SNOW COMPACTION METHOD FOR THE ANALYSIS OF RUNOFF
FROM RAIN ON SNOW1/

By

Frederick A. Bertle2/

Introduction

Adequate design of the spillway for a major storage reservoir requires the estimation of a synthetic maximum probable flood hydrograph. This maximum probable flood must represent a realistically critical combination of the major causative hydrological 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 snowpack will absorb the rainfall from the early part of the storm and release it later. As a result of the release of stored water from the snowpack, in addition to the melting of the snow and the rainfall itself, the runoff peak flow may be considerably more severe than would occur from the rainfall alone.

This paper describes a computational procedure for determining the water available for runoff from a situation of rain on snow. It includes an estimate of the shrinkage of the snowpack caused by the metamorphosis of the snow crystals with the addition of rainfall.

The computational procedure is an outgrowth of procedures developed by the Corps of Engineers and described in their Definite Project Report, "Pine Flat Dam and Reservoir--Kings River, California--Part I." Our procedure is basically a water-budget analysis which keeps track of the water in the snowpack until it is released to the ground for infiltration and runoff.

Laboratory Experiment

It is an observed fact that a fresh snowpack subjected to rainfall and melt undergo some compaction (or shrinkage) as water is added and that drainage from the snowpack does not take place until after the snow has reached a threshold density of approximately 40 to 45 percent. In order to evaluate the compaction due to added water, a simple laboratory experiment was performed by Messrs. W. U. Garstka, H. P. Grout, D. L. Miller, and G. E. Monfore of the Bureau of Reclamation in Denver, Colorado, on December 20, 1951. The night before, a large snowfall had occurred at near 0°F temperature. This fresh, dry, cold snow was shoveled into a plexiglass cylinder about 42-3/4 inches long and 9-1/8 inches in diameter. This cylinder full of snow was placed in a pan and set on a weighing scale in a controlled temperature cold room in the Concrete Laboratory. Cold water was sprinkled on the top of the column of snow and the shrinkage of the snow was observed. Figure 1 shows the equipment about 30 minutes after the test had begun. The column of snow, originally 42-3/4 inches high, has shrunk to 32-1/4 inches deep after the addition of 2.96 inches of water. The original snow in the full tube was dry with a density of 15.4 percent. After the addition of water and the compaction, the wet snow now has a density of 29.7 percent.

The results of the test are summarized on Figure 2, on which is plotted the depth in percent of initial depth vs the initial water content plus added water in percent of initial water content. The circles represent readings during the test. After the tube was filled outdoors, the snow was at a density of 15.4 percent and the point is plotted at 100 percent depth and 100 percent water content. During time the sample was moved indoors, the snow settled to 87 percent of depth and the density was now 17.7 percent. As water was added, the snow continued to shrink or compact as indicated by the decreasing

1/ Paper presented to the 33rd Annual Meeting of the Western Snow Conference, Colorado Springs, Colorado, April, 1965.

2/ Hydraulic Engineer, Division of Project Investigations, Office of Chief Engineer, Bureau of Reclamation, Denver, Colorado.

42 3/4"

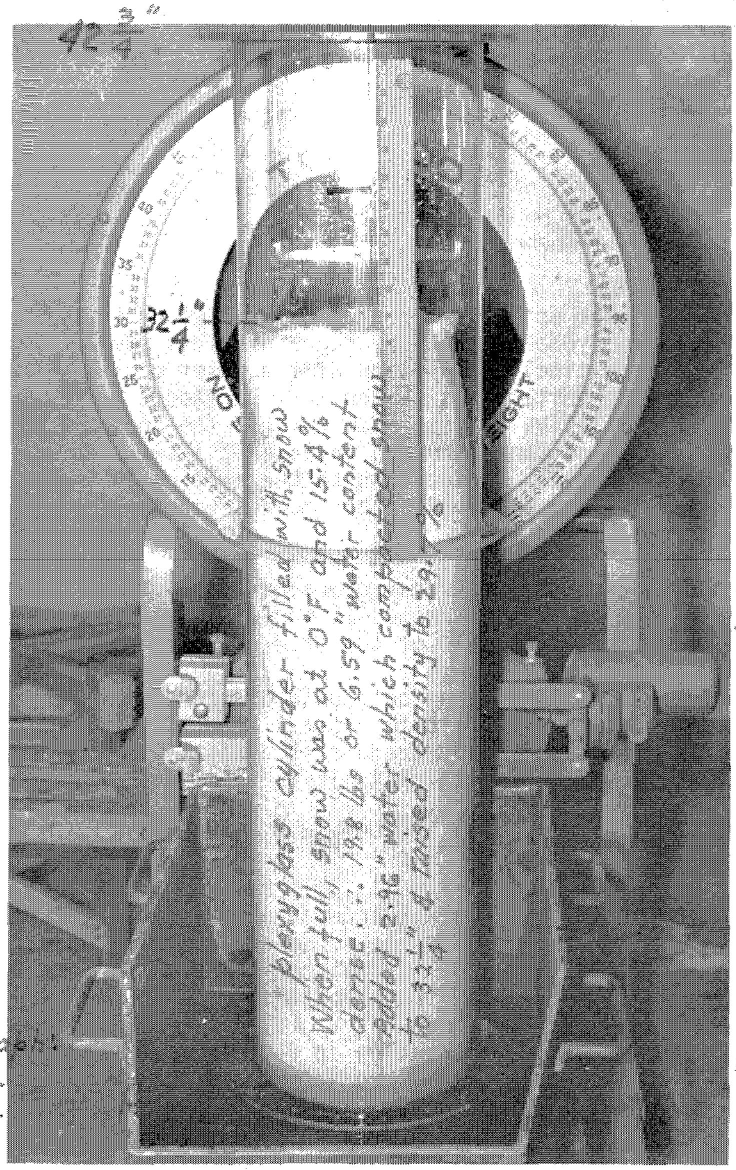


Figure 1.

USBR Procedure assumes:
1. Applicable to dry snow of any density.
2. Drainage would take place only when snow reaches 40-45% density.
3. No compaction after 40-45% density (the adopted threshhold density range).

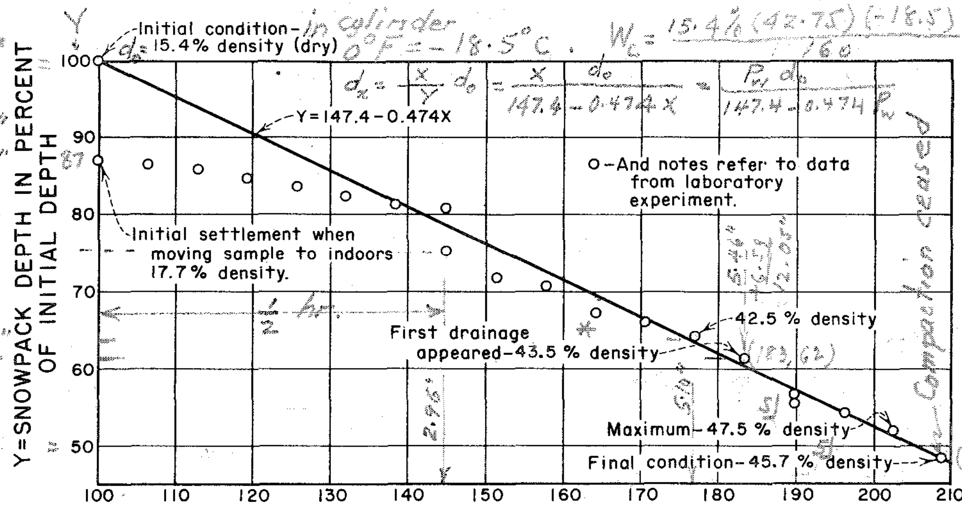
Comments:
1. Experiment shows that compaction cont'd from 26.5 to 20.3" from time of RO to cessation of compaction. ∴ Assumption 3 above is not valid.
2. My experience, with snow in its natural environment does not support a fixed density threshhold for appearance of RO under the snow pack.
3. Snow always dry at any density at temps. below 0°C. (Assumption 1)

Questions:

Did H_2O (Runoff) drain or remain in cylinder?
What was density of snow on ground before placing it in cylinder?
· What was the temp. of water added? (I assumed 0°C)
4. "Rain" vs. duration?
5] Re 47.5% & 45.7% in graph: Was RO H_2O subtracted? If not, these are in error.

Initial condition – in cylinder d_0 = 15.4% density (dry) 0°F = –18.5°C. $W_c = \frac{15.4\% (42.75)(-18.5)}{160} = 0.76"$

$d_x = \frac{x}{Y} d_0 = \frac{x\, d_0}{147.4 - 0.474X} = \frac{P_w\, d_0}{147.4 - 0.474 P_w}$



D_0 = 42.75" = 100; 38.48"; 37.2" 87; 34.20; 29.93; 26.5' → 27.4"; 25.65; 21.38 = 50

(208, 47.5) 67.5% dense with added H_2O

X = INITIAL WATER CONTENT PLUS ADDED WATER IN PERCENT OF INITIAL WATER CONTENT = $x D_0 d_0$

H_2O added → 0 0.66 1.32 1.98 2.64 3.30 3.96 4.62 5.28 5.94 6.59 7.2

FIGURE 2 - DECREASE IN SNOWPACK DEPTH DUE TO ADDITION OF WATER, weight & elapsed time

missing Rain application time scale here →

* Plotted at a point which shows density = 45.5%

5] 20.3%, 53% for the 47.5% density: 13.4" 22.5" → 59.5% with all added water remaining in. This obs'tion can not have density more than the last observation.

percentage of depth for each of the points. By the time the water content (W.C.) plus the added water was 177 percent of the initial W.C., the depth was only 64 percent of the original and the density was 42.5 percent. During this time 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 47-1/2 percent. Water was continually added until no further compaction took place. This final point had a density of 45.7 percent. The relationship between depth and accumulated water is represented by the straight line which has the equation:

$$Y = 147.4 - 0.47\,X$$

where: Y = snowpack depth in percent of initial depth
X = initial water content plus added water in percent of initial water content.

Application of Test Results

The results of the test were then adapted to the water budget of the snowpack by making a few simplifying assumptions. First we assumed that the compaction relationship would be applicable to dry snowpacks of any density. Secondly, we assumed that drainage would take place only after the snowpack had reached a threshold density of 40 to 45 percent. Thirdly, we assumed that no further compaction would take place after the threshold density had been reached.

The conditions of the snowpack at the adopted threshold density can be computed by the following three equations:

$$P_W = (147.4\ d_c) \,/\, (d_o + 0.474\ d_c)$$

$$P_D = (147.4\ d_o) \,/\, (d_o + 0.474\ d_c) = 147.4 - 0.474\ P_W$$

$$d_s = 0.678\ (d_o + 0.474\ d_c)$$

where:

P_W = accumulated water content in percent of initial water content

P_D = compacted depth in percent of initial depth

d_o = density of initial dry snowpack in percent

d_c = threshold density of compacted wet snowpack in percent

d_s = density of dry snow in compacted wet snowpack in percent.

Figure 3 illustrates pictorially the steps taken in the water budget analysis when there is no melting. In Figure 3 (a) we see the initial snowpack with a dry snow density of 10 percent. In Figure 3 (b) we have added 3 inches of rain. As indicated by our compaction curve, the snowpack has shrunk to 85.8 percent depth. Compaction will continue as we add water until the threshold density has been reached as in Figure 3 (c). In this case we assumed 40 percent as the threshold density. Since 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 when more rain is added, it causes an equivalent amount of drainage from the pack.

Figure 4 shows pictorially the water budget procedure when melting occurs but without rain. In this case we reduce the original snowpack by the amount of melt before we compute the compaction. The melt water is treated as though it were rain added to the reduced original snowpack. In this case it takes 5.1 inches of melt to bring the snowpack to 40 percent threshold density. With 10 percent dry density snow, the 5.1 inches of melt converts 51 inches depth of snow into 5.1 inches of water. The reduced original depth is now 49 inches. Using the snow compaction curve, this 49 inch depth is compacted to 50.9 percent of depth, or 25 inches deep, by the 5.1 inches of added melt water. At this point the snowpack has a density of 40 percent. However, the snow itself has a density of 19.6 percent. The difference between 19.6 and 40 percent density is due to the free

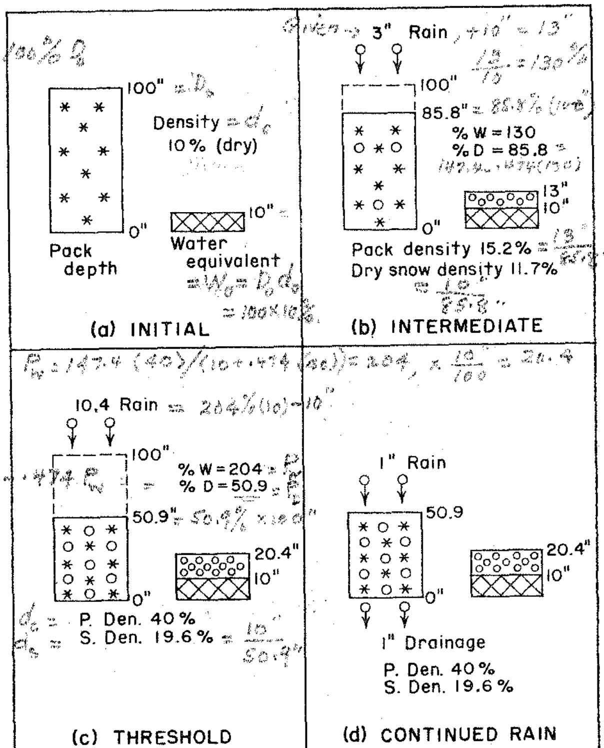


FIGURE 3 - COMPACTION AND DRAINAGE DUE TO RAIN-ON-SNOW WITHOUT MELTING.

Note: H_2O req'd to condition pack to yield R.O. = loss (if rain at 0°C) = 10.4" which is > Pack water. (I don't believe it!)

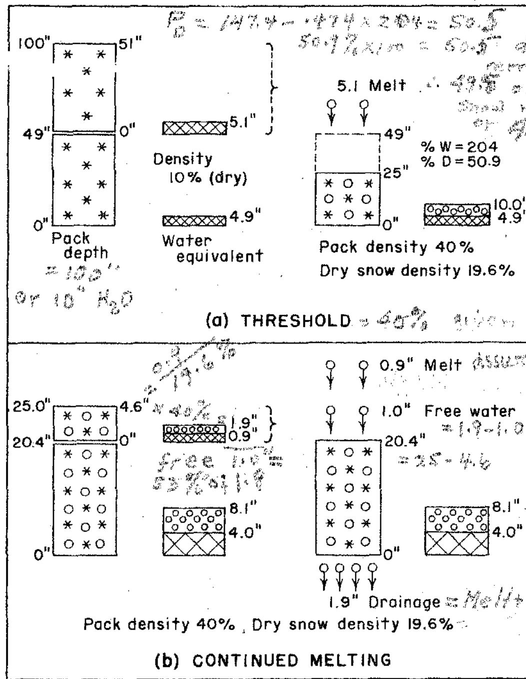


FIGURE 4 - COMPACTION AND DRAINAGE DUE TO SNOW MELT WATER WITHOUT RAIN.

$P_w = (147.4\,d_0)/(d_0 + .474\,d_c)$ (1)

$ = (147.4\,d_0)/(d_0 + .474\,d_c)$ (2)

$= 0.678\,(d_0 + .474\,d_c)$ (3)

= Accum. Water content in % of Initial W/W_0

= Compacted depth in % of initial D/D_0

d_0 = Initial density of Pack

d_c = Threshold density 40-45%

d_s = dry snow density

Depth required for 40% density of 5.3" rain: $0.40 = \frac{10+5.3}{D_c}$, $D_c = 38.2"$

$d_s = 0.678(10 + .474 \times 40) = 19.6\%$ is density of crystals in 38.2" compacted depth — or 7.5" WE. Total WE = 15.3. ∴ Melt + Rain = 15.3 − 7.5 = 7.8. ∴ Melt = 7.8 − 5.3 = 2.5". 2.5" Melt = 25" original snow. 7.5" " = 75" "

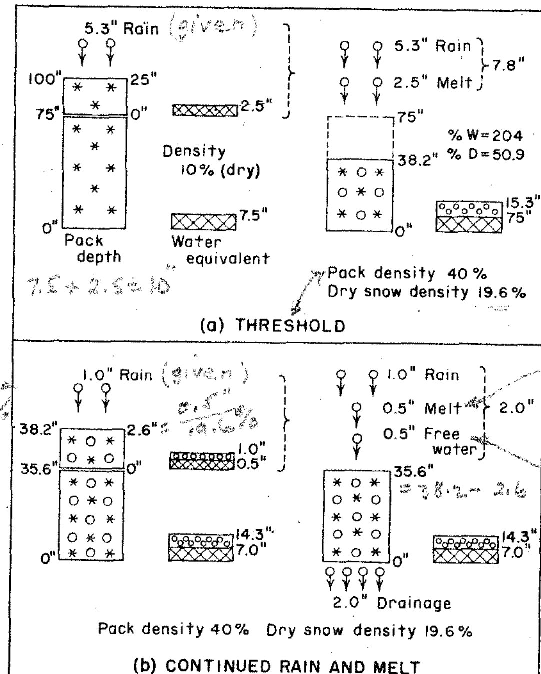


FIGURE 5 - COMPACTION AND DRAINAGE DUE TO RAIN AND SNOW MELT.

Note: In fig 5a one does not need to compute melt. Fixing 40% & Rain amount fixes melt amount — regardless of temp. of snow & air — very simple if it works in a lysimeter type of experiment.

water in the snowpack. Figure 4 (b) shows what happens as additional melt occurs. In this case we assumed 0.9 inch of melt. Since this melt will convert the snow crystals to water it will have a depth of 4.6 inches based on the 19.6 percent density of the snow only. Within that 4.6 inches of depth there is also 1 inch of free water, so that there will be a drainage of 1.9 inches of water from the ripe snowpack due to 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 that was held in the 2.6 inches of depth of snow that was melted.

In actual weather conditions, the situation is further complicated when there are alternating periods of rain-melt and snowfall. Under these conditions we keep track of 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 snowpack below. After that time, the total snowpack is again considered to be homogeneous.

All of these processes are accounted for in the tabular format that is used in the water budget procedure, with computations being made at the end of each selected interval of time.

Comparison with Observed Events

The December 1955 storm and flood illustrate the application of the overall procedure to a small, 51.5 square-mile drainage basin of the South Fork Yuba River near Cisco, California. Precipitation records at Cisco and at Soda Springs enabled us to make an estimate of the precipitation over the basin. Temperature and wind records at Blue Canyon just a few miles to the west enabled us to separate the periods of snowfall from rainfall, and to estimate the snowmelt potential by use of the Corps of Engineers' snowmelt equation. Figure 6 shows our results. This figure shows the period from morning of December 18 to noon of December 24, 1955. The top chart shows the 3 hour periods of rain and snowfall water contents as well as the estimated melt. The snowpack on the morning of December 18 was about 53 inches deep, with a water content of about 15 inches, and a density of about 28 percent. Using our snow compaction procedure, we computed the snowpack depth as shown by the broken line. The X's are observed measurements of snowpack depth at Soda Springs. The procedure showed that drainage from the snowpack did not occur until afternoon of December 21 as indicated by the second graph from the top. By applying these drainages to an infiltration curve and a unit hydrograph, we got the hydrograph shown as a broken line. This agrees favorably with the measured runoff. In this case we used a threshold density of 45 percent.

Two recent examples were also prepared from the records at Government Camp and Parkdale, Oregon, on the slopes of Mount Hood during the December 1964 event. Our attention was focused on these stations by the following quotation from the Special Weather Summary in the front of the Weather Bureau publication "Climatological Data, Oregon, December 1964":

> "During the 19th-20th, temperatures rose rapidly, accompanied by heavy rains to practically the crest of the Cascades. Usually by mid-December this would have been snow at the higher levels. In the first several hours the pre-existing snow blanket retained the rain in storage, rather than permitting its gradual runoff. As the rains continued, their intensity increased until finally almost the entire snowpack collapsed in a matter of a few hours. Typical was Government Camp, on the upper slopes of the Cascades, at an elevation of 3,900 feet. Here, on the morning of the 20th, snow depth was 55 inches, with a water content of about 5.44 inches. In the next 24 hours this packed down to 45 inches and stored up another 1.57 inches of rain. By the morning of the 23d, only 6 inches of snow remained, and nearly 9 inches of additional rain had fallen since the 21st. This same pattern of snow, followed by heavy rains, was occurring over the entire state."

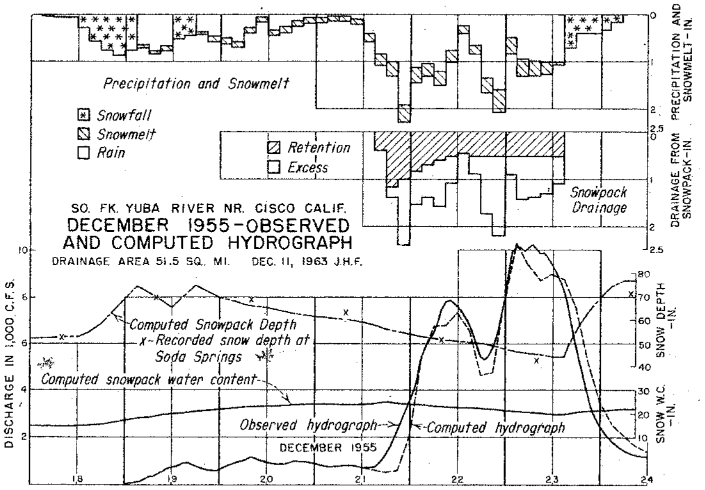


FIGURE 6

* Using threshhold density of 45%; (Very good check on snowpack depth) And using Corps-derived Melt-formula.

GOVERNMENT CAMP, OREGON – DECEMBER 1964				
Time	20/0800	21/0800	22/0800	23/0800
Precipitation		1.57	4.72	5.58
Snowmelt W.C. by Corps formula →		.21	1.14	2.98
Depth of melt at 9.9% = .21/.099		2.12	11.53	—
Depth of melt at 21.2%		—	—	14.07
Initial dry snow depth	55 − 2.12 =	52.88	41.35	
Initial W.C. (dry snow) at 9.9%	5.44	5.23	4.09	
Accum. W.C. (snow + water)		7.01	8.69	
% Of initial W.C. (212.5%)		134.0	212.5	
% Of initial depth (46.7%)		83.9	46.7	
Compacted depth		44.35	19.31	
Dry snow density (21.2%)		11.8	21.2	
Pack density (45%)	9.9	15.8	45.0	
Snow depth	55	44.35	19.31	5.24
Accum. W.C.	5.44	7.01	11.73	14.27
Max. allowable W.C. at 45%.			8.69	2.36
Drainage			3.04	11.91
Reported snow depth	55	45	20	6

FIGURE 7

% D₀ = 147.4 − .474 × 134 = 83.9
Compacted depth density = 7.01/44.35 = 15.8%
Free water in pack on 21/0800 = 1.57+.21 = 1.78
or 1.78"(5.44+.21) = 34%
& still not yielding RO.
% D₀ = 147.4 − .474 × 212.5 =

GOVERNMENT CAMP, OREGON – DECEMBER 1964						
Time	20/0800		21/0800	22/0800		23/0800
Precipitation		.59	.98	4.72	.10	5.48
Snowfall depth at 9.9%		6.00	—	—	1.00	—
Snowmelt W.C.		—	.20	1.14	—	2.97
Depth of melt at 9.9%		—	2.02	11.53	—	—
Depth of melt at 21.2%		—	—	—	—	14.02
Initial dry snow depth	55	61.00	58.98	47.45	1.00	1.00
Initial W.C. (dry snow)	5.44	6.03	5.83	4.69	.10	.10
Accum. W.C. (snow + water)			7.01	9.97		.21
% Of initial W.C. (212.5%)			120.2	212.5		212.5
% Of initial depth (46.7%)			90.4	46.7		46.7
Compacted depth			53.32	22.16		.47
Dry snow density (21.2%)			10.9	21.2		21.2
Pack density (45%)	9.9		13.2	45.0		45.0
Snow depth	55		53.32	22.16		8.61
Accum. W.C.	5.44		7.01	11.73		15.55
Max. allowable W.C. at 45%				9.97		3.87
Drainage				1.76		11.68
Reported snow depth	55		45	20		6

FIGURE 8

PARKDALE, OREGON – DECEMBER, 1964			
Time	21/0800	22/0800	23/0800
Precipitation		4.34	4.87
Snowmelt W.C.		1.20	3.36
Depth of melt at 18.4%		6.52	—
Depth of melt at 27.0%		—	12.46
Initial dry snow depth	27	20.48	
Initial W.C. (dry snow)	4.97	3.77	
Accum. W.C. (snow + water)		6.29	
% Of initial W.C. (166.9%)		166.9	
% Of initial depth (68.3%)		68.3	
Compacted depth		13.99	
Dry snow density (27.0%)		27.0	
Pack density (45%)	18.4	45.0	
Snow depth	27	13.99	1.53
Accum. W.C.	4.97	9.31	11.17
Max. allowable W.C. at 45%.		6.30	0.69
Drainage		3.01	10.48
Reported snow depth	27	14	3

FIGURE 9

If we accept the quoted statement that all of this precipitation was rainfall we get the following analysis as shown on Figure 7. Here we have a column for each day at the 8:00 a.m. time of observation. Amounts of precipitation recorded were 1.57 inches on December 21st, 4.72 inches on the 22d, and 5.58 inches on the 23d. Using maximum and minimum temperatures at Government Camp, the hourly temperatures at Portland, and wind speeds at Portland, and using the Corps of Engineers' snowmelt equation, we estimated the snowmelt potential to be 0.21 inch the first day, 1.14 inches the second day, and 2.98 inches the third day. At 8:00 a.m. on December 20th, the initial snow depth was 55 inches, with a water content of 5.44 inches. This is a dry snow density of 9.9 percent. On the first day the rainfall and melt will compact the snowpack. The snowmelt of 0.21 inch will reduce the initial snowpack by 2.12 inches on the basis of 9.9 percent density. The reduced initial depth is now 52.88 inches and the reduced initial water content of the dry snow remaining is 5.23 inches. The accumulated water content of snow and rain is 7.01 inches, which is 134 percent of the reduced initial dry snow water content. From our snow compaction relationship, the snowpack should be reduced to 83.9 percent of its reduced initial depth. This makes the snowpack 44.35 inches deep. The actually observed depth was 45 inches. No drainage occurs because the snowpack density is only 15.8 percent. During the second day the snowmelt of 1.14 inches reduces the initial depth by 11.53 inches based on the 9.9 percent density. The reduced initial depth is now 41.35 inches and the reduced initial water content of the dry snow is 4.09 inches. The snowmelt plus part of the rain brings the accumulated water content of snow and rain to 8.69 inches, which is 212.5 percent of the reduced initial dry snow water content. From our compaction curve, this reduces the snowpack to 46.7 percent depth, or a depth of 19.31 inches. The depth actually observed was 20 inches.

The snowpack is now at the threshold density of 45 percent. The remaining rain for the day drains through the snowpack supplying 3.04 inches of water which is available for infiltration and runoff. The dry snow portion of this 45 percent density snowpack has a density of 21.2 percent. The snowmelt that occurs on the third day (2.98 inches) is converted to a depth of 14.07 inches based on this 21.2 percent density. The resulting snowpack depth at 8:00 a.m. on the 23d is 5.24 inches. The depth actually observed was 6 inches.

This close an agreement suggests that the assumption that all of this precipitation fell as rain is reasonable. However, a closer look at the record showed that the observer had recorded snowfalls on the 21st and 23d. Taking these snowfalls into account, the following analysis was made as shown on Figure 8. The 6 inches of snowfall recorded at 8:00 a.m. on the 21st was assumed to fall at 9.9 percent density, with a water content of 0.59 inch. This snowfall was added to the preceding snowpack to give a new initial snowpack depth of 61 inches. The remaining precipitation and melt on the first day reduced the snowpack to 53.32 inches as compared with the actually recorded depth of 45 inches. The rain and melt on the second day reduced the snowpack depth to 22.16 inches as compared to a recorded depth of 20 inches. The snowpack is now at the threshold density of 45 percent and 1.76 inches of drainage has occurred. The 1 inch of snowfall on the 23d was considered as a separate top layer of snow. Enough of the rain was used to compact this top layer to a depth of 0.47 inch and 45 percent density. The remaining rain and melt reduced the total snowpack to 8.61 inches deep as compared with the recorded depth of 6 inches. You will note that the use of the recorded snowfall has caused us to miss the depth on the 21st but that we still have reasonably good agreement on the 22d and 23d.

A similar analysis was made for December 21 to 23 at Parkdale, also on the slopes of Mount Hood. This analysis is shown on Figure 9. The initial depth at 8:00 a.m. December 21 was 27 inches. From the preceding period of snowfall we estimated the water content to be 4.97 inches, with a density of 18.4 percent. Rain of 4.34 inches and 4.87 inches was recorded on the 22d and 23d, and the recorded snow depths were 14 and 3 inches, respectively. Our analysis computed depths of 13.99 inches and 1.53 inches.

SUMMARY

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 paper, which uses a water budget based on the concept of snow compaction and a threshold density, has been a valuable aid in our 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 a simple, straightforward procedure that is easy to use, and the examples cited illustrate that it gives realistic results. The procedure is described in more detail in a Bureau of Reclamation Engineering Monograph which is now in preparation.

LIST OF FIGURES