A SNOWPACK EVAPO-SUBLIMATION FORMULA 1/

497-69

By

George W. Peak 2/

Throughout the Rocky Mountain region, there are thousands of square miles of heavily producing watersheds lying in the alpine and subalpine zones. These areas are completely unprotected from the enormous evaporative and sublimative losses produced by wind, temperature and solar radiation.

The snowmelt-runoff equation that consists only of the forest protected snow course data, the soil moisture deficit and the late spring precipitation, is based on the assumption that there is little or no variation in alpine evapo-sublimation.

This paper consists of three parts: (1) The development of evaporation and sublimation formulae. (2) Automatic data processing, with these formulae, of Boise 750 mb temperature data and Lander solar radiation data. (3) The application of this processed data to the snowmelt-runoff analysis of a watershed.

It is in contrast to the first two papers on this subject where monthly values of evaporation factors were applied, statistically, to the runoff analysis.

Slide 1

This site on Casper Mountain is in the subalpine zone, at an elevation of 8,100 feet, and twelve miles from town. Wind velocities average 20 miles per hour.

The forest protected snowpack at this elevation averages about 60 inches on April 1, but very little snow is held on this unprotected ridge. The equipment shown consists of an anemometer, thermograph, sol-a-meter and the ice sample. Additional equipment includes an 8-inch precipitation scales, a base weight for scales correction and a sling psychrometer.

The Hogadon ski shelter is 100 yards to the east of this equipment. Bob Hardesty, the manager very kindly provided keys to the shelter for those times that it was necessary to stay all night on the mountain.

Plate I

This is a 24-hour section of the anemometer chart with recorded date of wind direction, wind run, temperatures in Fahrenheit, and solar radiation. The relative humidity is charted on a hygrograph or obtained once every hour with a sling psychrometer. A chart was developed to convert the loss from the 10-inch cube of ice to inches of evaporation or sublimation. In addition, the chart compensated for any change in the area of ice exposed.

Plate II

The 12-hour wind run versus the 12-hour sublimation in inches. The 12-hour periods are from 1800 hours to 0600 hours to eliminate insolation losses. Temperatures are always less than zero degrees centigrade. The curve is anchored at zero wind and zero sublimation. Of the eighteen samples obtained, eight of these were in dry air and provided a maximum rate of sublimation.

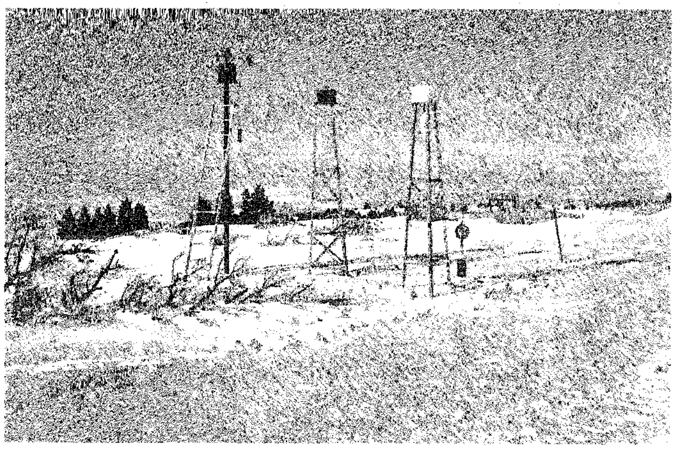
The equation for the curve is: $S_m^{12\ hr} = 0.00018 \text{Wind Run}$

Plate III

The deviations in inches from the curve of Plate II versus the degree centigrade for the 12-hour period.

1/ Presented at Western Snow Conference, April 15-17, 1969, Salt Lake City, Utah.

2/ Wyoming Snow Survey Supervisor, USDA, SCS, 345½ East Second St., Casper, Wyo.



Casper Mountain Evapo-Sublimation Data Site

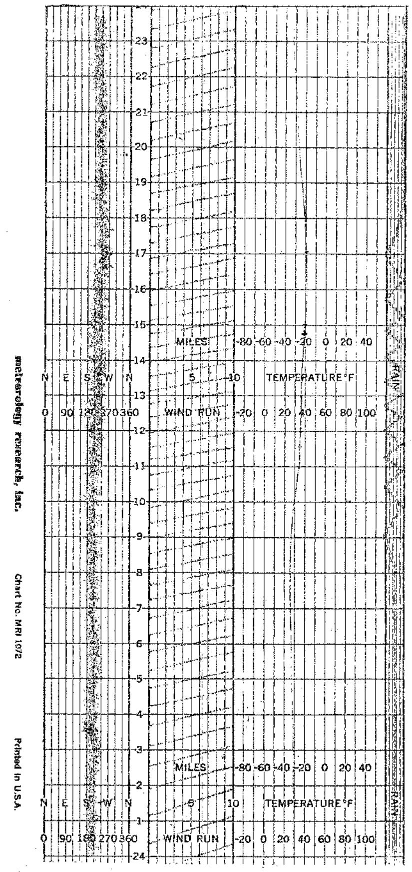
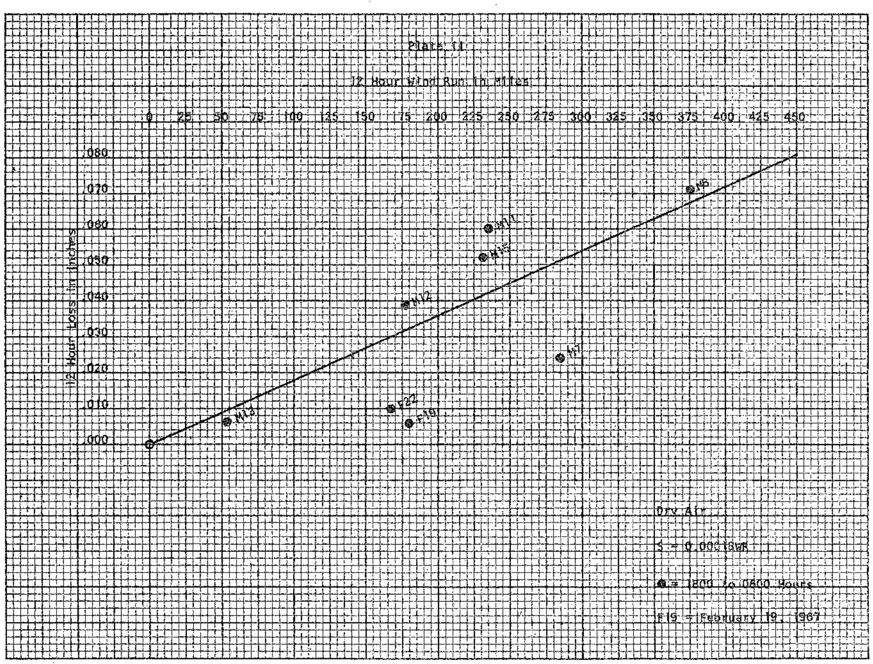


Plate I.



Maximum diffusivity with no wind is 0.021 inches of sublimation per 12 hours. Zero diffusivity is at -6.6°C. or 79DHC. Condensation occurs at still lower temperatures and no wind.

The graphical correlation of 1800 to 0600 hour data in dry air produces this formula for maximum sublimation:

$$S_m^{12hr} = 0.00018\text{Wind Run} + 0.000265\text{Degree Hours Centigrade} + 0.021$$

Plate IV

The same procedure is followed for the daylight hours of 0600 to 1800 in order to obtain insolation rates. The diffuse and solar radiation was converted to Langleys and plotted against the sublimation losses.

A Langley is the amount of heat required to raise a gram of water one degree centigrade. The slope of the curve is exactly the same as that for degree hours centigrade.

The intercept of the curve is at 92 Langleys. The period of sunshine for this time of year is 8 3/4 hours, which would indicate outgoing, or long wave, radiation of 0.17 Langleys per minute.

The maximum rate of radiation sublimation is then:

$$S_m^{12hr} = 0.000265(\text{Net Langleys})$$

The dry air formula for sublimation rates is then:

$$S_m^{12hr} = 0.00018WR + 0.000265DHC + 0.000265NL + 0.021$$

Combining Degree Hours and Net Langleys is permissable only if the areas exposed to both factors are identical. The areas exposed on the watershed are never identical.

Plate V

The development of a formula for evaporation is based on the temperature curve for sublimation.

The curve is anchored at the point of maximum diffusivity for zero temperatures and zero wind, given the same slope as that for sublimation, and extended into the evaporation area.

The combination of temperatures above freezing and insolation deteriorates the ice so rapidly it is necessary to eliminate solar radiation. The period extends from 1800 hours to 0600 hours.

In addition, relative humidity data were obtained once an hour with the sling psychrometer.

The points represent evaporation, in inches, versus the degree hours above 0°C.

Plate VI

The deviations from Plate V versus the wind run.

The slope of the curve is at a maximum for these data. The final plate in this series also indicates that the opportunity for evaporation is at a maximum. The dry air formula for wind is then:

$$E_m^{12hr} = 0.000555WR$$

Plate VII

The observed evaporation values versus the dry air formulae of Plates V and VI.

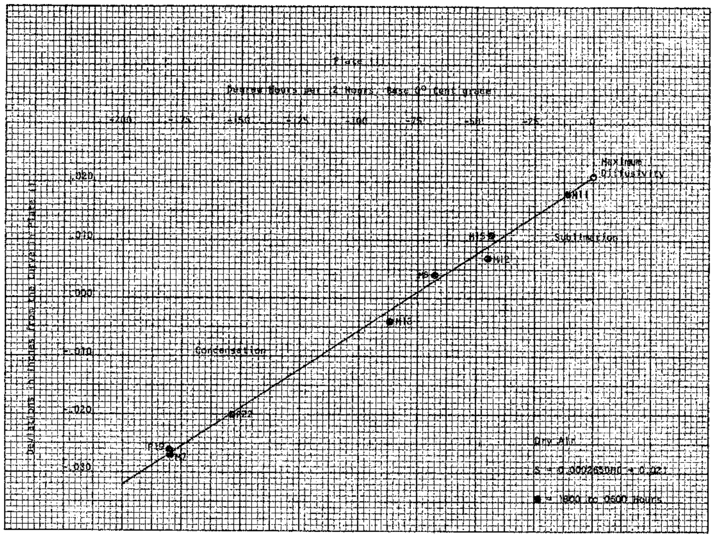


Plate III
Degree Hours per 12 Hours, Base 0° Centigrade
Deviations in Inches from the Curve
Maximum Diffusivity
Sublimation
Condensation
Dry Air
S = 0.000265DHC + 0.021
■ = 1800 to 0600 Hours

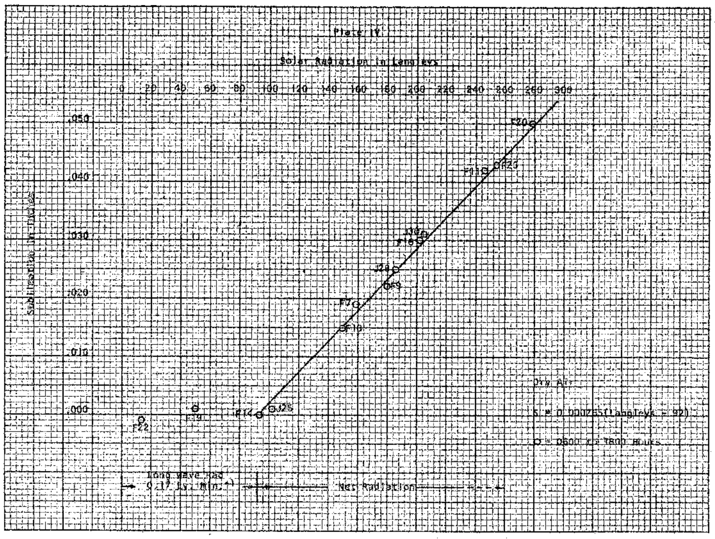


Plate IV
Solar Radiation in Langleys
Sublimation in Inches
Dry Air
○ = 0600 to 1800 Hours
Long Wave Rad
Net Radiation

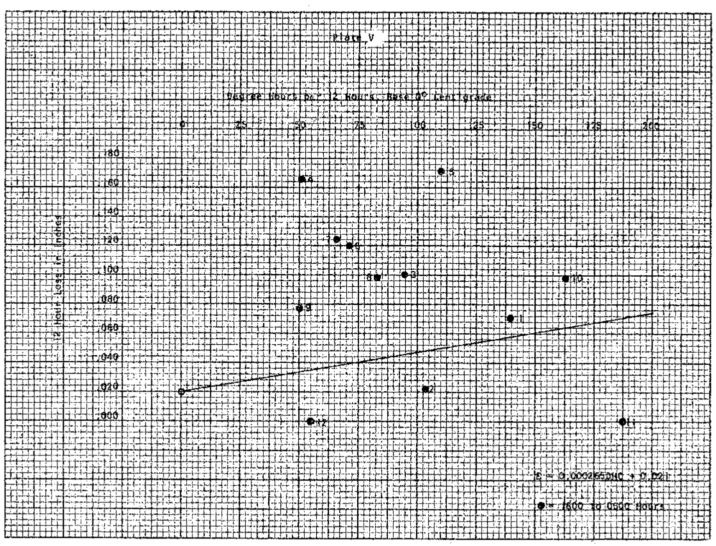


Plate V
Degree Hours per 12 Hours, Base 0° Centigrade
12 Hour Loss in Inches
S = 0.000265DHC + 0.021
● = 1600 to 0600 Hours

The ratio of the observed values and the computed values provides a percent of maximum evaporation; $\%E = (E_o / E_m) 100$.

This becomes the ordinate of the points in Plate IX.

Plate VIII

The curve for the saturation vapor pressure over ice, for positive degrees centigrade, is obtained by $RH_s = V_i / V_a$. RH_s is the relative humidity at saturation vapor pressure. V_i is the maximum vapor pressure for ice and is equal to 0.180 inches of mercury for 0°C and above. V_a is the maximum vapor pressure of water in inches of mercury, at a given temperature. RH_o is the observed relative humidity. The vapor deficit over ice is $1 - (V_a / V_i)RH_o$. This becomes the abscissa in Plate IX.

Plate IX

The percent of evaporation versus the vapor deficit over ice.

The coordinates of these points are determined by the procedures explained in Plates VII and VIII.

Plate X

Observed Evaporation versus Computed, or Net Evaporation.

$$E_n^{12hr} = (0.000555WR + 0.000265DHC + 0.021)\%EVD$$

Where %EVD is the percent of evaporation indicated by the vapor deficit.

AUTOMATIC DATA PROCESSING

Plate XI

Manes Barton, Staff Assistant, Soil Conservation Service and Arthur Crook, Wyoming Assistant Snow Survey Supervisor, developed a program that would process Winds Aloft data with the Casper Mountain formulae.

This is November 1965, 750 and 700 mb data recorded by the Weather Bureau at Lander, Wyoming.

The wind, temperature and dew point data are recorded at 12-hour intervals which are labeled Period 1 and Period 2.

Beginning on the left, we have the date and the percent of evapo-sublimation for Period 1. The third column is the number of inches of evaporation that occurred during the corresponding windrun. It is determined by 0.000555Wind Run multiplied by the percent of evaporation indicated by the vapor deficit.

The fourth column is the number of inches of evaporation determined by (.000265DHC + 0.021)%EVD. The fifth column is the number of inches of evaporation determined by (.000265Net Langleys)%EVD.

The balance of the columns in Period 1 are the processed sublimation data.

The monthly totals of each column are indicated by T.

The date of the initial snowpack accumulation is November 12. It is also the date on which evapo-sublimation starts.

THE SMITH'S FORK RUNOFF ANALYSIS

The Smith's Fork watershed is located at the west end of Wyoming on Commissary Ridge and the Tump Range. The seasonal snowmelt runoff averages 114,000 acre-feet of water.

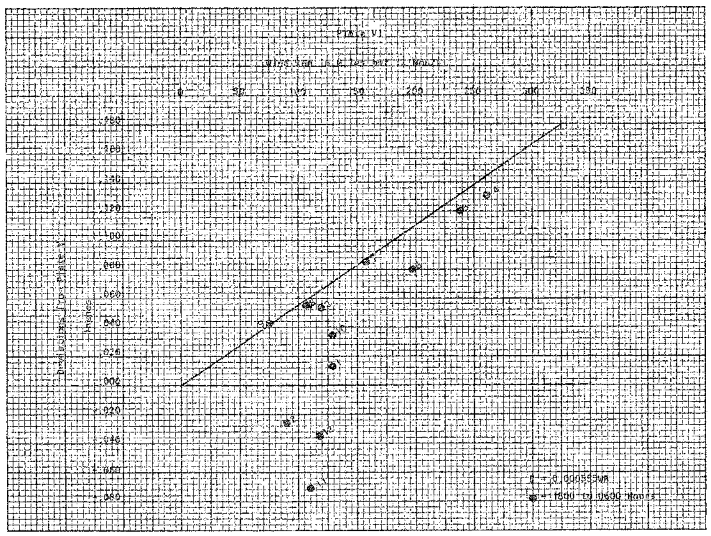


Plate VI
0 50 100 150 200 250 300 350
.180
.160
.140
.120
.100
.080
.060
.040
.020
.000
.020
.040
.060
.080
1800 to 0600 Hours

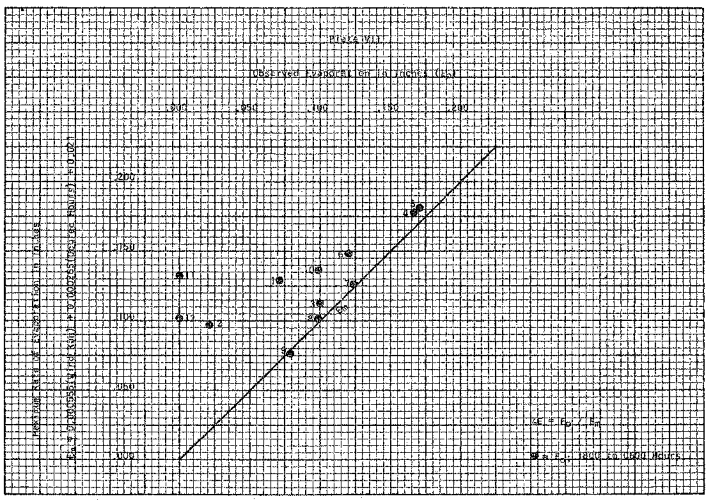


Plate VII
Observed Evaporation in Inches (Eo)
.000 .050 .100 .150 .200
.200
.150
.100
.050
.000
1800 to 0600 Hours

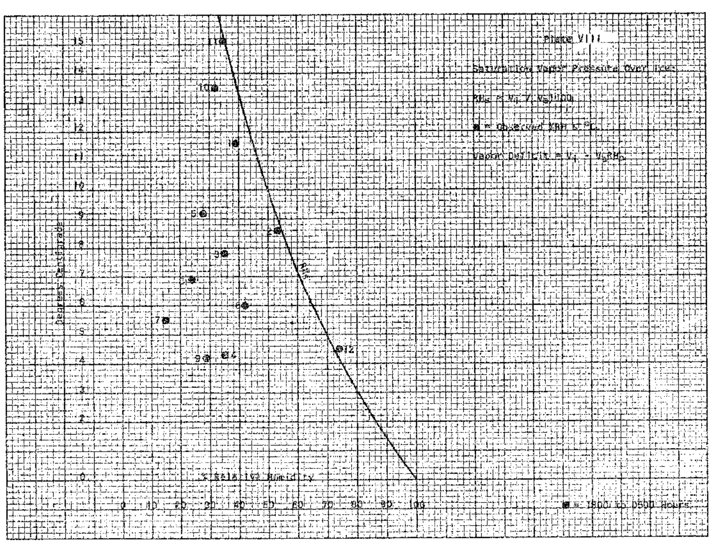
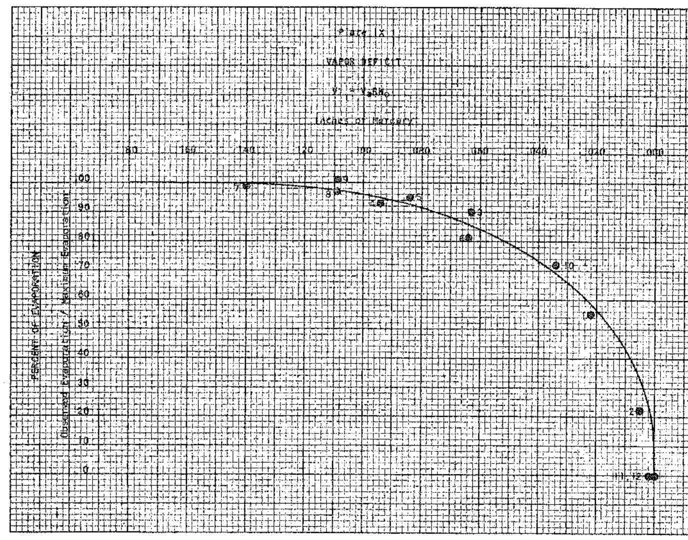
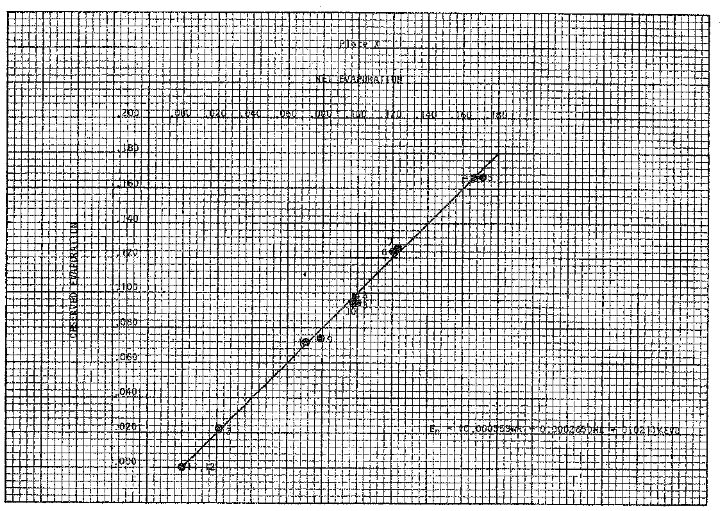


Plate VIII
Saturation Vapor Pressure Over Ice
Vapor Deficit
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Degrees Centigrade
Relative Humidity
0 10 20 30 40 50 60 70 80 90 100
1800 to 0600 Hours





	Period 1								Period 2									
	LDR 750 MYLLYBAR LEVEL				NOVMBR 1964													
	DAY	PVPG1	EWR1	EDH1	ERAD1	SWR1	SDH1	SRAD1	PVPG2	EWR2	EDH2	ERAD2	SWR2	SDH2	SRAD2	NLY	DAY	
	1	0.780	0.046	0.029	0.018	0.	0.	0.	0.930	0.194	0.037	0.021	0.	0.	0.	85	1	
	2	0.970	0.101	0.044	0.040	0.	0.	0.	0.840	0.064	0.030	0.043	0.	0.	0.	188	2	
	3	0.930	0.069	0.027	0.053	0.	0.	0.	0.990	0.	0.	0.	0.032	0.016	0.055	217	3	
	4	0.970	0.014	0.022	0.054	0.	0.	0.	0.970	0.029	0.031	0.084	0.	0.	0.	209	4	
	5	0.910	0.081	0.049	0.052	0.	0.	0.	0.940	0.072	0.046	0.055	0.	0.	0.	215	5	
	6	0.890	0.003	0.050	0.048	0.	0.	0.	0.960	0.072	0.036	0.052	0.	0.	0.	203	6	
	7	0.970	0.048	0.044	0.052	0.	0.	0.	0.970	0.087	0.032	0.057	0.	0.	0.	203	7	
	8	0.980	0.058	0.051	0.049	0.	0.	0.	0.980	0.204	0.050	0.049	0.	0.	0.	187	8	
	9	0.960	0.199	0.039	0.044	0.	0.	0.	0.960	0.129	0.034	0.044	0.	0.	0.	171	9	
	10	0.990	0.142	0.045	0.043	0.	0.	0.	0.930	0.042	0.027	0.041	0.	0.	0.	165	10	
Initial	11	0.960	0.172	0.027	0.	0.	0.	0.	0.960	0.	0.	0.	0.046	0.017	0.	0	11	Initial
Snowpack	12	0.980	0.	0.	0.	0.046	0.517	0.039	1.000	0.	0.	0.	0.057	0.000	0.040	152	12	Snowpack
	13	0.980	0.	0.	0.	0.037	0.016	0.	0.900	0.	0.	0.	0.017	0.506	0.	0	13	
	14	0.780	0.	0.	0.	0.030	-0.002	0.007	0.490	0.	0.	0.	0.028	-0.006	0.004	32	14	
	15	0.550	0.	0.	0.	0.018	-0.009	0.029	0.600	0.	0.	0.	0.014	-0.014	0.027	170	15	
	16	0.820	0.	0.	0.	0.012	-0.011	0.019	0.850	0.	0.	0.	0.032	-0.006	0.016	71	16	
	17	0.940	0.	0.	0.	0.009	0.002	0.013	0.770	0.	0.	0.	0.022	-0.004	0.011	54	17	
	18	0.510	0.	0.	0.	0.010	-0.004	0.021	0.650	0.	0.	0.	0.009	-0.009	0.027	159	18	
	19	0.830	0.	0.	0.	0.024	-0.003	0.037	0.920	0.	0.	0.	0.035	-0.000	0.041	168	19	
	20	0.980	0.	0.	0.	0.060	0.011	0.037	0.940	0.	0.	0.	0.085	0.019	0.036	145	20	
	21	0.900	0.	0.	0.	0.043	0.008	0.041	0.850	0.	0.	0.	0.028	0.005	0.039	174	21	
	22	0.890	0.046	0.029	0.032	0.	0.	0.	0.970	0.072	0.028	0.035	0.	0.	0.	135	22	
	23	0.970	0.101	0.027	0.042	0.	0.	0.	0.930	0.	0.	0.	0.009	0.014	0.040	163	23	
	24	0.960	0.	0.	0.	0.014	0.015	0.016	0.970	0.101	0.026	0.016	0.	0.	0.	61	24	
	25	0.760	0.091	0.028	0.031	0.	0.	0.	0.880	0.165	0.035	0.034	0.	0.	0.	153	25	
	26	0.890	0.212	0.020	0.002	0.	0.	0.	0.990	0.	0.	0.	0.056	0.006	0.001	9	26	
	27	0.970	0.	0.	0.	0.111	0.089	0.020	0.980	0.	0.	0.	0.084	-0.009	0.020	77	27	
	28	0.960	0.	0.	0.	0.060	-0.008	0.035	0.950	0.	0.	0.	0.082	0.004	0.034	137	28	
	29	0.970	0.	0.	0.	0.051	0.015	0.037	0.840	0.	0.	0.	0.040	0.006	0.032	143	29	
	30	0.930	0.	0.	0.	0.040	0.017	0.012	0.970	0.846	0.030	0.012	0.	0.	0.	48	30	
	T		1.484	0.529	0.567	0.564	0.673	0.399		1.475	0.442	0.506	0.679	0.045	0.425	3894.		

OTHER TOTALS PVAP= 3.930 WRE= 5718. DHE= 1718. ESNLY1= 3894.
SUB= 1.341 WRS= 8893. DHS= -2171. ESNLY2= 3894.

NEGATIVE SUBLT TOTALS SUB1= 0. WP1= 0. DH1= 0.
SUB2= 0. WR2= 0. DH2= 0.

COMPUTER PROCESSING

Net Evaporation 12hr⁻¹ = (.000535Wind Run + 0.000265Degree Hours + 0.000265Net Langleys + 0.021)%VPG

Net Sublimation 12hr⁻¹ = (.000180Wind Run + 0.000265Degree Hours + 0.000265Net Langleys + 0.021)%VPG

Where %VPG = % Evapo-sublimation indicated by the vapor deficit.

Plate XI.

There are six snow courses on the watershed, two at an average of 9,000 feet elevation, two at 8,400 feet and two at 7,700. In addition, the watershed has two Pearson precipitation gages, one at the Salt River Summit snow course and the other at the Kelly Ranger Station snow course.

The sources of the Winds Aloft data are Boise, Idaho and Lander, Wyoming.

The stream gaging station is near Border, Wyoming.

Plate XII

The average data of each pair of snow courses at high, medium and low elevation were weighted by computer analysis.

The basin precipitation column consists of the weighted water content minus the soil moisture deficit plus May precipitation.

The seasonal runoff period is from April 1 to September 30, and is scaled in thousands of acre-feet.

The dotted line is the mean curve of the precipitation column versus the ASROM.

The base curve is parallel to the mean curve and anchored at the point of zero runoff, or watershed field capacity.

Plate XIII

The deviations, in inches, from Plate XII were plotted against the wind and temperature evaporation data. The slope of the curve is 1:1.

Computer analysis indicated values of 75% for Boise data and 25% for Lander data.

The date of the initial snowpack accumulation is, now, determined by the LaBarge Guard Station pillow. Prior to this installation, the date of the initial accumulation was determined by snowfall records at Bondurant and South Pass.

Plate XIV

Net Langleys were determined by subtracting the maximum value of long wave radiation, for each month, throughout the winter. This data is plotted against the plus and minus deviations, in inches, of Plate XIII. It includes evaporation and sublimation.

The losses from solar and diffuse radiation data must be kept separate from the wind and temperature losses, since insolation is applicable to a different area of the watershed.

Plate XV

The sublimation indicated by the processed Winds Aloft data are plotted against the deviations from Plate XIV. The millibar level and weighting that was used for evaporation is also applied to sublimation.

Plate XVI

The curve values of Plate XIII minus the intercept, and the curve values of Plates XIV and XV are plotted against the deviations of Plate XII to determine the total evapo-sublimation losses.

Plate XVII

The deviations from the base curve of Plate XII are corrected by the total evapo-sublimation loss of Plate XVI, to obtain the Smith's Fork runoff equation and forecast formula.

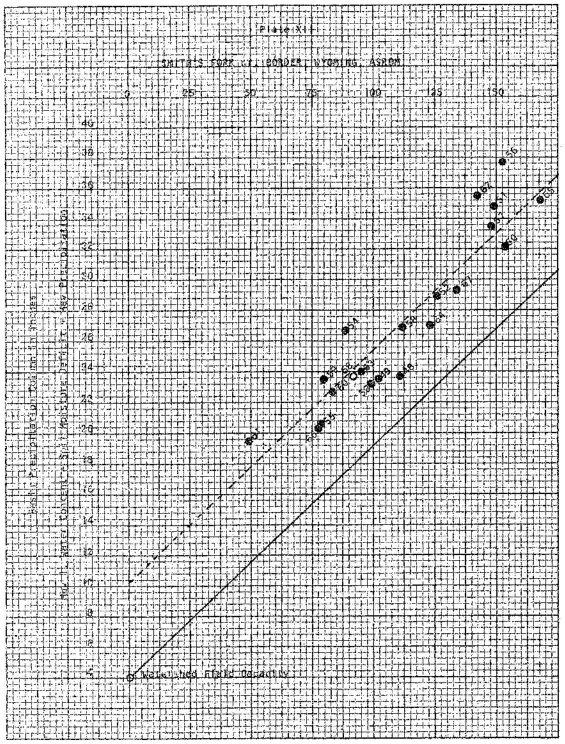


Plate XII
SMITHS FORK nr. BORDER, WYOMING, ASBOM
Watershed Field Capacity

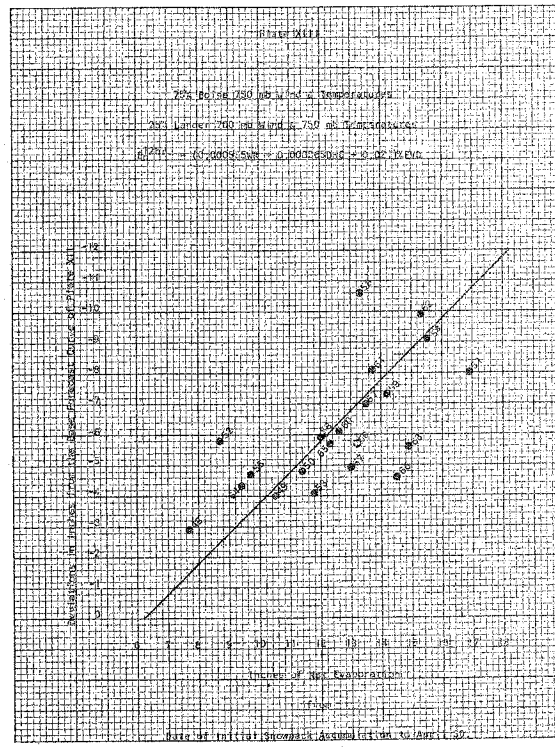


Plate XIII
75% Boise 750 mb Wind & Temperatures
25% Lander 700 mb Wind & 750 mb Temperatures
Inches of Net Evaporation
Date of Initial Snowpack Accumulation to April 30

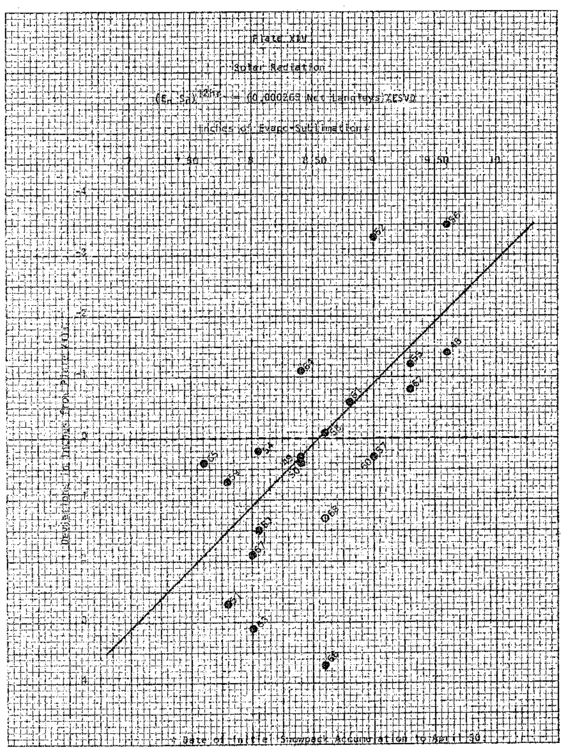


Plate XIV
Solar Radiation
Inches of Evapo-Sublimation
Date of Initial Snowpack Accumulation to April 30

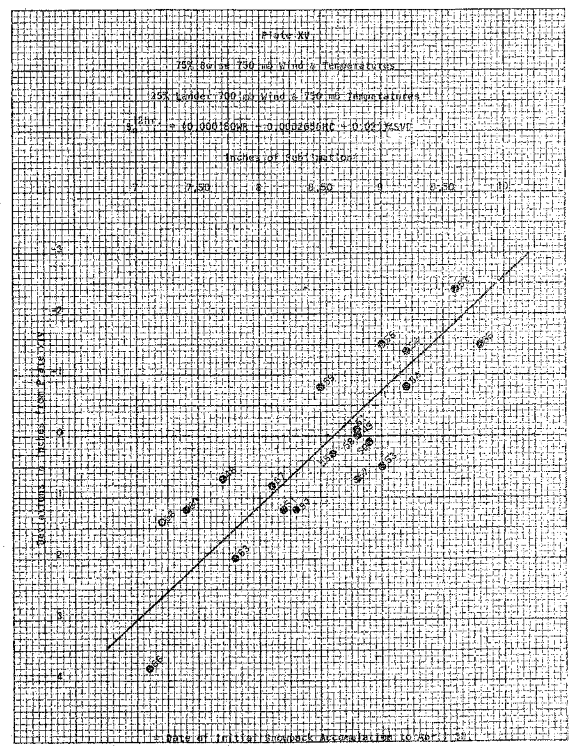


Plate XV
75% Boise 750 mb Wind & Temperatures
25% Lander 700 mb Wind & 750 mb Temperatures
Inches of Sublimation
Date of Initial Snowpack Accumulation to 30

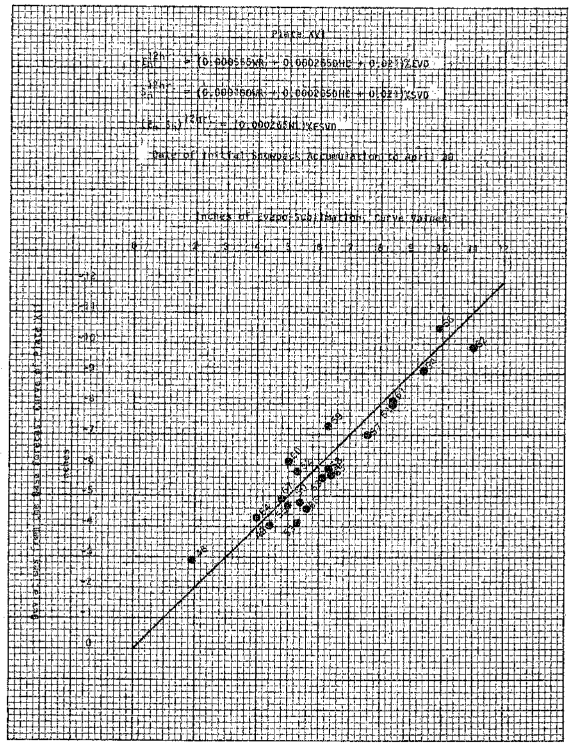


Plate XVI
(0.000555WR + 0.000265DHC + 0.021)%EVD
(0.000180WR + 0.000265DHE + 0.021)%SVD
(0.000265N1)%ESVD
Date of Initial Snowpack Accumulation to April 30
Inches of Evapo-Sublimation, Curve Values
0
2
3
4
5
6
7
8
9
10
11
12
Inches

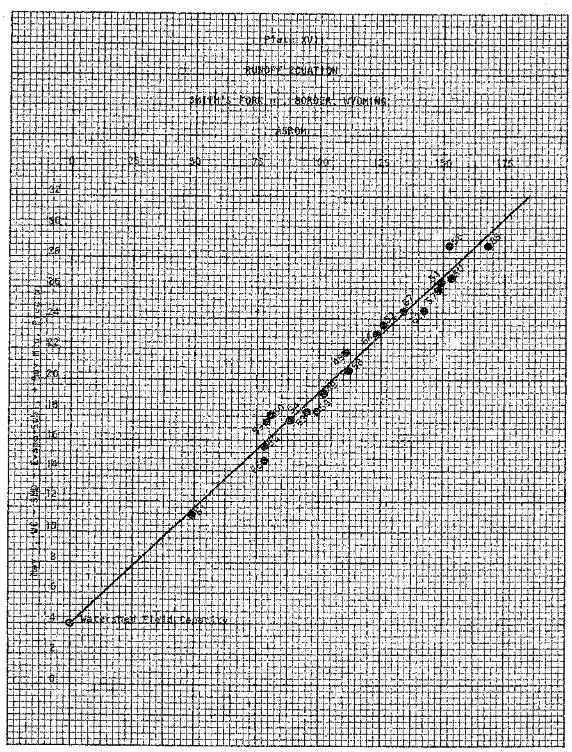


Plate XVII
RUNOFF EQUATION
SMITH'S FORK nr. BORDER, WYOMING
ASROM
0
25
50
75
100
125
150
175
Watershed Field Capacity

SUMMARY

Snowmelt-runoff equations for watersheds with alpine areas, or open range at deep snowpack elevations, must contain factors that adjust for the variable and substantial evapo-sublimation losses.

Weather Bureau stations gathering Winds Aloft data are widely scattered and not applicable to major sections of the Rocky Mountains. Furthermore, these data are "spot" measurements taken once every 12 hours and not at the hours best suited for analysis.

Radiation, in particular, must be on a local basis. The Soil Conservation Service now has 10 sol-a-meters in the state that will be of considerable help in another year or two.

Forecasts will not reach the accuracy desired until the alpine wind, temperature, insolation and humidity data become available.

ADDENDUM

Throughout the evaporation research, it was necessary to keep accurate records of the melt not accounted for by night time evaporation factors.

The equation for net melt was found to be: $M_n = (0.007DHC)\%MPVP$, where %MPVP is the percentage of melt indicated by the partial vapor pressure over ice.

The solution of the %MPVP may be had upon request.