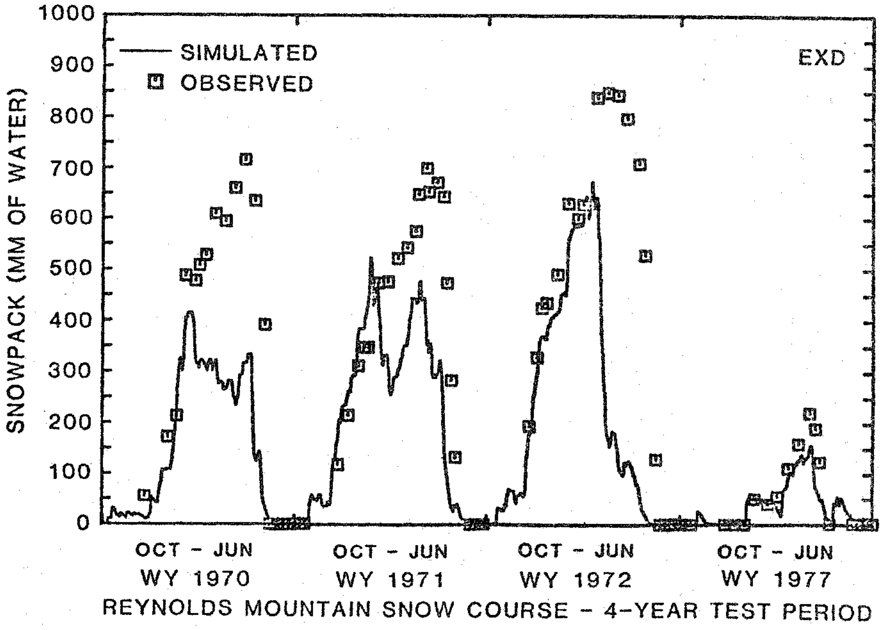
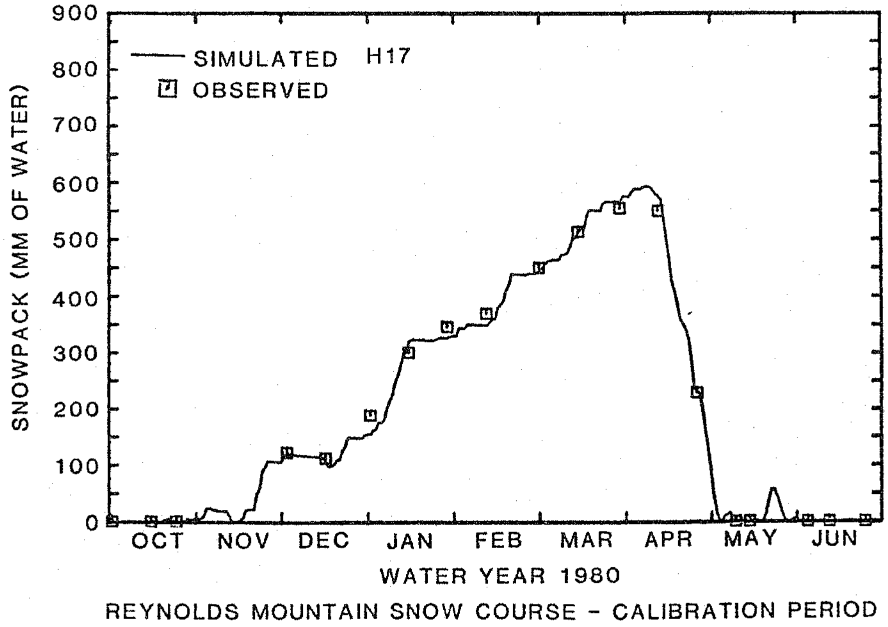


Figure 6

Snow Water Equivalent at the Reynolds Mountain Snow Course for the Calibration Water Year, 1980 (Above), and the Test 4-Years, 1970, 1971, 1972, and 1977 (Below), Snow Accumulation and Ablation Period (Simulated by Exponential Decay Model)



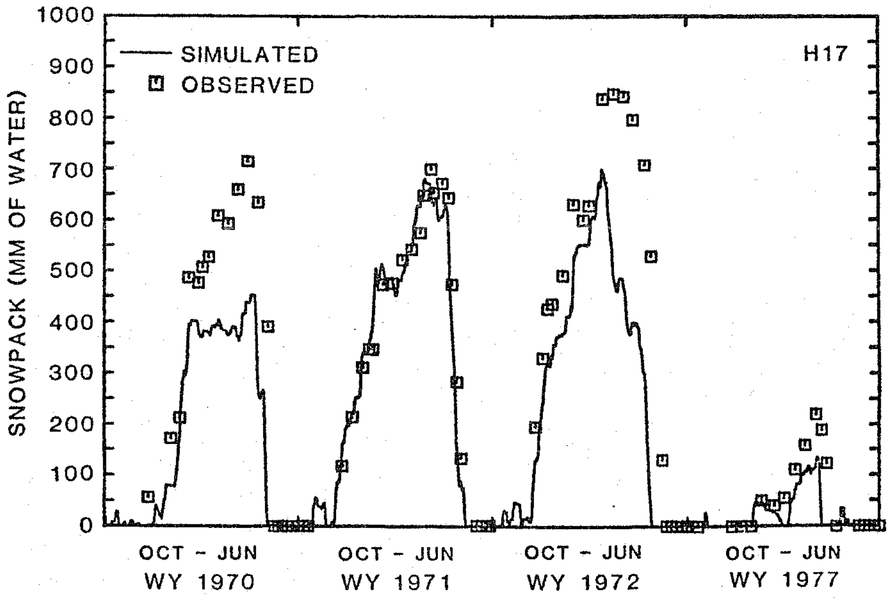


Figure 7

Snow Water Equivalent at the Reynolds Mountain Snow Course for the Calibration Water Year, 1980 (Above), and the Test 4-Years, 1970, 1971, 1972, and 1977 (Below), Snow Accumulation and Ablation Period (Simulated by the NWS HYDRO-17 Model)

MO-DA-YR is the date;
TMAX is the daily maximum temperature which has occurred since the previous report, in degrees Celsius;
TMIN is the daily minimum temperature which has occurred since the previous report, in degrees Celsius;
TAVE is the arithmetic average of TMAX and TMIN;
P is the accumulated precipitation which has occurred since the previous report, in mm of water;
MELT is the accumulated snowmelt which has occurred since the previous report, in mm of water;
RPSM is the accumulated rain plus snowmelt which has occurred since the previous report, in mm of water;
COVER is the percent snow cover on the reporting date;
TWE is the simulated snowpack snow water equivalent existing on the reporting date, in mm of water;
SWEOBS is the measured snowpack snow water equivalent existing on the reporting date, in mm of water;
DIFF is the difference between TWE and SWEOBS, in mm of water;
OBJ is the value of the objective function for the tabulation period; and
OAJ is the value of the bias function for the tabulation period.

Table 2

Summary of Calibration and Testing Results for the Five Snow Models Being Evaluated

MODEL	Calibration period Water year 1980			Test period - Water years 1970, 71, 72, and 77		
	Objective function[1] (mm)	Bias function[2] (mm)	Correl. coeff. r	Objective function (mm)	Bias function (mm)	Correl. coeff. r
ARS-CREAMS	410	-410	0.994	9443	-9189	0.853
TEMPERATURE MELT FACTOR	213	-206	0.997	8240	-7975	0.887
RADIATION MELT FACTOR	130	-50	0.998	11261	-10986	0.741
EXPONENTIAL DECAY	410	-6	0.984	10742	-9990	0.753
NWS HYDRO-17	144	-26	0.998	6824	-6824	0.905

[1] Objective function = $\sum \mathrm{ABS}(SWE_{com} - SWE_{obs})$

[2] Bias function = $\sum (SWE_{com} - SWE_{obs})$

CONCLUSIONS

The simulations shown for the 4-year test period illustrate a problem common to all of the temperature driven snowmelt models, premature melt both during the accumulation and melt phase of the year. Figure 7 shows that even the best model, NWS HYDRO-17, which performed quite well in 1971 and 1980, caused the simulated snowpack to melt prematurely during three of the test years. This is verified in Figure 8 which shows that the poor performance of the model in 1970 is caused primarily by premature melt early in the snow season and continuing throughout the snow accumulation period. This suggests that under certain conditions, the ambient air temperature fails as an index of the physical processes that cause the snow to accumulate and melt, and the inclusion of additional variables, such as solar radiation, wind run, and vapor pressure, would be necessary to improve the models. Overall, the algorithm employed in the NWSRFS model developed by Eric A. Anderson most closely matched the measured snow course values during the test period.

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REYNOLDS MOUNTAIN SNOW COURSE WY 1980 SWE SIMULATED BY NWS HYDRO-17 MODEL
----------------------------------------------------------------------------
MODEL PARAMETERS ARE AS FOLLOWS:
PAR NAME       VALUE           PAR NAME       VALUE
-----------------------------------------------------
  1 SCF        1.000             7 NMF        0.300
  2 MFMAX      4.800             8 TIPM       0.120
  3 MFMIN      2.000             9 MBASE      0.000
  4 UADJ       0.340            10 PXTEMP     0.000
  5 SI         0.000            11 PLWHC      0.010
  6 ADPT       3.000            12 DAYGM      0.300
-----------------------------------------------------
SNOW COVER DEPLETION CURVE PERCENT COVER VALUES
WE/AI  0.0    0.1    0.2    0.3    0.4    0.5    0.6    0.7    0.8    0.9    1.0
ADC    5.0    8.0   14.0   23.0   40.0   59.0   73.0   83.0   90.0   95.0  100.0

  SEQ  DAY MO-DA-YR   TMAX    TMIN    TAVE      P     MELT    RPSM   COVER     TWE  SWEOBS    DIFF
--------------------------------------------------------------------------------------------------
    1  274 10- 1-79  21.83   10.16   15.99    0.00    0.00    0.00    0.00    0.00    0.00    0.00
   15  288 10-15-79  22.38    2.38   12.38    7.32    0.00    7.32    0.00    0.00    0.00    0.00
   24  297 10-24-79  14.05   -4.29    4.88   61.98    5.84   61.98    0.00    0.00    0.00    0.00
   64  337 12- 3-79  11.83  -15.95   -2.06  160.93   32.20   42.77  100.00  118.17  121.92   -3.75
   78  351 12-17-79   6.27  -14.84   -4.29    1.27   11.62   12.13  100.00  107.31  111.76   -4.45

   94    2  1- 2-80   6.83  -15.40   -4.29   62.53   14.96   15.22  100.00  154.62  187.96  -33.34
  108   16  1-16-80   0.71  -17.06   -8.17  170.56    4.22    4.22  100.00  320.97  299.72   21.25
  122   30  1-30-80   0.16  -23.73  -11.79    9.30    4.21    4.21  100.00  326.05  345.44  -19.39
  136   44  2-13-80   2.94  -10.40   -3.73   26.39    4.21    4.21  100.00  348.23  368.30  -20.07
  155   63  3- 3-80   4.60   -9.29   -2.34  103.07    5.71    5.71  100.00  445.59  449.58   -3.99

  169   77  3-17-80   1.27  -15.40   -7.06   71.53    4.21    4.21  100.00  512.91  513.08   -0.17
  184   92  4- 1-80  -0.95  -14.29   -7.62   56.46    4.25    4.51  100.00  564.87  553.72   11.15
  198  106  4-15-80  10.16  -12.06   -0.95   28.68   18.57   18.57  100.00  574.98  548.64   26.34
  212  120  4-29-80  15.16   -4.29    5.44   12.95  346.02  358.98  100.00  228.95  228.60    0.35
  226  134  5-13-80  12.94   -5.95    3.49   30.12  244.96  259.08    0.00    0.00    0.00    0.00

  231  139  5-18-80  12.94   -4.84    4.05   10.34    1.70   10.34    0.00    0.00    0.00    0.00
  252  160  6- 8-80  20.16   -5.40    7.38  109.63   61.42  109.63    0.00    0.00    0.00    0.00
  260  168  6-16-80  17.38   -1.51    7.94    8.38    0.00    8.38    0.00    0.00    0.00    0.00
  273  181  6-29-80  20.71   -1.51    9.60    9.91    0.00    9.91    0.00    0.00    0.00    0.00
--------------------------------------------------------------------------------------------------
OBJ =     144.2351     OAJ =     -26.0613

REYNOLDS MOUNTAIN SNOW COURSE WY 1970 SWE SIMULATED BY NWS HYDRO-17 MODEL
USING MODEL PARAMETERS DERIVED FROM WY 1980 CALIBRATION
--------------------------------------------------------------------------------------------------
  SEQ  DAY MO-DA-YR   TMAX    TMIN    TAVE      P     MELT    RPSM   COVER     TWE  SWEOBS    DIFF
--------------------------------------------------------------------------------------------------
   63  335 12- 1-69  14.60  -17.62   -1.51   86.08   54.33   86.08    0.00    0.00   55.88  -55.88
   95    2  1- 2-70   7.94  -13.17   -2.62  138.73   32.31   59.85  100.00   78.89  172.72  -93.83
  108   15  1-15-70   0.71  -15.95   -7.62  101.73    3.91    3.91  100.00  176.71  213.36  -36.65
  120   27  1-27-70   4.05  -10.95   -3.45  268.20   27.93   50.76  100.00  394.14  487.68  -93.54
  134   41  2-10-70   8.49  -10.95   -1.23   10.13   19.78   19.78  100.00  384.50  477.52  -93.02

  140   47  2-16-70   6.83   -4.84    0.99   17.35   22.40   30.17  100.00  371.68  508.00 -136.32
  149   56  2-25-70   5.71   -8.73   -1.51   15.42    7.98    7.98  100.00  379.12  528.32 -149.20
  162   69  3-10-70   7.38   -9.84   -1.23   45.90   31.28   31.28  100.00  393.74  609.60 -215.86
  176   83  3-24-70   7.94   -8.17   -0.12   30.71   30.04   49.85  100.00  374.60  594.36 -219.76
  190   97  4- 7-70   8.49  -11.51   -1.51   17.91   21.84   21.84  100.00  370.67  660.40 -289.73

  204  111  4-21-70   6.83  -12.62   -2.90   82.12   14.66   14.66  100.00  438.12  716.28 -278.16
  218  125  5- 5-70  16.27  -11.51    2.38   17.35  165.37  165.37  100.00  290.10  635.00 -344.90
  232  139  5-19-70  19.60   -7.62    5.99   38.13  309.35  328.22    0.00    0.00  391.16 -391.16
  241  148  5-28-70  19.05    1.27   10.16   17.02    0.00   17.02    0.00    0.00    0.00    0.00
  246  153  6- 2-70  20.71   -0.40   10.16    0.00    0.00    0.00    0.00    0.00    0.00    0.00

  252  159  6- 8-70  22.94    1.83   12.38   11.02    0.00   11.02    0.00    0.00    0.00    0.00
  259  166  6-15-70  10.16   -0.40    4.88   18.01    0.00   18.01    0.00    0.00    0.00    0.00
  266  173  6-22-70  25.16    4.05   14.60    2.54    0.00    2.54    0.00    0.00    0.00    0.00
--------------------------------------------------------------------------------------------------
OBJ =    2398.0308     OAJ =  -2398.0308
```

Figure 8

Computer Output from the NWS HYDRO-17 Model (WY 1980 and WY 1970)

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