A WATER RESOURCES TECHNICAL PUBLICATION

ENGINEERING MONOGRAPH No. 35

Effect of Snow Compaction on Runoff From Rain on Snow

UNITED STATES DEPARTMENT
OF THE INTERIOR
BUREAU OF RECLAMATION

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Engineering Monograph No. 35

Effect of Snow Compaction on Runoff From Rain on Snow

By FREDERICK A. BERTLE

Division of Project Investigations
Office of Chief Engineer, Denver, Colorado

United States Department of the Interior • Stewart L. Udall, *Secretary*

BUREAU OF RECLAMATION

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B. P. Bellport, *Chief Engineer*

In its assigned function as the Nation's principal natural resource agency, the Department of the Interior bears a special obligation to assure that our expendable resources are conserved, that renewable resources are managed to produce optimum yields, and that all resources contribute their full measure to the progress, prosperity, and security of America, now and in the future.

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Preface

THE PROCEDURE described in this monograph is considered a significant advance in the science of hydrology. It makes possible for the first time the determination of the effect of rainfall on both the depth and water content of fresh snow. Development of the procedure is the result of laboratory experiment and subsequent analysis by a number of Bureau of Reclamation engineers and scientists. From this work, hydrologists can now analyze the effects of rain on snow in terms of runoff and possible flooding, and, in turn, they can predict the impact of such runoff on project development and operation.

The new hydrologic procedure is important in the planning of Bureau of Reclamation water resources projects in the western United States. Such progress provides the opportunity to achieve greater economy, efficiency, and safety in the development of the projects as well as in the design and operation of the individual hydraulic structures on the projects.

Summary

THE SNOW COMPACTION PROCEDURE, as illustrated by the examples given, has yielded acceptable results. The procedure allows much flexibility in the assumption of densities and threshold conditions, which the hydrologist must rationally determine from the available data.

The snow crystals in a fresh snowpack undergo changes, as free water is added, that result in a shrinkage (or compaction) of the snowpack. Free water is retained in the snowpack until the threshold density is attained. Subsequent melting releases this free water. The procedure described in this monograph, which uses a water budget based on the concept of snow compaction and a threshold density, has been a valuable aid in the Bureau of Reclamation design flood studies to estimate runoff from a design condition of warm rain on a relatively fresh snowpack. There are other procedures that utilize the concept of thermal quality of the snow and the concept of a maximum percentage of retained free water in the snow. However, the snow compaction procedure is straightforward and is easy to use; the examples cited illustrate that the procedure gives realistic results.

Acknowledgments

The author expresses his appreciation for the assistance of K. F. Frank and J. L. Woerner in the organization of material for this monograph. W. U. Garstka, H. P. Grout, D. L. Miller, and G. E. Monfore performed the laboratory experimental investigation. D. L. Miller made the preliminary applications of the laboratory test results to inflow design flood studies. The following personnel performed the computations for the application of the procedure to the reproduction of the December 1955 flood on the South Yuba River near Cisco, Calif.:

R. J. Bunker	R. W. Kennedy
J. H. Fenwick	J. C. Peters
W. U. Garstka	O. B. Ridgley
P. G. Grey	S. Schamach
R. C. James	

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Notation

d_p = density of total snowpack, including free water, which is the ratio of water equivalent of snowpack to depth of snowpack, expressed in percent.

d_{pt} = threshold pack density at which compaction ceases and drainage from the snowpack begins.

d_s = density of dry snow in the snowpack.

d_{so} = initial dry snow density of the snowpack.

d_{st} = density of the dry snow in the snowpack when the snowpack is at the threshold pack density, d_{pt}

k = basin constant in snowmelt equation representing the relative exposure to wind.

M = total daily snowmelt in inches.

M_3 = snowmelt for 3-hour period in inches.

P_D = depth of snow during compaction, expressed as a percentage of the initial depth.

P_{Dt} = value of P_D when the snowpack is at its threshold density.

P_w = total water content of the snowpack, expressed as a percentage of the initial water content.

P_{wt} = value of P_w when the snowpack is at its threshold density.

R = rainfall depth in inches.

T_a = ambient air temperature, °F.

T_d = dewpoint temperature, °F.

V = wind velocity in miles per hour.

$W.C.$ = equivalent water content of snowpack in inches.

Δ = increment.

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Introduction

ADEQUATE DESIGN of the spillway at a major storage reservoir requires the derivation of a synthetic maximum probable flood. This maximum probable flood must represent a realistically critical combination of the maximized causative hydrologic factors. In many areas of the western United States, the maximum floods occur as the result of an extreme rain falling on a relatively fresh snow cover. The fresh snow can be expected to melt during the rainstorm and thereby increase the volume of the runoff flood. In addition, the snowpack will absorb the rainfall from the early part of the storm and release it later. As a result of the storage and later release of the earlier rainfall, in addition to the melting of the snow and the later rainfall, the runoff peak flow may be considerably more severe or less severe than would occur from the rainfall alone.

This monograph describes a computational procedure for determining the water available for runoff and its time of occurrence resulting from a rain-on-fresh-snow condition. It includes an estimate of the shrinkage of the snow pack caused by the metamorphosis of the crystalline structure with the addition of rainfall. Examples are given showing the use of the procedure with assumed design storm conditions. Also, the procedure is used to reproduce an observed flood which verifies the accuracy of the method and assumptions.

A computational procedure for predicting runoff from a rain-on-snow storm using the concept of a threshold density was developed originally by the U.S. Corps of Engineers.[1] This concept has been expanded in this monograph to recognize the shrinking of the snowpack as water is added. The procedure described is basically a water-budget analysis which accounts for the water in the snowpack until it is released in drainage. The procedure is intended for use in an inflow design flood study in which a design rain occurs on a fresh snowpack.

[1] Numbers designate publications in "List of References."

Snow Compaction Relationship

Laboratory Test

A FRESH SNOWPACK subjected to rainfall and melting will undergo some compaction as water is added, and significant drainage from the snowpack will take place when the snowpack has reached a threshold density of from 40 to 45 percent. To evaluate the compaction resulting from added water, W. U. Garstka, H. P. Grout, D. L. Miller, and G. E. Monfore of the Bureau of Reclamation conducted a laboratory experiment on December 20, 1951. Fresh snow, which had fallen at approximately 0° F. the night before, was shoveled into a large plexiglass cylinder. This cylinder full of snow was set in a pan and placed on a weighing scale in a controlled temperature cold room. Cold water was sprinkled on top of the snow column in 1-pound increments, and the shrinkage of the snow was observed. Figure 1 shows the equipment about 30 minutes after the test had begun. The test data are given in the Appendix.

The results of the test are summarized as figure 2, in which are plotted the depth of snowpack in percent of initial depth versus the initial water content plus the added water in percent of initial water content. After the cylinder was filled outdoors, the snow had a density of 15.4 percent, and the point is plotted at 100-percent depth and 100-percent water content. During the time the sample was moved indoors, the snow compacted to 87 percent of depth and the density was 17.7 percent. As water was added, the snow continued to compact, as indicated by the decreasing percentage of depth for each of the points. By the time the water content was 177 percent of the initial water content, the depth was 64 percent of the original depth and the density was 42.5 percent. Prior to this point in the test, the added water was retained in the snow.

Drainage of water out of the bottom of the snow column was first observed at the next point when the density was 43.5 percent. The maximum density during the test was 47.5 percent. Water was added until no further compaction took place, and after the excess water was allowed to drain out, the final density was 45.7 percent. The relationship

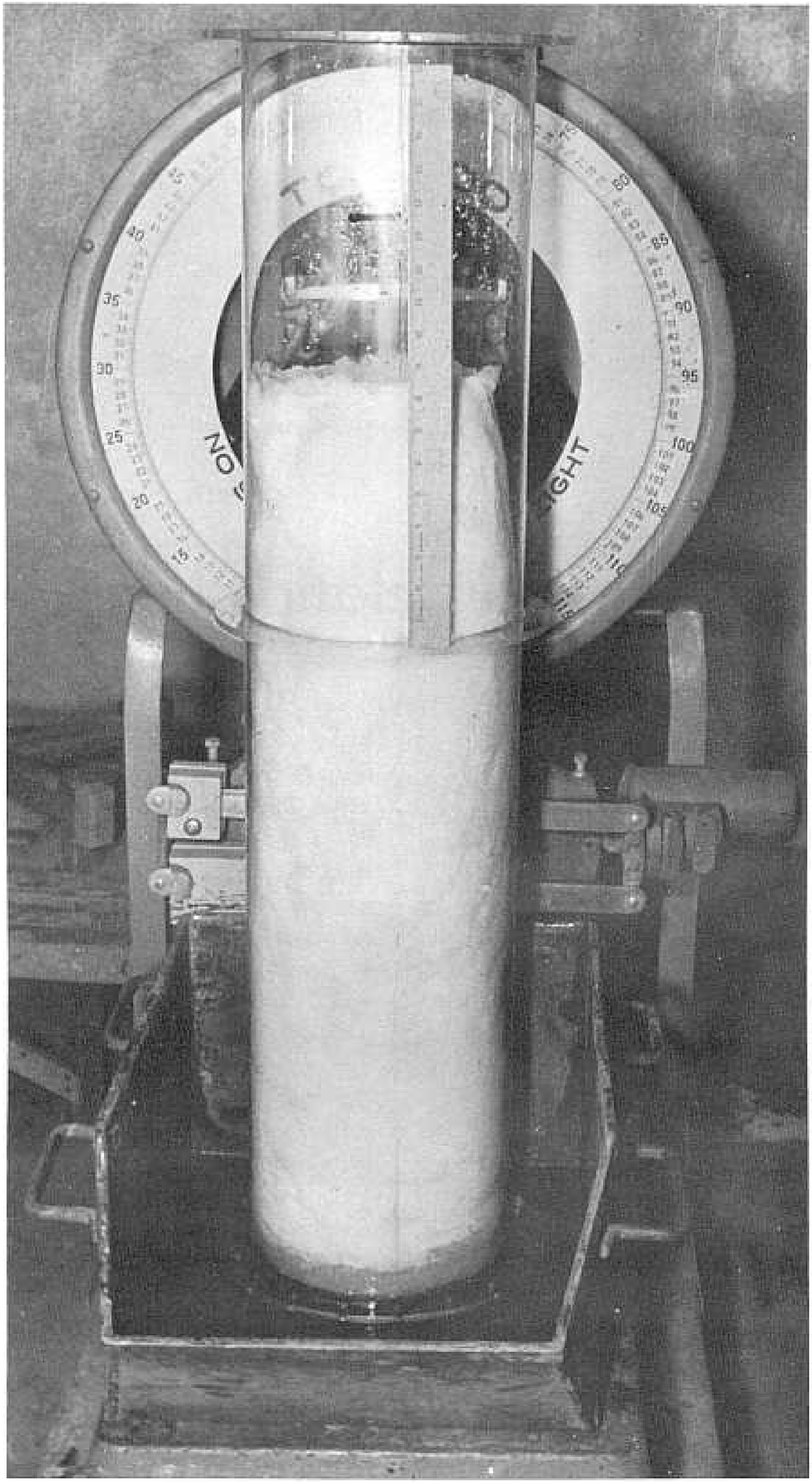

Figure 1.—*Snow compaction experiment after 30 minutes. The column of snow, originally 42.75 inches deep, has compacted to 32.25 inches after the addition of 2.97 inches of water.*

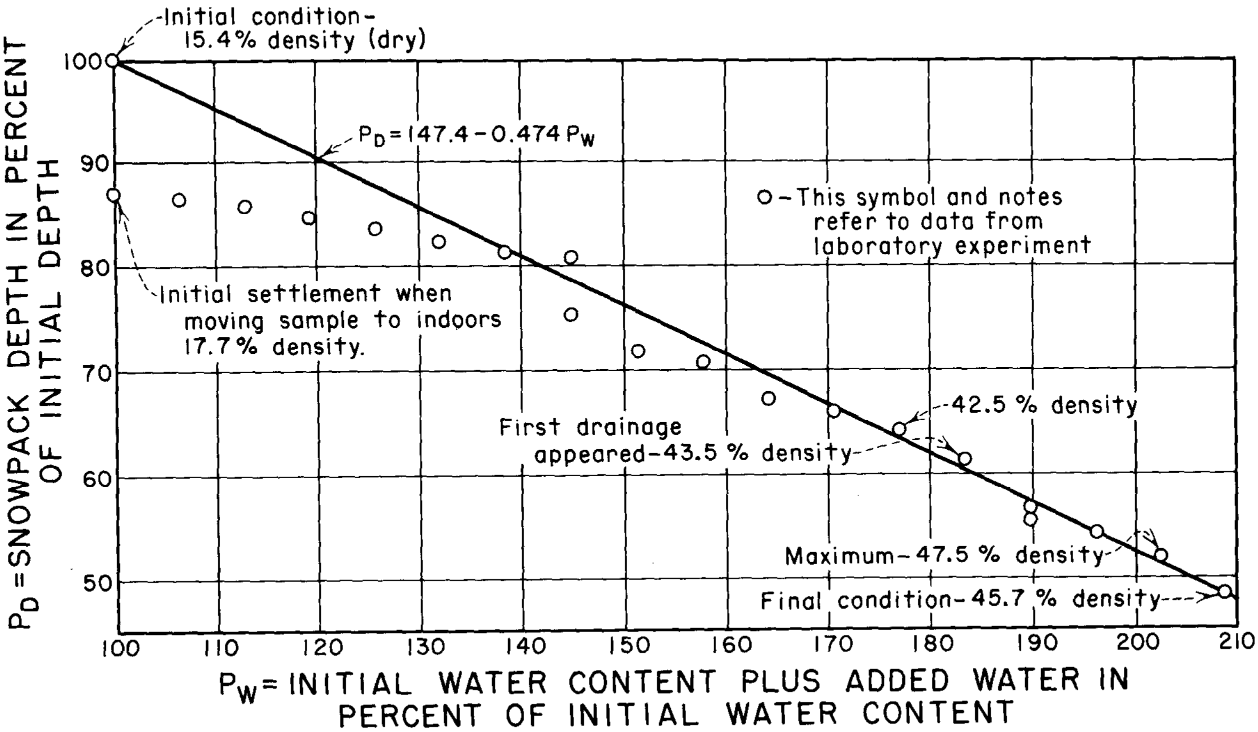

FIGURE 2.—*Decrease in snowpack depth due to addition of water.*

between depth and accumulated water is represented by the straight line having the equation:

$$P_D = 147.4 - 0.474\ P_w \qquad (1)$$

where: P_D = snowpack depth in percent of initial depth

P_w = accumulated water content in percent of initial water content.

Application of Test Results

The results of the snow compaction test may be adapted to the water budget of the snowpack if some simplifying assumptions are made.

The following assumptions do not exactly represent the physical processes in nature. However, they yield consistent results which are adequate for the extreme conditions assumed in an inflow design study.

a. The snowpack is homogeneous and free water in the snowpack is distributed evenly throughout the depth of the pack.

b. The compaction curve, figure 2, defines the compaction effect of free water on a fresh snowpack which has a density less than the assumed threshold density. Threshold densities range from 40 to 45 percent. No compaction takes place after threshold density has been reached.

c. Drainage occurs only after the snowpack has reached its threshold density.

The conditions of the snowpack at the adopted threshold density can be computed by the following three equations which were derived from equation 1. Table 1 shows the computed values for threshold densities of 40 and 45 percent.

$$P_{wt} = 147.4\ d_{pt}/(d_{so} + 0.474\ d_{pt}) \qquad (2)$$

$$P_{Dt} = 147.4\ d_{so}/(d_{so} + 0.474\ d_{pt}) \qquad (3)$$

$$d_{st} = 0.678\ (d_{so} + 0.474\ d_{pt}) \qquad (4)$$

where: P_{wt} = threshold accumulated water content in percent of initial water content,

P_{Dt} = threshold depth in percent of initial depth,

d_{so} = density of initial dry snowpack in percent,

d_{pt} = threshold density of compacted wet snowpack in percent,

d_{st} = threshold density of dry snow in compacted wet snowpack in percent.

Basic Data

Use of the snow-compaction procedure, either for design storm conditions or for observed events, requires knowledge or assumption of initial and subsequent basic data. The initial depth of the snowpack and its density or water content must be known. In succeeding intervals of time, the precipitation in inches of water must be known. If this precipitation falls as snow, its density must be known. The potential snowmelt during each interval may be computed by an empirical snowmelt equation such as equations 5 and 6[2].

For open or partly forested areas (mean canopy cover less than 80 percent)

$$M=(0.029+0.0084kV+0.007R)(T_a-32)+0.09. \quad (5)$$

For heavily forested areas (mean canopy cover more than 80 percent)

$$M=(0.074+0.007R)(T_a-32)+0.05 \quad (6)$$

where: M = total daily snowmelt in inches,

k = basin constant that reflects the relative exposure of the basin to wind. The value of k varies from 1.0 for unforested plains with a mean canopy cover of less than 10 percent to 0.3 for forested areas with a mean canopy cover of 80 percent,

V = mean wind velocity at the 50-foot level in miles per hour,

R = total daily precipitation in inches,

T_a = mean temperature of saturated air at the 10-foot level in ° F. As the air is assumed to be saturated during the periods of rainfall, the air temperature is assumed to be the same as the dewpoint temperature.

Equation 5 may be used to compute the snowmelt for any size of interval of time by dividing the first, second, and last coefficients (0.029, 0.0084, and 0.09) by the number of time intervals in a day and using values of V, R, and T_a for the shorter time interval. Equation 6 may be modified in a similar manner by adjusting the first and last coefficients (0.074 and 0.05).

It is generally necessary to separate a drainage basin into elevation zones and compute the drainage from each zone separately. The division of the basin area into zones according to elevation permits the use of different initial snow conditions for each of the elevation zones. Also, the wind speeds, temperatures, and precipitation will vary with elevation, and the factors producing drainage and the time of runoff may vary considerably from zone to zone.

Snowmelt Budget

Figure 3 illustrates pictorially the steps taken in the water budget analysis when there is no melting. In figure 3(a) the initial snowpack has a dry snow density of 10 percent. After adding 3 inches of rain as in figure 3(b), the compaction curve indicates that the snowpack has shrunk to 85.8-percent depth. Compaction will continue as water is added until the assumed threshold density of 40 percent has been reached as in figure 3(c). As there was no melting, the snow crystals themselves now have a density of 19.6 percent due to the shrinkage. Figure 3(d) shows that as more rain is added, an equivalent amount of drainage from the pack occurs.

Figure 4 shows pictorially the water budget procedure when melting occurs but without rain. The original snowpack is reduced by the amount of melt before compaction is computed. The melt water is treated as though it were rain added to the reduced original snowpack. It takes 5.1 inches of melt to bring the snowpack to 40-percent threshold density. With 10-percent dry density snow, 5.1 inches of melt water are equivalent to 51 inches of snow. Using the snow compaction curve, the reduced original depth of 49 inches is compacted to

50.9 percent of depth, or 25 inches, by the 5.1 inches of added melt water. At this point, the snowpack has a density of 40 percent. However, the dry snow has a density of only 19.6 percent. The difference between 19.6- and 40-percent density is due to the free water in the snowpack. Figure 4(b) shows what happens as additional 0.9 inch of melt occurs. Because this water results from the melting of snow crystals only, the depth of snow melted is 4.6 inches based on the 19.6-percent density of dry snow at threshold conditions. Within that 4.6 inches of depth there is also approximately 1 inch of free water; accordingly, there will be a drainage of 1.9 inches of water from the ripe snowpack resulting from a melt of only 0.9 inch.

Figure 5 shows the assumed conditions when both rain and melt occur. After the snow has reached the threshold density, the addition of 1 inch of rain accompanied by 0.5 inch of melt causes a drainage of 2 inches of water from the pack. The additional 0.5 inch of water came from the free water held in the 2.6 inches of snow that was melted.

TABLE 1.—*Threshold conditions of a snowpack subjected to snowmelt and rainfall*

Initial density of pack d_{so}	Threshold compacted conditions [1]					
	Threshold density d_{pt}=40 percent			Threshold density d_{pt}=45 percent		
	p_{Dt}	P_{wt}	d_{st}	p_{Dt}	P_{wt}	d_{st}
10	50.9	203.6	19.6	47.0	211.7	21.3
11	54.1	196.8	20.3	50.2	205.2	21.9
12	57.1	190.5	21.0	53.1	199.0	22.6
13	60.0	184.5	21.7	55.8	193.2	23.3
14	62.6	178.5	22.4	58.4	187.8	24.0
15	65.1	173.6	23.0	60.9	182.6	24.6
16	67.5	168.7	23.7	63.2	177.7	25.3
17	69.7	164.0	24.4	65.4	173.1	26.0
18	71.8	159.5	25.1	67.5	168.6	26.7
19	73.8	155.3	25.8	69.4	164.5	27.4
20	75.7	151.3	26.4	71.3	160.5	28.0
21	77.5	147.5	27.1	73.1	156.7	28.7
22	79.2	143.9	27.8	74.8	153.1	29.4
23	80.8	140.9	28.5	76.5	149.6	30.1
24	82.3	137.3	29.1	78.0	146.3	30.8
25	83.8	134.1	29.8	79.5	143.2	31.4
26	85.2	131.2	30.5	81.0	140.1	32.1
27	86.6	128.3	31.2	82.3	137.2	32.8
28	87.9	125.6	31.9	83.7	134.5	33.5
29	89.1	122.9	32.5	84.9	131.8	34.1
30	90.3	120.4	33.2	86.2	129.2	34.8
31	91.5	118.0	33.9	87.3	126.8	35.5
32	92.6	115.7	34.6	88.4	124.4	36.2
33	93.6	113.5	35.3	89.5	122.1	36.9
34	94.6	111.3	35.9	90.6	119.9	37.5
35	95.6	109.3	36.6	91.6	117.8	38.2
36	96.6	107.3	37.3	92.6	115.7	38.9
37	97.5	105.4	38.0	93.5	113.7	39.6
38	98.4	103.5	38.6	94.4	111.8	40.2
39	99.2	101.7	39.3	95.3	109.9	40.9
40	100.0	100.0	40.0	96.1	108.2	41.6
41				97.0	106.4	42.3
42				97.8	104.7	43.0
43				98.5	103.1	43.6
44				99.3	101.5	44.3
45				100.0	100.0	45.0

[1] Conditions for other assumed threshold densities may be derived from equations 2, 3, and 4.

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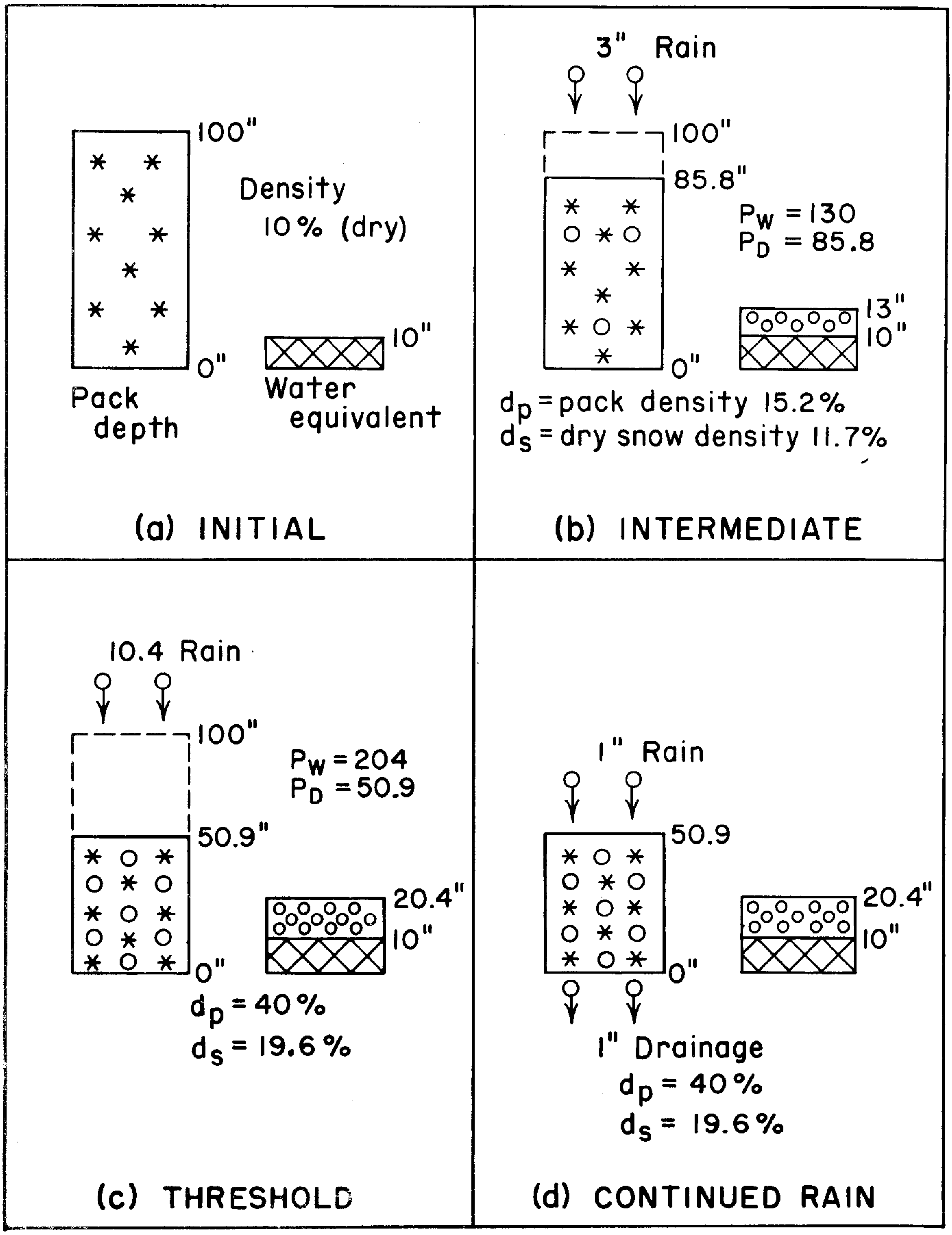

FIGURE 3.—*Compaction and drainage due to rain on snow without melting.*

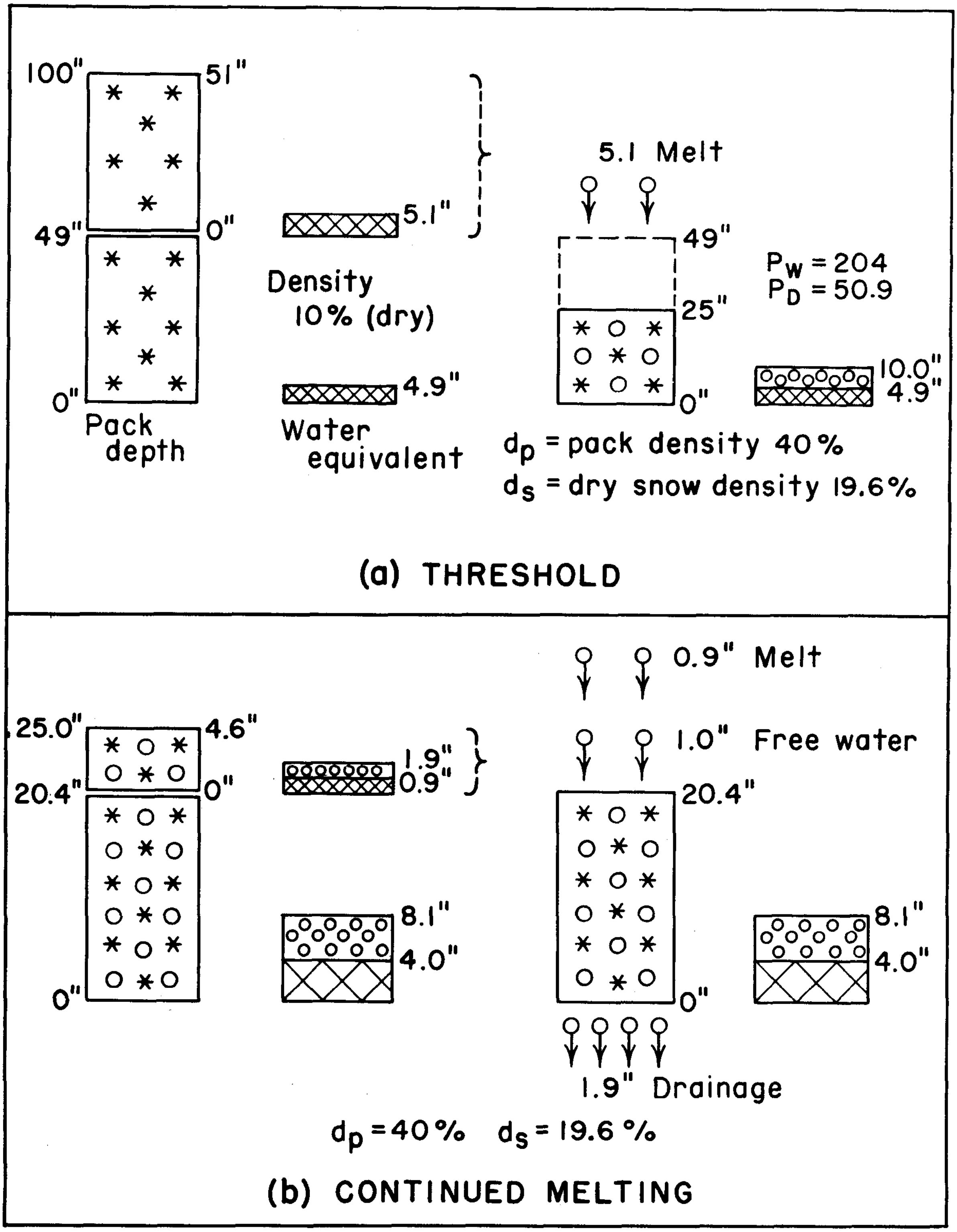

FIGURE 4.—*Compaction and drainage due to snowmelt water without rain.*

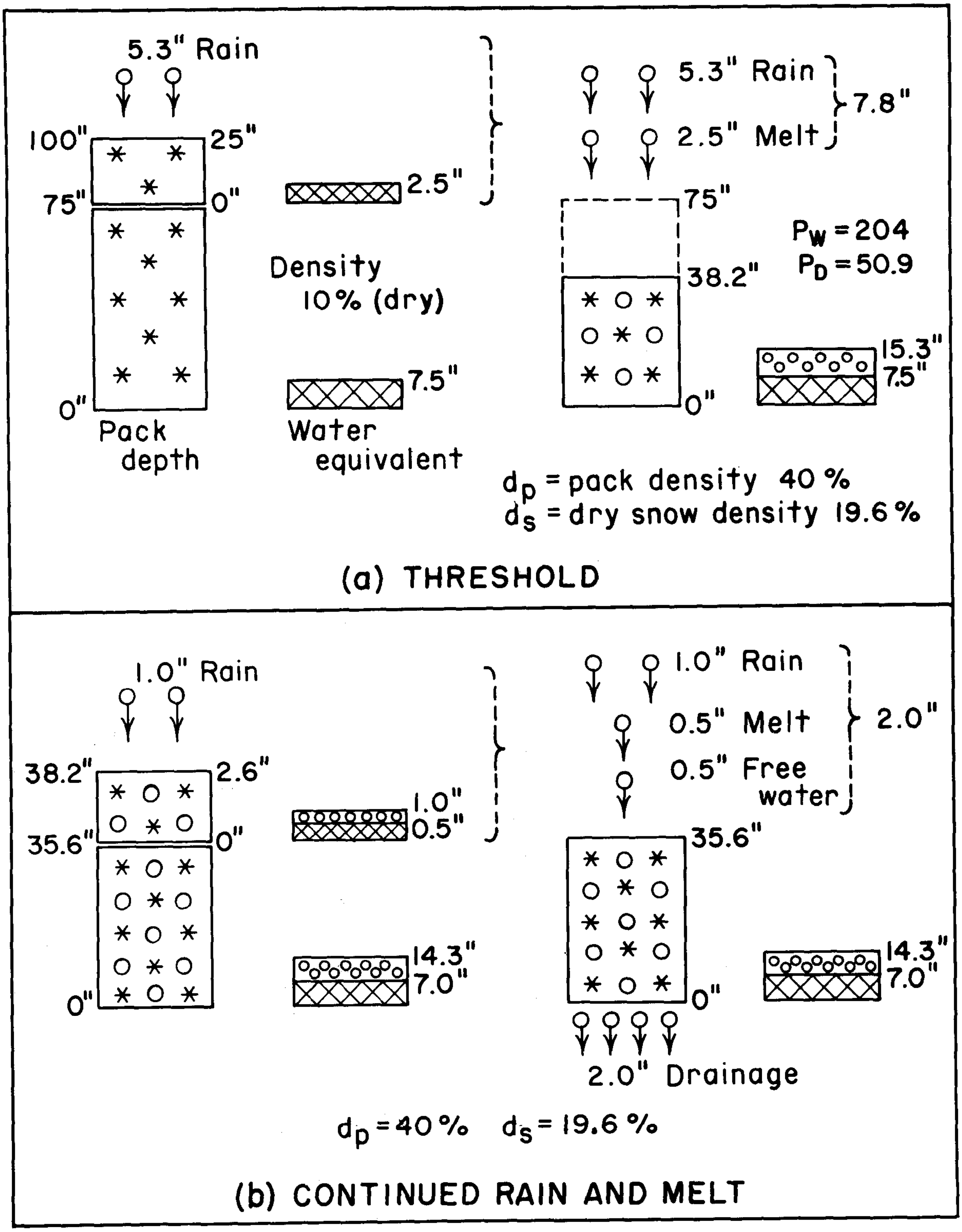

FIGURE 5.—*Compaction and drainage due to rain and snowmelt.*

In actual weather conditions, the situation is further complicated when there are alternating periods of rain and snowfall. In the assumed design storm conditions used in a synthetic design flood study, the new snowfalls are usually assumed to have the same density as the initial dry snow density of the original snowpack. In studies of actual storm events, the new snowfalls may occur at differing densities. In an analysis of a storm which has alternating periods of rain and snowfall, the simplest procedure is to average the new snowfalls into the entire snowpack and treat the snowpack as a homogeneous unit. When the new snowfalls have differing densities, the assumed initial dry snow density of the entire snowpack will change as the new snowfalls are averaged in. An alternative procedure is to analyze the basic lower snowpack and each additional layer of new snow separately. Subsequent periods of rain and melt are used to compact the top layer of new snow and each layer in turn until the top layers are reduced to the same density as the main snowpack. After that time, the total snowpack is again considered to be homogeneous.

Description of Forms

In the water budget procedure, the processes of snowmelt, rainfall, drainage, etc., are accounted for in a tabular form, form A, as illustrated in figure 6, on which computations are made at the end of each selected interval of time. An expanded form, form B, as illustrated in figure 7, can be used if it is desired to account for the upper layers of new snow separately.

A description of the lines on form A (figure 6) is given here for future reference.

Line Description

1 Time at end of interval.

Storm data—lines 2 through 4.

2 Increment of precipitation.

3 Increment of snowfall depth at the assumed fresh snow density. During periods when the temperature is 32° F. or less and snowmelt potential is zero, the precipitation is assumed to occur as snowfall.

4 Increment of potential snowmelt. These values may be computed from known or assumed values of precipitation, temperature, and wind velocity by use of the Corps of Engineers formula, equation 5 or 6.

Melt from snowpack before reaching threshold density—lines 5 and 6.

5 Increment of water content of melt. This entry is the same as the potential snowmelt (line 4) prior to the time that the snowpack has ripened to the threshold density.

6 Increment of depth of melt. Depth of melt is computed by dividing the water content of melt (line 5) by the density (expressed as a decimal) of the original snowpack.

Melt from snowpack after reaching threshold density—lines 7 and 8.

7 Increment of water content of melt. This entry is the same as the potential snowmelt (line 4) after the snowpack has ripened to the threshold density.

8 Increment of depth of melt. Depth of melt is computed by dividing the water content of melt (line 7) by the threshold density (expressed as a decimal) of the dry snow of the compacted snowpack. The threshold dry snow density is computed by equation 4, or may be read from table 1 for threshold densities of either 40 or 45 percent.

Snowpack before reaching threshold density—lines 9 through 16.

9 Initial dry snow depth. This is an accumulation of the initial depth of the snowpack (first entry on line 9) plus the increments of snowfall depth on line 3 and decreased by the increments of depth of melt on line 6.

10 Initial water content, dry snow. This is an accumulation of the initial water content of the snowpack (first entry on line 10) plus the increments of precipitation on line 2 during those periods having snowfall and decreased by the increments of water content of melt on line 5.

11 Accumulated water content, dry snow plus water. This is an accumulation of the initial water content of the snowpack (first entry on line 11) plus the increments of precipitation on line 2.

12 Percent of initial water content. This is the ratio of line 11 to line 10 expressed as per-

RAIN-ON-SNOW COMPUTATIONS **FORM A**

Project STAMPEDE DAM

Elevations 8000 to 9000 ft. Area 7.2 Sq. Mi. Initial density 13.0 %

Avge. Elev. 8500 ft. 5.5 % of basin. Threshold density 40.0 % Zone I

DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
Time at end of interval (Hrs.)	1	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120
STORM DATA																						
ΔPrecipitation	2		1.64	1.79	1.48	1.30	1.20	0.69	0.47	0.27	0.03	0.15	0.12	0.42	2.21	3.08	3.41	0.67	2.75	1.87	2.89	3.62
ΔSnowfall Depth at 13.0 %	3		12.62	13.77	11.38	10.00	9.23	5.31														
ΔPotential Snowmelt W.C.	4								0.03	0.05	0.14	0.11	0.05	0.14	0.33	0.41	0.44	0.47	0.88	0.91	0.78	0.55
MELT FROM SNOWPACK BEFORE REACHING THRESHOLD DENSITY																						
ΔW.C. of Melt	5								0.03	0.05	0.14	0.11	0.05	0.14	0.33	0.41	0.44	0.40				
ΔDepth of Melt at 13.0 %	6								0.23	0.38	1.08	0.85	0.38	1.08	2.54	3.15	3.38	3.08				
MELT FROM SNOWPACK AFTER REACHING THRESHOLD DENSITY																						
ΔW.C. of Melt	7																	0.07	0.88	0.91	0.78	0.55
ΔDepth of Melt at 21.7 %	8																	0.32	4.06	4.19	3.59	2.53
SNOWPACK BEFORE REACHING THRESHOLD DENSITY																						
Initial Dry Snow Depth	9	65.40	78.02	91.79	103.17	113.17	122.40	127.71	127.48	127.10	126.02	125.17	124.79	123.71	121.17	118.02	114.64	111.56				
Initial W.C. (dry snow)	10	8.50	10.14	11.93	13.41	14.71	15.91	16.60	16.57	16.52	16.38	16.27	16.22	16.08	15.75	15.34	14.90	14.50				
Accum. W.C. (dry snow + water)	11	8.50	10.14	11.93	13.41	14.71	15.91	16.60	17.07	17.34	17.37	17.52	17.64	18.06	20.27	23.35	26.76	26.76				
Percent of Initial W.C.	12	100.0						100.0	103.0	105.0	106.0	107.7	108.8	112.3	128.7	152.2	179.6	184.5				
Percent of Initial Depth	13	100.0						100.0	98.6	97.6	97.2	96.4	95.8	94.2	86.4	75.3	62.3	60.0				
Compacted Depth	14	65.40	78.02	91.79	103.17	113.17	122.40	127.71	125.70	124.05	122.49	120.66	119.55	116.53	104.69	88.87	71.42	66.94				
Dry Snow Density (%)	15	13.0						13.0	13.2									21.7				
Pack Density (%)	16	13.0						13.0	13.6	14.0	14.2	14.5	14.8	15.5	19.4	26.3	37.5	40.0				
SNOWPACK AFTER REACHING THRESHOLD DENSITY																						
Snow Depth	17																	66.62	62.56	58.37	54.78	52.25
Accum. W.C.	18																	27.43	29.40	26.89	26.24	25.53
Max. Allowable W.C. at 40.0 %	19																	26.65	25.02	23.35	21.91	20.90
EXCESS WATER AVAILABLE FOR RUNOFF																						
ΔDrainage from Snowpack	20																	0.78	4.38	3.54	4.33	4.63
ΔInfiltration Loss 0.15 in/hr	21																	0.78	0.90	0.90	0.90	0.90
ΔExcess Water from Zone	22																	0	3.48	2.64	3.43	3.73
ΔEquiv. Basin-wide Excess	23																	0	0.19	0.15	0.19	0.21

Figure 6.—*Example I. Rain-on-snow computations without intermittent snowfalls.*

FORM B

Project HYPOTHETICAL

Sheet 1 of 1

RAIN-ON-SNOW COMPUTATION-WITH INTERMITTENT SNOWFALLS

By________ Date________

Elevations above 9000 ft. Avge. Elev.______ft. Area______Sq. Mile 11.8 % of basin. Initial density 11.0 % Threshold density 40.0 % Zone______

	DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
	Time at end of interval (Hrs.)	1	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120
Storm data	Δ Precipitation	2		0.37	1.11	0.25	0.33	0.17	0.33	1.23	0.20	0.45	1.15	3.95	1.73	1.15	0.75	0.37	0.25	0.33	1.23	1.15	3.95
	Δ Snowfall Depth at 11.0 %	3		3.36		2.27	3.00	1.55	3.00		1.82	4.09						3.36	2.27	3.00			
	Δ Potential Snowmelt W.C.	4			0.04					0.19			0.11	0.42	0.29	0.11	0.10				0.19	0.11	0.42
Melt from top layer	Δ W.C. of Melt	5								0.17			0.11								0.19		
	Δ Depth of Melt at 11.0 %	6								1.55			1.00								1.73		
Melt from pack before threshold	Δ W.C. of Melt	7			0.04					0.02				0.42									
	Δ Depth of Melt at 11.0 %	8			0.36					0.18				3.82									
Melt from pack after threshold	Δ W.C. of Melt	9													0.29	0.11	0.10					0.11	0.42
	Δ Depth of Melt at 20.3 %	10													1.43	0.54	0.49					0.54	2.07
Top layer of new snow	Initial Dry Snow Depth	11				2.27	5.27	6.82	9.82	8.27	1.82	5.91	4.91					3.36	5.63	8.63	6.90		
	Initial W.C. (dry snow)	12				0.25	0.58	0.75	1.08	0.91	0.20	0.65	0.54					0.37	0.62	0.95	0.76		
	Accum. W.C. (dry snow + water)	13				0.25	0.58	0.75	1.08	1.08	0.20	0.65	0.73					0.37	0.62	0.95	1.49		
	Percent of Initial W.C.	14				100.0			100.0	118.2			135.6					100.0		100.0	196.8		
	Percent of Initial Depth	15				100.0	.		100.0	91.4			83.1					100.0		100.0	54.1		
	Compacted Depth	16				2.27	5.27	6.82	9.82	7.56	1.82	5.91	4.08					3.36	5.63	8.63	3.73		
	Dry Snow Density (%)	17				11.0			11.0	12.0			13.2					11.0			20.3		
	Layer Density (%)	18				11.0	11.0	11.0	11.0	14.2	11.0	11.0	18.0					11.0	11.0	11.0	40.0		
Intermediate top layer plus lower pack	Initial Dry Snow Depth	19								65.81			70.54										
	Initial W.C. (dry snow)	20								7.24			7.76										
	Accum. W.C. (dry snow + water)	21								8.56			10.52								14.95		
	Compacted Depth	22								60.15			58.62								37.37		
Lower snowpack before reaching threshold	Initial Dry Snow Depth	23	54.54	57.90	57.54	57.54	57.54	57.54	57.54	65.63	65.63	65.63	70.54	66.72									
	Initial W.C. (dry snow)	24	6.00	6.37	6.33					7.22			7.76	7.34									
	Accum. W.C. (dry snow + water)	25	6.00	6.37	7.48					9.79			11.59	14.45									
	Percent of Initial W.C.	26	100.0		118.2					135.6			149.4	196.8									
	Percent of Initial Depth	27	100.0		91.4					83.1			76.6	54.1									
	Compacted Depth	28	54.54	57.90	52.59	52.59	52.59	52.59	52.59	54.54	54.54	54.54	54.03	36.10				33.64	33.64	33.64			
	Dry Snow Density (%)	29	11.0		12.0					13.2			14.4	20.3									
	Pack Density (%)	30	11.0	11.0	14.2	14.2	14.2	14.2	14.2	18.0	18.0	18.0	21.5	40.0				40.0	40.0	40.0			
Snowpack after threshold	Snow Depth	31	54.54	57.90	52.59	54.86	57.86	59.41	62.41	54.54	56.36	60.45	54.03	36.10	34.67	34.13	33.64	37.00	39.27	42.27	37.37	36.83	34.76
	Accumulated W.C.	32												15.54	16.18	15.02	14.40				15.64	16.10	18.68
	Max. Allowable W.C. at 40.0 %	33												14.45	13.87	13.65	13.46				14.95	14.73	13.90
Excess water available for runoff	Δ Drainage from Snowpack	34												1.09	2.31	1.37	0.94	0	0	0	0.69	1.37	4.78
	Δ Infiltration Loss 0.15 in/hr	35												0.90	0.90	0.90	0.90				0.69	0.90	0.90
	Δ Excess Water from Zone	36												0.19	1.41	0.47	0.04				0	0.47	3.88
	Δ Equivalent Basin-wide Excess	37												0.02	0.17	0.06	0	0	0	0	0	0.06	0.46

Figure 7.—*Example II.-A. Rain-on-snow computations with intermittent snowfalls analyzed separately.*

cent. The limiting value when the snow pack is at threshold conditions may be computed from equation 2 or may be read from table 1 for threshold conditions of either 40 or 45 percent.

13 Percent of initial depth. This represents the compaction due to the effect of snowmelt and rainfall. It is computed by equation 1 or may be read from figure 2. The limiting value when the snowpack is at threshold conditions may be computed from equation 3 or may be read from table 1 for threshold conditions of either 40 or 45 percent.

14 Compacted depth. This is computed by multiplying the initial depth from line 9 by the percent of initial depth from line 13 (expressed as a decimal).

15 Dry snow density. This is the density of only the dry snow in the compacted snowpack. It is computed by dividing the initial water content of dry snow (line 10) by the compacted depth (line 14) and expressing it as a percentage. The limiting value when the snowpack is at threshold conditions may be computed from equation 4 or may be read from table 1 for threshold conditions of either 40 or 45 percent.

16 Pack density. This is the density of the snowpack including the free water within it. It is computed by dividing the accumulated water content (line 11) by the compacted depth (line 14) and expressing it as a percentage. The limiting value will be the assumed threshold density for the snowpack.

Snowpack after reaching threshold density—lines 17 through 19.

17 Snow depth. This line is normally not used until the snowpack has reached threshold conditions. The first entry at the time when the snowpack reaches threshold conditions is equal to the compacted depth (line 14) minus the increment depth of melt (line 8) for the time period. Subsequent values of snow depth are derived by successively decreasing the snow depth by the increment depth of melt from line 8.

18 Accumulated water content. The first entry is made at the time when the snowpack reaches threshold conditions and will be the accumulation of the initial water content of the snowpack (first entry on line 10) plus all the precipitation on line 2 up to and including this time. Subsequent values of accumulated water content are derived by adding the increment of precipitation during the time period from line 2 to the preceding entry in line 19.

19 Maximum allowable water content. This is the maximum water content of the snowpack at the threshold density that can be retained without drainage. It is computed by multiplying the snow depth (line 17) by the threshold density expressed as a decimal.

Excess water available for runoff—lines 20 through 23.

20 Increment of drainage from snowpack. This is computed by subtracting line 19 from line 18. No drainage will occur until the threshold conditions have been reached.

21 Increment of infiltration loss. This is the known or assumed loss during the selected interval of time.

22 Increment of excess water from the zone. This is computed by subtracting the loss (line 21) from the drainage (line 20).

23 Increment of equivalent basinwide excess. This is computed by multiplying the excess water (line 22) by the ratio of the area of the zone to the total drainage basin. The equivalent excesses from each of the zones are added together for their respective time intervals to determine the basinwide excesses.

The following notes describe the entries in form B, figure 7, when it is desired to keep track of the top new layers of snow separately. Lines 1 through 4, 7 through 10, and 23 through 37 on form B are the same as lines 1 through 23 on form A. Additional lines 5 and 6 and 11 through 18 are included in form B to account for the new upper snow layers. The top layers are analyzed separately until they reach a density that is the same as the lower snowpack. After that time, the top layers are assumed to be homogeneous with the lower snowpack. To establish the conditions when each layer reaches this point of homogeneity, the precipitation and snowmelt during that increment of time must be separated into those parts that are added to the top layer and those parts are added to the homogeneous snowpack including the upper layers.

Lines 19 through 22 are used to indicate the characteristics of the total snowpack at this point of homogeneity when only part of the precipitation and snowmelt during that increment of time is needed to bring the snowpack to a homogeneous condition.

When using form B and before the snowpack has reached its threshold condition, line 31 can be used to indicate the total depth of the snow. These entries will be the sum of the compacted depth of each layer from line 16 plus the compacted depth of the main snowpack from line 28.

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Examples of Rain-on-Snow Computations

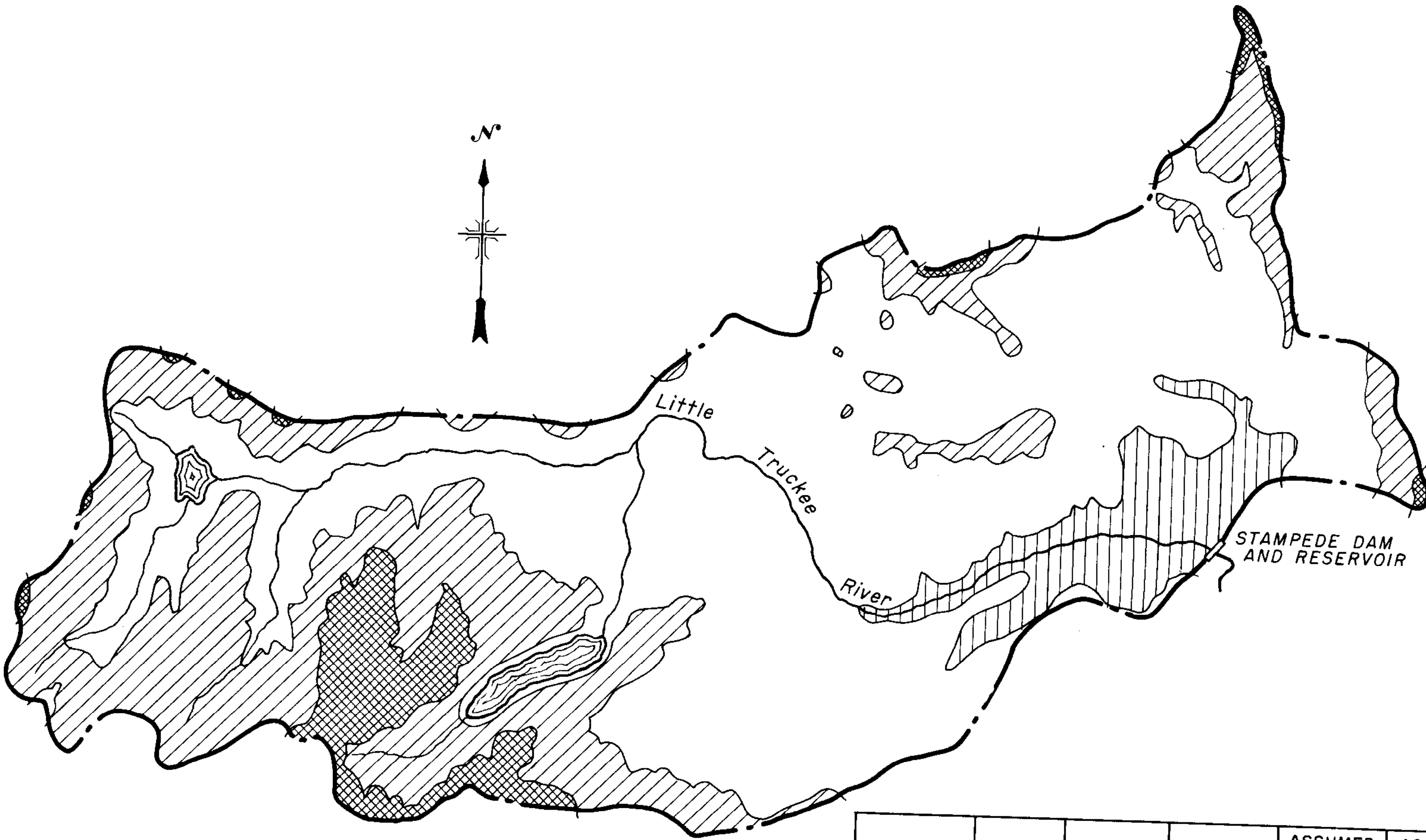
Example I—Rainstorm Without Intermittent Snowfall

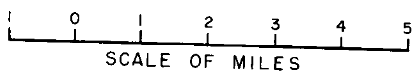
An inflow design flood for the proposed Stampede Dam and Reservoir resulted from the analysis of a design rain-on-snow storm with an initial period of snowfall at the upper elevations. The computations made for that study will be used to illustrate the procedure. Stampede damsite is on the Little Truckee River in the Sierra Nevada Mountains northwest of Truckee, Calif. The drainage basin area, shown as figure 8, was divided into four elevation zones to permit the assumption of different initial conditions for each zone. The table in figure 8 shows that the snowpack was assumed to be deeper at higher elevations and that dry snow densities were less than in the lower zones.

Dividing the basin into elevation zones permitted an allowance to be made for the severity and nature of the precipitation falling at the various levels of altitude throughout the basin. For example, it was assumed that in elevation zone I (8,000–9,000 feet) precipitation occurred exclusively in the form of snow during the first 36 hours of the storm; whereas in elevation zone III (6,000–7,000 feet), snowfall occurred only during the first 6 hours of the storm. Potential snowmelt values were also different in the various elevation zones reflecting the variation in temperature, windspeed, and precipitation at the different elevations.

To compute the basin water excess caused by a rainstorm over the basin, a separate analysis must be carried out for each elevation zone. Elevation zone I, covering the basin area between 8,000 and 9,000 feet of altitude, has been selected to demonstrate the details of the computation procedure. The sample calculations and the form used for the computation procedure are shown in figure 6. Form A is used here as there is no intermittent snowfall.

The analysis in this example is based on an assumed threshold pack density of 40 percent. This assumption implies that the density of the snowpack increases, under the action of rain and melt water, until it attains the specified value of 40 percent and thereafter remains constant at that value. The threshold conditions (P_{Dt}, P_{wt}, d_{st}), which apply for this example, were read from table 1.





		ELEVATION RANGE	AREA (SQ. MI.)	PERCENT OF BASIN AREA	ASSUMED INITIAL DENSITY	ASSUMED INITIAL WATER CONTENT (IN.)	ASSUMED INITIAL SNOW DEPTH (IN.)
Elevation Zone I	(cross-hatched)	8-9000	7.2	5.5	13.0	8.50	65.40
Elevation Zone II	(diagonal hatched)	7-8000	33.1	25.5	15.0	6.80	45.33
Elevation Zone III	(blank)	6-7000	81.5	62.7	17.0	4.60	27.06
Elevation Zone IV	(vertical hatched)	5-6000	8.2	6.3	19.0	1.60	8.42
			130.0	100.0			

FIGURE 8.—*Drainage basin above Stampede damsite.*

For the purpose of identification, the columns are labeled alphabetically and the lines numerically. Any entry can then be identified by a notation such as B9, which refers to the number 78.02 in figure 6. The storm duration was 120 hours.

The data of the storm to be analyzed resulted from a design storm study and are listed on lines 2, 3, and 4. Line 2 is the increment of precipitation during the period of time; line 3 is the snowfall depth (if the temperature was less than 32° F.), and line 4 is the potential snowmelt. Potential snowmelt was computed by the Corps of Engineers snowmelt equation. The density of newly fallen snow was assumed to be the same as that of the original dry snowpack. Data of the condition of the original snowpack before the beginning of the storm are listed in column A, lines 9 through 16.

Snowfall during the first 36 hours of the storm merely increases the pack depth. B3 (12.62) is added to A9 (65.40) to give B9 (78.02). B2 (1.64) is added to A10 (8.50) to give B10 (10.14). This process is continued until G9 and G10 have been computed. The pack density (line 16) remains the same throughout this period.

The first period of snowmelt is encountered in column H; therefore the precipitation during this period is assumed to be rain. Since the new snow and the original pack have the same density, the entire pack is homogeneous; therefore the melt, 0.03, in H4 is transferred to H5. The corresponding depth of melt at the initial density of 13 percent is 0.23 which is entered in H6. The following order of computations is followed for lines 9 through 16.

Dry Snow Depth, H9=G9−H6; 127.48=127.71−0.23.

Dry Snow *W.C.*, H10=G10−H5; 16.57=16.60−0.03. Check: H10=13 percent of Dry Snow Depth, H9; 16.57=(0.13)(127.48).

Accumulated *W.C.*, H11=G11+H2; 17.07=16.60+0.47.

Percent *W.C.*, $H12=\frac{(100)(H11)}{(H10)}$;

$$103.0=\frac{(100)(17.07)}{(16.57)}.$$

Percent Depth from figure 2=H13=98.6 or compute from equation 1; 98.6=147.4−(0.474)(103.0).

Compacted Depth, $H14=\frac{(H13)(H9)}{(100)}$;

$$125.70=\frac{(98.6)(127.48)}{(100)}.$$

Dry Snow Density, $H15=\frac{(100)(H10)}{(H14)}$;

$$13.2=\frac{(100)(16.57)}{(125.70)}.$$

Pack Density, $H16=\frac{(100)(H11)}{(H14)}$;

$$13.6=\frac{(100)(17.07)}{(125.70)}.$$

No drainage occurs when the pack density is less than 40 percent. Computational procedure from the 42d hour to the 90th hour is the same as above. Rainfall and snowmelt are compacting the snowpack and increasing its density to 37.5 percent as computed in space P16.

During the next time interval column Q at the 96th hour, the adopted threshold density, d_{pt}, will be exceeded if the calculations are continued in the same manner as above. The computation procedure for the transition period, Q, is therefore adjusted so that the pack density may be brought to the exact value of 40 percent. The threshold values read from table 1 of percent water content, 184.5; percent depth, 60; dry snow density, 21.7; and pack density, 40, are entered into spaces Q12, Q13, Q15, and Q16, respectively.

Next, the accumulated total water content in P11 (26.76) is transferred to space Q11. (It is temporarily assumed that a portion of the snowmelt will bring the pack to threshold density.) The dry snow content, Q10 (14.50), is computed by dividing the accumulated water content, Q11 (26.76), by the percent water content at threshold conditions, Q12 (184.5). The difference between the values, P10 and Q10, is the amount of melt water used in bringing the snowpack to threshold pack density. This difference (0.40 inch) is entered into space Q5. The difference between the potential snowmelt (0.47 inch) and the previously computed value (0.40 inch) is 0.07 inch which is entered in space Q7 and will be applied to the pack after it has reached threshold conditions. If the difference between the values in P10 and Q10 had been greater than the available melt water (0.47 inch), some of the rainwater, Q2, would have been used to bring the snowpack to threshold density by increasing the accumulated water content in space Q11.

The next step in the example of figure 6 is to compute the depth of melt, Q6 (3.08), at the 96th hour by dividing the water content of the portion of snowmelt before threshold, Q5 (0.40), by the initial snowpack density, 13.0 percent. Then the initial dry snow depth Q9=P9−Q6; 111.56 =114.64−3.08. The compacted depth, Q14, is computed by multiplying Q9 by the percent depth at threshold conditions, Q13. The quotients $\frac{Q10}{Q14}$ and $\frac{Q11}{Q14}$ should as a check equal the threshold densities, Q15 and Q16, respectively. Lines 9 through 16 may subsequently be omitted since the entire pack is now at threshold density.

The portion of snowmelt remaining after the pack has reached threshold density is converted to an equivalent depth of melt at the threshold density of dry snow (21.7 percent) and is entered in Q8. During the remainder of the rainstorm, all the potential snowmelt increments are converted to an equivalent depth of melt at the threshold density of dry snow.

The snowpack depth after reaching threshold density, Q17, is the compacted depth, Q14, reduced by the depth of the melt, Q8. The accumulated water content of the entire snowpack, Q18, is P11 plus the total increment of rain, Q2. It has been assumed that the maximum density of the pack cannot exceed the threshold density of 40 percent. Therefore, the maximum allowable water content, Q19, is 40 percent of the snow depth, Q17.

Drainage from the snowpack, Q20, is the difference between the accumulated water content, Q18, and the maximum allowable water content, Q19. A retention loss rate will have been determined prior to the study and the total loss computed for

TABLE 2.—*Basin contribution, rain-on-snow analysis—Stampede damsite.*

Hour	Excess runoff (inches)					
	Zone I 8–9000	Zone II 7–8000	Zone III 6–7000	Zone IV 5–6000	Total	Accumulated total
0						
6	0	0	0	0	0	0
12	0	0	0	0. 04	0. 04	0. 04
18	0	0	0	0. 03	0. 03	0. 07
24	0	0	0	0. 04	0. 04	0. 11
30	0	0	0. 25	0	0. 25	0. 36
36	0	0	0. 09	0	0. 09	0. 45
42	0	0	0	0	0	0. 45
48	0	0	0	0	0	0. 45
54	0	0	0	0	0	0. 45
60	0	0	0	0	0	0. 45
66	0	0	0	0	0	0. 45
72	0	0	0. 09	0	0. 09	0. 54
78	0	0. 26	1. 09	0. 02	1. 37	1. 91
84	0	0. 75	1. 60	0. 04	2. 39	4. 30
90	0	0. 83	1. 72	0. 05	2. 60	6. 90
96	0	0. 18	0	0	0. 18	7. 08
102	0. 19	0. 89	0. 61	0. 03	1. 72	8. 80
108	0. 15	0. 69	0. 24	0	1. 08	9. 88
114	0. 19	0. 86	0. 59	0. 03	1. 67	11. 55
120	0. 21	0. 97	0. 99	0. 06	2. 23	13. 78

the time interval is entered on line 21. In the example all the drainage is lost to infiltration in column Q. The excess water from the zone is the difference between the drainage and infiltration loss. The excess water from the zone is multiplied by the ratio of zonal area to the total basin area to determine the equivalent basinwide excesses in line 23. The computations in lines 17 through 23 are carried out to the end of the storm.

The same analysis as described here for zone I was carried out for all other elevation zones in the basin in the original study. After the increments of equivalent basinwide water excess were calculated for every time interval in all elevation zones, the answers were compiled as shown in table 2. These basinwide excesses were then used to compute a flood hydrograph by the unit hydrograph method.

Example II—Rain on Snow With Intermittent Snowfalls

The computational procedure described in the previous example may be expanded to account for intermittent periods of snowfall by either of two procedures: (1) analyze each new layer of snowfall separately until it has reached the same density as the lower snowpack, or (2) average the new snowfalls into the entire snowpack. The two methods, using a hypothetical example, are described below.

A. *Analyzing each new layer separately*

A hypothetical example that illustrates this procedure is shown in figure 7 using form B. The storm data are entered on lines 2, 3, and 4. The newly fallen snow is assumed to form a snow layer with a density less than that of the partially compacted main lower snowpack. This top layer of new snow is analyzed separately until it has reached the same density as the main lower snowpack. After the snowpack has attained a uniform density throughout its depth, increments of rain and melt are applied to the entire snow depth, and the calculations are carried forward in the same manner as described earlier for example I.

Conditions of the snowpack before the storm begins are summarized in column A. The initial period of snowfall in column B merely increases the depth of the original main snowpack. During the next period (column C), the snowmelt and rainfall compact the snowpack to a density of 14.2 percent as shown by the entry in space C30.

Snowfall occurs during the next four periods (columns D, E, F, and G) and forms a top layer of snow at 11-percent density. An account of this top layer is kept separately on lines 11 through 18 since this layer is at a different density than the main snowpack below. The original depth and compacted depth of the lower main snowpack on lines 23 and 28 do not change during this period. The total depth of the entire snowpack is the sum of the compacted depth of the top layer on line 16 and the compacted depth of the lower main snowpack on line 28. For convenience this total depth is entered on line 31.

During the next time interval (column H) only part of the potential snowmelt (0.17 from space H5) is needed to bring the top layer to a density of 14.2 percent, the same as the lower main snowpack. Note that the entries in spaces H14, H15, H17, and H18 are the same as those in spaces C26, C27, C29, and C30, respectively. At this point, midway in time interval H, the top layer and the lower main snowpack are homogeneous at a density of 14.2 percent. The characteristics of the combined homogeneous snowpack at this time are summarized in spaces H19, H20, H21, and H22.

The balance of the snowmelt and precipitation during time period H is applied to the homogeneous snowpack as shown by the entries on lines 7, 8, and 23 through 30 in column H. At the end of period H, the entire snowpack is at a density of 18.0 percent. Snowfall occurs during the next two time intervals, and a new top layer is formed at 11-percent density as indicated by the entries on lines 11 through 18.

In the next time period (column K) all of the snowmelt and some of the rainfall are needed to bring the top layer to a density of 18.0 percent, the same as the lower snowpack. Note that the entries in spaces K14, K15, K17, and K18 are the same as those in spaces H26, H27, H29, and H30, respectively. At this point, midway in time interval K, the characteristics of the combined homogeneous snowpack are summarized in spaces K19, K20, K21, and K22. The balance of the rainfall during time period K is applied to the homogeneous snowpack as shown on lines 23 through 30 in column K. At the end of period K, the combined homogeneous snowpack is at a density of 21.5 percent.

All of the snowmelt and part of the rainfall in column L are used to bring the snowpack to threshold conditions as shown by lines 7, 8, and 23 through 30. The balance of the rainfall causes drainage as indicated on lines 31 through 37. During the next three time periods, M, N, and O, the snowmelt and rainfall cause drainage from the snowpack which remains at threshold conditions.

Subsequent snowfall in periods P, Q, and R forms a new top layer at 11-percent density. The entire snowpack now consists of a lower main snowpack at threshold density with a depth of 33.64 inches as shown on line 28 and a top layer of snow at 11-percent density with a depth shown on line 16. The total depth of the entire snowpack is the sum of these two lines which is shown on line 31.

The snowmelt and part of the rainfall during period S compact the top layer to the threshold density of 40 percent as shown on lines 5, 6, and 11 through 18. The balance of the rainfall during time period S causes drainage as derived on lines 31 through 37. The entries on lines 21 and 22 in column S are inmaterial, but they would be necessary if only part of the snowmelt had been needed to bring the top layer to threshold density. In that special case, the depth S31 would be equal to the depth S22 minus the depth S10. During the remainder of the storm, the snowmelt and rainfall cause continued drainage from the snowpack.

B. *Averaging the new snowfall into the entire snowpack*

The hypothetical example that illustrates this procedure is shown in figure 9. The storm data recorded on lines 2, 3, and 4 are the same as those used in figure 7. Conditions of the fresh snowpack before the storm begins are summarized in column A. An initial period of snowfall during the first time period increases the depth and water content of the original snowpack (lines 9, 10, and 11) in column B. During the next period snowmelt and rainfall occur and are applied to the snowpack as shown in column C. At the end of 12 hours, the compacted depth is 52.59 inches and the snowpack density is 14.2 percent.

During the following four periods (columns D, E, F, and G), additional snowfall occurs. The initial dry snow depth (line 9) is increased by the increments of snowfall depth from line 3. Both the initial water content of dry snow (line 10) and the accumulated water content of dry snow and water (line 11) are increased by the increments of precipitation from line 2. The compacted snow depths (line 14) are computed from the snow compaction relationship. The pack densities on line 16 will gradually decrease because of the addition of the new dry snow. The density of the initial dry snow as represented by the entries in lines 9 and 10 will remain at 11 percent because the new snowfalls are at the same density as the original snowpack. If the new snowfall had occurred at a different density, the initial dry snow density computed by dividing line 10 by line 9 would also change. It would then be necessary to compute that new initial dry snow density because the threshold limiting values for lines 12, 13, and 15 will also change as will the density used for the melt computations on lines 5 through 8. An example showing that type of computation is given in example III–B in the following section with the analysis of the December 1955 flood event on the South Yuba River in California.

Additional melt occurs in column H and more new snow is added in columns I and J. The subsequent melt and rainfall in columns K and L are sufficient to bring the snowpack to threshold conditions, and some drainage occurs in column L.

During the next three time periods, the snowpack is at threshold condition, and the melt and rainfall cause drainage. Computations are made using lines 7, 8, and 17 through 23 as had been done in the preceding example. However, because there will be future new snowfalls in successive time periods, it will also be necessary to record the initial conditions of the snowpack in column M through column O using lines 5, 6, 9, 10, 11, and 14. During this period, the initial depth on line 9 will be reduced by the incremental melt depth from line 6. The initial water content on line 10 will be reduced by the melt water content from line 5. The accumulated water content on line 11 will be the same as that on line 19 since the pack is at threshold conditions and cannot have any larger water content. The compacted depth on line 14 is the same as the depth computed on line 17. If lines 12 and 13 were used to compute the compacted depth, the compacted depth so computed would be identical (within rounding off errors) to the compacted depth derived on line 17.

The new snowfalls in columns P, Q, and R are added to the snowpack using lines 9 through 16.

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RAIN-ON-SNOW COMPUTATIONS

FORM A

Project __HYPOTHETICAL____

Elevations __above________9000___ft. Area___________Sq. Mi. Initial density___11.0___% Zone________

Avge. Elev.____________ft. ___11.8____% of basin. Threshold density_40.0_%

DESCRIPTION		A	B	C	D	E	F	G	H.	I	J	K	L	M	N	O	P	Q	R	S	T	U
Time at end of interval (Hrs.)	1	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120
STORM DATA																						
ΔPrecipitation	2		0.37	1.11	0.25	0.33	0.17	0.33	1.23	0.20	0.45	1.15	3.95	1.73	1.15	0.75	0.37	0.25	0.33	1.23	1.15	3.95
ΔSnowfall Depth at 11.0 %	3		3.36		2.27	3.00	1.55	3.00		1.82	4.09						3.36	2.27	3.00			
ΔPotential Snowmelt W.C.	4			0.04					0.19			0.11	0.42	0.29	0.11	0.10				0.19	0.11	0.42
MELT FROM SNOWPACK BEFORE REACHING THRESHOLD DENSITY																						
ΔW.C. of Melt	5			0.04					0.19			0.11	0.42	0.29	0.11	0.10				0.19		
ΔDepth of Melt at 11.0 %	6			0.36					1.73			1.00	3.82	2.64	1.00	0.91				1.73		
MELT FROM SNOWPACK AFTER REACHING THRESHOLD DENSITY																						
ΔW.C. of Melt	7													0.29	0.11	0.10					0.11	0.42
ΔDepth of Melt at 20.3 %	8													1.43	0.54	0.49					0.54	2.07
SNOWPACK BEFORE REACHING THRESHOLD DENSITY																						
Initial Dry Snow Depth	9	54.54	57.90	57.54	59.81	62.81	64.36	67.36	65.63	67.45	71.54	70.54	66.72	64.08	63.08	62.17	65.53	67.80	70.80	69.07		
Initial W.C. (dry snow)	10	6.00	6.37	6.33	6.58	6.91	7.08	7.41	7.22	7.42	7.87	7.76	7.34	7.05	6.94	6.84	7.21	7.46	7.79	7.60		
Accum. W.C. (dry snow + water)	11	6.00	6.37	7.48	7.73	8.06	8.23	8.56	9.79	9.99	10.44	11.59	14.45	13.87	13.65	13.46	13.83	14.08	14.41	14.96		
Percent of Initial W.C.	12	100.0		118.2	117.5	116.6	116.2	115.5	135.6	134.6	132.7	149.4	196.8				191.8	188.7	185.0	196.8		
Percent of Initial Depth	13	100.0		91.4	91.7	92.1	92.3	92.7	83.1	83.6	84.5	76.6	54.1				56.5	58.0	59.7	54.1		
Compacted Depth	14	54.54	57.90	52.59	54.85	57.85	59.40	62.44	54.54	56.39	60.45	54.03	36.10	34.67	34.13	33.64	37.02	39.32	42.27	37.37		
Dry Snow Density (%)	15	11.0											20.3							20.3		
Pack Density (%)	16	11.0	11.0	14.2	14.1	13.9	13.9	13.7	18.0	17.4	17.3	21.5	40.0	40.0	40.0	40.0	37.4	35.8	34.1	40.0		
SNOWPACK AFTER REACHING THRESHOLD DENSITY																						
Snow Depth	17												36.10	34.67	34.13	33.64				37.37	36.83	34.76
Accum. W.C.	18												15.54	16.18	15.02	14.40				15.64	16.11	18.68
Max. Allowable W.C. at 40.0 %	19												14.45	13.87	13.65	13.46				14.96	14.73	13.90
EXCESS WATER AVAILABLE FOR RUNOFF																						
ΔDrainage from Snowpack	20												1.09	2.31	1.37	0.94	0	0	0	0.68	1.38	4.78
ΔInfiltration Loss 0.15 in/hr	21												0.90	0.90	0.90	0.90				0.68	0.90	0.90
ΔExcess Water from Zone	22												0.19	1.41	0.47	0.04				0	0.48	3.88
ΔEquiv. Basin-wide Excess	23												0.02	0.17	0.06	0	0	0	0	0	0.06	0.46

FIGURE 9.—*Example II–B. Rain-on-snow computations with intermittent snowfalls averaged into snowpack.*

The melt and rainfall in column S are sufficient to again bring the snowpack to threshold conditions and cause drainage.

Example III—Reproduction of an Observed Flood

The rain-on-snow compactional procedure was used to reconstruct the December 1955 storm and flood for a 51.5-square-mile drainage basin of the South Yuba River near Cisco, Calif. The drainage basin outline and location of the three weather stations used in the analysis, Blue Canyon, Cisco Ranger Station, and Soda Springs, are shown in figure 10.

The antecedent snowpack depth and density and daily snowfall densities were established from the records at Soda Springs and Cisco Ranger Station. Daily records of both precipitation and snowfall throughout the storm indicated that the density of fresh fallen snow varied, which had to be accounted for in the computational procedure. Pertinent climatological data from the Soda Springs record are listed in table 3.

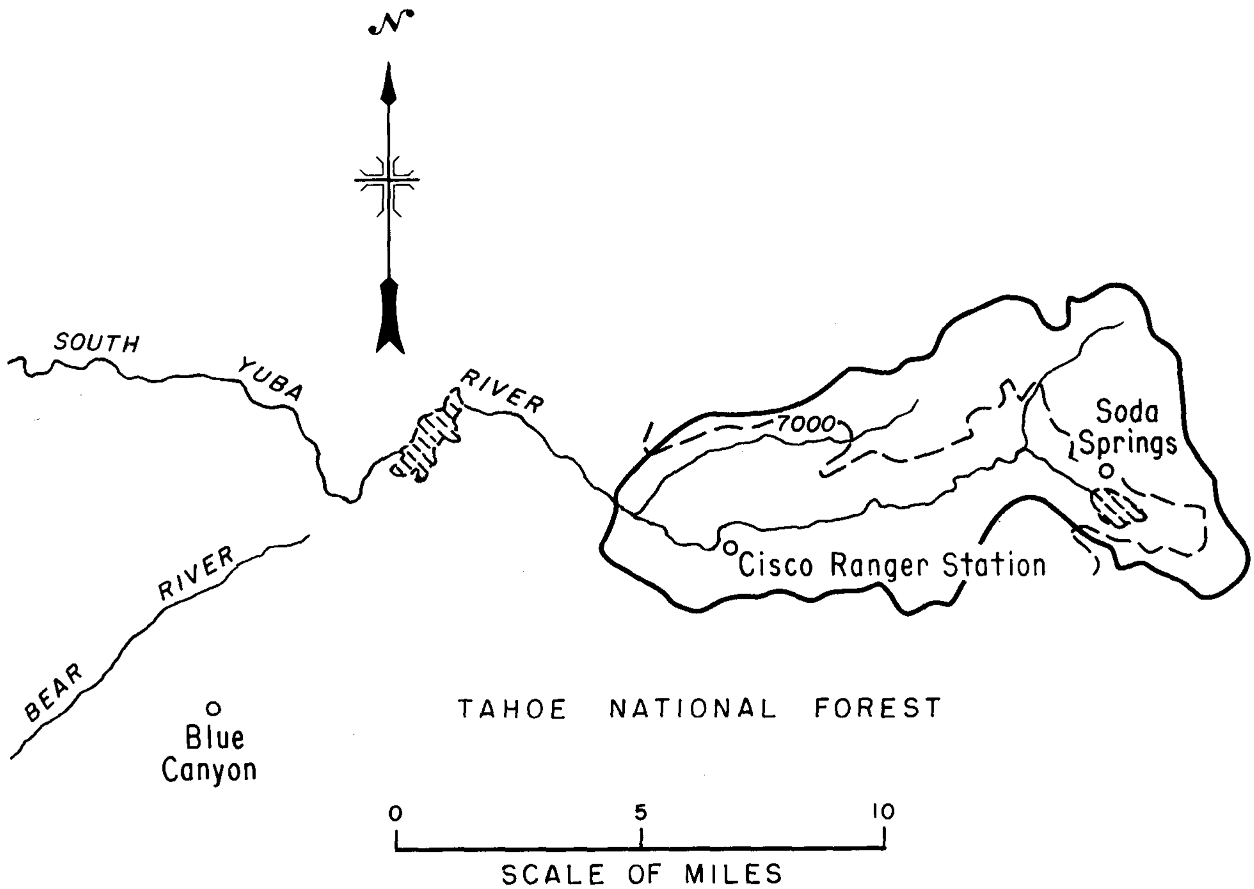


FIGURE 10.—*Drainage basin, South Yuba River near Cisco, Calif. Drainage area is 51.5 square miles.*

From the hourly records available at both Soda Springs and Cisco Ranger Station, the weighted average increments of precipitation were derived for the entire basin. These were accumulated in 3-hour increments for the subsequent analysis.

Potential snowmelt was computed by the Corps of Engineers snowmelt equation. Hourly temperature and wind speed records at Blue Canyon were used to determine the periods of snowfall and to provide the factors necessary to compute potential snowmelt.

Because of the saturated air condition, dewpoint

TABLE 3.—*Summary of climatological data—Soda Springs, Calif.,*[1] *December 1955*

Day	Precipitation (inches)	Snowfall depth (inches)	Snowfall density [2] (percent)	Snow on ground (inches)	Temp. (°F) max.	Temp. (°F) min.	Accumulated precipitation [3] (inches)	Pack density [4] (percent)
1	1.01	12.0	8	30	42	14	8.40	28
2	0.56	8.0	7	37	28	13	8.96	24
3	0.02	trace		36	25	15	8.98	25
4				35	29	−4	8.98	26
5				35	29	−4	8.98	26
6	2.74	14.0	20	46	35	25	11.72	25
7	0.33	1.0	33	46	36	4	12.05	26
8				45	38	7	12.05	27
9	1.19	7.0	17	50	34	26	13.24	26
10				49	43	10	13.24	27
11				47	45	14	13.24	28
12				46	52	13	13.24	29
13				45	51	8	13.24	29
14				44	54	13	13.24	30
15				43	53	13	13.24	31
16	0.32	2.0	16	44	42	22	13.56	31
17	0.64	3.0	21	47	33	23	14.20	30
18	0.58	6.0	10	53	34	23	14.78	28
19	4.16	22.0	19	70	35	24	18.94	27
20	2.35	5.0	47	69	28	29	21.29	31
21	0.64			64	38	33	21.93	34
22	6.69			52	43	35	28.62	55
23	7.04			43	42	37	35.66	
24	4.07	30.0	14	71	38	22		
25	0.11	1.0	11	71	32	25		
26	1.53	7.0	22	73	37	30		
27	1.20	7.0	17	79	36	4		
28	0.57	11.0	5	86	27	14		
29	0.02	1.0	2	83	25	9		
30				81	20	−8		
31	0.40	6.0	7	84	28	6		

[1] Observed at 8 a.m.
[2] Derived from precipitation and snowfall depth.
[3] Accumulated from November 12.
[4] Derived from accumulated precipitation and snow on ground.

temperatures were used in place of ambient air temperatures. These temperatures were adjusted to an average basin elevation of 7,000 feet by use of the proper tables.[3] The wind speeds at Blue Canyon were averaged for 3-hour periods and adjusted to the basin mean elevation of 7,000 feet.*

*The procedure for adjusting windspeeds for elevation was developed in a special study, dated September 1963, by S. Schamach of the Office of Chief Engineer, Bureau of Reclamation, Denver, Colo.

Equation 5 was modified for a 3-hour period as follows:

$$M_3=(0.00362+0.00105\ kV+0.007\ R)(T_d-32)+0.0112 \quad (5a)$$

where: M_3 = snowmelt for 3-hour period in inches

k = 0.7 (assumed for Yuba River Basin)

V = Blue Canyon wind velocity in miles per hour adjusted for elevation

R = incremental average rainfall over basin in inches

T_d = dewpoint temperature, °F., at Blue Canyon adjusted for elevation.

TABLE 4.—*Snowmelt computations—South Yuba River near Cisco, Calif.*

Time Dec. 1955	V (m.p.h.)	T_d (°F.)	R (in.)	M_3 [1] (in.)	Time Dec. 1955	V (m.p.h.)	T_d (°F.)	R (in.)	M_3 [1] (in.)
15/1800	14	26	0. 04	0	20/0300	31	36	0. 49	0. 13
2100	9	28	0. 10	0	0600	31	36	0. 57	0. 13
2400	10	28	0. 06	0	0900	29	36	0. 28	0. 12
16/0300	10	28	0. 04	0	1200	24	36	0. 06	0. 10
0600	9	28	0. 02	0	1500	24	36	0. 32	0. 11
0900	10	28	0. 02	0	1800	23	37	0. 26	0. 12
1200	14	29	0. 13	0	2100	22	37	0. 13	0. 11
1500	19	30	0. 16	0	2400	27	37	0. 06	0. 13
1800	21	30	0. 21	0	21/0300	25	36	0. 07	0. 10
2100	15	29	0. 12	0	0600	23	36	0. 04	0. 09
2400	13	30	0. 04	0	0900	23	37	0. 03	0. 11
17/0300	12	29	0. 06	0	1200	23	37	0. 09	0. 12
0600	12	29	0. 04	0	1500	27	38	0. 41	0. 17
0900	12	29	0. 04	0	1800	27	40	0. 83	0. 25
1200	11	28	0. 08	0	2100	30	41	1. 00	0. 31
1500	18	30	0. 22	0	2400	33	41	1. 92	0. 38
1800	19	29	0. 13	0	22/0300	32	41	1. 12	0. 33
2100	14	28	0. 07	0	0600	30	40	1. 04	0. 27
2400	15	29	0. 04	0	0900	32	40	1. 20	0. 30
18/0300	18	29	0	0	1200	29	40	0. 76	0. 25
0600	20	29	0. 02	0	1500	22	39	0. 24	0. 16
0900	22	29	0. 03	0	1800	24	39	0. 66	0. 19
1200	24	27	0. 03	0	2100	33	40	1. 35	0. 31
1500	23	26	0. 27	0	2400	45	42	1. 59	0. 49
1800	35	27	0. 56	0	23/0300	43	40	0. 50	0. 32
2100	44	29	0. 75	0	0600	48	40	0. 95	0. 38
2400	45	31	0. 86	0	0900	51	38	1. 01	0. 30
19/0300	44	32	0. 75	0	1200	51	37	1. 02	0. 25
0600	43	33	0. 63	0. 05	1500	50	33	1. 02	0. 06
0900	41	33	0. 76	0. 05	1800	38	29	0. 72	0
1200	46	34	0. 66	0. 10	2100	17	26	0. 42	0
1500	43	32	0. 52	0	2400	--------	23	0. 42	0
1800	30	31	0. 44	0	24/0300	--------	22	0. 34	0
2100	33	33	0. 38	0. 04	0600	--------	21	0. 17	0
2400	30	35	0. 46	0. 11	0900	--------	21	0. 01	0

[1] Snowmelt in inches computed by equation 5a.

Table 4 shows the computed snowmelt in 3-hour increments and the factors V, T_d, and R. It was assumed that there is no potential snowmelt when temperatures were 32° F. or less.

A. *Analyzing each new layer separately*

The reconstruction of the storm beginning at 3 p.m. December 15 and ending 9 a.m. December 24 is computed in figure 11 (4 sheets). The analysis was made on form B, wherein each new snow layer was analyzed separately. The initial snow depth was 43 inches with a density of 31 percent as estimated from the record at the Soda Springs station. Snowfall from 3 p.m. on December 15 to 3 a.m. on December 19 was deposited at various densities, and, therefore, these are recorded separately as layers 1 through 4.

Three periods of melt occurred from 3 a.m. to 12 m. on December 19. The first two periods of melt and rainfall were completely absorbed by the top layer, No. 4, and resulted in a top layer density of 28.7 percent. More water was necessary to bring the top layer to the same density as the lower snowpack, which had a density of 31 percent. It was found that all the snowmelt in the next period plus a portion of the rainfall was necessary to bring the top layer, No. 4, to 31-percent density. In a manner similar to that explained in example II–A, the portion of rainwater used in bringing the next two layers to a density of 31 percent was computed. There was not enough water to bring the intermediate top layer No. 1, to 31-percent density; therefore, this layer had to be supplied water in a subsequent period. To simplify the computational procedure, the assumption was made that the top layer is brought to 31-percent density first, then underlying intermediate layers from the top to the lower snowpack.

Snowfall followed, depositing a new top layer, No. 5, at 10-percent density. In subsequent periods of snowmelt, this top layer was first brought to 31-percent density before bringing the intermediate top layer, No. 1, to 31-percent density. When all top layers had reached the density of the original snowpack, the combined homogeneous snowpack at 31-percent density was assumed to be dry. The water used to compact the upper layers is assumed to have refrozen in the snowpack. Subsequent snowmelt and rainwater were applied to the entire homogeneous pack.

The processes of snowfall, melt, and rainfall continued until the snowpack reached the assumed threshold density of 45 percent. Thereafter, drainage from the pack occurred until another period of snowfall was encountered. The computations were terminated on December 24, when it was evident that the period of drainage from 3 p.m. on December 21 to 3 p.m. on December 23 had caused the observed flood as shown in figure 12. A graphic record of the storm data and computations are also shown in figure 12.

A variable retention rate was assumed during the initial 18 hours of drainage. Thereafter, a constant retention of 0.17 inch per hour was assumed as shown by the insert in figure 12. The retention curve was constructed in such a manner as to produce a computed volume of excess equal to that of the net observed flood hydrograph; that is, the hydrograph remaining after base flow was subtracted from the observed hydrograph.

The resulting excesses were applied to the 3-hour unit hydrograph also shown in figure 12. A lag time of 8 hours for the 51.5-square-mile drainage area was applied to a dimensionless unitgraph developed on the North Yuba River at New Bullards Bar damsite in deriving the 3-hour unitgraph. An assumed base flow was added to the computed net hydrograph which resulted in the reconstructed hydrograph as shown in figure 12. Except for slight variations, which must be expected in any reconstruction, the computed hydrograph generally agrees with the observed hydrograph. Also the computed snowpack depths agree well with the recorded depths.

B. *Averaging the new snowfall into the entire snowpack*

The example of computations in figure 11 and illustrated in figure 12 was based on an analysis in which the new snow layers were individually brought to the density of the main snowpack. If the new snow layers had been averaged into the snowpack, the computations would have appeared as shown in figure 13 following the procedure described in example II–B. Note that the resulting snow depths and drainage amounts were slightly different than those computed in figure 11. However, the differences are well within the range of accuracy that can be expected in hydrologic analyses of this type, and the two results can be considered to be essentially identical.

RAIN-ON-SNOW COMPUTATION-WITH INTERMITTENT SNOWFALLS

FORM B
Project South Yuba River near Cisco, California, December 1955
Sheet 1 of 4

By__________ Date__________

Elevations 5600 to 8000 ft. Avge. Elev. 7000 ft. Area 51.5 Sq. Mile. 100 % of basin. Initial density 31.0 % Threshold density 45.0 % Zone__________

	DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
	Time at end of interval (Hrs.)	1	15/3P	6P	9P	12P	16/3A	6A	9A	12A	3P	6P	9P	12P	17/3A	6A	9A	12A	3P	6P	9P	12P	18/3A
Storm data	Δ Precipitation	2		0.04	0.10	0.06	0.04	0.02	0.02	0.13	0.16	0.21	0.12	0.04	0.06	0.04	0.04	0.08	0.22	0.13	0.07	0.04	0
	Δ Snowfall Depth at --- % varies	3		0.15	0.37	0.22	0.15	0.07	0.07	0.50	0.62	0.81	0.46	0.15	0.23	0.15	0.15	0.80	2.20	1.30	0.70	0.40	0
	Δ Potential Snowmelt W.C.	4																					
Melt from top layer	Δ W.C. of Melt	5																					
	Δ Depth of Melt at --- % varies	6		← Layer No. 1 @ 27% →						← Layer No. 2 @ 26% →								← Layer No. 3 @ 10% →					
Melt from pack before threshold	Δ W.C. of Melt	7																					
	Δ Depth of Melt at 31.0 %	8																					
Melt from pack after threshold	Δ W.C. of Melt	9																					
	Δ Depth of Melt at 35.5 %	10																					
Top layer of new snow	Initial Dry Snow Depth	11		0.15	0.52	0.74	0.89	0.96	1.03	0.50	1.12	1.93	2.39	2.54	2.77	2.92	3.07	0.80	3.00	4.30	5.00	5.40	5.40
	Initial W.C. (dry snow)	12		0.04	0.14	0.20	0.24	0.26	0.28	0.13	0.29	0.50	0.62	0.66	0.72	0.76	0.80	0.08	0.30	0.43	0.50	0.54	0.54
	Accum. W.C. (dry snow + water)	13		0.04	0.14	0.20	0.24	0.26	0.28	0.13	0.29	0.50	0.62	0.66	0.72	0.76	0.80	0.08	0.30	0.43	0.50	0.54	0.54
	Percent of Initial W.C.	14		100.0																			
	Percent of Initial Depth	15		100.0																			
	Compacted Depth	16		0.15	0.52	0.74	0.89	0.96	1.03	0.50	1.12	1.93	2.39	2.54	2.77	2.92	3.07	0.80	3.00	4.30	5.00	5.40	5.40
	Dry Snow Density (%)	17		27.0	27.0	27.0	27.0	27.0	27.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	10.0	10.0	10.0	10.0	10.0	10.0
	Layer Density (%)	18		27.0	27.0	27.0	27.0	27.0	27.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	10.0	10.0	10.0	10.0	10.0	10.0
Intermediate top layer plus lower pack	Initial Dry Snow Depth	19																					
	Initial W.C. (dry snow)	20																					
	Accum. W.C. (dry snow + water)	21																					
	Compacted Depth	22																					
Lower snowpack before reaching threshold	Initial Dry Snow Depth	23	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00
	Initial W.C. (dry snow)	24	13.33																				
	Accum. W.C. (dry snow + water)	25	13.33																				
	Percent of Initial W.C.	26	100.0																				
	Percent of Initial Depth	27	100.0																				
	Compacted Depth	28	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00
	Dry Snow Density (%)	29	31.0																				
	Pack Density (%)	30	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
Snowpack after threshold	Snow Depth	31	43.00	43.15	43.52	43.74	43.89	43.96	44.03	44.53	45.15	45.96	46.42	46.57	46.80	46.95	47.10	47.90	50.10	51.40	52.10	52.50	52.50
	Accumulated W.C.	32																					
	Max. Allowable W.C. at 45.0 %	33																					
Excess water available for runoff	Δ Drainage from Snowpack	34	Main																				
	Δ Infiltration Loss	35	pack	← Main pack plus Layer No. 1 →						← Main pack plus Layers No. 1 and 2 →								← Main pack plus					
	Δ Excess Water from Zone	36	only																Layers No. 1, 2, and 3				
	Δ Equivalent Basin-wide Excess	37																					

FIGURE 11.—*Sheet 1 of 4. Example III-A. Rain-on-snow computations with intermittent snowfalls analyzed separately, South Yuba River near Cisco, Calif.*

RAIN-ON-SNOW COMPUTATION-WITH INTERMITTENT SNOWFALLS

FORM B
Project South Yuba River near Cisco, California, December 1955
Sheet 2 of 4

By__________ Date__________

Elevations 5600 to 8000 ft. Avge. Elev. 7000 ft. Area 51.5 Sq. Mile. 100 % of basin. Initial density 31.0 % Threshold density 45.0 % Zone__________

	DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
	Time at end of interval (Hrs.)	1	18/6A	9A	12A	3P	6P	9P	12P	19/3A	6A	9A	12A →				3P	6P	9P	12P →			
Storm data	Δ Precipitation	2	0.02	0.03	0.03	0.27	0.56	0.75	0.86	0.75	0.63	0.76	0.66				0.52	0.44	0.38	0.46			
	Δ Snowfall Depth at --- % varies	3	0.20	0.30	0.20	1.80	3.73	5.00	5.73	5.00			(0.04)	(0.50)	(0.10)	(0.02)	5.20	4.40		(0.16)	(0.01)	(0.29)	
	Δ Potential Snowmelt W.C.	4									0.05	0.05	0.10						0.04	0.11			
Melt from top layer	Δ W.C. of Melt	5									0.05	0.05	0.10						0.04	0.11			
	Δ Depth of Melt at --- % varies	6	Layer No. 3 →								0.33	0.33	0.67						0.40	1.10			
Melt from pack before threshold	Δ W.C. of Melt	7																					
	Δ Depth of Melt at 31.0 %	8			← Layer No. 4 @ 15% →											L. 1	← Layer No. 5 @ 10%						
Melt from pack after threshold	Δ W.C. of Melt	9											L. 4	L. 3	L. 2				→	L. 5	L. 1		
	Δ Depth of Melt at 35.5 %	10											ends	ends	ends					ends	ends		
Top layer of new snow	Initial Dry Snow Depth	11	5.60	5.90	0.20	2.00	5.73	10.73	16.46	21.46	21.13	20.80	20.13	5.90	3.07	1.03	5.20	9.60	9.20	8.10	1.03		
	Initial W.C. (dry snow)	12	0.56	0.59	0.03	0.30	0.86	1.61	2.47	3.22	3.17	3.12	3.02	0.59	0.80	0.28	0.52	0.96	0.92	0.81	0.28		
	Accum. W.C. (dry snow + water)	13	0.56	0.59	0.03	0.30	0.86	1.61	2.47	3.22	3.85	4.61	4.65	1.09	0.90	0.30	0.52	0.96	1.34	1.50	0.31		
	Percent of Initial W.C.	14									121.5	147.8	154.0	184.7	112.5	107.1			145.7	185.2	110.7		
	Percent of Initial Depth	15									89.8	77.3	74.4	59.9	94.1	96.6			78.3	59.6	94.9		
	Compacted Depth	16	5.60	5.90	0.20	2.00	5.73	10.73	16.46	21.46	18.97	16.08	14.98	3.52	2.90	0.99	5.20	9.60	7.20	4.84	0.99		
	Dry Snow Density (%)	17											20.2	16.8	27.6	28.3							
	Layer Density (%)	18	10.0	10.0	15.0	15.0	15.0	15.0	15.0	15.0	20.3	28.7	31.0	31.0	31.0	30.3	10.0	10.0	18.6	31.0	31.0		
Intermediate top layer plus lower pack	Initial Dry Snow Depth	19											(57.98)	(61.50)	(64.40)					(69.24)	(70.23)		
	Initial W.C. (dry snow)	20											(17.98)	(19.07)	(19.97)					(21.47)	(21.78)		
	Accum. W.C. (dry snow + water)	21											17.98	19.07	19.97					21.47	21.78		
	Compacted Depth	22											57.98	61.50	64.40					69.24	70.23		
Lower snowpack before reaching threshold	Initial Dry Snow Depth	23	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00				(64.40	64.40	64.40	64.40		(70.23	70.23	
	Initial W.C. (dry snow)	24														(19.97					(21.78	21.78	
	Accum. W.C. (dry snow + water)	25														19.97					21.78	22.07	
	Percent of Initial W.C.	26																			100.0	101.3	
	Percent of Initial Depth	27																			100.0	99.4	
	Compacted Depth	28	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00				64.40	64.40	64.40	64.40		70.23	69.81	
	Dry Snow Density (%)	29																					
	Pack Density (%)	30	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0				31.0	31.0	31.0	31.0		31.0	31.6	
Snowpack after threshold	Snow Depth	31	52.70	53.00	53.20	55.00	58.73	63.73	69.46	74.46	71.97	69.08				65.39	70.59	74.99	72.59			69.81	
	Accumulated W.C.	32																					
	Max. Allowable W.C. at 45.0 %	33																					
Excess water available for runoff	Δ Drainage from Snowpack	34														new main pack plus Layer No. 1						new main pack begins	
	Δ Infiltration Loss	35			← Main pack plus Layers No. 1, 2, 3, and 4 →												← Main pack plus						
	Δ Excess Water from Zone	36	→			NOTE: Figures in parentheses, lines 19, 20, 23, and 24, are											Layers No. 1 and 5 →						
	Δ Equivalent Basin-wide Excess	37				based on the assumption that the snowpack at 31 percent																	
						is still dry.																	

FIGURE 11.—*Sheet 2 of 4. Example III–A. Rain-on-snow computations with intermittent snowfalls analyzed separately, South Yuba River near Cisco, Calif.*

RAIN-ON-SNOW COMPUTATION—WITH INTERMITTENT SNOWFALLS

FORM B
Project South Yuba River near Cisco, California, December 1955
Sheet 3 of 4

By__________________ Date____________

Elevations 5600 to 8000 ft. Avge. Elev. 7000 ft. Area 51.5 Sq. Mile. 100 % of basin. Initial density 31.0 % Threshold density 45.0 % Zone_______________

	DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
	Time at end of interval (Hrs.)	1	20/3A	6A	9A	12A	3P	6P	9P	12P	21/3A	6A	9A	12A	3P	6P	9P	12P	22/3A	6A	9A	12A	3P
Storm data	Δ Precipitation	2	0.49	0.57	0.28	0.06	0.32	0.26	0.13	0.06	0.07	0.04	0.03	0.09	0.41	0.83	1.00	1.92	1.12	1.04	1.20	0.76	0.24
	Δ Snowfall Depth at ___% varies	3																					
	Δ Potential Snowmelt W.C.	4	0.13	0.13	0.12	0.10	0.11	0.12	0.11	0.13	0.10	0.09	0.11	0.12	0.17	0.25	0.31	0.38	0.33	0.27	0.30	0.25	0.16
Melt from top layer	Δ W.C. of Melt	5																					
	Δ Depth of Melt at ___% varies	6	← Melt depth at 31% →																				
Melt from pack before threshold	Δ W.C. of Melt	7	0.13	0.13	0.12	0.10	0.11	0.12	0.11	0.13	0.10	0.09	0.11	0.12	0.17	0.25							
	Δ Depth of Melt at 31.0 %	8	0.42	0.42	0.39	0.32	0.35	0.39	0.35	0.42	0.32	0.29	0.35	0.39	0.55	0.81	← Melt depth at 35.5%						
Melt from pack after threshold	Δ W.C. of Melt	9															0.31	0.38	0.33	0.27	0.30	0.25	0.16
	Δ Depth of Melt at 35.5 %	10															0.87	1.07	0.93	0.76	0.84	0.70	0.45
Top layer of new snow	Initial Dry Snow Depth	11																					
	Initial W.C. (dry snow)	12																					
	Accum. W.C. (dry snow + water)	13																					
	Percent of Initial W.C.	14																					
	Percent of Initial Depth	15																					
	Compacted Depth	16																					
	Dry Snow Density (%)	17																					
	Layer Density (%)	18																					
Intermediate top layer plus lower pack	Initial Dry Snow Depth	19																					
	Initial W.C. (dry snow)	20																					
	Accum. W.C. (dry snow + water)	21																					
	Compacted Depth	22																					
Lower snowpack before reaching threshold	Initial Dry Snow Depth	23	69.81	69.39	69.00	68.68	68.33	67.94	67.59	67.17	66.85	66.56	66.21	65.82	65.27	64.46							
	Initial W.C. (dry snow)	24	21.65	21.52	21.40	21.30	21.19	21.07	20.96	20.83	20.73	20.64	20.53	20.41	20.24	19.99							
	Accum. W.C. (dry snow + water)	25	22.56	23.13	23.41	23.47	23.79	24.05	24.18	24.24	24.31	24.35	24.38	24.47	24.88	25.33							
	Percent of Initial W.C.	26	104.2	107.5	109.4	110.2	112.3	114.1	115.4	116.4	117.3	118.0	118.8	119.9	122.9	126.8							
	Percent of Initial Depth	27	98.0	96.4	95.5	95.2	94.2	93.3	92.7	92.2	91.8	91.5	91.1	90.6	89.1	87.3							
	Compacted Depth	28	68.41	66.89	65.90	65.38	64.37	63.39	62.66	61.93	61.37	60.90	60.32	59.63	58.16	56.27							
	Dry Snow Density (%)	29														35.5							
	Pack Density (%)	30	33.0	34.6	35.5	35.9	37.0	37.9	38.6	39.1	39.6	40.0	40.4	41.0	42.8	45.0							
Snowpack after threshold	Snow Depth	31	68.41	66.89	65.90	65.38	64.37	63.39	62.66	61.93	61.37	60.90	60.32	59.63	58.16	56.27	55.40	54.33	53.40	52.64	51.80	51.10	50.65
	Accumulated W.C.	32														25.71	26.32	26.85	25.57	25.07	24.89	24.07	23.24
	Max. Allowable W.C. at 45.0 %	33														25.32	24.93	24.45	24.03	23.69	23.31	23.00	22.79
Excess water available for runoff	Δ Drainage from Snowpack	34														0.39	1.39	2.40	1.54	1.38	1.58	1.07	0.45
	Δ Infiltration Loss	35														0.39	1.16	0.98	0.83	0.70	0.59	0.51	0.45
	Δ Excess Water from Zone	36														0	0.23	1.42	0.71	0.68	0.99	0.56	0
	Δ Equivalent Basin-wide Excess	37																					

FIGURE 11.—*Sheet 3 of 4. Example III-A. Rain-on-snow computations with intermittent snowfalls analyzed separately, South Yuba River near Cisco, Calif.*

RAIN-ON-SNOW COMPUTATION-WITH INTERMITTENT SNOWFALLS

FORM B

Project South Yuba River near Cisco, California, December 1955

Sheet 4 of 4

By__________ Date__________

Elevations 5600 to 8000 ft. Avge. Elev. 7000 ft. Area 51.5 Sq. Mile. 100 % of basin. Initial density 31.0 % Threshold density 45.0 % Zone__________

DESCRIPTION			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
	Time at end of interval (Hrs.)	1	22/6P	9P	12P	23/3A	6A	9A	12A	3P	6P	9P	12P	24/3A	6A	9A							
Storm data	△ Precipitation	2	0.66	1.35	1.59	0.50	0.95	1.01	1.02	1.02	0.72	0.42	0.42	0.34	0.17	0.01							
	△ Snowfall Depth at --- % varies	3									11.43	6.67	6.67	5.40	2.70	0.16							
	△ Potential Snowmelt W.C.	4	0.19	0.31	0.49	0.32	0.38	0.30	0.25	0.06													
Melt from top layer	△ W.C. of Melt	5																					
	△ Depth of Melt at --- % varies	6									← Layer No. 6 @ 6.3% →												
Melt from pack before threshold	△ W.C. of Melt	7																					
	△ Depth of Melt at ___%	8	← Melt depth at 35.5% →																				
Melt from pack after threshold	△ W.C. of Melt	9	0.19	0.31	0.49	0.32	0.38	0.30	0.25	0.06													
	△ Depth of Melt at ___%	10	0.54	0.87	1.38	0.90	1.07	0.84	0.70	0.17													
Top layer of new snow	Initial Dry Snow Depth	11									11.43	18.10	24.77	30.17	32.87	33.03							
	Initial W.C. (dry snow)	12									0.72	1.14	1.56	1.90	2.07	2.08							
	Accum. W.C. (dry snow + water)	13									0.72	1.14	1.56	1.90	2.07	2.08							
	Percent of Initial W.C.	14																					
	Percent of Initial Depth	15																					
	Compacted Depth	16									11.43	18.10	24.77	30.17	32.87	33.03							
	Dry Snow Density (%)	17																					
	Layer Density (%)	18									6.3	6.3	6.3	6.3	6.3	6.3							
Intermediate top layer plus lower pack	Initial Dry Snow Depth	19																					
	Initial W.C. (dry snow)	20																					
	Accum. W.C. (dry snow + water)	21																					
	Compacted Depth	22																					
Lower snowpack before reaching threshold	Initial Dry Snow Depth	23																					
	Initial W.C. (dry snow)	24																					
	Accum. W.C. (dry snow + water)	25																					
	Percent of Initial W.C.	26																					
	Percent of Initial Depth	27																					
	Compacted Depth	28									44.18	44.18	44.18	44.18	44.18	44.18							
	Dry Snow Density (%)	29																					
	Pack Density (%)	30																					
Snowpack after threshold	Snow Depth	31	50.11	49.24	47.86	46.96	45.89	45.05	44.35	44.18	55.61	62.28	68.95	74.35	77.05	77.21							
	Accumulated W.C.	32	23.45	23.90	23.75	22.04	22.08	21.66	21.29	20.98													
	Max. Allowable W.C. at 45.0 %	33	22.55	22.16	21.54	21.13	20.65	20.27	19.96	19.88													
Excess water available for runoff	△ Drainage from Snowpack	34	0.90	1.74	2.21	0.91	1.43	1.39	1.33	1.10													
	△ Infiltration Loss	35	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	← Main pack plus												
	△ Excess Water from Zone	36	0.39	1.23	1.70	0.40	0.92	0.88	0.82	0.59	Layer No. 6 →												
	△ Equivalent Basin-wide Excess	37																					

Figure 11.—*Sheet 4 of 4. Example III-A. Rain-on-snow computations with intermittent snowfalls analyzed separately, South Yuba River near Cisco, Calif.*

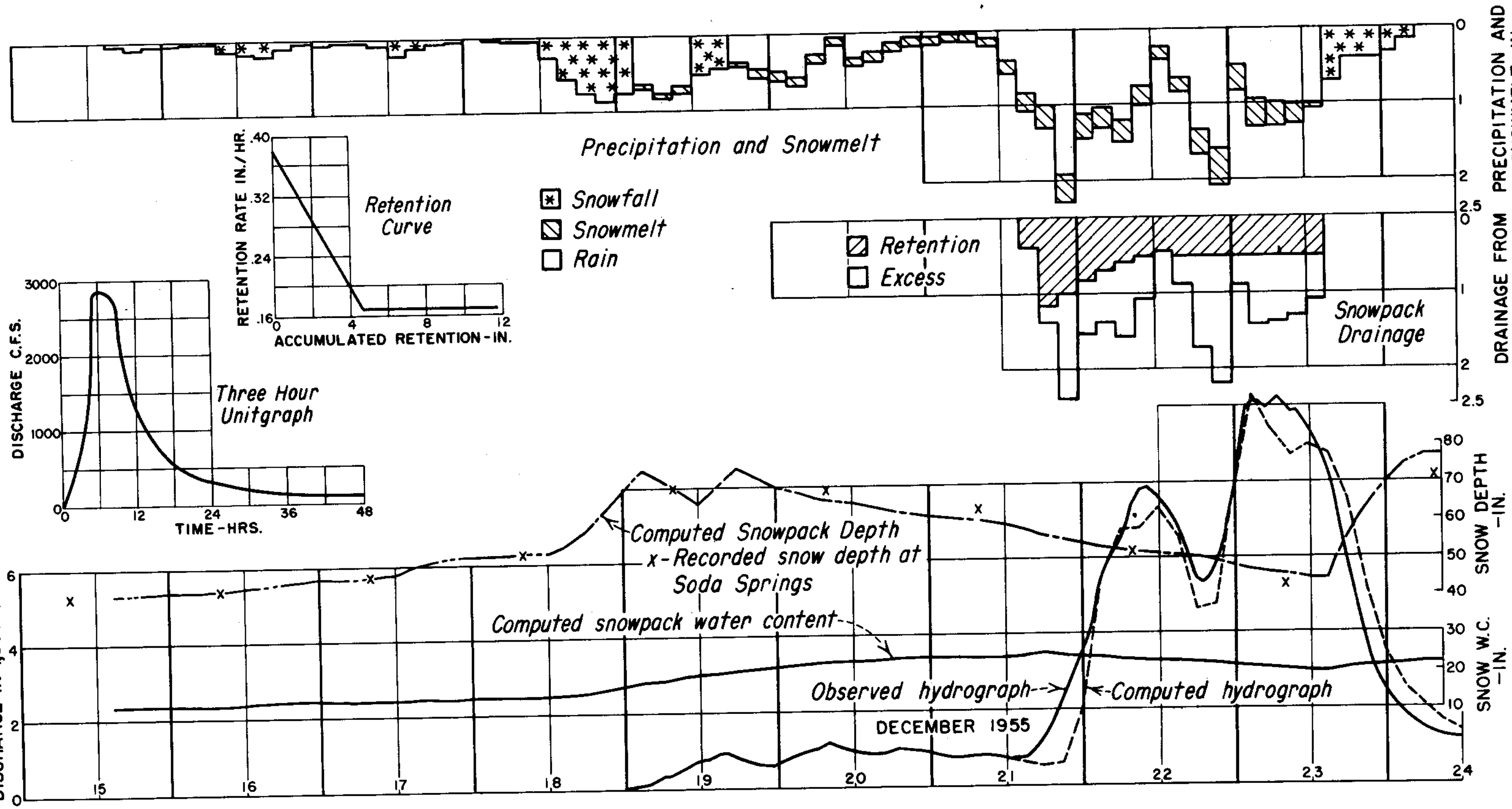


FIGURE 12.—*Observed and computed hydrograph—South Yuba River near Cisco, Calif., December 1955. Drainage area is 51.5 square miles.*

RAIN-ON-SNOW COMPUTATIONS (averaging all layers) **FORM A** Project South Yuba River near Cisco, California, December 1955

Elevations 5600 to 8000 ft. Area 51.5 Sq. Mi. Initial density ____ %
Avge. Elev. 7000 ft. 100 % of basin. Threshold density 45.0 % Zone ____ Sheet 1 of 6

DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M
Time at end of interval (Hrs.)	1	15/3P	6P	9P	12P	16/3A	6A	9A	12A	3P	6P	9P	12P	17/3A
STORM DATA														
ΔPrecipitation	2		0.04	0.10	0.06	0.04	0.02	0.02	0.13	0.16	0.21	0.12	0.04	0.06
ΔSnowfall Depth at --% varies	3		0.15	0.37	0.22	0.15	0.07	0.07	0.50	0.62	0.81	0.46	0.15	0.23
ΔPotential Snowmelt W.C.	4													
MELT FROM SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	5		←	Layer	No. 1 @	27%		→	Layer	No. 2 @	26%			
ΔDepth of Melt at --% varies	6								←					
MELT FROM SNOWPACK AFTER REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	7													
ΔDepth of Melt at ___%	8													
SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
Initial Dry Snow Depth	9	43.00	43.15	43.52	43.74	43.89	43.96	44.03	44.53	45.15	45.96	46.42	46.57	46.80
Initial W.C. (dry snow)	10	13.33	13.37	13.47	13.53	13.57	13.59	13.61	13.74	13.90	14.11	14.23	14.27	14.33
Accum. W.C. (dry snow + water)	11	13.33	13.37	13.47	13.53	13.57	13.59	13.61	13.74	13.90	14.11	14.23	14.27	14.33
Percent of Initial W.C.	12	100.0						100.0						
Percent of Initial Depth	13	100.0						100.0						
Compacted Depth	14	43.00	43.15	43.52	43.74	43.89	43.96	44.03	44.53	45.15	45.96	46.42	46.57	46.80
Dry Snow Density (%)	15	31.0						30.9						
Pack Density (%)	16	31.0	31.0	31.0	30.9	30.9	30.9	30.9	30.9	30.8	30.7	30.7	30.6	30.6
SNOWPACK AFTER REACHING THRESHOLD DENSITY														
Snow Depth	17													
Accum. W.C.	18													
Max. Allowable W.C. at 45.0 %	19													
EXCESS WATER AVAILABLE FOR RUNOFF														
ΔDrainage from Snowpack	20													
ΔInfiltration Loss	21													
ΔExcess Water from Zone	22													
ΔEquiv. Basin-wide Excess	23													

RAIN-ON-SNOW COMPUTATIONS (averaging all layers) **FORM A** Project South Yuba River near Cisco, California, December 1955

Elevations 5600 to 8000 ft. Area 51.5 Sq. Mi. Initial density ____ %
Avge. Elev. 7000 ft. 100 % of basin. Threshold density 45.0 % Zone ____ Sheet 2 of 6

DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M
Time at end of interval (Hrs.)	1	17/6A	9A	12A	3P	6P	9P	12P	18/3A	6A	9A	12A	3P	6P
STORM DATA														
ΔPrecipitation	2	0.04	0.04	0.08	0.22	0.13	0.07	0.04	0	0.02	0.03	0.03	0.27	0.56
ΔSnowfall Depth at --% varies	3	0.15	0.15	0.80	2.20	1.30	0.70	0.40	0	0.20	0.30	0.20	1.80	3.73
ΔPotential Snowmelt W.C.	4													
MELT FROM SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	5			←	Layer	No. 3 @	10%				→	Layer	No. 4 @ 15%	
ΔDepth of Melt at --% varies	6	→	→									←		
MELT FROM SNOWPACK AFTER REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	7													
ΔDepth of Melt at ___%	8													
SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
Initial Dry Snow Depth	9	46.95	47.10	47.90	50.10	51.40	52.10	52.50	52.50	52.70	53.00	53.20	55.00	58.73
Initial W.C. (dry snow)	10	14.37	14.41	14.49	14.71	14.84	14.91	14.95	14.95	14.97	15.00	15.03	15.30	15.86
Accum. W.C. (dry snow + water)	11	14.37	14.41	14.49	14.71	14.84	14.91	14.95	14.95	14.97	15.00	15.03	15.30	15.86
Percent of Initial W.C.	12		100.0								100.0			
Percent of Initial Depth	13		100.0								100.0			
Compacted Depth	14	46.95	47.10	47.90	50.10	51.40	52.10	52.50	52.50	52.70	53.00	53.20	55.00	58.73
Dry Snow Density (%)	15		30.6								28.3			
Pack Density (%)	16	30.6	30.6	30.3	29.4	28.9	28.6	28.5	28.5	28.4	28.3	28.3	27.8	27.0
SNOWPACK AFTER REACHING THRESHOLD DENSITY														
Snow Depth	17													
Accum. W.C.	18													
Max. Allowable W.C. at 45.0 %	19													
EXCESS WATER AVAILABLE FOR RUNOFF														
ΔDrainage from Snowpack	20													
ΔInfiltration Loss	21													
ΔExcess Water from Zone	22													
ΔEquiv. Basin-wide Excess	23													

FIGURE 13.—*Plate 1 of 3. Example III–B. Rain-on-snow computations with intermittent snowfalls averaged into the snowpack, South Yuba River near Cisco, Calif.*

RAIN-ON-SNOW COMPUTATIONS (averaging all layers)

FORM A South Yuba River near Cisco, California. Project __December 1955__

Elevations 5600 to 8000 ft. Area 51.5 Sq. Mi. Initial density ____ %
Avge. Elev. 7000 ft. 100 % of basin. Threshold density 45.0 % Zone ____ Sheet 3 of 6

DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M
Time at end of interval (Hrs.)	1	18/9P	12P	19/3A	6A	9A	12A	3P	6P	9P	12P	20/3A	6A	9A
STORM DATA														
ΔPrecipitation	2	0.75	0.86	0.75	0.63	0.76	0.66	0.52	0.44	0.38	0.46	0.49	0.57	0.28
ΔSnowfall Depth at ___% varies	3	5.00	5.73	5.00				5.20	4.40					
ΔPotential Snowmelt W.C.	4				0.05	0.05	0.10			0.04	0.11	0.13	0.13	0.12
MELT FROM SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	5	Layer No. 4 @ 15%			← @	24.5% →		L. 5 @ 10%		← @	22.8%			
ΔDepth of Melt at ___% varies	6			→	0.20	0.20	0.41	←	→	0.18	0.48	0.57	0.57	0.53
MELT FROM SNOWPACK AFTER REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	7													
ΔDepth of Melt at ___%	8													
SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
Initial Dry Snow Depth	9	63.73	69.46	74.46	74.26	74.06	73.65	78.85	83.25	83.07	82.59	82.02	81.45	80.92
Initial W.C. (dry snow)	10	16.61	17.47	18.22	18.17	18.12	18.02	18.54	18.98	18.94	18.83	18.70	18.57	18.45
Accum. W.C. (dry snow + water)	11	16.61	17.47	18.22	18.85	19.61	20.27	20.79	21.23	21.61	22.07	22.56	23.13	23.41
Percent of Initial W.C.	12			100.0	103.7	108.2	112.5	112.1	111.9	114.1	117.2	120.6	124.6	126.9
Percent of Initial Depth	13			100.0	98.2	96.1	94.1	94.3	94.4	93.3	91.8	90.2	88.3	87.2
Compacted Depth	14	63.73	69.46	74.46	72.92	71.17	69.30	74.36	78.59	77.50	75.82	73.98	71.92	70.56
Dry Snow Density (%)	15			24.5					(22.8)					
Pack Density (%)	16	26.1	25.2	24.5	25.8	27.6	29.2	28.0	27.0	27.9	29.1	30.5	32.2	33.2
SNOWPACK AFTER REACHING THRESHOLD DENSITY														
Snow Depth	17													
Accum. W.C.	18													
Max. Allowable W.C. at 45.0 %	19													
EXCESS WATER AVAILABLE FOR RUNOFF														
ΔDrainage from Snowpack	20													
ΔInfiltration Loss	21													
ΔExcess Water from Zone	22													
ΔEquiv. Basin-wide Excess	23													

NOTE: Density in H15 is the new initial dry snow density of the pack. Subsequent melt occurring prior to reaching threshold will occur at this density. Threshold conditions are based on this new dry snow density.

RAIN-ON-SNOW COMPUTATIONS (averaging all layers)

FORM A South Yuba River near Cisco, California, Project __December 1955__

Elevations 5600 to 8000 ft. Area 51.5 Sq. Mi. Initial density ____ %
Avge. Elev. 7000 ft. 100 % of basin. Threshold density 45.0 % Zone ____ Sheet 4 of 6

DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M
Time at end of interval (Hrs.)	1	20/12A	3P	6P	9P	12P	21/3A	6A	9A	12A	3P	6P	9P	12P
STORM DATA														
ΔPrecipitation	2	0.06	0.32	0.26	0.13	0.06	0.07	0.04	0.03	0.09	0.41	0.83	1.00	1.92
ΔSnowfall Depth at ___%	3													
ΔPotential Snowmelt W.C.	4	0.10	0.11	0.12	0.11	0.13	0.10	0.09	0.11	0.12	0.17	0.25	0.31	0.38
MELT FROM SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	5					@ 22.8%								→
ΔDepth of Melt at 22.8%	6	0.44	0.48	0.53	0.48	0.57	0.44	0.39	0.48	0.53	0.75	1.10	1.36	1.67
MELT FROM SNOWPACK AFTER REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	7												← @ 29.	9% →
ΔDepth of Melt at 29.9%	8												1.04	1.27
SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
Initial Dry Snow Depth	9	80.48	80.00	79.47	78.99	78.42	77.98	77.59	77.11	76.58	75.83	74.73	73.37	71.70
Initial W.C. (dry snow)	10	18.35	18.24	18.12	18.01	17.88	17.78	17.69	17.58	17.46	17.29	17.04	16.73	16.35
Accum. W.C. (dry snow + water)	11	23.47	23.79	24.05	24.18	24.24	24.31	24.35	24.38	24.47	24.88	25.61	25.16	24.58
Percent of Initial W.C.	12	127.9	130.4	132.7	134.3	135.6	136.7	137.6	138.7	140.1	143.9	150.3		
Percent of Initial Depth	13	86.8	85.6	84.5	83.7	83.1	82.6	82.2	81.7	81.0	79.2	76.2		
Compacted Depth	14	69.86	68.48	67.15	66.11	65.17	64.41	63.78	63.00	62.03	60.06	56.94	55.90	54.63
Dry Snow Density (%)	15											29.9		
Pack Density (%)	16	33.6	34.7	35.8	36.6	37.2	37.7	38.2	38.7	39.4	41.4	45.0	45.0	45.0
SNOWPACK AFTER REACHING THRESHOLD DENSITY														
Snow Depth	17											56.94	55.90	54.63
Accum. W.C.	18											25.71	26.61	27.08
Max. Allowable W.C. at 45.0 %	19											25.61	25.16	24.58
EXCESS WATER AVAILABLE FOR RUNOFF														
ΔDrainage from Snowpack	20											0.10	1.45	2.50
ΔInfiltration Loss	21											0.10	1.20	1.01
ΔExcess Water from Zone	22											0	0.25	1.49
ΔEquiv. Basin-wide Excess	23													

FIGURE 13.—*Plate 2 of 3. Example III–B. Rain-on-snow computations with intermittent snowfalls averaged into the snowpack, South Yuba River near Cisco, Calif.*

RAIN-ON-SNOW COMPUTATIONS (averaging all layers) **FORM A** Project South Yuba River near Cisco, California, December 1955

Elevations 5600 to 8000 ft. Area 51.5 Sq. Mi. Initial density ____ %
Avge. Elev. 7000 ft. 100 % of basin. Threshold density 45 % Zone ____ Sheet 5 of 6

DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M
Time at end of interval (Hrs.)	1	22/3A	6A	9A	12A	3P	6P	9P	12P	23/3A	6A	9A	12A	3P
STORM DATA														
ΔPrecipitation	2	1.12	1.04	1.20	0.76	0.24	0.66	1.35	1.59	0.50	0.95	1.01	1.02	1.02
ΔSnowfall Depth at ____ %	3													
ΔPotential Snowmelt W.C.	4	0.33	0.27	0.30	0.25	0.16	0.19	0.31	0.49	0.32	0.38	0.30	0.25	0.06
MELT FROM SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	5	←				@ 22.8%								→
ΔDepth of Melt at 22.8 %	6	1.45	1.18	1.31	1.10	0.70	0.83	1.36	2.15	1.40	1.67	1.32	1.10	0.26
MELT FROM SNOWPACK AFTER REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	7	←				@ 29.9%								→
ΔDepth of Melt at 29.9 %	8	1.10	0.90	1.00	0.84	0.54	0.64	1.04	1.64	1.07	1.27	1.00	0.84	0.20
SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
Initial Dry Snow Depth	9	70.25	69.07	67.76	66.66	65.96	65.13	63.77	61.62	60.22	58.55	57.23	56.13	55.87
Initial W.C. (dry snow)	10	16.02	15.75	15.45	15.20	15.04	14.85	14.54	14.05	13.73	13.35	13.05	12.80	12.74
Accum. W.C. (dry snow + water)	11	24.09	23.68	23.23	22.86	22.61	22.32	21.86	21.12	20.64	20.07	19.62	19.24	19.15
Percent of Initial W.C.	12													
Percent of Initial Depth	13													
Compacted Depth	14	53.53	52.63	51.63	50.79	50.25	49.61	48.57	46.93	45.86	44.59	43.59	42.75	42.55
Dry Snow Density (%)	15													
Pack Density (%)	16	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
SNOWPACK AFTER REACHING THRESHOLD DENSITY														
Snow Depth	17	53.53	52.63	51.63	50.79	50.25	49.61	48.57	46.93	45.86	44.59	43.59	42.75	42.55
Accum. W.C.	18	25.70	25.13	24.88	23.99	23.10	23.27	23.67	23.45	21.62	21.59	21.08	20.64	20.26
Max. Allowable W.C. at 45.0 %	19	24.09	23.68	23.23	22.86	22.61	22.32	21.86	21.12	20.64	20.07	19.62	19.24	19.15
EXCESS WATER AVAILABLE FOR RUNOFF														
ΔDrainage from Snowpack	20	1.61	1.45	1.65	1.13	0.49	0.95	1.81	2.33	0.98	1.52	1.46	1.40	1.11
ΔInfiltration Loss	21	0.86	0.73	0.61	0.52	0.49	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
ΔExcess Water from Zone	22	0.75	0.72	1.04	0.61	0	0.44	1.30	1.82	0.47	1.01	0.95	0.89	0.60
ΔEquiv. Basin-wide Excess	23													

RAIN-ON-SNOW COMPUTATIONS (averaging all layers) **FORM A** Project South Yuba River near Cisco, California, December 1955

Elevations 5600 to 8000 ft. Area 51.5 Sq. Mi. Initial density ____ %
Avge. Elev. 7000 ft. 100 % of basin. Threshold density 45.0 % Zone ____ Sheet 6 of 6

DESCRIPTION		A	B	C	D	E	F	G	H	I	J	K	L	M
Time at end of interval (Hrs.)	1	23/6P	9P	12P	24/3A	6A	9A							
STORM DATA														
ΔPrecipitation	2	0.72	0.42	0.42	0.34	0.17	0.01							
ΔSnowfall Depth at 6.3 %	3	11.43	6.67	6.67	5.40	2.70	0.16							
ΔPotential Snowmelt W.C.	4													
MELT FROM SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	5	← Layer No. 6 @ 6.3% →												
ΔDepth of Melt at ____ %	6													
MELT FROM SNOWPACK AFTER REACHING THRESHOLD DENSITY														
ΔW.C. of Melt	7													
ΔDepth of Melt at ____ %	8													
SNOWPACK BEFORE REACHING THRESHOLD DENSITY														
Initial Dry Snow Depth	9	67.30	73.97	80.64	86.04	88.74	88.90							
Initial W.C. (dry snow)	10	13.46	13.88	14.30	14.64	14.81	14.82							
Accum. W.C. (dry snow + water)	11	19.87	20.29	20.71	21.05	21.22	21.23							
Percent of Initial W.C.	12	147.6	146.2	144.8	143.8	143.3	143.3							
Percent of Initial Depth	13	77.4	78.1	78.8	79.2	79.5	79.5							
Compacted Depth	14	52.09	57.77	63.54	68.14	70.55	70.68							
Dry Snow Density (%)	15						21.0							
Pack Density (%)	16	38.1	35.1	32.6	30.9	30.1	30.0							
SNOWPACK AFTER REACHING THRESHOLD DENSITY														
Snow Depth	17	52.09	57.77	63.54	68.14	70.55	70.68							
Accum. W.C.	18													
Max. Allowable W.C. at 45.0 %	19													
EXCESS WATER AVAILABLE FOR RUNOFF														
ΔDrainage from Snowpack	20													
ΔInfiltration Loss	21													
ΔExcess Water from Zone	22													
ΔEquiv. Basin-wide Excess	23													

FIGURE 13.—*Plate 3 of 3. Example III–B. Rain-on-snow computations with intermittent snowfalls averaged into the snowpack, South Yuba River near Cisco, Calif.*

TABLE 5.—*Summary of weight and volume relationships in a snowpack*

Initial snowpack at 100 percent thermal quality			Compacted snowpack											
			At threshold density 40 percent						At threshold density 45 percent					
Density	Percent of volume		Density of dry snow only	Percent of weight		Percent of volume			Density of dry snow only	Percent of weight		Percent of volume		
	Snow	Air		Snow[1]	Water	Snow	Water	Air		Snow[1]	Water	Snow	Water	Air
5	5.4	94.6	16.2	40.5	59.5	17.6	23.8	58.6	17.9	39.8	60.2	19.5	27.1	53.4
10	10.9	89.1	19.6	49.0	51.0	21.3	20.4	58.3	21.3	47.3	52.7	23.2	23.7	53.1
15	16.3	83.7	23.0	57.5	42.5	25.0	17.0	58.0	24.6	54.7	45.3	26.7	20.4	52.9
20	21.7	78.3	26.4	66.0	34.0	28.7	13.6	57.7	28.0	62.2	37.8	30.4	17.0	52.6
25	27.2	72.8	29.8	74.5	25.5	32.4	10.2	57.4	31.4	69.8	30.2	34.1	13.6	52.3
30	32.6	67.4	33.2	83.0	17.0	36.1	6.8	57.1	34.8	77.3	22.7	37.8	10.2	52.0
35	38.0	62.0	36.6	91.5	8.5	39.8	3.4	56.8	38.2	84.9	15.1	41.5	6.8	51.7
40	43.5	56.5	40.0	100.0	0	43.5	0	56.5	41.6	92.5	7.6	45.2	3.4	51.4
45	48.9	51.1	---	---	---	---	---	---	45.0	100.0	0	48.9	0	51.1
			Data from laboratory experiment											
			Snowpack at density 42.5 percent just before drainage began						Snowpack at density 45.7 percent at end of experiment after drainage had ceased					
15.4	16.7	83.3	24.0	56.5	43.5	26.1	18.5	55.4	31.8	69.6	30.4	34.6	13.9	51.5

[1] Same as "Thermal Quality."

Comparison With Other Procedures

TABLE 5 INDICATES the relative amounts of snow and water in the compacted snowpacks for various assumed initial snowpack densities. The relative amounts are expressed as percentages of the total snowpack weight and as percentages of the total snowpack volume. The relative amounts observed in the laboratory experiment are also shown. The values in the table are an extrapolation from the single laboratory experiment.

The relative amount of snow expressed as percent of weight is identical to thermal quality. Thermal quality is defined by the Corps of Engineers as "the ratio of the heat necessary to produce a given amount of water from snow to the amount of heat required to produce the same quantity of melt from pure ice at 32° F."[4] In the laboratory experiment when the snow was at 42.5-percent density, just before drainage began, the thermal quality was 56.5 percent and the free water amounted to 43.5 percent of the snowpack by weight. At the end of the experiment after drainage had ceased, the density was 45.7 percent, the thermal quality was 69.6 percent, and the free water was 30.4 percent of the snowpack, by weight. In table 5 the compacted snowpacks at threshold conditions have thermal qualities that vary from 40 to 100 percent and free water contents that vary from 60 to 0 percent, by weight, depending on the initial condition of the snowpack. It will also be noted that in all cases, the unoccupied air spaces in the compacted snowpacks represent from 51 to 59 percent of the snowpack volume.

Some investigators compute the amount of water storage in the snowpack on the assumption of a limiting lower value of thermal quality or an upper limit of liquid water-holding capacity. The Corps of Engineers states that "Thermal qualities ranged from 80–110 percent. Generally low thermal quality values were obtained during times of high melt when samples of snow contained melt water in transit or in excess of the liquid water-holding capacity of the snow."[5] Bernard and Wilson state that "Coarse grainy snow may have a minimum quality of 70 percent or 80 percent. New snow, of finer particle size, has been observed to have qualities of less than 50 percent in small shallow patches."[6]

The complement of thermal quality is the liquid water-holding capacity which is expressed as percent, by weight, of the total snowpack. The

Corps of Engineers recommends that the maximum free water for the snowpack be 10 percent, which includes the water in transit of 6 percent of the snowpack water equivalent.[7] Another reference states "Experiments on liquid-water-holding capacity of snow are limited. Nearly all are for spring snow of densities above 35 percent, while densities of winter snowpacks usually range from 10 to 35 percent. In this range, no observations of liquid-water-holding capacities are available. * * * It is pointed out that the liquid-water-holding capacities of snow, as discussed in the preceding paragraphs, represent conditions where free drainage of the snowpack is assured. In flat areas, horizontal drainage through channels is impeded by the lack of sufficient slope. Thus, portions of the snowpack in foothills and flat lands may hold liquid water far in excess of that for mountainous areas where free drainage is rapid."[8]

These quotations regarding thermal quality and liquid-water-holding capacity may, at first glance, appear to dispute the assumptions used in the snow compaction procedure. However, as stated, those observations were based mainly on spring snowpacks of densities above 35 percent. In table 5 it will be noted that for those snowpacks having initial densities above 35 percent, the thermal qualities and percentage of water do not differ significantly from the limits quoted. An old spring snowpack that has lain on the ground for a considerable length of time has been subjected to periods of thaw and refreezing which will cause the snow grains to be coarser with a reduction in water-holding capacity. The snow compaction procedure is designed to be used with a new light-density snowpack which is assumed to have been deposited relatively recently, and was followed immediately by a steady, short duration rainfall. This fresh snow can be expected to have finer grains with a resultant larger water-holding capacity, such as referred to by Bernard and Wilson. The laboratory experiment values in table 5 also show that the water-holding capacity can be quite large for an initially low-density fresh snow subjected to an immediate application of water.

In the snow compaction procedure it is assumed that no drainage will occur until the snowpack has reached its threshold density and that thereafter it will undergo no further compaction. Actually, in the laboratory experiment it was observed that some compaction did take place after the threshold density had been reached. Also, field observers have noted instances when drainage had occurred at widely differing densities. However, these observations appear to be more the exceptions than the general rule. The assumption of a threshold density of 40 to 45 percent gives reasonable results for the use intended, particularly when the main interest is in the drainage from rain on snow associated with the large runoff events.

Appendix—Data From Laboratory Experiment

Appendix A

TABLE 6.—*Observers' notes—Consolidation of snow due to the addition of water—Laboratory experiment*

Time (hr.-min.)	Snow depth (inches)	Gross weight (pounds)	Remarks
1325	----------	----------	Sample tube set outside to cool.
1338	42.75	52.2	Tube filled with snow outside.
1341	37.25	52.2	Test begun in controlled temperature room. Temperatures: Snow 28° F., water 37° F.
1349	37.00	53.2	Room temperature 42° F.
1350	36.75	54.2	Snow saturated to 8 inches, dry below.
1354	36.25	55.2	
1355	35.75	56.2	
1356	35.25	57.2	Bottom snow unchanged.
1358	----------	57.2	
1359	34.75	58.2	
1400	34.625	59.2	Bottom snow unchanged.
1403	----------	----------	Microscope slide taken.
1406	----------	----------	Temperatures: Water 38° F., room 42.5° F.
1408	----------	----------	First appearance of water in snow at bottom.
1411	32.25	59.2	Picture taken.
1412	30.75	60.2	Bottom snow saturated but no drainage.
1414	30.25	61.2	Bottom snow saturated but no drainage.
1417	28.75	62.2	Bottom snow saturated 2¼ inches deep but no drainage.
1418	28.25	63.2	No drainage.
1419	27.50	64.2	Bottom snow saturated 2¾ inches deep but no drainage.
1421	26.25	65.2	Bottom snow saturated 3¼ inches deep, drainage water in gravel pan ¼ inch deep.
1423	24.25	66.2	
1425	23.75	66.2	Drainage water in gravel pan 7/16 inch deep.
1428	23.25	67.2	Bottom snow saturated 3¾ inches deep, drainage water in gravel pan ⅝ inch deep.
1433	----------	----------	Drainage water in gravel pan 13/16 inch deep.
1434	22.25	68.2	Bottom snow saturated 4¼ inches deep, drainage water in gravel pan ⅞ inch deep.
1444	----------	----------	Bottom snow saturated 3¾ inches deep, drainage water in gravel pan 1 3/16 inches deep.
1446	----------	59.0	After emptying the gravel pan.
1447	20.75	60.0	Water passes through. Microscope slide taken.
1452	----------	59.0	After emptying the gravel pan.
1455	----------	----------	Picture taken 1455 to 1500 hours.
1500	20.75	59.0	Room temperature 41° F. End of test.

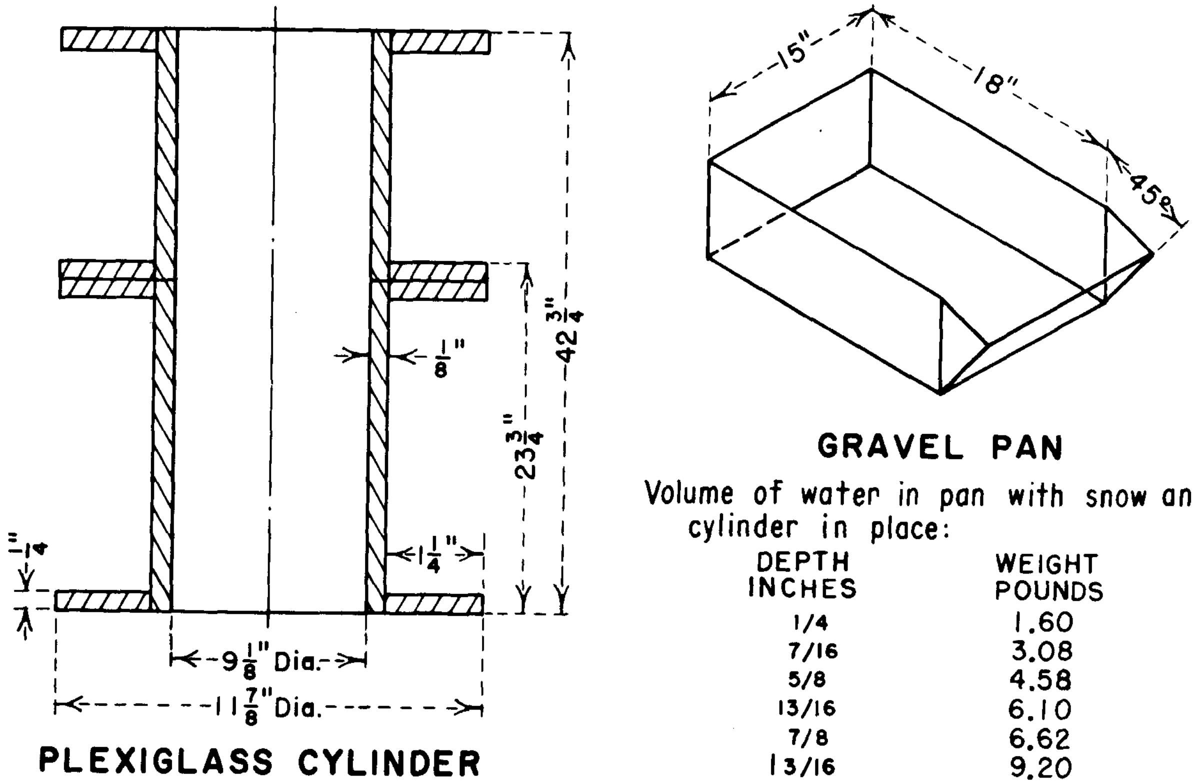
Date of test: Dec. 20, 1951.
Observers: W. U. Garstka
H. P. Grout
D. L. Miller
G. E. Monfore.

Appendix B

TABLE 7.—*Computation of snow compaction curve from results of laboratory experiment*

Time (hr.-min.)	Snow depth (inches)	P_D depth in percent of initial depth	Water added (inches)	Accumulated water (inches)	P_w accumulated water in percent of initial water	Increment of drainage (inches)	Accumulated drainage (inches)	Water content of snow pack (inches)	Snow pack density (percent)
1338	42.75	100	[1] 6.6032	6.60	100			6.60	15.4
1341	37.25	[2] 87.1	0.0	6.60	100			6.60	17.7
1349	37.00	86.5	0.4233	7.03	106.4			7.03	19.0
1350	36.75	86.0	0.4233	7.45	112.8			7.45	20.3
1354	36.25	84.8	0.4232	7.87	119.2			7.87	21.7
1355	35.75	83.6	0.4233	8.30	125.6			8.30	23.2
1356	35.25	82.5	0.4233	8.72	132.1			8.72	24.7
1359	34.75	81.3	0.4233	9.14	138.5			9.14	26.3
1400	34.625	81.0	0.4233	9.57	144.9			9.57	27.6
1411	32.25	75.4	0.0	9.57	144.9			9.57	29.7
1412	30.75	71.9	0.4233	9.99	151.3			9.99	32.5
1414	30.25	70.8	0.4232	10.41	157.7			10.41	34.4
1417	28.75	67.3	0.4233	10.84	164.1			10.84	37.7
1418	28.25	66.1	0.4233	11.26	170.5			11.26	39.9
1419	27.50	64.3	0.4233	11.68	176.9			11.68	42.5
1421	26.25	61.4	0.4233	12.11	183.3	0.6773	0.68	11.43	43.5
1423	24.25	56.7	0.4232	12.53	189.7				
1425	23.75	55.6	0.0	12.53	189.7	0.6264	1.30	11.23	47.3
1428	23.25	54.4	0.4233	12.95	196.2	0.6349	1.94	11.01	47.4
1434	22.25	52.0	0.4233	13.38	202.6	0.8635	2.80	10.57	47.5
1446			0.0	13.38	202.6	1.0921	3.89	9.48	
1447	20.75	48.5	0.4233	13.80	209.0				
1452	20.75	48.5	0.0	13.80	209.0	0.4233	4.32	9.48	45.7
1500	20.75	48.5	0.0	13.80	209.0	0.0	4.32	9.48	45.7

[1] Water equivalent of initial dry snow sample.
[2] Initial compaction caused by moving the sample into the laboratory.
A representative line drawn through the initial point and the points for accumulated water greater than 138 percent has the equation: $P_D=147.4-0.474P_w$.



Volume of water in pan with snow and cylinder in place:

DEPTH INCHES	WEIGHT POUNDS
1/4	1.60
7/16	3.08
5/8	4.58
13/16	6.10
7/8	6.62
13/16	9.20

FIGURE 14.—*Dimensions of equipment used in laboratory experiment.*

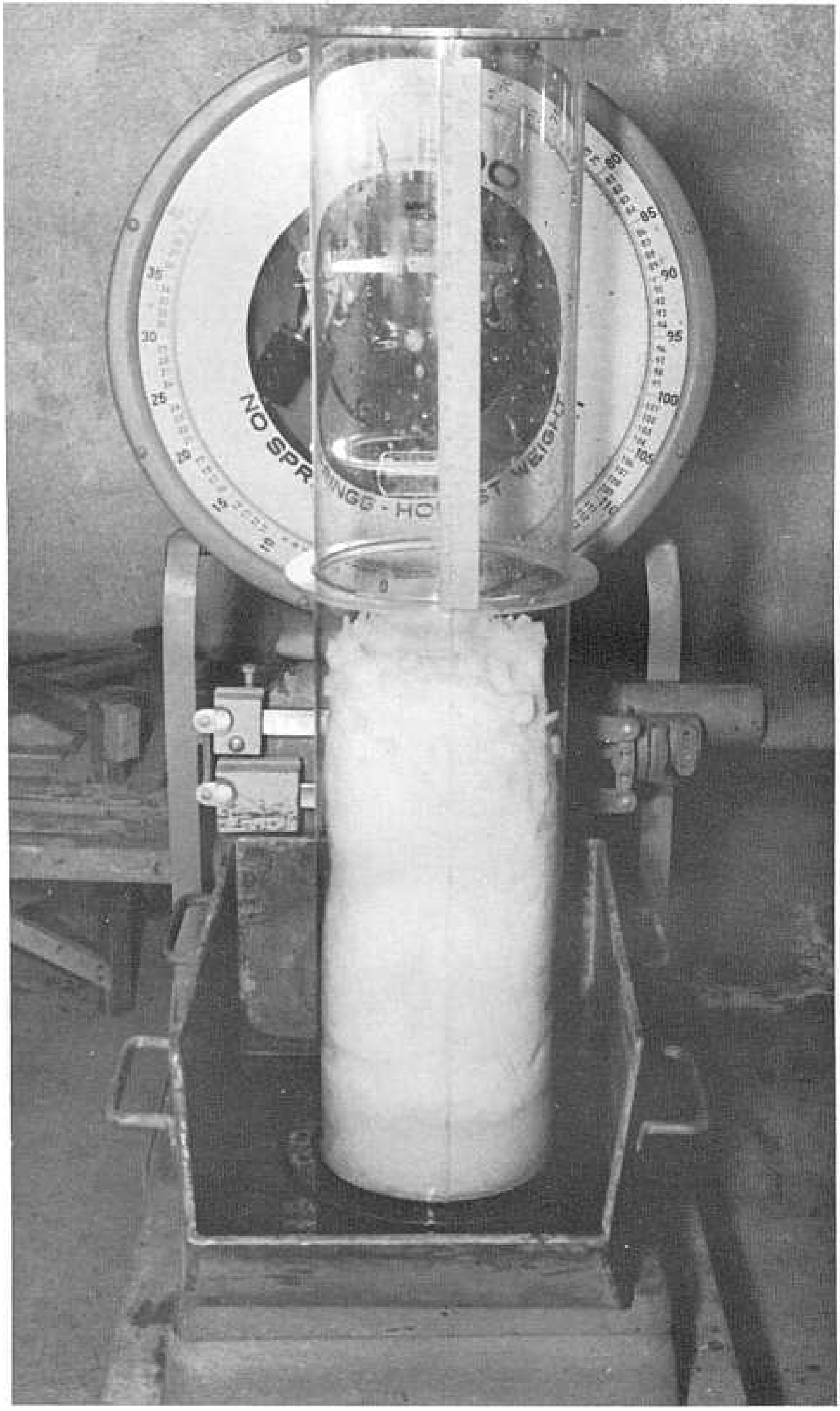


FIGURE 15.—*Snow compaction experiment after 79 minutes. Snow depth is 20.75 inches after 7.20 inches of water had been added. Density is 45.7 percent and 4.32 inches of water have drained out of the bottom.*

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8. Reference 4, p. 303.

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