CHAPTER 8 - EFFECT OF SNOWPACK CONDITION ON RUNOFF

8-01. INTRODUCTION

8-01.01 General. - The storage effect of the snowpack is important in the evaluation of both the volume and the time distribution of runoff. For equal melt values and losses, generated runoffs may not be the same because of the snowpack condition. An initially "cold" (sub-freezing) snow will freeze a certain amount of liquid water entering it and thereby raise the temperature of the snow to the melting point. An additional amount is required to satisfy the liquid-water-holding capacity before the snow will release any water by gravity. If, however, the entire snowpack is already saturated and conditioned to yield water, all inflow will pass through the pack to the ground without depletion; the time delay depends mainly on the depth of snow, the resistance to flow, and the rate of inflow. In order to assess the snowpack condition and its effect upon runoff, it is necessary first to understand the changing character of the snowpack and the processes of heat and water-vapor transfer within the pack. Special experiments on the storage and transit of liquid water in the snowpack at CSSL, although somewhat meager and inconclusive, furnish information which serves as a guide to solution of problems involving storage and travel time of water in the snowpack.

8-01.02 The physical properties, which affect the liquid-water retention and detention capacities of the snow, continue to change from the time of deposition to melt. Even during the active melt season the proportions of ice, liquid water, and air are not constant. Likewise, the permeability and diffusivity of the snowpack to heat, air, and water are continually changing.

8-01.03 Character of the snowpack. - Snow is a precipitate. Ice crystals are formed in the atmosphere at temperatures below freezing by sublimation of water vapor on hygroscopic nuclei. Many different types of crystals form, depending on the shape of the nucleus, the rate of sublimation, and the turbulence of the air. An excellently illustrated discussion of the relation between snow crystal types, forms, mass, rate of fall, and crystal habits is found in Snow Crystals by Nakaya.11/ Because of the usual dendritic structure of these crystals, new-fallen snow is generally of low density. With time, however, the snowpack undergoes a change: the original, delicate crystals of snow become coarse grains, and the density of the pack increases. There is no definite time at which the change takes place from crystalline forms characteristic of new-fallen snow to coarse grains in the snowpack. The crystalline structure of the snow, as used in this chapter, is a general term referring to classification of either the snow crystals themselves, or the snow grains resulting from metamorphism of the snowpack. The change from a loose, dry, and subfreezing snowpack of low density to a coarse, granular, and moist snowpack of high density is spoken of as "ripening" of the snowpack. A "ripe" snowpack is said to be "primed" to produce runoff (barring temporary ponding due to resistance to flow or inadequate channel capacity). A ripe snowpack is not necessarily homogeneous; it is generally striated with ice planes and ice lenses. Density of the snowpack, which is an easily measurable element, appears to be a single variable that integrates fairly well the effect of the other physical properties of the snow. It has been used for defining the affinity of the snow for water, as well as the thermal properties of snow. Knowledge of the factors affecting the metamorphism of the snowpack will facilitate the understanding and solution of the heat transfer, the liquid-water storage, and transmission problems in snow hydrology.

8-02. METAMORPHISM OF THE SNOWPACK

8-02.01 General. - The change in the character of the snowpack has been studied at length in connection with the use of snow as an engineering material. No consideration will be given here to variation in such structural qualities as hardness, strength, or trafficability. The hydrologist's concern with the metamorphism of the snowpack is primarily limited to the function of the snowpack as a deterrent to runoff. The presentation in this section is intended to give the hydrologist a limited summary of the effects of the metamorphism of the snowpack as regards its role in the hydrologic cycle.

8-02.02 Factors affecting the metamorphism of snow. - Time is the principal factor to be considered in the metamorphism of snow. The several physical processes contributing to metamorphism of snow are: (1) heat exchange at the snow surface by radiation, convection, and condensation; (2) percolation of melt or rain water through the snowpack; (3) internal pressure due to the weight of the snow; (4) wind; (5) temperature and water-vapor variation within the snowpack; and (6) heat exchange at the ground surface. The effects of these processes which are of hydrologic importance are: (1) change in density as the result of change in crystal forms and displacement of the crystalline particles with respect to one another; (2) formation of ice planes; (3) change in air, water, and heat permeability and diffusivity; (4) change in liquid-water-holding capacity; and (5) change in temperature of the snowpack.

8-02.03 Structure of the snowpack. - As each new layer of snow is deposited, its upper surface is subjected to weathering effects of radiation, rain and wind, the under-surface to ground heat, and the interior to the action of the percolating water and water vapor. As a result, the snowpack is stratified, showing distinct layers of individual snow-storm deposits. Early in the season a granular layer is formed at the ground surface when the ground is unfrozen.

8-02.04 The change in the form of the snow crystals is believed to result from sublimation (evaporation from and condensation onto crystal surfaces) and from the action of percolating water. 1/ 4/ Due to temperature differences, air is in continuous motion within the snowpack, carrying with it heat and water vapor. This activity results in rounding off of snow crystals and growth of some at the expense of others. The circulating air (saturated with water vapor) tends to equalize the temperature and vapor pressure within the snowpack. Impermeable ice planes deflect but do not prevent the movement of the air, just as they deflect or impede the downward percolation of water. The areal extent of such impermeable planes is not great. Observations of percolation paths made at the three snow laboratories, using fuchsine dye to trace the water, indicate many weaknesses in the seemingly impermeable ice planes through which air and water can pass. As a result of the flow of air and water in the snowpack, the pack tends to become homogeneous with respect to temperature, liquid-water content, grain size, and density, as the season progresses.

8-02.05 Nocturnal snow crust. - During the melt season, on clear nights, a relatively shallow surface layer of the snowpack generally cools considerably below $0^{\circ}C$ due to outgoing longwave radiation; the liquid water will freeze, but below this surface layer, the snow remains at $0^{\circ}C$ and liquid water continues to drain, until the remaining liquid water in the pack equals the liquid-water-holding capacity. The combined effect of air and heat diffusion causes the surface layer to cool each night to a depth of about 10 inches. There is a change in the crystalline structure of the surface layer due to this alternately freezing and thawing effect.

8-02.06 Air permeability of the snowpack. - It was pointed out in the preceding paragraphs that the circulation of air within the pack is partially responsible for the snow metamorphism. Measurements reported by Bader and others 1/ show that air permeability varies widely within the snowpack and with time, just as the crystalline structure and porosity do. An important function of this moving air is the transportation of water vapor from high to low-temperature areas. As a result, ice lenses and ice planes will increase in size, and some crystals will grow at the expense of others.

8-02.07 Flow of moisture. - The relative magnitudes of moisture moving in snow in the form of water vapor and that moving in liquid form by capillary action have not been determined. Experiments conducted by Hadley and Eisenstadt 7/ on thermally-actuated moisture migration in granular media appear to indicate that the movement of moisture by vapor diffusion in the direction of heat flow in snow may be insignificant compared to the capillary movement of liquid water. Section 8-05 deals with the measurement, storage and movement of liquid water in snow, which is of particular hydrologic significance in evaluating the effect of the snowpack on runoff.

8-02.08 Density of new-fallen snow. - The density of new-fallen snow varies widely with the size, shape, and type of snow crystals, as well as with the temperature, humidity, and wind speed of the air through which they fall. The two primary factors are air temperature and wind. Diamond and Lowry 5/ correlated the density of new snow as measured at CSSL with surface air temperature and found an average increase in density of 0.0036 g/cc per degree F increase in surface air temperature at the time of deposition. Figure 4, plate 8-1, shows a plot of their data relating density of new snow with surface air temperatures. Rikhter 12/ reported densities of new-fallen snow varying with surface wind, and ranging from 0.06 for calm conditions to 0.34 for snow deposited during gale winds. Changes in density of new snow are rapid and variable during the first few hours after deposition. Therefore, daily measurements of density reflect considerable variability due to the varying time of deposition and settlement conditions during the 24-hour period. For practical use, an assumed average density of 0.10 g/cc for converting depth of new snow to water equivalent, from once-daily measurements, will suffice in most cases for an average measure of precipitation.

8-02.09 Snowpack density characteristics. - The average density of a basin snowpack varies widely with space and time. Generally speaking, the average pack density increases with time, declines slightly with each new snow, but regains its former density soon thereafter with the settlement of the new snow. This is illustrated in figure 1, plate 8-1, by the daily density graph for an accumulating snowpack at WBSL headquarters. The depth of the snow increased almost continuously from 1 inch on 4 December 1949, to 165 inches on 15 January 1950, during which time the mean daily air temperatures were below freezing. On 12 January a deep pit was dug and densities at various levels were observed. As shown in figure 2, the densities varied from 0.07 g/cc for the new-fallen snow at the surface to 0.38 g/cc near the bottom of the pack. Wind, melt, and rain augmented the rate of settlement of new snow. The striated structure of the snowpack was caused by the succession of new snow layers on the more dense snow of greater age upon which they were laid. In general, the density of the pack varies directly with depth, but there is considerable variation as a result of individual ice lenses, ice planes, and buried snow crusts.

8-02.10 Snowpack density changes. - Rapid settling and compacting of the snowpack begins immediately following deposition, and then continues more slowly throughout the accumulation period into the ablation period. The change in form and displacement of individual particles within the snow matrix cause the settlement. The volume of voids gradually decreases from a maximum value when snow is newly deposited to a minimum amount during the melt season, and approaches zero whenever ice is formed. There are several physical processes contributing to settlement through change in crystal form and displacement, as follows: (1) percolation of melt or rain water which freezes with the pack; (2) plastic deformation of the snow matrix, from weight of overlying snow causing reduction in voids; and (3) transport of water vapor due to temperature and vapor-pressure gradients and convection of air within the snowpack. The relative importance of the processes varies with the temperature and precipitation conditions, as well as the original snow condition, and, to a considerable extent, to the length of time that each process has been operating, jointly or singly.

8-02.11 Continuous observations of snowpack conditions, CSSL, 1952-1953. - During the 1952-53 water year at CSSL, SIPRE performed observations of snowpack conditions, as outlined in paragraph 2-07.04. These observations provided a continuous record of depth and time distribution of the crystalline structure, temperature, density, and the horizons of the principal layers of the snowpack for the entire season of snow accumulation and ablation. Isopleths of temperature and density and the positions of the settling-meter markers (see paragraph 2-07.05) are plotted in figure 4, plate 8-2. Daily values of incident and reflected shortwave radiation, maximum and minimum temperature, precipitation in forms of both rain and snow, and mean daily outflow of Castle Creek, are plotted for the same time period. Selected vertical profiles of crystalline structure, temperature and density are shown for the same period on figure 1, plate 8-3. Inspection of these diagrams shows the nature of change of the snowpack condition with respect to time, and the accompanying meteorological conditions producing the change. Special attention is drawn to the rain-on-snow condition which occurred on 8-9 January 1953 and was reported on in Research Note 18. Approximately 4.8 inches of rain fell within a 40-hour period, with air temperatures averaging nearly 40°F. While the temperature condition of the snowpack changed abruptly with the onset of rain and melt, the change in density was very slight. The settlement of the individual snow layers, as marked by the settling-meter measurements, proceeded uniformly at its slow rate through the storm period, unaffected by the several inches of liquid water passing through the snowpack.

8-02.12 Application to snow hydrology. - While the study of snow metamorphism is complex and there is much to be understood about the processes of change, yet in hydrologic application, problems concerning the physical nature of the snowpack can be resolved by evaluation of its "cold content" and the retentivity and permeability of liquid water within the snow-ice matrix. The temperature of the pack may be determined by direct measurement, obviating the evaluation of heat flow into or away from the snowpack prior to the runoff period. The amount of liquid water existing in the snowpack at a specific time may also be determined by actual measurement, but where such measurements are lacking, estimates must be made on the basis of limiting conditions and prior history of the snowpack.

8-02.13 Summary. - Only the highlights of the complex phenomenon of snow metamorphism, pertinent to the storage effect of the snowpack on the amount and time distribution of the runoff, are mentioned. Reference is made to de Quervain, 4/ Hughes, 9/ and Bader 1/ for more complete information on the metamorphism of snow. It was stated that metamorphic processes begin at the point of snow origin and continue until the snow has disappeared. Even during their fall, the individual snow crystals grow together and break apart before hitting the ground. Compaction and settling begin immediately at a very rapid rate and follow a decay type of function with respect to time as shown in figure 4, plate 8-2. Besides compaction, the snowpack undergoes crystalline transformation by the processes of sublimation, melting and refreezing. To determine the storage potential of a natural snowpack and the transmission rate of water, one must appraise the stage of metamorphism of snow. At present the aggregate effect of metamorphism on runoff can best be defined by the depth, density, temperature and liquid water content of the natural snowpack at a particular date and on the march of the previous weather to which the snow was subjected. Factors neither measured nor experimentally determined must, of necessity, be assumed in order to effect a reasonable solution of water storage and transmission problems in snow hydrology.

8-02.14 As a result of the combined action of these factors, the snowpack becomes more compact, striated, and granular as the season progresses. Finally it reaches a "ripe old age" in spring, when only the upper surface undergoes appreciable changes, as manifested in the formation of the nocturnal snow crust and daytime thaw. Ripeness of snow should not be defined solely by its density. In snow hydrology, ripeness is associated with the readiness of the snowpack to transmit and discharge liquid water entering at its surface, regardless of season or density. For hydrologic purposes, therefore, snow is considered to be ripe when it contains all the water it can hold against gravity, i.e., when it is primed.

8-03. HEAT TRANSFER WITHIN THE SNOWPACK

8-03.01 General. - One of the processes involved in conditioning the snowpack to produce runoff is transmission of heat within the snowpack. During the spring melt season, the pack is normally at a temperature of $0^{\circ}C$, except for the nocturnal crust layer, and whatever heat is applied at the surface is converted to melt. During the winter, on the other hand, the pack is often sub-freezing, and heat must be transferred downward from the surface and upward from the ground to meet the thermal deficiency before appreciable runoff may occur. The transfer of heat may be accomplished by conduction, convection and diffusion of air and water vapor within the snowpack, or percolation and refreezing of liquid water from surface melt or rainfall. In hydrologic application the total heat deficit of the snowpack may be treated as an initial loss that must be satisfied before runoff occurs. Accordingly the processes of heat transfer are incidental to the evaluation of the total heat deficit. A general background in the theory of heat exchange within the snowpack is useful, however, in evaluating observed conditions of snowpack temperature and assessing expected changes.

8-03.02 Thermal properties of snow. - The transmission of heat by snow depends on its thermal properties, which are:

(1) the latent heat of fusion, which is the heat energy per gram of snow required for change from solid to liquid state without change in temperature. The latent heat of fusion for snow may be equal to or less than that for ice, depending upon the amount of liquid water in the snow.

(2) thermal quality, which, as defined in paragraph 5-01.05, is 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.

(3) specific heat (c_p), which, in c.g.s. units, is the heat in calories required to raise the temperature of one gram of snow one degree centigrade.

(4) heat conductivity (k_c) or heat permeability, which is a measure of the time rate of heat transfer. It is expressed as calories transmitted through 1 cc of snow in 1 sec when the temperature difference between two opposite faces is 1° C.

(5) diffusivity (k_d), which is related to the specific heat and thermal conductivity as follows:

$$k_d = \frac{k_c}{\rho c_p}$$

where ρ is the density of the snow. Note that ρc_p is the heat capacity or the specific heat by volume (cal/cc/deg C). Diffusivity may also be called the temperature conductivity of the snow, because, it is the temperature change in degrees centigrade that occurs in one second, when the temperature gradient is 1° C/cm for each cm depth.

8-03.03 Experimental work. - Differences in the stage of metamorphism of the layers of a natural snowpack make the determination of its thermal properties exceedingly difficult. Specifically, the factors affecting the thermal conductivity and diffusivity of snow are: (1) the structural and crystalline character of the snowpack, (2) the degree of compaction, (3) the extent of ice planes, (4) the degree of wetness, and (5) the temperature of the snow. Experimental work shows that density is a satisfactory index of the thermal properties of the snow shown in the following table:

Density, ρ	Specific heat, c_p		Conductivity, k_c			Diffusivity, k_d
	By weight	By volume	Acc. to Kondrat'eva	Acc. to Abel's	Acc. to Jansson	
g/cc	cal/g/°C	cal/cc/°C	cal/cm²/°C/cm/sec			°C/cm²/sec
1.000(Water)	1.0	1.0000	0.00130+			0.00130
0.900(Ice)	0.5	0.4500	0.00535+			0.0119
0.540	0.5	0.2700	0.00246*		0.00162+	0.00911
0.500*	0.5	0.2500	0.00205*	0.00170*	0.00095*	0.00820*
0.440*	0.5	0.220	0.00167*	0.00132*	0.00089*	0.00760*
0.365*	0.5	0.1825	0.00110*	0.00091*	0.00075*	0.00603*
0.351*	0.5	0.1755	0.00087*	0.00084*	0.00072*	0.00494*
0.340*	0.5	0.1700	0.00075*	0.00079*	0.00070*	0.00441*
0.330*	0.5	0.1650	0.00070*	0.00074*	0.00068*	0.00422*
0.250	0.5	0.1250	0.00042*		0.00053+	0.00336
0.130	0.5	0.0650	0.00011*		0.00029+	0.00169
0.050	0.5	0.0250	0.00002*		0.00010+	0.00080
0.001(Air)+	0.24				0.00006+	

+ From Beskow 2/ pp. 108, 118.
* From Kondrat'eva 10/ pp. 10, 12.

From observations at CSSL, as reported in Technical Report 3, the relation between heat conductivity and density of snow was computed by linear regression to be

$$k_c\,(10^4) = 22.7\rho - 0.46$$

Kondrat'eva 10/ suggests the use of

$$k_d = 0.0133\rho \quad \text{and } k_c = 0.0068\rho^2, \text{ for } \rho < 0.35 \text{ g/cc; and}$$

$$k_d = 0.0165\rho \quad \text{and } k_c = 0.0085\rho^2, \text{ for } \rho > 0.35$$

For $0.14 < \rho < 0.34$, Abel's gives $k_c = 0.0068\rho^2$.

For $0.08 < \rho < 0.50$, Jansson gives $k_c = 0.00005 + 0.0019\rho + 0.006\rho^4$.

For $0.10 < \rho < 0.60$, Devaux gives $k_c = 0.00007 + 0.007\rho^2$.

Attention is called to the fact that experimental work on thermal properties of the snow has been generally conducted with homogeneous dry snow, often after subjecting it to artificial compaction to attain density variation. In contrast, the natural snowpack consists of several snow layers of varying thicknesses and of different character (resulting from the seasonal snow storms), separated by ice planes.

8-03.04 Volume of air space. - The air space and the absolute porosity of the snow may be computed by considering a unit volume of snow, in which

$$P = 1 - \frac{\rho}{0.92} = 1 - 1.09\rho \qquad (8\text{-}1)$$

Here P is the portion of voids or air space in the unit volume considered and ρ is the density of snow. The large percentage of air (with very low heat conductivity, 0.000057) in the snowpack makes the snow a good insulating material. Even for extremely cold weather, the heat transmitted through the snowpack is small. The density of the pack reaches its maximum value in late melt season and seldom exceeds 0.55 g/cc. During the accumulation period, the density may be as low as 0.05 g/cc for a cold new snow and as high as 0.35 g/cc for the pack as a whole. Thus the snow layers may contain 95 to 62 percent air by volume during the accumulation period, or as little as 40 percent during the melt season.

8-03.05 <u>Theory of heat flow</u>. - In a natural snowpack the heat-transfer phenomenon is complicated by the simultaneous occurrence of many heat-exchange processes. As a result of temperature differences, air transports heat and water vapor by convection within the snowpack. Upon reaching a cold surface, some water vapor condenses and yields its heat of vaporization (approximately 600 cal/g). The transport of warm air is greatest when the temperature decreases upward. If, on the other hand, temperature decreases with depth, convection of air within the pack is suppressed. Due to the low heat conductivity of snow, the amplitude of the temperature wave diminishes rapidly with depth below the snow surface. Rain and melt water freezes within the cold (sub-freezing) layers and warms the pack by heat of fusion (80 cal/g). These two processes tend to change the conductivity and diffusivity of the snow throughout the pack and influence the heat transfer rates. The surface layer of the pack is subjected to heating and cooling effects of shortwave and longwave radiation, convection, and condensation, in amounts shown in chapter 5; ground heat flows upward, causing a reduction in the cold content of the snowpack or melting it at the bottom. Ground melt is also discussed in chapter 5. Furthermore, the absorption and transmission of heat by snow vary with the topography of the drainage basin and with the character of the individual layers of the snowpack, just as the structure, the liquid-water content, the porosity and the temperature of the snow vary. Thus, the ever-changing physical and thermal properties of the basin snowpack together with the variation in weather make the theory of heat flow in snow much more complicated than that for homogeneous solids. Variations in the composition and density between layers are of such magnitude that only average values of thermal properties can be used in the application of the fundamental heat flow principles. That is, a homogeneous snowpack (isotropic solid) of small depth is assumed, the temperature-time curve for any level or in any direction in the pack is considered to be straight or sinusoidal, and at any instant the temperature curve has the shape of a damped wave. None of these assumptions is strictly valid. The snowpack is a crystalline and anisotropic solid, in which certain directions are more favorable for conduction of heat than others. The temperature wave is complex; the character of snow varies from layer to layer, and the liquid water content varies with time and temperature. Therefore, the theoretical heat flow computations yield results which are little more than of qualitative significance. Even though the magnitude of heat flow in snow is probably smaller than the errors of some observations and assumptions used in hydrologic studies, a knowledge of the fundamental principles of heat exchange processes within the snowpack is of great value to the hydrologist. Recognition of the order of magnitudes and time lag of heat flow will enable him to make proper allowances. Some special hydrologic problems may require the application of the fundamental principles of heat flow, approximate as they may be. A brief review of these principles is presented in the following paragraphs.

8-03.06 A temperature gradient is established within the snowpack as the result of heat transfer at the surface layers. The temperature gradient is defined as the change in temperature per unit change in depth. Thus, the slopes of the temperature-depth curves, shown in figure 1, plate 8-3, represent the temperature gradients. A straight temperature-depth relationship indicates that the inflow and outflow of heat for any layer are equal. A curved relationship indicates a change in gradient or unequal inflow and outflow, with consequent changes in the temperature of the layers.

8-03.07 Temperature gradients in the snowpack are more pronounced in winter than in spring. When the snowpack reaches an isothermal condition at $0^{\circ}C$, molecular conduction of heat ceases, and heat energy is spent in melting the snow. But the cooling effect of the nocturnal radiation (particularly for open sites) still remains an effective factor in setting temperature gradients within the top 2 to 15 inches of the snowpack. It is apparent that the solution of heat transfer problems requires knowledge of (1) density of the snow, (2) temperature gradients in the snowpack, and (3) thermal properties, including specific heat, conductivity, and diffusivity for the given snow condition.

8-03.08 Inasmuch as the hyd_ologist is only indirectly concerned with heat transfer within the snowpack, the relative importance of the subject in applied snow hydrology does not warrant inclusion herein of detailed derivations of heat transfer equations. Reference is made to Wilson 15/ and Kondrat'eva 10/ for description of conductive heat flow equations for the snowpack.

8-03.09 Applying Fourier's expression 3/ to a snowpack of $0^{\circ}C$ whose surface is suddenly cooled to and is maintained at $-10^{\circ}C$, Wilson demonstrated how slow the diffusion of heat is through the snow and how the temperature varies with depth and time after the sudden cooling. The following tabulation lists the change of temperature that would occur at three levels of an initially isothermal snowpack whose density is 0.20 and k_c is 0.0003, as computed by Wilson for the sudden change from 0° to $-10^{\circ}C$ at the surface:

Time in hours	Temperature in °C		
	10 cm depth	25 cm depth	50 cm depth
1	-0.7	0.0	0.0
4	-2.2	-0.3	0.0
8	-3.9	-0.7	0.0
24	-6.4	-2.2	-0.4
48	-7.8	-3.8	-1.1

8-03.10 Temperature distribution in nocturnal snow crusts. - It was pointed out that nocturnal snow crusts occur on clear nights during the melt season. The depth of penetration of the sub-freezing temperatures has been computed theoretically by methods presented by Beskow 2/, to be about 13 inches. The depth should be considerably smaller than this, chiefly because of the latent heat supplied by refreezing of melt water and to a small extent the convection and condensation heat from air flowing onto the cold surface layer. In view of these facts one may assume (in this case) that the magnitude of the maximum depth of penetration of the cold wave or of the frost line is approximately 10 inches. Observations of snow temperatures in the crust layer were made in connection with the operation of the lysimeter at CSSL during May, 1954. A plot of snow temperatures against depth and time are shown in figures 2 and 3 of plate 8-3, showing the progress of cooling through a typical night with clear skies, and the subsequent warming with the onset of energy input from solar radiation.

8-04. THE SNOWPACK TEMPERATURE

8-04.01 General. - The external factors affecting the flow of heat to the snowpack have been described in chapter 5, and the processes of heat transfer within the pack were discussed in the preceding section. The resulting variations in snowpack temperature affect the water-storage potential of the snowpack and with it the runoff from snowmelt or rain. Much of the winter and early spring surface melt is stored in the snowpack, contributing little or nothing to runoff. The amount of liquid water lost to runoff because of the cold content is a function of the snow temperature below 0°C. It accounts for the gradual increase in ablation of snowpack per unit of heat absorbed or in degree-day factor. Obviously, snow temperature must be considered in hydrologic problems involving early season runoff. Unfortunately, it is not yet a regularly observed element, and no simple relationship is available for estimating it from independent data. Generally, snowpack conditions are observed by digging a pit, but an approximate temperature, moisture, and structural profile of the pack can be obtained by use of the Mt. Rose sampling tube, Weston metallic thermometers and visual observations of the core, as illustrated in plate 8-10.

8-04.02 Laboratory observations. - Continuous observations of snowpack temperatures made at CSSL and UCSL provide a basis for estimating the range in temperature to be expected and the variations that occur through the season. Data for the 1948-49 water year for these two areas were selected to show the variation of the temperature profile of the snowpack with time. The isotherms of snowpack temperature are plotted on plate 8-4, as a time function, for both CSSL and UCSL for the 1948-49 water year. Daily values of maximum, minimum and mean air temperatures are also plotted on the same time scale. The snow and ground temperatures for specified levels above and below the ground surface are shown on plate 8-5 for the same period. The previously referenced snow structure data at CSSL for the 1952-53 water year, shown on plates 8-2 and 8-3, indicate the snowpack temperature variation and gradients for that year. Inspection of these charts reveals the nature of the temperature gradients of the snowpack and how they change with time and weather.

8-04.03 The cold content of the snowpack. - The hydrologist is primarily interested in the temperature and density profiles of the snowpack and how they affect the cold content of the snow, for the evaluation of runoff potential in the winter and early spring months. The cold content is defined as the heat required per unit area to raise the temperature of the snowpack to $0^{\circ}C$. It is convenient to express it in inches of liquid water (produced at the surface by either rain or melt) which, upon refreezing within the pack, will warm the pack to $0^{\circ}C$. The relationship may be expressed as

$$W_c = \frac{\rho D T_s}{160} \qquad (8\text{-}2)$$

where W_c is the cold content in equivalent inches of liquid water, ρ is density in g/cc, D is the depth in inches, and T_s is the average snowpack (or snow layer) temperature deficit below $0^{\circ}C$.

8-04.04 As a means of estimating the cold content of the upper 24 inches of the snowpack from current temperature data, the empirical relationship shown on figure 1, plate 8-6 was derived on the basis of deep pit observations at CSSL. This diagram relates the cold content of the upper two feet of the snowpack to the average temperature of the preceding 3 days. It is assumed that the temperature of the snowpack below the upper two feet changes slowly, and the cold content for the lower layers can be estimated from previously obtained snow temperature data.

8-04.05 The cold content of the crust layer represents the only deficiency of heat in the snowpack during the active melt season. The penetration of cold from nocturnal cooling has been discussed in paragraph 8-02.05. A cold content of about 0.1 inch is an average value for nighttime crust formed under clear skies in the open. The liquid-water deficiency (to be discussed later) developed in the surface snow layer by virtue of the refreezing of its free water, represents an additional amount of about 0.15 inch of melt, so that the daily average water equivalent of total heat deficit in the crust layer to produce runoff is about 0.25 inch of melt. This deficit is approximately 15 percent of the average daytime energy input for clear weather spring-time melt in the open, and must be supplied each morning before there can be an appreciable contribution to runoff. Knowledge of the order of magnitude of the snow-crust deficiency is of value when results of a snowmelt study must be interpreted with respect to errors of observations, assumptions, and omission. Reference is again made to figures 2 and 3 of plate 8-3, which show the progressive cooling of the crust layer during a typical clear night at CSSL, during the active melt period. In plate 8-9, the amount of daytime energy expanded to balance this deficit is illustrated.

8-05. LIQUID WATER IN SNOW

8-05.01 <u>Movement of water in snow</u>. - Water moves within the snowpack in both the vapor and liquid phase. While the movement of water vapor is important to metamorphism of the snowpack (see paragraph 8-02.04), the order of magnitude is low in comparison with liquid water transport. Liquid water moves by gravitational and capillary forces in all directions. After the snow reaches its liquid-water-holding capacity, the downward movement is dependent entirely upon gravitational force.

8-05.02 Conditions of liquid water in the snowpack. - The snow is said to be dry when its temperature is below 0°C. At 0°C, the degree of wetness depends on the availability of liquid water and the liquid-water-holding capacity of the snowpack. Winter rains or melt may bring the snowpack to its liquid-water-holding capacity commensurate with the stage of metamorphism of the snow. Subsequent weather will change the character of the snow and with it the liquid-water-holding capacity. Generally, however, the snow is cold and dry in winter. The forms in which liquid water exists in the snowpack are:

(1) hygroscopic water, which is adsorbed as a thin film on the surfaces of the snow crystals, and unavailable to runoff until the snow crystal has melted or changed its form.

(2) capillary water, which is held by surface tension in the capillary spaces around the snow particles. Capillary water is free to move under the influences of capillary forces, but it is not available to runoff until the snow melts or the spacing between crystals changes.

(3) gravitational water, which is in transit through the snowpack under the influence of gravity. It drains from the pack and is available for runoff.

8-05.03 The hydrologist is concerned with both liquid water content, f_p, (as determined by actual measurement of liquid water in the snowpack) and the liquid-water-holding capacity, f_p'', which is defined as the maximum amount it can hold against gravity at a given stage of metamorphism and density. The difference between the two quantities represents the amount of liquid-water storage capacity (in excess of the cold content of the pack) and is termed the liquid-water deficiency, f_p'. Liquid-water content in excess of the liquid-water-holding capacity represents a condition where liquid water excesses are flowing through the pack. The amount of liquid water is expressed in percent by weight. The total liquid-water-holding capacity of the snowpack can be integrated over a basin area, through use of snowpack data representative of various elevation zones or areas.

8-05.04 Determination of the liquid water in the snowpack. - The temperature of the snowpack limits the requirements for determination of liquid-water content. If the temperature of the snow is below 0°C, the snow is dry, and no measurements for liquid-water content are necessary. The liquid-water-holding capacity of the snow of certain character is determined from measurements of its liquid-water content after drainage of the excess gravitational water. The most commonly used method for measuring the liquid water is the calorimetric method, by use of the thermos bottles as calorimeters, as outlined in Technical Report 1. Other methods include measurements of electrical capacitance in a parallel plate condenser having snow as its dielectric 6/, by differences in snow compaction 14/, or by use of a centrifuge.

8-05.05 While calorimetry is commonly used to measure liquid-water content, it is an indirect method. The state or degree of dampness is described by the thermal quality of the snow, which is defined in paragraph 8-03.02. Both liquid water and thermal quality are usually measured in percent by weight. The complement of the thermal quality (for thermal qualities less than 100 pct) is the percentage of water in the snow matrix. Thermal qualities in excess of 100 percent indicate no liquid water in the snow and temperatures below 0°C. The percentage above 100 percent is proportional to the cold content of the snowpack.

8-05.06 Observations of thermal quality at the snow laboratories. - The thermal quality of the snow at the snow laboratories was determined by the calorimetric method. 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. Measurements generally were taken randomly, with sampling inadequate to represent completely time, areal, and depth variations; however, in May 1948, observations were made at CSSL at four-hour intervals, over a period of two days when active melt was in progress, for six layers in the snowpack. The results of these observations are shown in figure 4, plate 8-7, along with hydrometeorological elements preceding and during the measurement period. While there is considerable variability due to errors in measurement, the diurnal fluctuation in thermal quality (and hence liquid-water content) in the various snow layers is well defined. The drainage of liquid water through the pack is shown by the time displacement of the maximum and minimum values in the lower layers. Also, it should be noted that after nighttime drainage, liquid water for the pack as a whole averaged about 3 percent, but that maximum values of 10 percent occurred during the day from the effect of water in transit. The diurnal fluctuation in density during these observations is also shown on this diagram and appears to be closely related to changes in liquid water.

8-05.07 Qualitative field tests. - The calorimetric method is not well suited for field determination of the liquid-water content of the snow. A qualitative evaluation of liquid water can be had by the "wetness test",13/ wherein the observer notes the character of the snow, cools his gloves to snow temperature, squeezes a sample and records the appearance and the degree of compaction when pressure is released. His notes will show the snow "dry" when a snowball cannot be made; "moist" when liquid water is not obvious but a snowball can be made; "wet" when liquid water is visible; and "slushy" when water drains out of the snow with slight pressure. Noting the elevation and exposure of the site, the temperature, density, date, and hour of the day may be of great value in evaluating the seasonal and areal variations in the wetness of the snowpack. Exposure is an important factor in the priming of the snowpack by surface melt. Snow surveys at CSSL show that the snowpack on southerly exposed areas reaches its liquid-water-holding capacity about 15 days earlier (and for the same date about 1500 feet higher in elevation) than northerly exposed snow.

8-05.08 Variability of liquid-water-holding capacity.- Most of the available thermal quality data for the snow laboratories was obtained during the active melt period at one site, when the snowpack density was relatively high and often included water in transit through the snowpack. A considerable number of the thermal quality observations at the snow laboratories represent results of trials for acquiring speed and consistency, and cannot be considered adequate for analysis. Furthermore, pertinent and associated information on the density and character of the snow were not always recorded. Consequently, the thermal-quality data from the laboratories are inadequate for precise analysis of the liquid-water content of the snow. The basinwide variability cannot be evaluated except in a general way, and only approximate percentages can be recommended for use in hydrology. A snowpack at 0°C has a liquid-water-holding capacity of approximately 2 to 5 percent by weight, depending on the density and depth; the mass of ice layers; the size, shape and spacing of snow crystals; and the degree of channelization and honeycombing. It is difficult, if not impossible, to evaluate the individual influence of each of these factors on the liquid-water-holding capacity of a basin snowpack. Therefore, the liquid-water-holding capacity of snow may be related to density. As shown in figure 6, plate 8-7, the affinity of snow for liquid water increases with increasing snowpack density. Unfortunately, the number of thermal-quality determinations for snow of less than 40-percent density is insufficient to indicate if the decrease in liquid-water-holding capacity with decreasing snow density continues for very low snow densities. Additional measurements are required to determine the liquid-water-holding capacities in this range.

8-05.09 An approximation of the liquid-water-holding capacity of snow can be obtained from the heat-balance equation for the surface layer during clear nights in spring. This layer begins to cool at the snow surface just before sundown and continues for approximately 12 hours. The frost line reaches a maximum depth at about 0600 hours. The difference between total heat loss and the maximum cold content represents the heat gain from freezing of liquid water (not in transit) in the snowpack. The computed liquid water content for the snow crust as shown in the previously referenced observations at CSSL (plate 8-3) would be approximately 4 percent, which agrees with thermal quality determinations for liquid water in a pack after drainage.

8-05.10 Recommended liquid-water-holding capacities. - 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. From the results of observations of thermal quality shown on plate 8-7, and from Gerdel's study of transmission of water through the snow, 6/ between 2 to 5 percent by weight is recommended for the liquid-water-holding capacity of snow. Additional observations are required to establish the relationship between snow density and liquid-water-holding capacity.

8-05.11 The lack of information on the capacity of the snow to retain liquid water against gravity, as a function of some index of the stage of metamorphism, constitutes a major gap in knowledge of the storage effect of the snow on runoff. Streamflow forecasts require estimates of the basin snow temperatures and probable liquid-water content of snow at various elevations. These estimates cannot be made with confidence unless systematic observations of these snowpack conditions are made or computed from empirical relations based on adequate experimental data. The above range of values is presented as a guide for use where observations are lacking.

8-05.12 It is pointed out that the liquid-water-holding capacity of snow, as discussed in the preceding paragraphs, represents 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.

8-06. TRANSMISSION AND TRAVEL TIME OF WATER THROUGH THE SNOWPACK

8-06.01 General. - The condition of the snowpack determines the amount of storage and the rate of downward movement of water. The temperature, size, shape, surface area, and spacing of the snow crystals, channelization stage, and melt and rainfall intensities control retention and detention of water as it moves downward through the snowpack. Since many of these factors are continuously changing, neither the storage nor the rate of movement can remain constant. The time of travel of water in unprimed snow may be considerable, particularly when the snow is striated with ice planes which are flat or concave upward. By the time water reaches the ground surface, a water course is established in the snowpack. After this, the travel time is relatively short, being primarily a function of the snow depth. The time of travel through the established water courses in the snowpack continues to vary, because, under the action of the percolating water, the crystalline structure of the snowpack continues to change, and erosion and more extensive channelization progresses, with the consequent release of some liquid water held against gravity.

8-06.02 Experimental work. - It is impossible to estimate quantitatively the variation in travel time of water through a natural snowpack except in a general way, using laboratory experiments as guide. Electric snow-moisture meters, such as Gerdel used in CSSL, are probably the best method at present for qualitatively determining the travel time of water through the snowpack. Figure 5, plate 8-7, illustrates the results of his tests and show the rate of drainage of water through three layers of the snowpack. The following table summarizes Gerdel's results on the transmission of water through snow. 6/

Snow density	Probe spacing	Water applied	Transmission rate*	Liquid water content** Initial	Peak	End	Duration of observation
g/cc	in	in	in/min	pct	pct	pct	min
0.35	25	2.0	1.1	4.0	16.2	5.5	19
0.35	41	2.0	1.1	1.4	9.3	1.1	19
0.	7	0.8	0.9	3.8	6.2	1.1	18
0.40	17	0.5	3.7	4.1	6.2	1.7	18
0.46	6	2.0	12.0	6.0	10.7	5.1	48
0.46	12	2.0	16.0	4.0	9.8	0.9	48
0.46	18	2.0	18.0	4.0	10.3	0.9	48
0.46	6	2.0	24.0	5.0	10.3	2.6	35
0.46	12	2.0	24.0	2.9	10.3	0.7	35
0.46	6	2.0	24.0	3.0	10.3	2.0	35

* Computed from time interval between peak flow and spacing of capicitor probes.
** Interpolated from calibration curve derived from capacitance readings and calorimetric measurements on three or more snow samples, collected during each experiment.

In general, it is seen from Gerdel's work that the transmission rate increased with increasing densities. This may reflect the effect of changing structure of the snowpack as the season progresses, rather than a direct relationship to density. Horton 8/ theorized transmission rates in snow on the basis of void spaces, as is done for other porous media, and according to his theory, transmission rates through snow would increase markedly for decreasing densities. This is in direct conflict with results obtained from Gerdel's experiments.

8-06.03 The depth of penetration of water. - In a snowpack of uniform texture, the depth of penetration of water varies directly with the amount of water entering the snowpack and inversely with the storage deficiency. The latter is a function of the snow temperature and the liquid-water-holding capacity. For instance, for a cold snow,

$$D = \frac{t\,(i_r + m)}{\rho\left(\frac{T_s}{160} + \frac{f''_p}{100}\right)} \qquad (8\text{-}3)$$

in which $\underline{D}$ is the depth of penetration in inches; $\underline{i_r}$ and $\underline{m}$ are the rain and melt intensities in inches per hour; $\underline{t}$ is the duration in hours; $\underline{\rho}$ is the density of snow in g/cc; $\underline{T_s}$ is the temperature of the snow in °C below freezing; and $\underline{f_p''}$ is the liquid-water-holding capacity of the snow in percent. For a moist snow, $T_s = 0°C$, and if the liquid-water deficiency is $\underline{f_p'}$, then

$$D = \frac{100\ t\ (i_r + m)}{\rho\ f_p'} \qquad (8\text{-}4)$$

For a completely primed snowpack, where $f_p' = 0$, the entire depth will be penetrated regardless of the magnitude of water entering the snowpack.

8-06.04 Method of travel. - Storage of water begins at the snow surface where melt (or rain and melt) enters the snowpack. The priming or conditioning of the snow (to pass water through it) begins with this surface layer, which is generally homogeneous. The conditioning of the snowpack progresses downward in a path of least resistance from one layer to another. Upon meeting an ice plane, the water flows over the surface until a weak point allows part or all of the water to enter and spread in the layer below. In this zigzag manner water finally reaches the ground surface. The phenomenon is illustrated in figure 3, plate 8-1, for a cold, unripe snow. Depending on the slope, curvature, and degree of impermeability of the ice planes which separate different layers of snow deposits, water may reach the ground surface before the entire snowpack is saturated or conditioned to yield runoff. That is, some cells in the snow matrix may not yet have become accessible to the conditioning action of the infiltrating water when runoff appears.

8-06.05 Examples of time of travel. - The lysimeters at CSSL provided an opportunity to study transmission of water vertically through the snowpack. In Research Note 4, rates of outflow from artificial sprinkling of the snowpack at the headquarters lysimeter were determined and storage delay within the snowpack was evaluated by means of distribution graphs. Research Note 18 describes the effect of storage and transmission of water through the snow for the natural rain-on-snow occurrence of 8 January 1953, at the same lysimeter. Clear-weather melt studies for the 1954 season at the Lower Meadow lysimeter also provide factual data on delay to runoff by the snow, through evaluation of the diurnal fluctuation of heat supply to the snow surfaces.

8-06.06 The rain-on-snow event described in Research Note 18 provided an excellent opportunity to study both storage and transmission of liquid water in the snowpack. A rain of about 4.9 inches, augmented with melt of 1.9 inches, entered a cold and dry snowpack in a period of about 2 days. Plate 8-8 shows a mass curve of the water balance of the snowpack for the storm period. The snowpack at the beginning of rain was 84 inches deep, with an average density of approximately .31 g/cc, a water equivalent of 26.7 inches, and an average temperature of $-3.0^{\circ}C$. The liquid water required to warm the pack to $0^{\circ}C$ and supply the liquid-water-holding capacity were computed to be 0.8 in. Rain and melt in excess of this amount was available for runoff. Delay to runoff of the liquid-water excess is illustrated by inflow and outflow hydrographs shown on figure 4, plate 8-9. At the headquarters lysimeter, the time delay through the snowpack was about 2 hours. A plot of outflow for the Lower Meadow lysimeter is superimposed on the same graph. The runoff deficiency at the Lower Meadow lysimeter in the early part of the storm was due to the configuration of the ice planes, causing an indeterminable part of the water to flow outside the lysimeter boundaries until channels of flow through the ice planes were developed.

8-06.07 The lysimeter outflow for daily melt contribution during rain-free periods is shown in figures 1-3, plate 8-9, for clear, partly cloudy, and cloudy days. Here, inflow at the surface is computed by energy-transfer equations as described in chapter 5. Observed outflows show the net effect of time delay to runoff caused by the snowpack. Liquid-water deficiency in the crust layer, due to nighttime heat loss, must first be satisfied before water is available for runoff the next day, and it is indicated by shading on the diagram. The time of peak flow is displaced approximately 3 hours in these cases. Here, the snowpack depth averaged about 48 inches for conditions in figures 1 and 2 and 40 inches for figure 3. Densities averaged 0.50 g/cc.

8-06.08 A study was made of time of diurnal peak discharges in Castle Creek, CSSL, to determine changes in peak lag time resulting from varying snowpack conditions. From 5 years of study, it was determined that early in the melt season, (usually about 1 May), Castle Creek peaks daily at about midnight, but the peak advances to about 1700 hours after a week or two of active melt and occurs at about this hour for the remainder of the season. While the time of peak discharge is a function of both natural basin storage and the storage effect of the snowpack, the change in peaking time is caused primarily by change in snowpack conditions.

In hydrologic studies, after the melt season has progressed for a relatively short period, changes in travel time caused by change in snowpack conditions are not significant, and the use of an average storage time is justified.

8-06.09 The February 1951 rain-on-snow analysis for Mann Creek, WBSL, described in Research Note 24, is discussed in chapter 9. While the study was complicated in the initial part of the storm by precipitation in the form of both rain and snow, by storage of snow and liquid water in the trees, and by uncertainties of melt computations, fairly definite evaluation can still be made of the effect of the snowpack on runoff. In general, the lag time between peak inflow and outflow increased about 2 hours from that which would occur for bare ground conditions. The snow depth averaged about 5 feet. Appraisal of the storage effect of the pack is shown in plates 9-1 and 9-2.

8-06.10 Horizontal drainage. - Where horizontal drainage is inadequate (as in the Great Plains, in contrast to mountainous regions), the delay to runoff caused by the snowpack may be much larger than that required for the vertical transit of water through the pack alone. Unfortunately, adequate information on horizontal flow rates and the stage of metamorphism of the snowpack is not available.

8-07. STORAGE POTENTIAL AND TIME DELAY TO RUNOFF

8-07.01 General. - The preceding sections have considered separately the processes involved in conditioning the snowpack to produce runoff and the methods for evaluating amount of storage of liquid water that results from a given snowpack condition. This section deals with the problem of combining amounts numerically, for the purpose of applying the theory to project basins, and estimating the time and storage required to prime the snowpack for given rain or melt rates and snowpack conditions. In formulating storage and time delay it is assumed that the snowpack is homogeneous; the storage is a direct function of the cold content and liquid-water deficiency; and the total time delay is a function of the rate of inflow. It is therefore assumed that the total storage potential of the snowpack must be satisfied before runoff occurs. Actually, the pack is not homogeneous. Some water will appear at the bottom of the pack before the entire pack is primed. The storage potential in the snowpack decreases gradually as the percolating water disintegrates the ice planes shielding the cold cells.

8-07.02 The storage potential of the snowpack is the sum of its cold content (expressed in inches of liquid water) and its liquid-water-holding capacity. These amounts are small relative to the total energy required to melt the snowpack, and constitute an initial loss before runoff occurs. The energy required to condition the pack, in percent of the energy required to melt it, is

$$E = \frac{T_s}{1.6} + f_p'' \qquad (8\text{-}4)$$

where E is equivalent energy to condition the snowpack in percent of melt energy, T_s is the average snow temperature below zero, in $^{\circ}C$, and f_p'' is the liquid-water-holding capacity of the snowpack in percent. Thus, with an average snowpack temperature of $-5^{\circ}C$, and liquid-water-holding capacity of 3 percent, the total energy required to condition the snowpack is only 6 percent of that required to melt it. This energy is normally supplied during the transition between the accumulation and melt periods, so that its effect on flows during the active spring melt season may be ignored. In the winter, however, the magnitude of storage potential in the snowpack may be an appreciable part of the runoff quantity, depending upon snowpack condition. An example is presented in this section to show how to estimate the storage effect over a basin.

8-07.03 Basic data requirements. - The condition of the snowpack can be determined by direct observation, augmented by estimates based on day-to-day variations in the meteorologic regime. In mountainous areas, elevation differences must be taken into account, and sampling points should adequately represent all elevations within the basin. Time frequency of sampling is dependent upon known conditions of the snowpack. Information required is temperature, depth, density, liquid-water content (when applicable), and structural characteristics such as crystalline types and locations of ice planes. Plate 8-10 shows the type of information as obtained during January 1952 on the west slope of the Sierra Nevada along U. S. Highway 40. Various elevations ranging from 3000 feet msl to 6900 feet msl were sampled by means of digging snowpits, in order to assess the storage potential of the snowpack in the Yuba and American River basins. Also shown on the plate is a method for determining the temperature and structural profile of the snowpack by use of a Mt. Rose snow sampler and Weston bi-metallic thermometers. A means of estimating snow temperatures in the top 2 feet of the snowpack from air temperatures of the preceding 3 days is shown in figure 1, plate 8-6.

8-07.04 <u>Formulas for computing runoff delay</u>. - In order to evaluate the storage of liquid water and time delay to runoff in a given elevation zone, basic storage equations are presented. The cold content may be represented by the equivalent liquid water requirement,

$$W_c = \frac{W_o T_s}{160} \qquad (8\text{-}5)$$

where W_c is the liquid water in inches to raise the temperature of the pack to 0°C, W_o is the initial water equivalent of the snowpack in inches, and T_s is the average snowpack temperature in $^\circ$C below zero. Neglecting the small amount of warming by rain heat, the time in hours, t_c, required to warm the pack to 0°C is

$$t_c = \frac{W_o T_s}{160\ (i_r + m)} \qquad (8\text{-}6)$$

where i_r is the rainfall intensity and m is the melt rate in inches per hour. Additional storage of liquid water to satisfy the liquid-water deficiency may be expressed as

$$S_f = \frac{f'_p}{100}(W_o + W_c) \qquad (8\text{-}7)$$

where S_f is the water stored and f'_p is the liquid-water deficiency in percent. The time required to store S_f may be represented by t_f as follows:

$$t_f = \frac{S_f}{i_r + m} = \frac{f'_p\ (W_o + W_c)}{100\ (i_r + m)} \qquad (8\text{-}8)$$

The total storage potential of liquid water not available for runoff is

$$S_p = W_c + S_f \qquad (8\text{-}9)$$

where S_p is "permanent" storage, in that it is not available for runoff until the snowpack is melted. Transitory storage constitutes an additional delay to runoff. Initially, the transitory storage up to the instant runoff began would be

$$S_t = D\,\frac{(i_r + m)}{v_t} \qquad (8\text{-}10)$$

where S_t is the transitory storage in inches, D is the snowpack depth in feet and v_t is the transmission rate in ft/hr. The time (in hours) is simply

$$t_t = \frac{D}{v_t} \qquad (8\text{-}11)$$

so that

$$S_t = \frac{W_o}{\rho\, v_t}(i_r + m) \qquad (8\text{-}12)$$

and, since $D = W_o/\rho$

$$t_t = \frac{W_o}{\rho\, v_t} \qquad (8\text{-}13)$$

Total storage of liquid water before appreciable runoff occurs is

$$S = W_c + S_f + S_t \qquad (8\text{-}14)$$

or, adding (8-5), (8-7), and (8-12), and assuming W_c is negligibly small in comparison with W_o,

$$S = W_o\left[\frac{T_s}{160} + \frac{f'_p}{100} + \frac{(i_r + m)}{\rho\, v_t}\right] \qquad (8\text{-}15)$$

The time required to produce runoff is

$$t = t_c + t_f + t_t \qquad (8\text{-}16)$$

or

$$t = W_o\left[\frac{T_s}{160\,(i_r + m)} + \frac{f'_p}{100\,(i_r + m)} + \frac{1}{\rho\, v_t}\right] \qquad (8\text{-}17)$$

After runoff has begun, the delay caused by transitory storage in the snowpack is negligibly small in comparison with the usual magnitude of natural basin storage times. As the inflow continues, and the drainage channels within the pack become more efficient in transmission of water, there is an indeterminate amount of previously withheld water which is released to runoff. The actual magnitude of this effect is unknown and represents a gap in basic knowledge.

8-07.05 Example of storage potential evaluation. - The data shown on plate 8-10 provide the basis for a numerical example of storage potential of the snowpack over a basin, summarized from an analysis contained in Technical Bulletin 17. Through use of principles set forth in the preceding sections of this chapter, the storage potential of the snowpack is evaluated for each of 5 elevations and is expressed as inches depth of inflow from rain and melt required before runoff appears at the bottom of the snowpack. From assumed rates of rainfall and snowmelt, the time required to condition the snowpack to produce runoff is computed. Table 8-1 lists values of snowpack conditions, liquid-water deficiencies and assumed rates of rainfall and snowmelt, from which components of storage and time delay are computed step by step and combined to show the total effect of the snowpack on runoff. The general equations for computing each value are shown in the table.

8-07.06 For this example, the total storage of water within the snowpack before runoff appeared from the bottom of the snowpack varied from 0.08 inches at 3000 feet msl to 2.86 inches at 6900 feet msl. For an assumed rate of rain plus melt of 0.12 inch per hour, the corresponding total time delay before water was available for runoff ranged from 0.7 hour to 24 hours. For a snowpack about 15 feet deep, after the initial storage requirement of water within the snowpack has been satisfied, additional inflow from rain or melt will pass through the snowpack with a maximum time of transitory storage (t_s) of 4 hours. The average time delay of transitory storage for the basin as a whole would be less, and accordingly, may usually be ignored when considering the magnitude of total basin storage time.

8-07.07 The variation of the storage potential with elevation, for this example, is shown by curve A, figure 2, plate 8-6. Curve B in the same figure illustrates the variation with respect to elevation of the elapsed time from beginning of rain and melt before appearance of flow at the bottom of the snowpack, for the assumed inflow rate of 0.12 inch per hour. Both curves are expressed in terms of unit snowpack water equivalents, from data contained in lines 25 and 26 of table 8-1. These curves apply only to conditions for the illustrative example. Similar curves can be derived for assumed or observed snowpack conditions and for unit rates of inflow. By combining such curves with area-elevation data for a given basin, a general solution for a given snowpack condition can be made.

8-07.08 Total basin storage potential. - In addition to the storage potential of the snowpack itself, storage of water in the soil beneath the snowpack and ponding caused by the presence of a snowpack should be considered in assessing the total basin storage potential. In many cases, the soil has reached its liquid-water-holding capacity in advance of runoff-producing rain or melt, particularly for areas where fall and early-winter rains normally saturate the soil in advance of the major snowpack accumulation. In such cases, the soil remains at or near liquid-water-holding capacity through the winter season. Even for this type of area, however, below normal early-season rainfall may cause a soil moisture deficit which might be carried over through the winter period. The effect of ponding resulting from the presence of a snowpack is important for areas with relatively flat slopes, such as in meadows or plains. Where ponding occurs, the time delay to runoff is increased, and the duration and total amount of infiltration increased as well. The relative magnitude of the effect of ponding is dependent upon the percentage of area on which ponding is likely to occur.

8-08. SUMMARY AND CONCLUSIONS

8-08.01 General. - The effect of varying snowpack conditions on runoff from either rainfall or snowmelt is one of the basic considerations of snow hydrology. Divergent opinions exist as to the storage effect of the snowpack. They range from considering the snowpack to be a vast "sponge" capable of retaining large quantities of liquid water, to the assumption that storage in the snowpack is negligible in any basin study. Actually, there are times when either viewpoint may be correct, and there is no generalization which is universally applicable. The important consideration is that the actual snowpack condition be evaluated in order to properly assess its immediate storage potential. Winter runoff, in particular, is affected by the snowpack condition. In the active spring melt period, on the other hand, within the first week or two of melt, the snowpack becomes fully conditioned to produce runoff so that daily melt or rainfall quantities pass through the pack virtually without loss, except for the minor effect of the nocturnal crust layer. The storage potential within the snowpack, therefore, should be considered in connection with winter or early spring runoff from a rain-on-snow situation. In order to evaluate the storage potential of the snowpack, it is necessary to understand: (1) basic changes in the character of the snowpack through its metamorphism and the processes that cause the changes; (2) heat and water vapor transfer within the snowpack and their relation to meteorologic variables; (3) the cold content of the snowpack; (4) the liquid-water-holding capacity of the snowpack; (5) liquid-water transmission rates; (6) the determination of basinwide snowpack character and evaluation of changes between observations; and (7) methods of analyzing snowpack condition and inflow rates on basin areas for estimating the net effect of the snowpack on runoff.

8-08.02 Snowpack character. - The basin snowpack consists of individual snow crystals, ice planes and communicating air spaces, which may or may not contain liquid water. The volume of air space is at a maximum in a new-fallen snow. This volume decreases very rapidly at first, then gradually reaches a minimum at the end of the season. The rate of settlement and compaction of the pack is primarily a time function of several processes causing changes in form and displacement of crystals within the snowpack. An important function of the air in the snow matrix is the transportation of heat and water vapor from high to low temperature areas. This activity results in rounding off of the snow crystals and growth of some at the expense of others and tends to reduce the depth of penetration of cold into the snowpack. Impermeable ice planes deflect but do not prevent the movement of the air within the snow.

8-08.03 Conditioning of the snowpack. - In general, during the winter period the snowpack loses heat to the atmosphere and gains heat from the ground, resulting in the establishment of a thermal gradient within the pack. (For deep snowpacks, the temperature at the ground surface is usally $0^{\circ}C$). The snowpack continues to remain cold (sub-freezing) until the melt and rainwater and the diffusion of heat cause the snow temperature to rise to the melting point. Liquid water entering a cold snowpack freezes within the pack, becomes part of it, and increases the temperature within the snowpack. Snow at $0^{\circ}C$ will impound additional water on crystal surfaces and in air spaces as hygroscopic and capillary water. Such water (held against gravity) also becomes part of the snowpack and is retained until the snow has melted. Pockets or cells of snow which are cold and dry may exist in an otherwise wet snowpack as the result of ice planes which have not yet disintegrated to allow the snow to become fully conditioned. The conditioning of the snowpack from surface water progresses downward in a path of least resistance as one layer after another is completely saturated and yields water to the layer below. Neither the retentivity or permeability of the snow is constant. Therefore, the transmission rates and water storage capacity of the snow vary with the character or the stage of the metamorphism of the individual snow layers. Except for density, no other characteristic of the snowpack element is regularly observed in a project basin. Therefore, density must be used as an index of the general character of the snow as it affects storage.

8-08.04 Evaluation of basin snowpack storage potential. - The storage effect of the snowpack for drainage basins in mountainous regions may be approximated by dividing the basin into homogeneous topographic units or elevation zones. In the lower portions of the basin, the snowpack may be in condition to yield any rain and melt that may enter the pack. At higher levels the snowpack may be at $0^{\circ}C$ but may possess a liquid-water deficit. At still higher levels the snowpack may be cold and dry, a condition for optimum storage of liquid water.

8-08.05 Direct evaluation of storage potential of the snowpack requires observations of depth, density, water equivalent, temperature, moisture content, and character of snowpack for representative areas or zones of elevations within a basin. Such observations are best made by digging snowpits, but cores from snow sample tubes may be utilized. Precise field determinations of liquid-water content of snow are difficult to obtain, but wetness tests may provide qualitative data. Changes in the conditions of snowpack temperature and moisture, subsequent to the time of observation, may be determined on the basis of meteorologic variables.

8-08.06 Evaluation of the snowpack condition for representative zones may be obtained by direct observation or from estimates, and the storage potential and corresponding time delay to runoff may be evaluated on the basis of the example outlined in section 8-07. Combining amounts in each elevation zone, in conjunction with area-elevation relationships, gives the total basin storage effect of the snowpack. The time and frequency with which such evaluations are necessary, varies with the changing conditions of the snowpack. In the active spring melt period, time delay to runoff from storage of liquid water in the snowpack may be ignored.

8-08.07 A snowpack 180 inches deep, with 35 percent density, and an average temperature of $-5^{\circ}C$, would store about 4.0 inches of liquid water before water would become available for runoff. This represents a near-maximum amount of storage for the mountains of western United States. In mountainous areas, slopes are usually sufficient to effect horizontal drainage of the snowpack, and ponding of water within the snowpack is generally minor. In plains areas, however, large amounts of water are frequently ponded within the snowpack as the result of choking of horizontal drainages by snow. The condition of soil moisture is an additional factor affecting runoff and should be evaluated in the total basin storage potential.

8-08.08 A major deficiency in the adequate assessment of storage potential is the lack of observational data on the basic snowpack characteristics involved. In general, snowpack temperatures and liquid-water content are not observed as hydrologic elements in project basins, and until such time as they are, the hydrologist must base his estimates of storage delay on experience and judgment. Additional basic research is also required on metamorphism of the snowpack, as applied to hydrology, in order to understand better the processes affecting the changes of the snowpack condition.

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TABLE 8-1

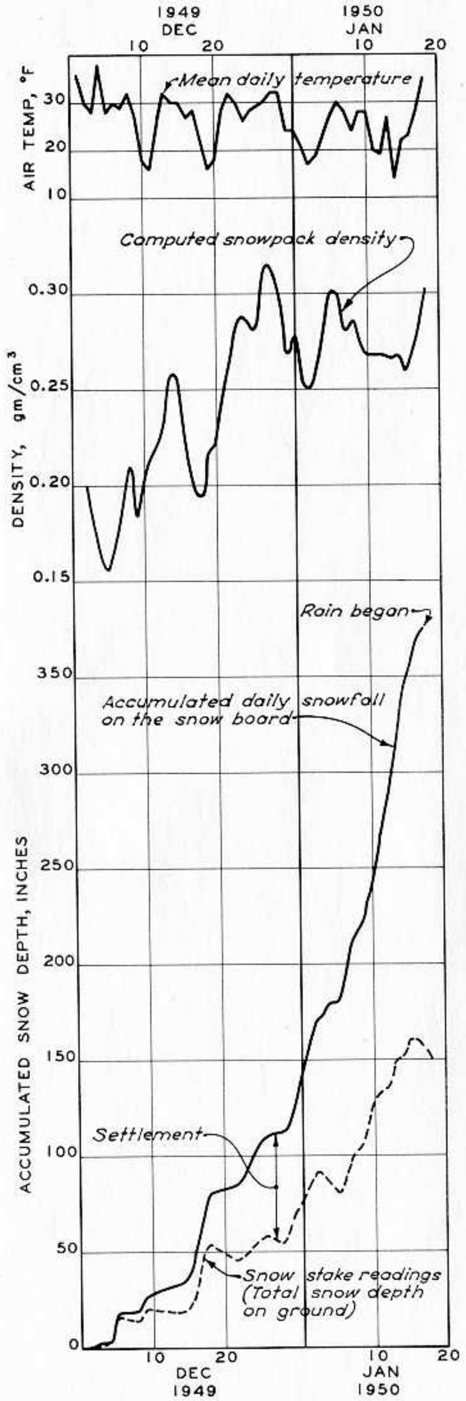
STORAGE POTENTIAL OF THE SNOWPACK 27 JANUARY 1952 1/

American River Basin, California

LINE	ITEM	ELEVATION 6900	6000	5000	4000	3000	UNIT	SYMBOL	EQUIVALENT	REMARKS
1	Initial snow depth	172	161	98	58	25	in.	D		Observed
2	Initial snow density	0.28	0.30	0.38	0.36	0.40	g/cc	ρ		Observed
3	Initial snowpack water equivalent	48.5	48.3	37.2	20.9	10.0	in.	W_o	ρD	
4	Initial snow temperature	-3.0	-2.5	0	0	0	°C	T_s		Observed
5	Percentage liquid water holding capacity									
	a. Before drainage	3.0	3.0	3.0	3.0	2.0	pct.	f''_{p_1}		
	b. After drainage	2.0	2.0	2.0	2.0	0	pct.	f''_{p_2}		
6	Initial liquid water content of snow	0	0	0	0.63	0.20	in.	W_f		Assumed
7	Air temperature	5.0	5.0	5.0	6.0	6.0	°C	T_a		Forecast
8	Snowmelt	0.04	0.04	0.04	0.05	0.06	in./hr.	m		Est. from temp. forecast
9	Rainfall	0.08	0.08	0.08	0.07	0.06	in./hr.	i_r		Forecast
10	Inflow	0.12	0.12	0.12	0.12	0.12	in./hr.		$i_r + m$	Line 8 + Line 9
11	Water equivalent of cold content of snow 2/	0.91	0.73	0	0	0	in.	W_c	$-W_o T_s / 160$	
12	Time required to raise snow temperature to 0°C	7.6	6.1	0	0	0	hr.	t_c	$W_c/(i_r + m)$	Line 11 / Line 10
13	Water equivalent when snow reaches 0°C	49.4	48.8	37.2	20.9	10.0	in.		$W_o + W_c$	Line 3 + Line 11
14	Liquid water holding capacity	1.48	1.46	1.12	0.63	0.20	in.	S_f	$f_p (W_o + W_c)/100$	Line 13 x Line 5a/100
15	Liquid water deficiency	1.48	1.46	1.12	0	0	in.	S'_f	$S_f + W_f$	Line 14 + Line 6
16	Time required to contain liquid water equal to capacity	12.3	12.2	9.3	0	0	hr.	t_f	$S'_f / (i_r + m)$	Line 15 / Line 10
17	Travel rate of water in a primed snow	43	43	40	40	36	in./hr.	v_t		
18	Time of travel through snowpack 3/	4.0	3.7	2.5	1.5	0.7	hr.	t_t	D/v_t	Line 1 / Line 17
19	Transitory storage (water in transit) in snowpack	0.48	0.44	0.30	0.18	0.08	in.	S_t	$t_t (i_r + m)$	Line 18 x Line 10
20	Total storage time from beginning of rain to appearance of runoff	23.9	22.6	11.8	1.5	0.7	hr.	t	$t_c + t_f + t_t$	Line 12 + Line 16 + Line 18
21	Total storage in snowpack when runoff appears	2.86	2.71	1.42	0.18	0.08	in.	S	$W_c + S_f + S_t - W_f$	Line 11 + Line 14 + Line 19 - Line 6
	a. From rain	1.91	1.81	0.94	0.11	0.04	in.	P_r	$t\, i_r$	Line 20 x Line 9
	b. From melt	0.95	0.90	0.48	0.07	0.04	in.	M	$t\, m$	Line 20 x Line 8
22	Liquid water present in snow when runoff appears	1.96	1.90	1.42	0.81	0.28	in.		$S_f + S_t$	Line 14 + Line 19
23	Snowpack water equivalent when runoff appears	51.4	51.0	37.7	21.0	10.0	in.	W	$W_o + S$	Line 3 + Line 21
24	Total water deficiency at beginning of rain (includes cold content)	2.39	2.19	1.12	0	0	in.		$W_c + S'_f$	Line 11 + Line 15
25	Storage time	0.493	0.468	0.317	0.072	0.070	hr./in.		t / W_o	Line 20 / Line 3
26	Average water deficiency	0.049	0.045	0.031	0	0	in./in.		W / W_o	Line 24 / Line 3
27	Water released to runoff by the decrease in storage potential	0.49	0.48	0.37	0.21	0	in.		$W_o (f''_{p_1} - f''_{p_2})$	(Line 5a - Line 5b) x Line 3

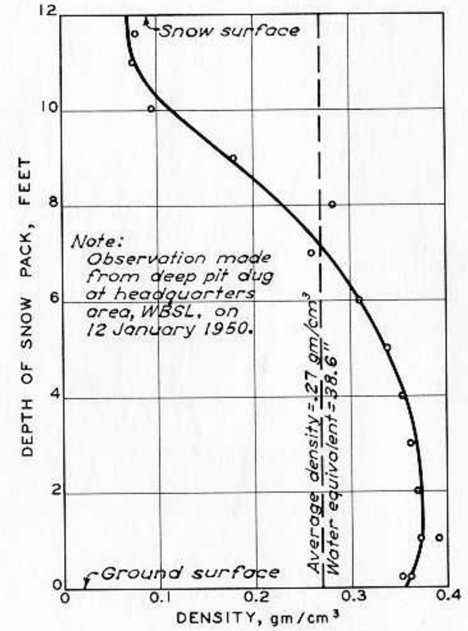
Notes:

1/ See figure 2, plate 8-6 for basinwide variation in the storage potential.
2/ The terms "cold content" and "heat deficiency" are synonymous, 0°C being the reference temperature.
3/ Change in snowpack depth and water equivalent during priming period is ignored in items 18 through 27. This omission is within the accuracy of the approximations.



COMPACTION OF WINTER SNOW

FIGURE 1

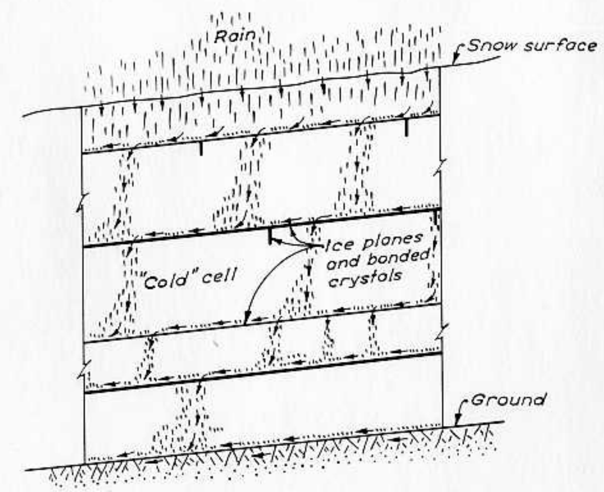


DENSITY VARIATION IN A WINTER SNOW PACK, WBSL 12 JANUARY 1950

FIGURE 2

NOTES for FIGURE 1:

1. Observations made at headquarters, Station 1-A, WBSL (El. 4230), during period of snow accumulation, December and January, 1949-50.
2. During period shown, air temperature was continuously below freezing except for very short periods, and precipitation was entirely in the form of snow. Melt at the air-snow interface would be negligible.
3. Effect of ground melt is assumed to be negligible for the period shown.
4. Variation of average density was computed from the summation of daily increments of precipitation catch at Station 1-B, adjusted to the water equivalent of the snow stake computed from the mean density of snow on 12 January.
5. The mean density of new snow for the period 5 January through 18 January, computed from daily snow board measurements of water equivalent and depth, is 0.09 gm/cm³. On the basis of average temperatures during the remainder of the storm periods, the average density of new fallen snow is estimated to be 0.11 gm/cm³ for the entire period.
6. During this storm period, the average precipitation catch at the snow stake was about 115% of the catch at the snow board.

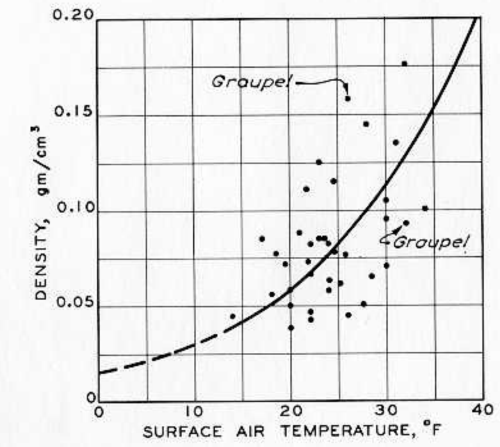


SCHEMATIC DIAGRAM ILLUSTRATING THE FLOW OF WATER WITHIN THE SNOW PACK

FIGURE 3

NOTES:

1. Ice planes and bonded crystals of varying thickness and permeability are usually formed during clear weather between snowstorms as a result of melt water refreezing during the night and also as a result of sublimation process within the snow pack. Crusts may also form from the action of wind, and cooling of surface-snow matrix by evaporation.
2. "Cold" cells of temperature below melting point continue to exist in the snow pack between ice planes and water courses until the ice planes have disintegrated and allowed the percolating water to reach these cells or sufficient heat has penetrated to raise the temperature to 0°C.
3. Capillary water is stored near the ground and above the ice planes and in small voids between snow crystals. In addition water is also held against gravity on snow particles by adhesion or surface tension.



DENSITY OF NEW FALLEN SNOW

FIGURE 4

NOTES:

1. Density measurements were made by SIPRE personnel at CSSL headquarters (El. 6900). Air temperatures were taken at about the time of density measurements at 4 feet above snow surface.
2. Times of accumulation of snow before observation were variable and were always less than 24 hours. The average time was probably in the range between 6 and 12 hours. The results, therefore, cannot be applied directly to the usually observed 24-hour snowfalls.
3. Variability is also introduced into the above relationship as the result of varying rates of snow accumulation which have not been considered.

GENERAL NOTE:

Snow densities in gm/cm³ on this plate are equivalent to commonly used densities in percent, divided by 100.

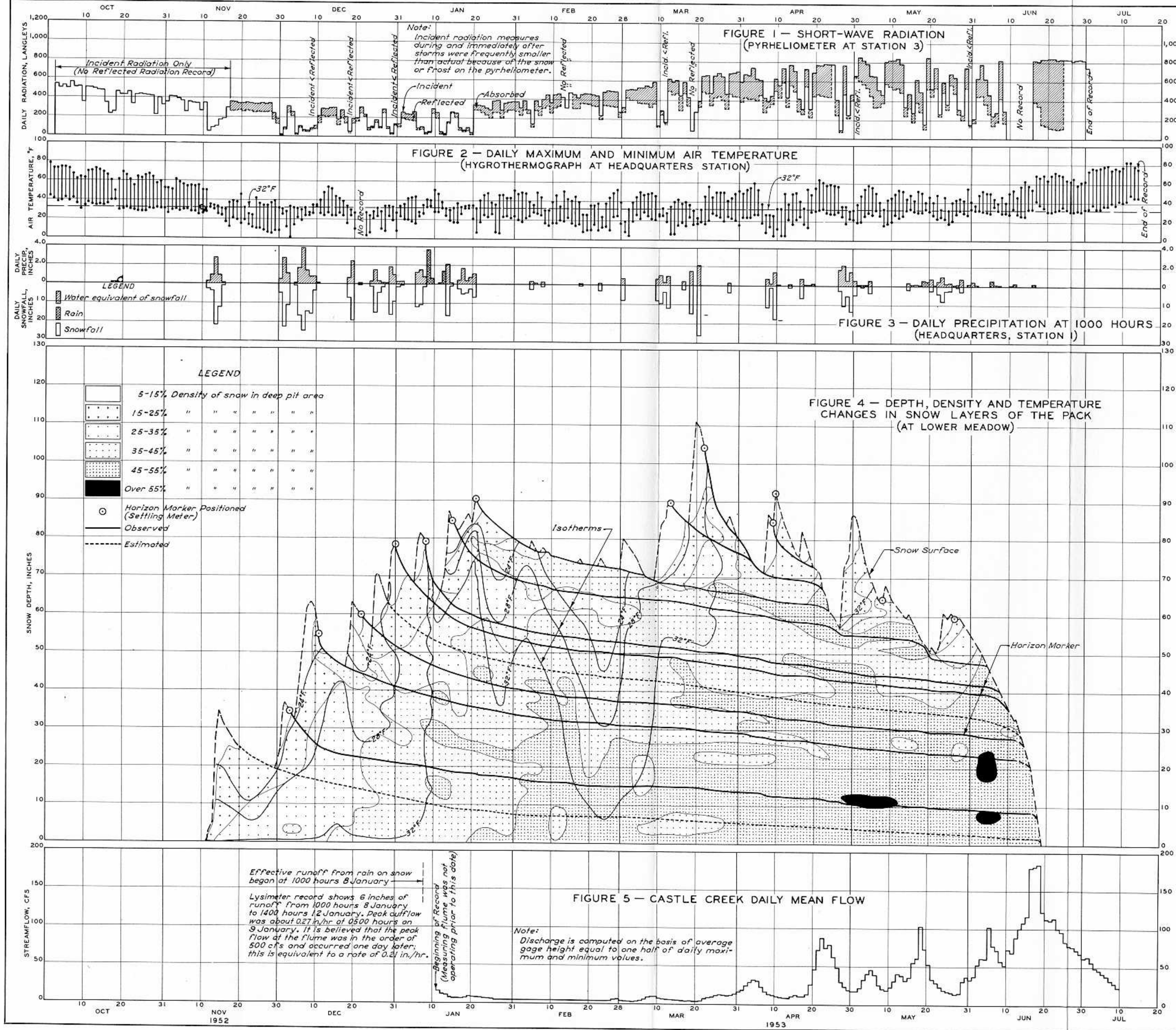
SNOW INVESTIGATIONS
SUMMARY REPORT
SNOW HYDROLOGY

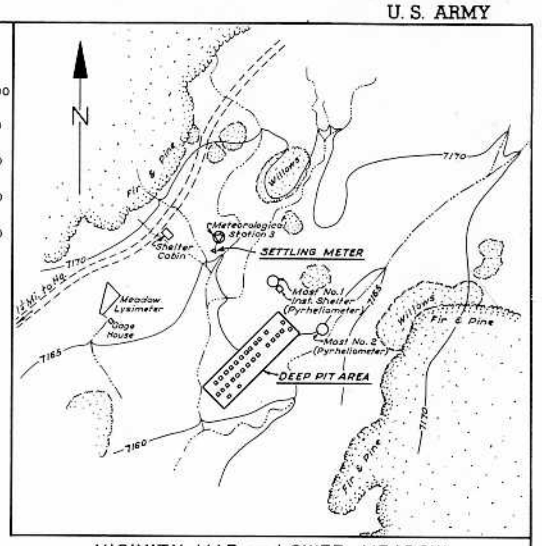
DENSITY AND STRUCTURE OF WINTER SNOWPACK

OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS — U.S. ARMY

PREPARED: R.B.B.	SUBMITTED: R.B.B.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: B.J.	APPROVED: D.M.R.	PD-20-25/46

PLATE 8-1





VICINITY MAP — LOWER MEADOW

SCALE IN FEET

Notes:

1. Settling meter readings, showing positions of snow layers in the snow pack continuously through the season were obtained from the Snow, Ice, and Permafrost Research Establishment installation at CSSL Lower Meadow (Station 3) during the 1952-1953 season. The slide wire settling meter is described in SIPRE translation No. 14, "Snow and its Metamorphism" ("Der Schnee und Seine Metamorphose", Beitrage zur Geologie der Schweiz, Geotechnische Serie, Hydrologie, Lieferung 3, Bern (1939)).
2. Temperature and density profiles of the snow pack were obtained from deep snow pits, dug individually at the deep pit area at the Lower Meadow, CSSL, (see Vicinity Map, above), at approximately one week intervals. Observations were made, under supervision of SIPRE, generally between 1000 and 1700 hours.
3. No attempt was made to show the average temperature of the surface snow layer, where daily freezing and thawing is affected by the diurnal change in heat supply at the surface of the snow pack. Note sudden change in thermal character of snow pack during occurance of rain on 8-9 January 1953.
4. Snow densities were determined by weighing horizontal samples taken with standard 500 cc steel cylinders from south wall of snow pits. The average density of the snow pack by this method is one to five percent smaller than the density of a vertical core sampled by a Mount-Rose snow tube, because the horizontal samples from the pack do not contain all ice lenses, while the vertical core in a Mount-Rose tube contains all layers through the entire snow pack.
5. Plots of daily short-wave radiation, maximum and minimum temperatures, precipitation, snowfall, and streamflow in Castle Creek, show the march of hydrometeorologic events during snow accumulation and melt periods.
6. Castle Creek discharge (Figure 5) was computed on the basis of average gage heights equal to one-half of the daily maximum and minimum values.
7. Daily maximum and minimum temperatures and daily precipitation and snowfall were obtained from records for Station 1, CSSL, located approximately 1 1/4 miles Southwest of the Lower Meadow (Station 3).
8. Deep pit site went bare when basin snow cover was about 50%.
9. See Figure 1, Plate 8-3 for snow classification, temperature, and density profiles.

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

SNOWPACK CHARACTERISTICS CSSL, 1952 - 53

OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS — U. S. ARMY

PREPARED: R.B.G.-R.M.	SUBMITTED: R.B.B.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: B.V.	APPROVED: D.M.R.	PD-20-25/47

PLATE 8-2

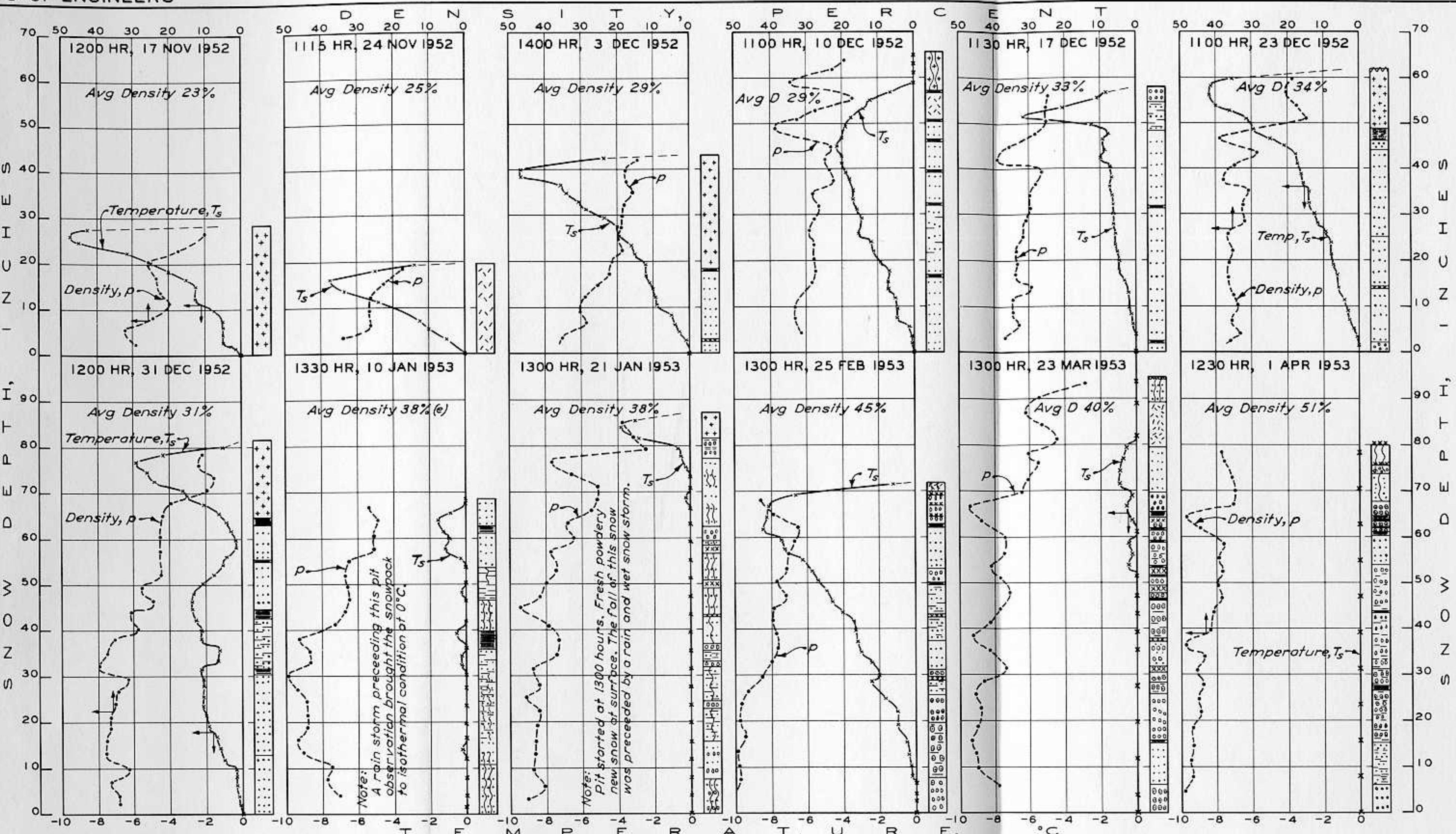


FIGURE 1 — DEEP PIT OBSERVATIONS, CSSL, 1952-53 WATER YEAR

NOTES for FIGURE 1:—

1. Average pack density determined by vertical sample with Mt. Rose sampler.
2. Horizontal density samples taken with 500 cc cylindrical sample tubes at positions indicated thus: •. They are taken in homogenous horizons and do not include ice layers.
3. Temperature in °C taken with Weston bimetallic dial thermometers at positions indicated thus: ××.
4. 0°C isothermal condition of the snowpack continued after 1 April except nightly cooling effect of the surface layer by the outgoing longwave radiation.
5. Observations made at Lower Meadow, CSSL, under direction of SIPRE.
6. Only selected observations are shown to illustrate progress of change, also see Plate 8-1.

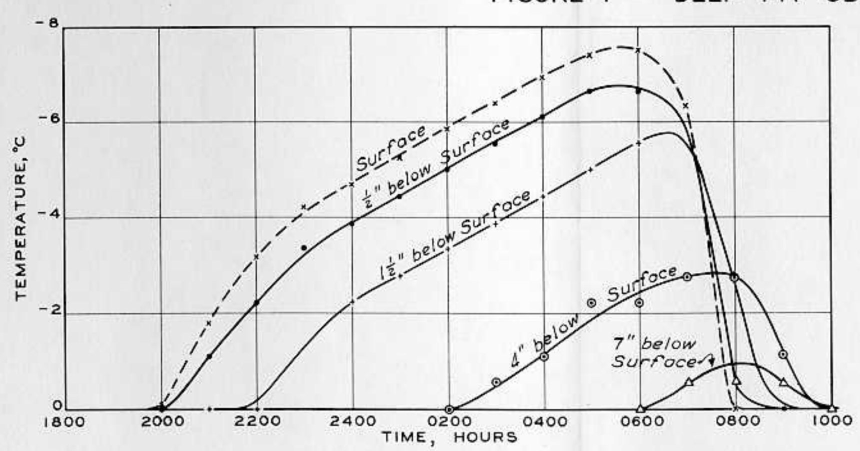


FIGURE 2 — NIGHTTIME COOLING IN SURFACE LAYER OF INITIALLY MOIST SNOW, 12-13 MAY 1954

NOTES for FIGURES 2 and 3:—

1. Observations made at Lower Meadow, CSSL, in connection with lysimeter studies of snowmelt.
2. Air and snow temperatures obtained by use of Thermohms from which continuous records were obtained through the night.

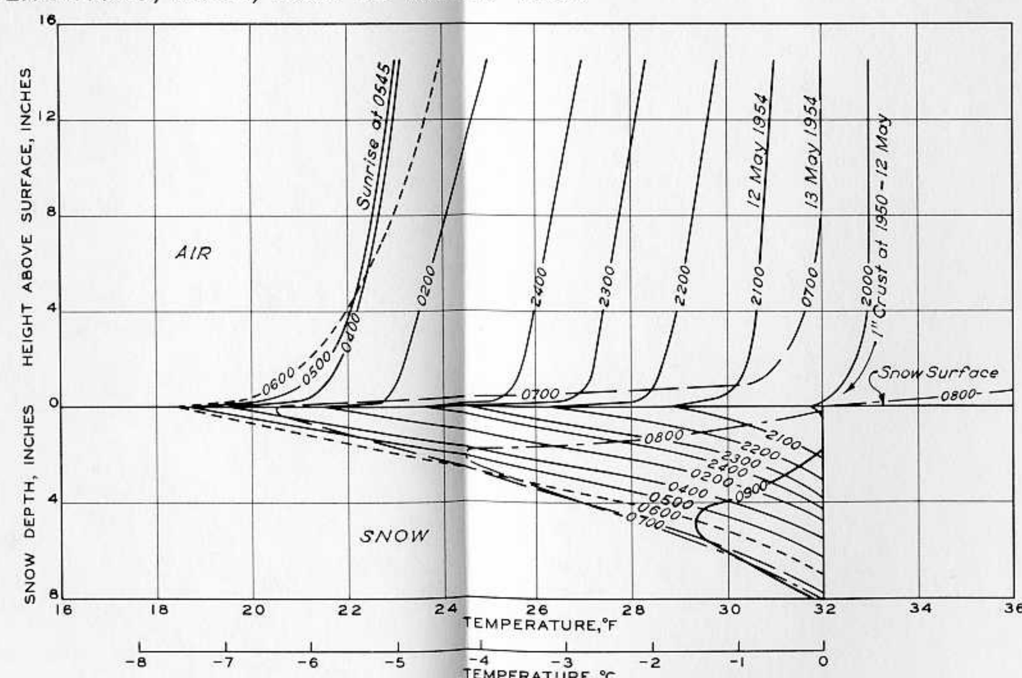


FIGURE 3 — TEMPERATURE PROFILES NEAR SNOW SURFACE DURING NIGHT OF 12-13 MAY 1954

SNOW INVESTIGATIONS SUMMARY REPORT
SNOW HYDROLOGY

SNOWPACK CHARACTERISTICS CSSL

OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION CORPS OF ENGINEERS U. S. ARMY

PREPARED: DM-PBB SUBMITTED: PBB TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: RV APPROVED: DMR

PD-20-25/48

PLATE 8-3

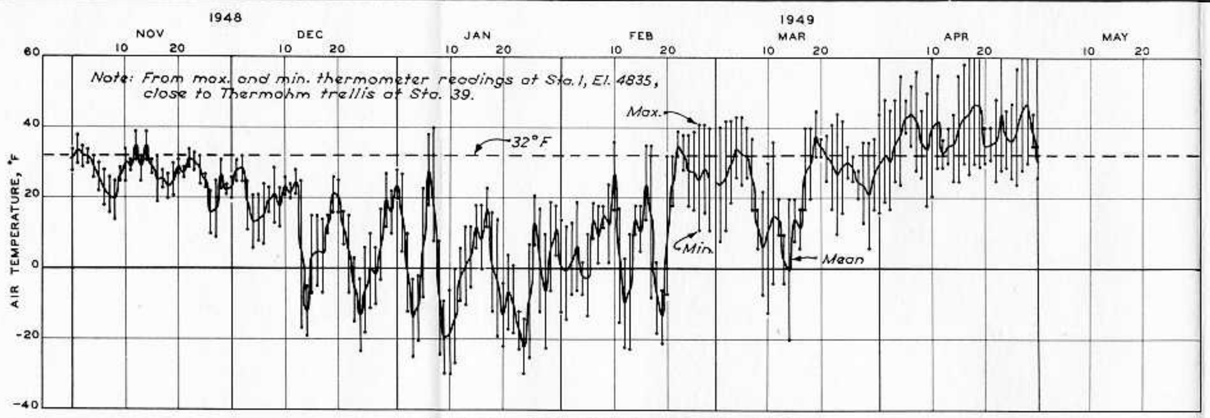


FIG. I - AIR TEMPERATURE, UCSL

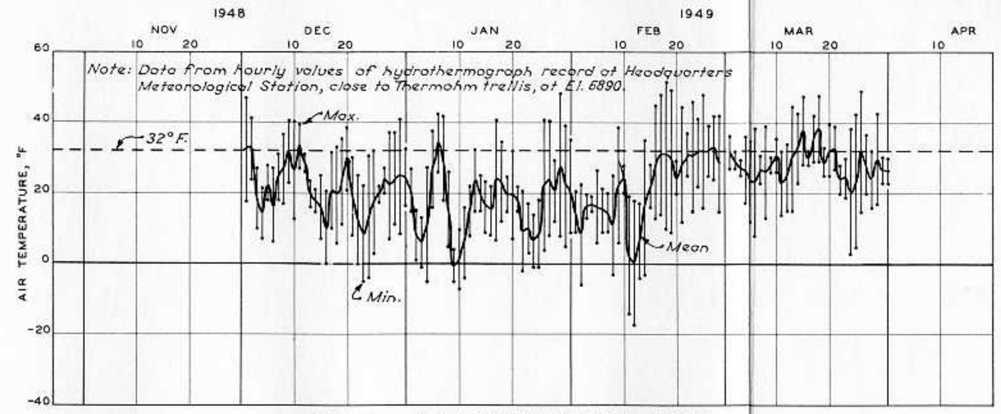


FIG. 3 - AIR TEMPERATURE, CSSL

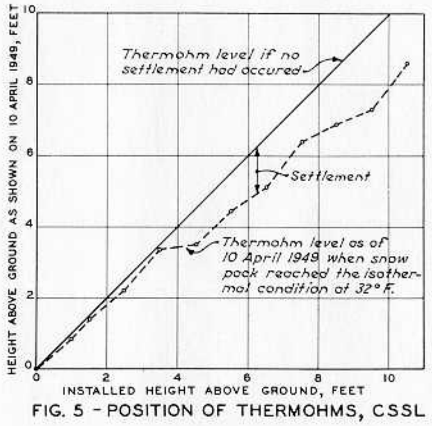


FIG. 5 - POSITION OF THERMOHMS, CSSL

Notes:

1. Temperatures within the snow pack were measured on a trellis by Thermohms suspended at different heights above ground surface and were recorded every fifteen minutes on a recorder chart.
2. Snow depth was noted usually once a day at the trellis. Snow depth at CSSL after 3 March 1949 was estimated from the daily snow stake readings near the trellis.
3. Figure 5 shows the shift in the position of Thermohms at CSSL as of 10 April 1949 when the pack was excavated and the new heights were determined. No such information is available for UCSL.
4. Estimated values are shown by dotted lines.
5. The isotherms shown represent average of daily max. and min. temperatures as obtained at each Thermohm level within the snow pack. The temperature pattern near the surface of the snow is affected by the diurnal pattern of the air temperature above it, and snow surface temperature data are not available to show the temperature variations near the surface. The figures show the seasonal trend and relatively rapid response of snow temperature to that of surface air.

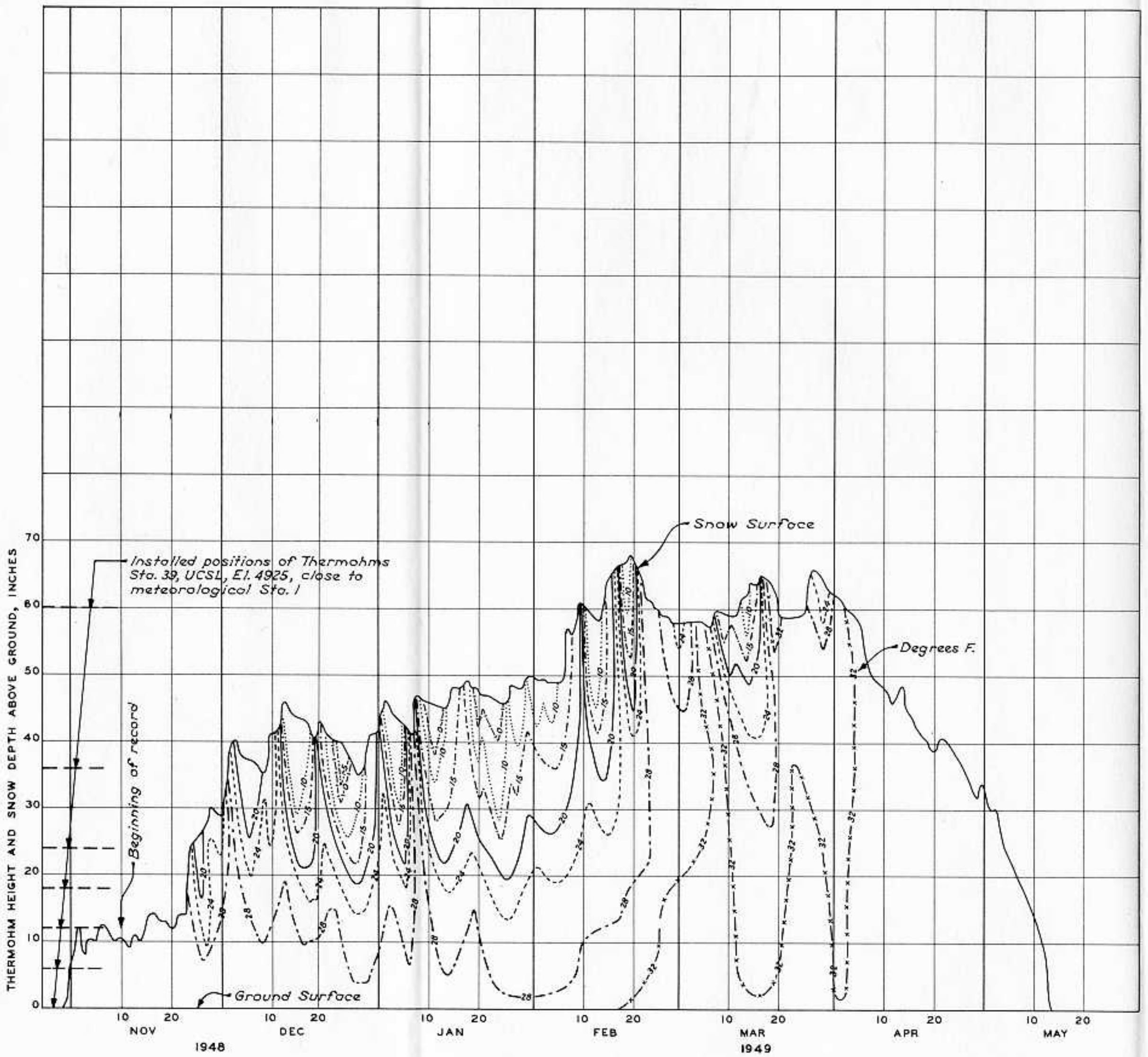


FIG. 2 - ISOTHERMS IN SNOW PACK, UCSL

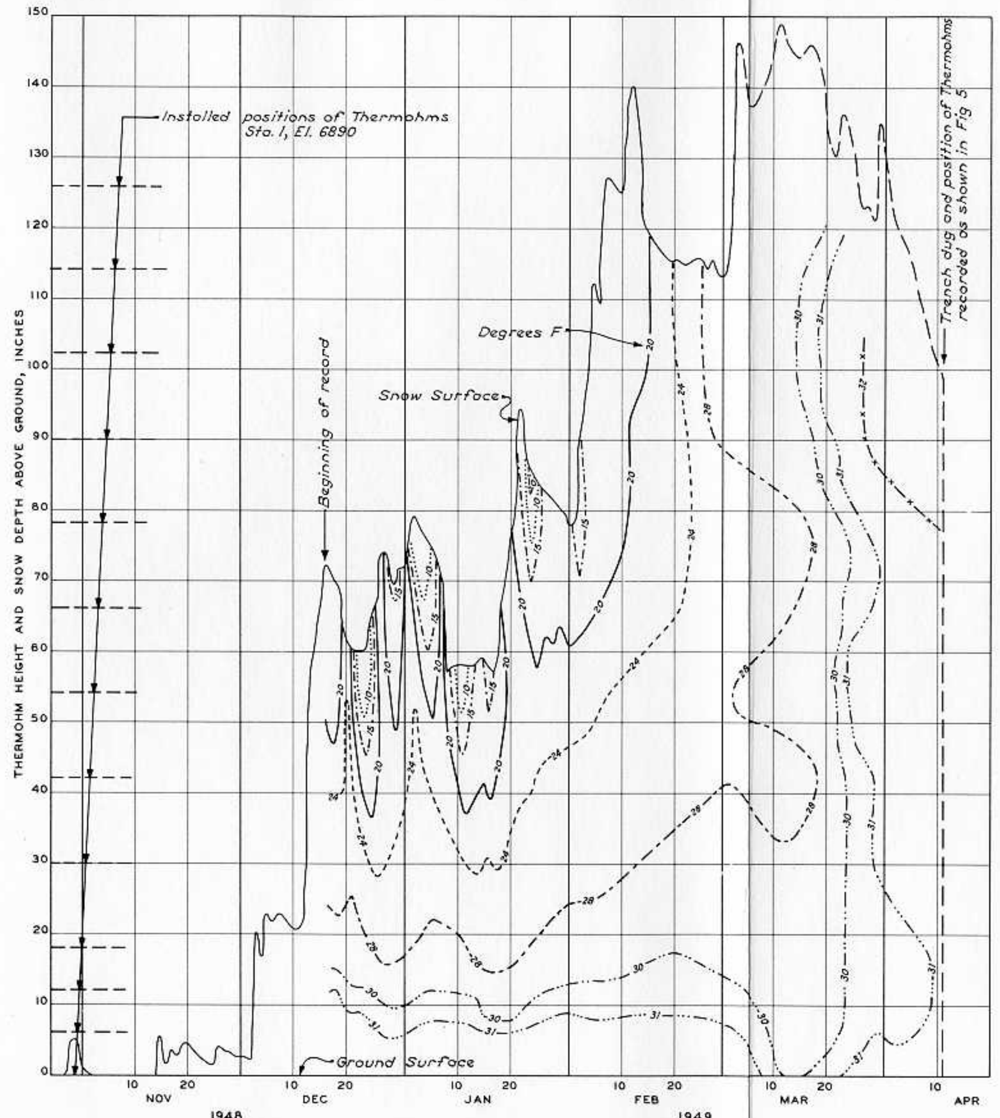


FIG. 4 - ISOTHERMS IN SNOW PACK, CSSL

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

SNOWPACK TEMPERATURES
UCSL AND CSSL, 1948 - 49

SHEET 1 OF 2

OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS U. S. ARMY

PREPARED: PBB-PM SUBMITTED: PBB
DRAWN: WJM APPROVED: DMR

TO ACCOMPANY REPORT DATED 30 JUNE 1956

PD-20-25/49

PLATE 8 - 4

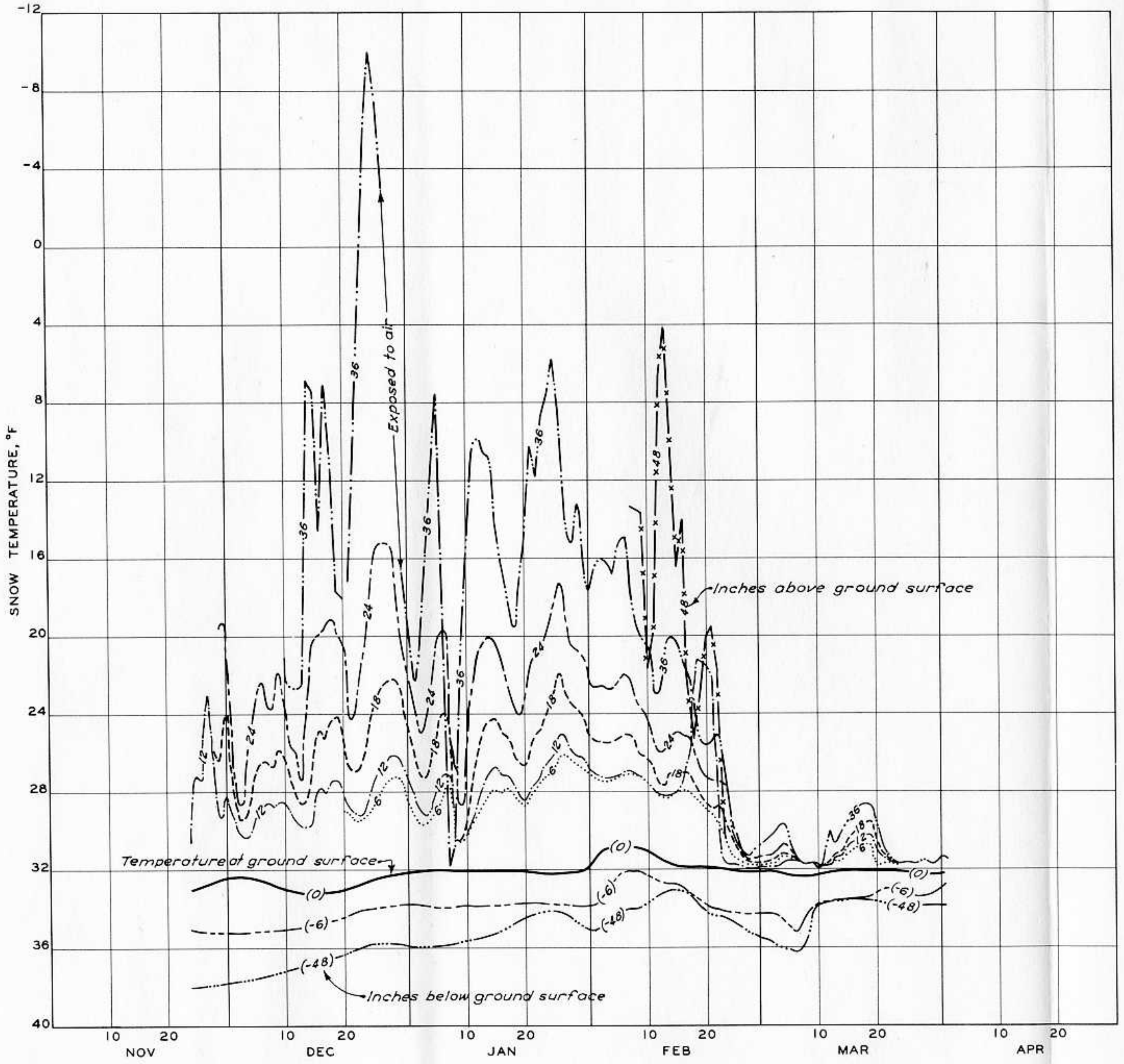


FIGURE 1 — SNOW AND GROUND TEMPERATURES, UCSL

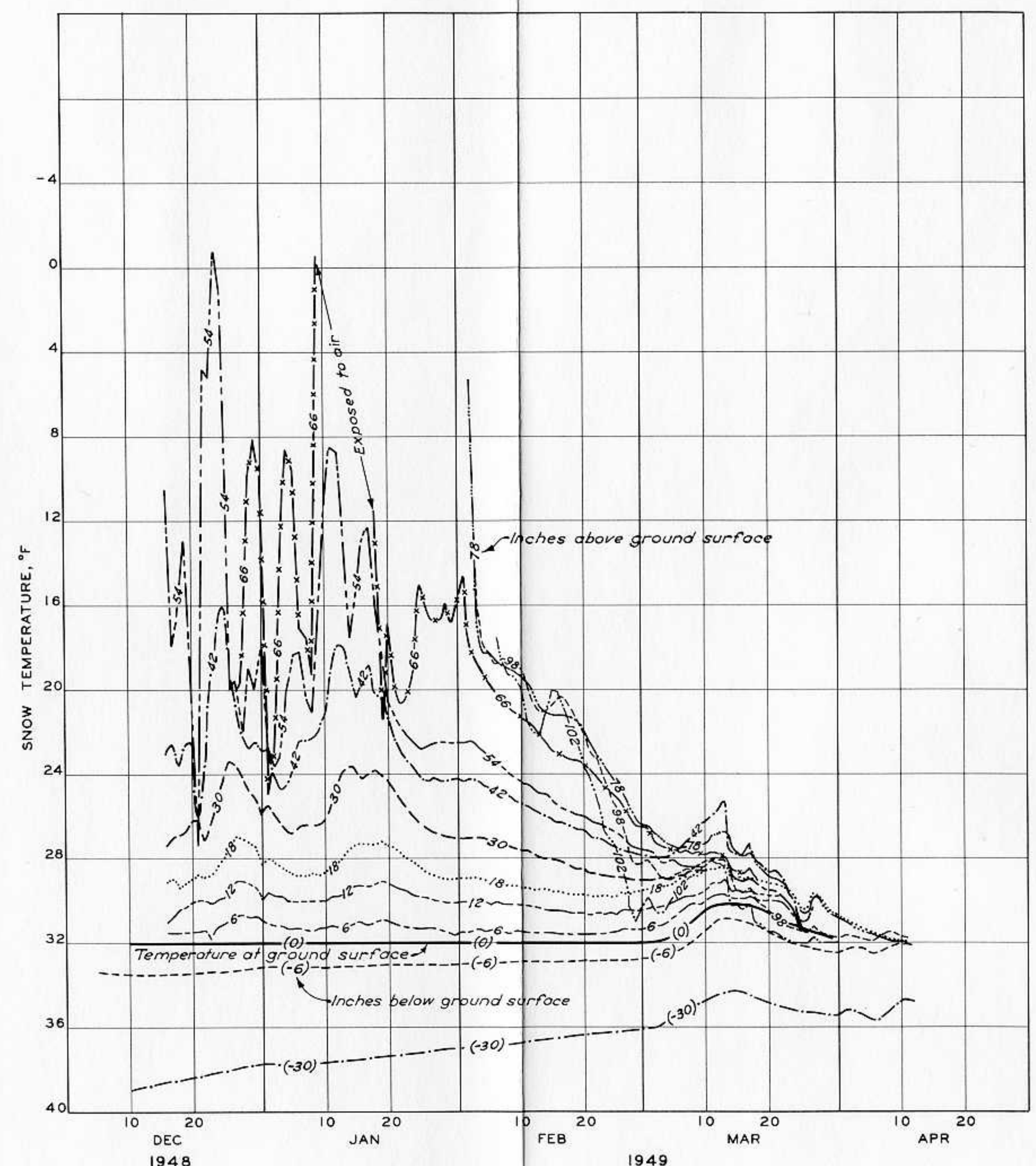


FIGURE 2 — SNOW AND GROUND TEMPERATURES, CSSL

Notes:

1. *Data for temperature variation of various levels in snow pack and ground obtained from Thermohm data for Station 39 at UCSL and Station I at CSSL.*
2. *Snow depths and air temperatures for this period as shown on Plate 8-4.*
3. *All temperatures on these figures are those recorded at 0700 of each day.*
4. *Surface layers show larger temperature variations with respect to time. The amplitude of these variations diminishes with increasing depth of snow from the surface.*
5. *When the snow pack reaches the isothermal condition at 32°F, there may still occur diurnal temperature variation in the "crust" layer (averaging about 6" in depth), which freezes by night and thaws during the day.*

SNOW INVESTIGATIONS
SUMMARY REPORT
SNOW HYDROLOGY

SNOWPACK TEMPERATURES
UCSL AND CSSL, 1948-49

SHEET 2 OF 2

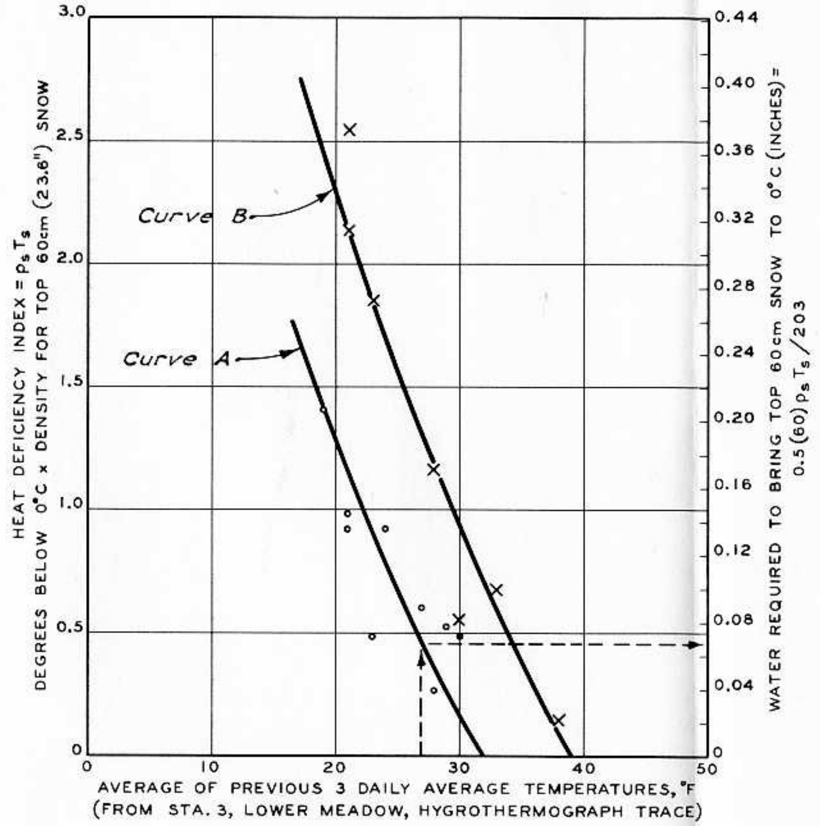
OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS U. S. ARMY

PREPARED: P.M. SUBMITTED: P.B.B.
DRAWN: B.V. APPROVED: D.M.R.

TO ACCOMPANY REPORT DATED 30 JUNE 1956

PD-20-25/50

PLATE 8-5

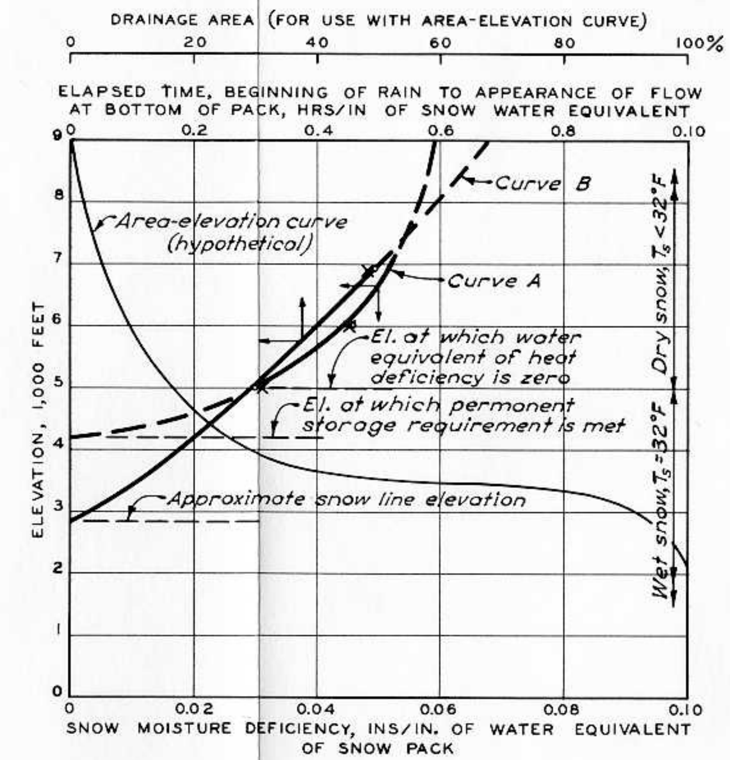


COLD CONTENT AND MOISTURE DEFICIENCY (TOP 60 CM OF SNOW)

FIGURE 1

Notes:

1. The curves are based on weekly snow pit observations and temperature data at Lower Meadow for 1952-53 season.
2. Curve A – Used when preceding 3 days are generally overcast.
3. Curve B – Used when preceding 3 days are generally clear.
4. Below 60 cm depth, the snow pack temperature does not change appreciably between observations.
5. Example:
   The average temperature for the 3 days preceding the rainfall is 27°F, and the weather is overcast. From Curve A, water required to raise the temperature of the top 24 inches (60 cm) of snow pack to 32°F is 0.07 inches. The remainder of the pack (60 inches) has a temperature of approximately 29°F and a density of 0.32 and requires 0.22 inches of water ($\doteq 60 \times 0.32 \times 0.5 \times 1.7/80$). Thus a total of approximately 0.29 inches is required to raise the temperature of the snow pack to 32°F at this site.
6. Symbols:
   ρ_s = snowpack density, T_s = snowpack temperature



ILLUSTRATIVE EXAMPLE OF DETENTION OF RUNOFF BY SNOW PACK OVER BASIN

FIGURE 2

Notes:

1. Curve A represents evaluation of snow moisture deficiency over basin, as a function of elevation, in terms of unit water equivalent of snow pack.
2. Curve B represents time for water to reach bottom of snow pack, including time required to snow moisture deficiency and time for transit of water through pack, on the basis of an assumed rate of inflow at top of pack of 0.12 inches per hour, including rain and snow melt.
3. Data for these curves derived from analysis of 27 January 1952 snow surveys along U.S. Highway 40, between Auburn and Soda Springs, California, and apply only to that condition. For other locations and conditions, similar curves can be constructed from observations of snow characteristics which adequately sample basin conditions, particularly with regard to elevation differences.
4. Use of a basin area-elevation curve (such as hypothetical one shown) allows direct reading of (1) snow-covered area, (2) area of snowpack primed to yield runoff directly without storage, since temperature and water-holding requirements are satisfied, (3) area of snowpack at 32°F with moisture deficiency, thus requiring storage, and (4) area of snowpack at <32°F, which will store water to satisfy both temperature and water-holding requirements before yielding runoff.

SNOW INVESTIGATIONS SUMMARY REPORT

SNOW HYDROLOGY

COLD CONTENT AND MOISTURE DEFICIENCY OF THE SNOWPACK

OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS U.S. ARMY

PREP.: P.B.B. SUBM.: P.B.B. DRAWN: B.K. APPR.: D.M.R.

TO ACCOMPANY REPORT DATED 30 JUNE 1956

PD-20-25/51

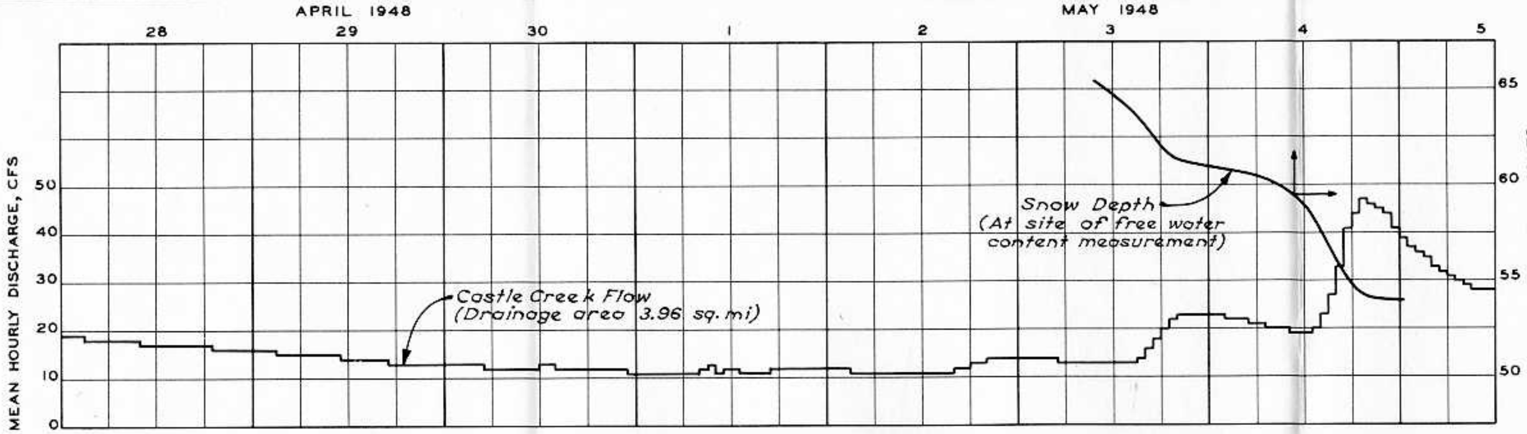


FIGURE 1 - DISCHARGE & SNOW DEPTH

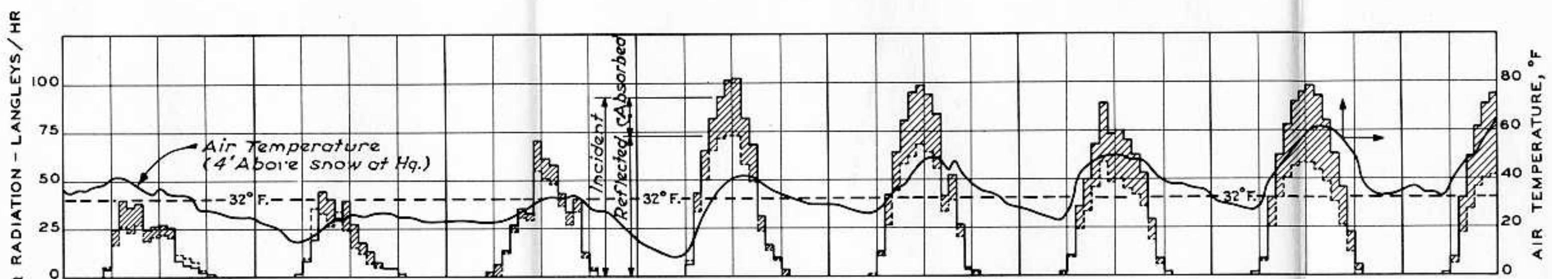


FIGURE 2 - SOLAR RADIATION & TEMPERATURE

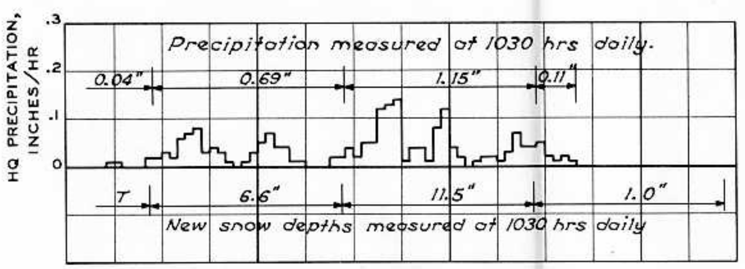
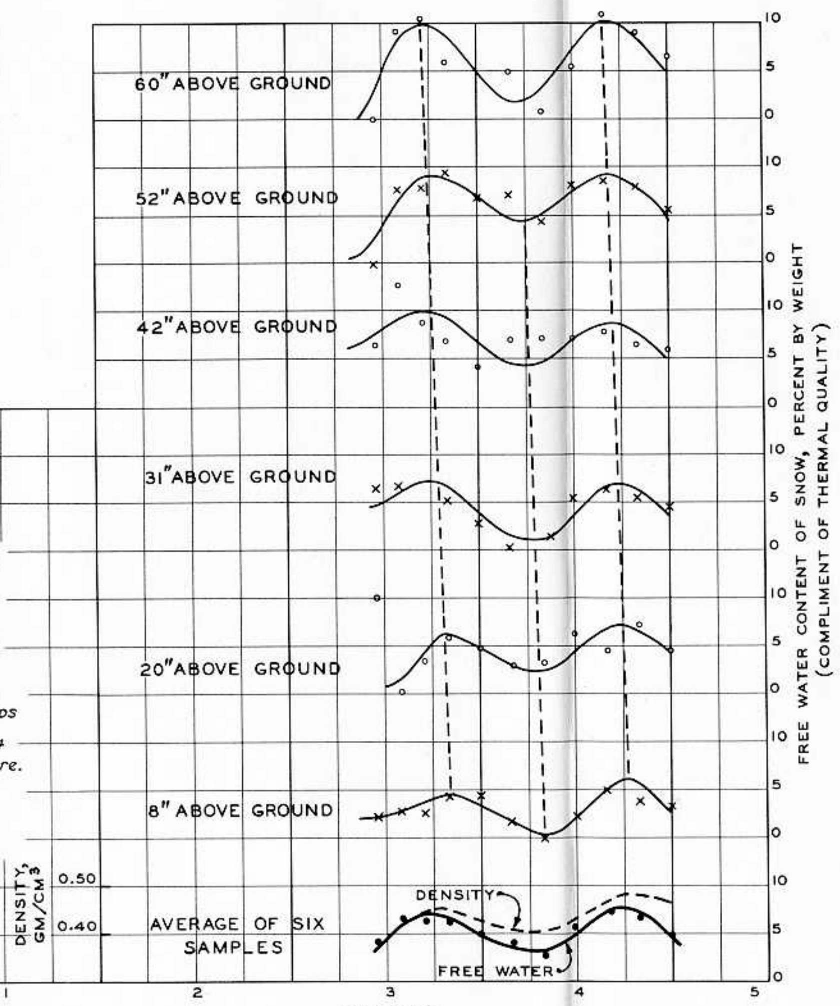


FIGURE 3 - PRECIPITATION

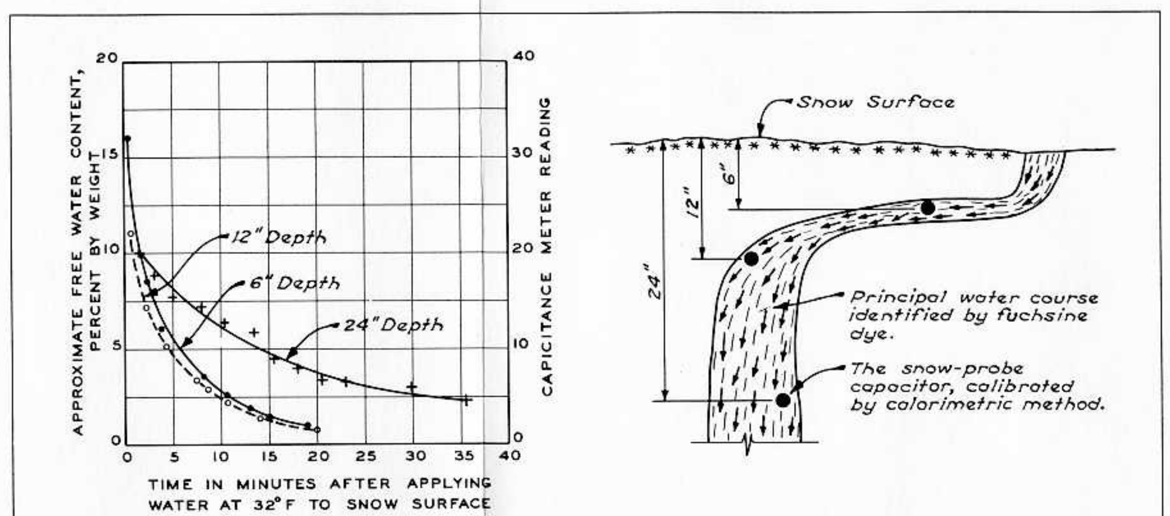


Note:
The measurements shown in Fig. 4 were made at a level site near headquarters building, CSSL, elevation 6900 ft. The snow pack consisted of six distinct layers, separated by ice planes. Colorimeter measurements were made on horizontal snow core samples from each layer.

Free water draining through a snow pack is rarely of uniform distribution, except perhaps in the surface layer. A measurement at a particular point indicates conditions at that point or of another identical sample elsewhere.

The depth of snowpack was 65 inches at 1100 hours on 3 May. It was 54 inches deep at 2400 hours on 4 May, most of the shrinkage being in the upper two layers.

FIGURE 4 - DIURNAL VARIATION IN FREE WATER CONTENT OF SNOWPACK

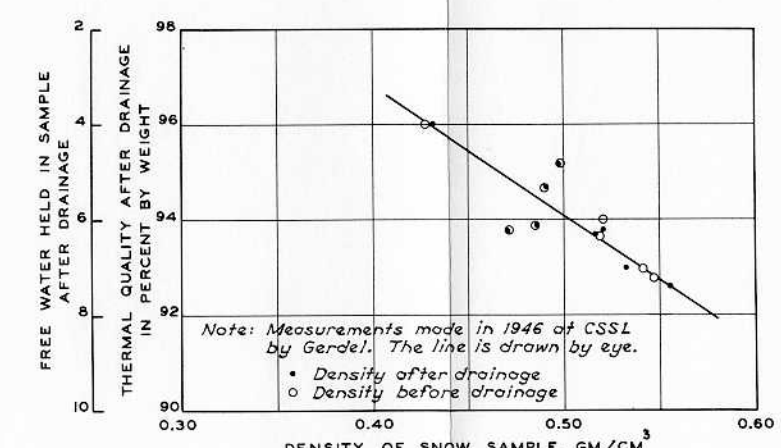


WATER MOVEMENT THROUGH SNOW DETERMINED BY CAPACITANCE METER

SCHEMATIC DIAGRAM OF WATER COURSE THROUGH SNOW PACK

FIGURE 5

Notes:
1. Data for Figure 5 were determined by Dr. R.W. Gerdel from measurements made in May, 1948 at CSSL. See Transactions, AGU, June, 1954 for description of instrument and methods used.
2. Density of snow was 0.46 gm/cm³ before experiment.
3. Temperature of liquid water and snow pack at 32°F before and after experiment.



WATER HOLDING CAPACITY OF "RIPE" SNOW

FIGURE 6

Note:
Snow densities in gm/cm³ on this plate are equivalent to commonly used densities in percent, divided by 100.

SNOW INVESTIGATIONS SUMMARY REPORT

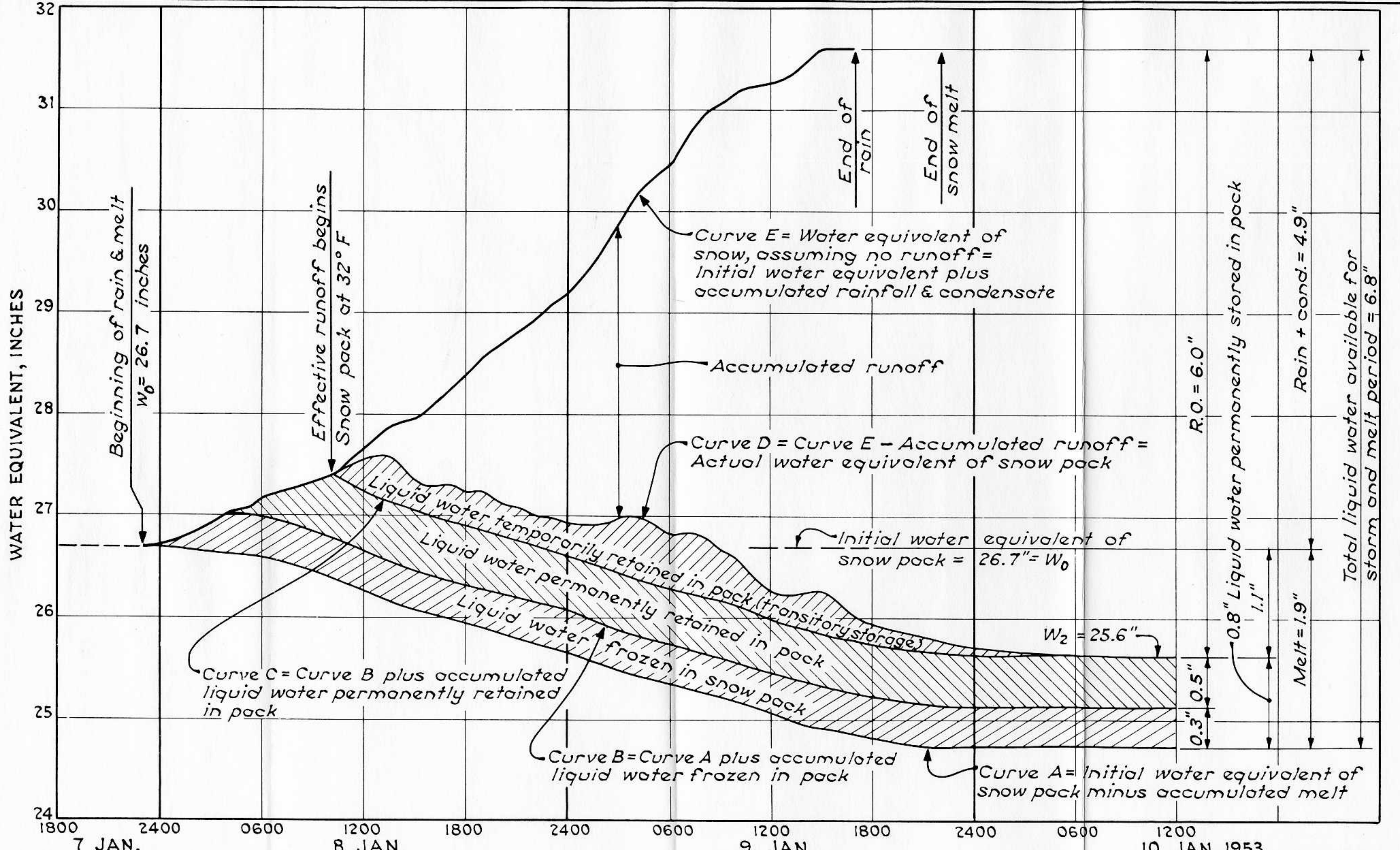
SNOW HYDROLOGY

LIQUID WATER IN SNOW

OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS U. S. ARMY

PREPARED: PBB-PM SUBMITTED: PBB
DRAWN: WJM APPROVED: DMR
TO ACCOMPANY REPORT DATED 30 JUNE 1955

PD-20-25/52



Note:
Of the liquid water entering the snow pack, 0.3" is used in raising the temperature of pack to 32° F. and approximately 0.5" is permanently retained in pack. The remainder (6.0") of the inflow appeared as runoff.

SNOW INVESTIGATIONS

SNOW HYDROLOGY

SNOWPACK WATER BALANCE DURING RAIN ON SNOW

CSSL HEADQUARTERS LYSIMETER

OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION CORPS OF ENGINEERS U. S. ARMY

PREP: PBB	SUBM: PBB	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: WJM	APPR: DMR	PD-20-25/53

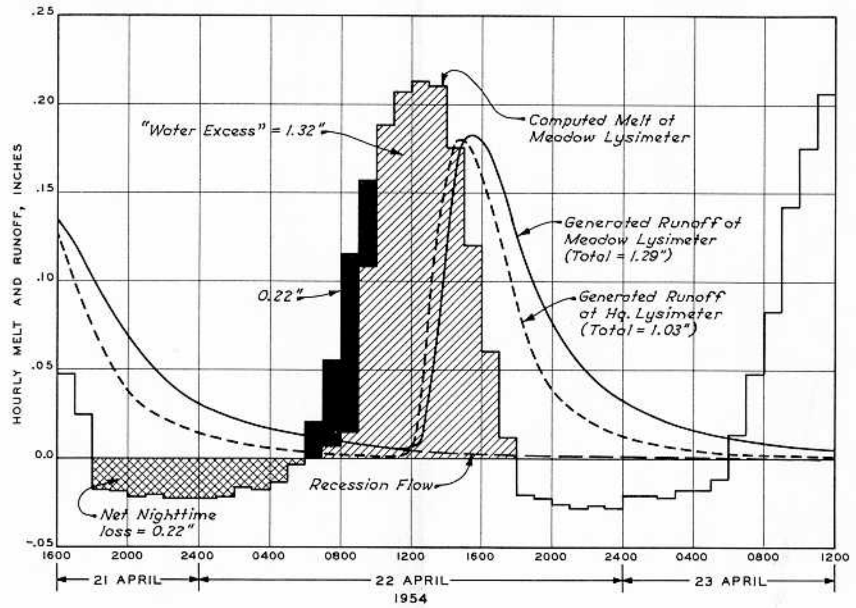


FIGURE 1 – CLOUDLESS DAY

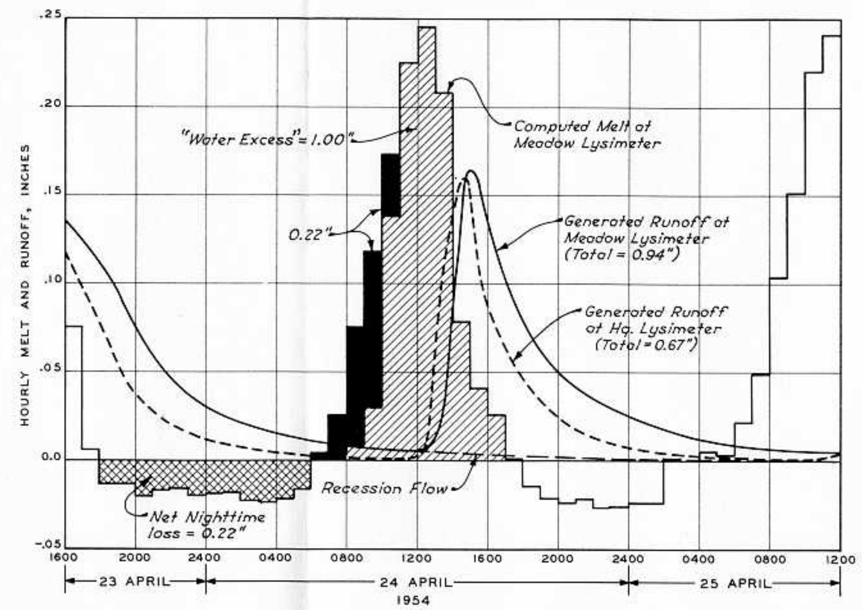


FIGURE 2 – PARTLY CLOUDY DAY

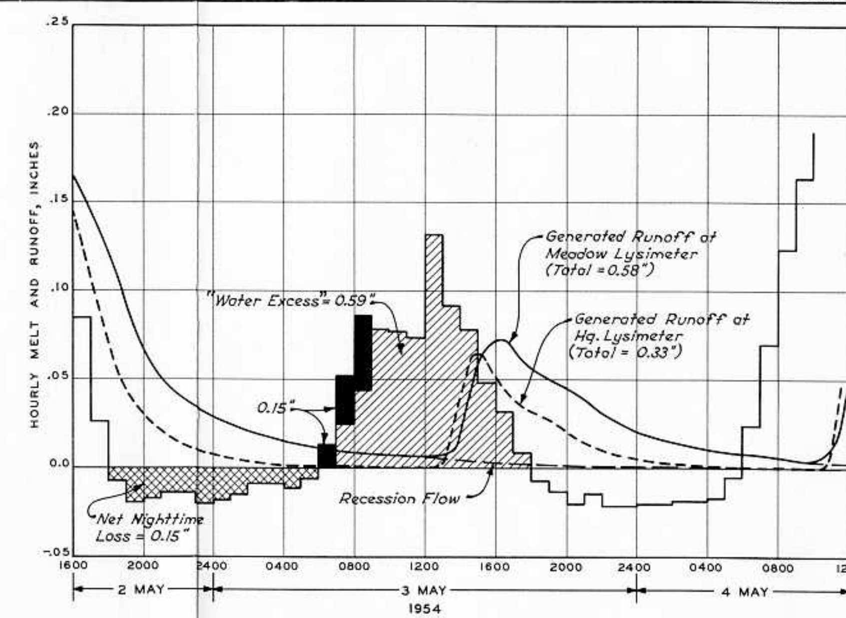


FIGURE 3 – CLOUDY DAY

NOTES for FIGURES 1, 2, & 3

1. Character of snow pack in Meadow lysimeter:

DATE	DEPTH	AVG. DENSITY	AVG. TEMP.
22 April	54	0.50	0° C.
24 "	45	0.51	0° C.
3 May	43	0.52	0° C.

2. For the computation of the hourly snow melt by heat balance the 24-hour day was taken from 1900-1800 hours. See Research Note No. 25.

3. The time distribution of the portion of daytime melt going into "permanent storage" or being used up in reducing the cold content of the snow is only an approximation to illustrate the penetration and melting effect of solar radiation below the "cold" surface layer, as well as a likely small amount of surface melt water which may pass through the cold zone without refreezing, before the entire crust reaches the melting point.

4. The following comments are offered to explain the deficiency in runoff at Headquarters snow lysimeter
   a. Snow melt at Headquarters lysimeter is approximately 5 per cent less than that of the Lower Meadow lysimeter.
   b. The snow pack at Headquarters lysimeter was in its natural form on the rock foundation. The continuous ice planes in the snow pack impeded and undoubtedly caused a portion of the melt water to reach outside the area of the lysimeter. In contrast, the Lower Meadow lysimeter snow was separated from the natural snow cover by a half inch slot. Thus all surface melt was led to the impervious floor (18 inches below the bottom of the snow pack) and thence to the gage tank.

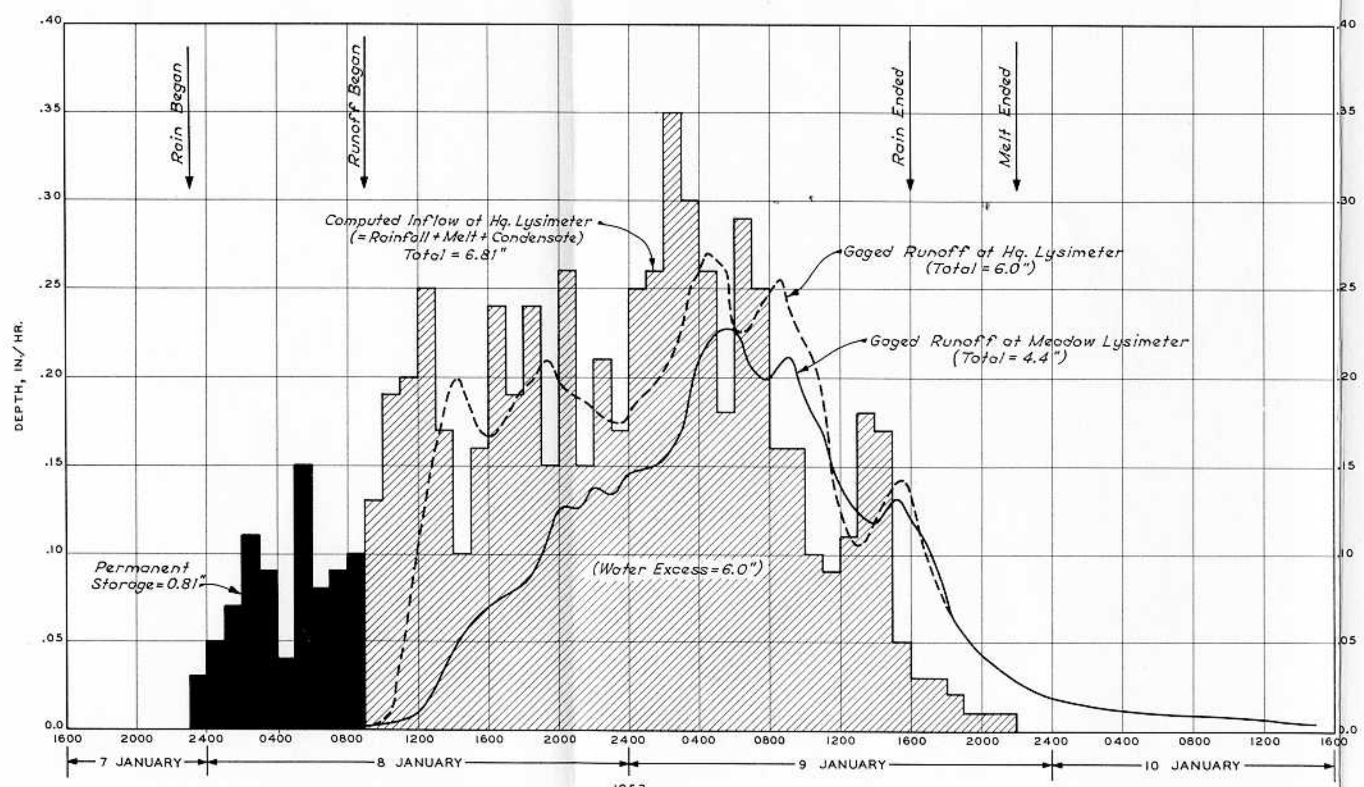


FIGURE 4 – RAIN ON SNOW

NOTES for FIGURE 4

1. Before beginning of rain, depth, average density, and temperature of the snow pack at Headquarters lysimeter were 84", 0.32 and -3° C., respectively.

2. Rainfall at Headquarters Friez gage was 4.8" against 4.3 at Meadow Stevens gage.

3. The deficiency in runoff at the Meadow lysimeter was due to dome-like configuration of the ice planes. Prior to the disintegration of the ice planes, melt and rainwater passing through the pack ran over the ice planes to outside the boundary of the lysimeter. At headquarters lysimeter, it is believed that the ice planes were not as impervious and contribution from outside the lysimeter area equalled the inflow lost from the lysimeter area.

4. The analysis of this rain on snow event and the reconstitution of the runoff hydrograph at Headquarters lysimeter are in Research Note No. 18, 15 May 1954.

LEGEND

Water equivalent of night-time heat loss from snow

Liquid water from melt or rain which upon refreezing within the "cold" layers of snow pack releases its latent heat of fusion and raises the temperature of snow to the melting point and also provides for liquid water adsorbed on the snow crystals. In spring, it is the melt-water equivalent of heat gain required to replenish night-time heat loss from the surface layer. Such water does not contribute to the "water excess" or runoff until it has melted.

"Water excess" or inflow. On clear days it is that portion of snow melt which passes through the pack and appears as runoff.

GENERAL NOTES

1. Drainage areas:
   Meadow lysimeter 600 sq. ft.
   Headquarters lysimeter 1300 sq. ft.
2. Details of construction of lysimeters are shown in Research Notes Nos. 18 and 25.

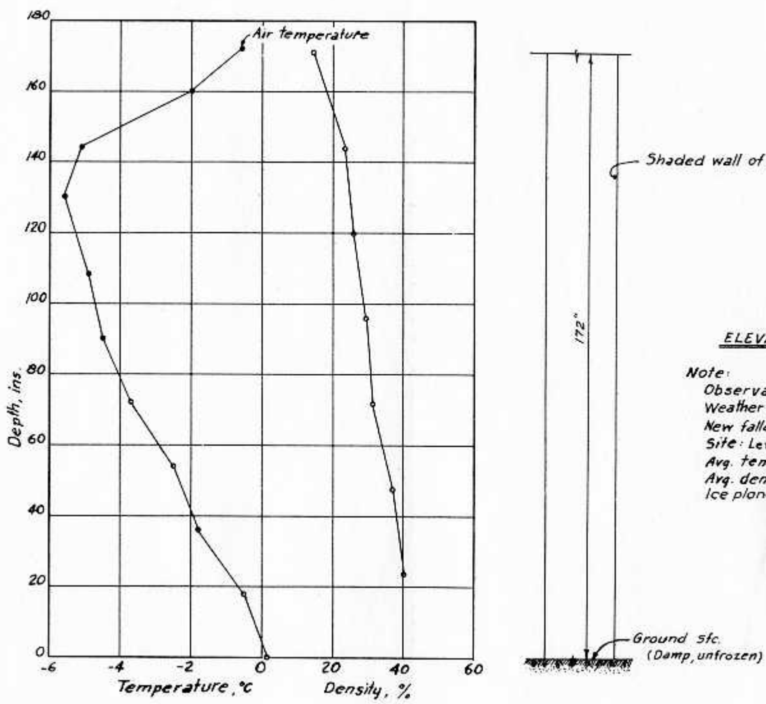
SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

LYSIMETER RUNOFF HYDROGRAPHS

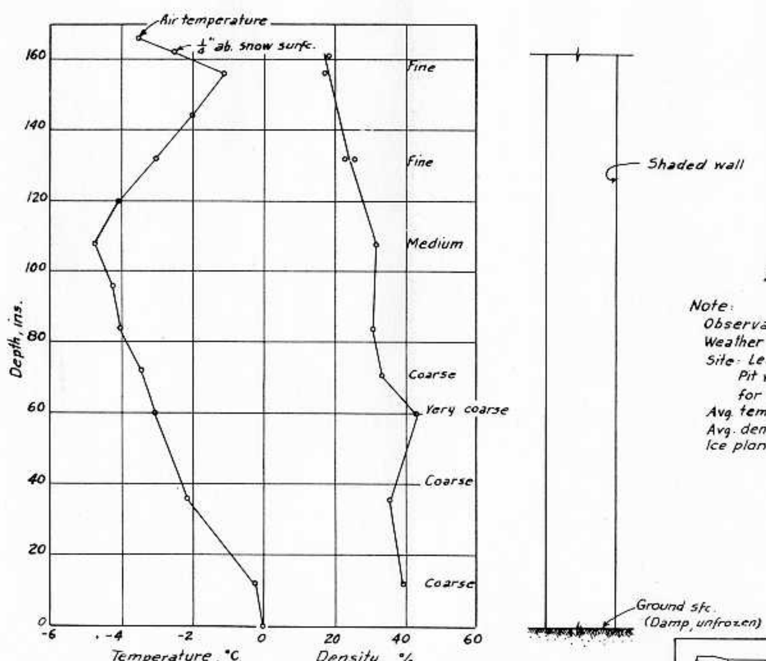
OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS U. S. ARMY

PREPARED: PBB	SUBMITTED: PBB	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: WJM	APPROVED: DMR	PD-20-25/54



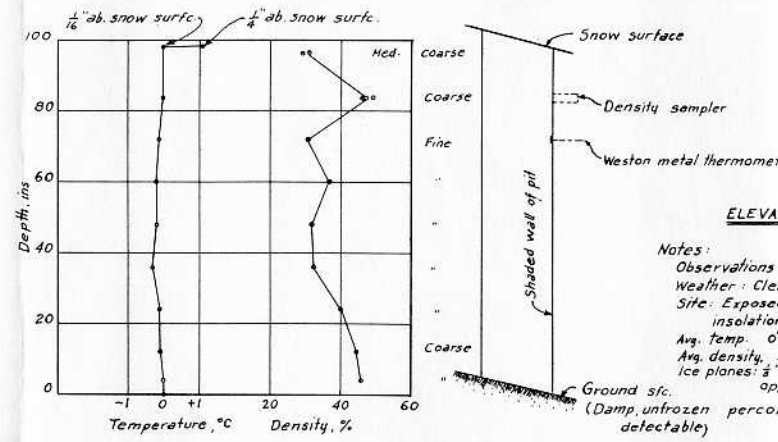
ELEVATION 6900'

Note:
Observations taken 24 Jan. 1952, 1500 to 1600 hrs.
Weather: Continous snow, Wind 1-2 mi/hr.
New fallen snow density, 7.5 to 18.6 % measured.
Site: Level, 20' N of HQ lysimeter north wall.
Avg. temp. of pack, -3°C
Avg. density, 28 %
Ice planes: $\frac{1}{8}$" to $\frac{1}{4}$" thick, not impermeable; no apparent free water



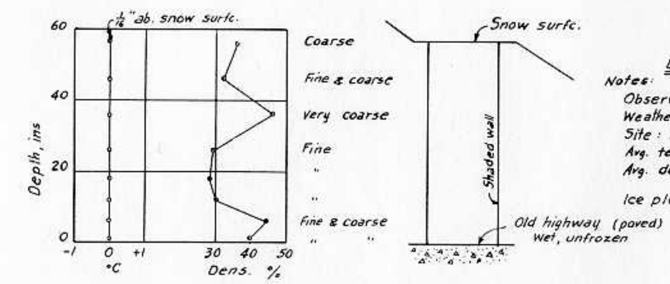
ELEVATION 6000'

Note:
Observations taken 27 Jan. 1952, 1530 to 1700 hrs.
Weather: Clear & calm
Site: Level, exposed to full insolation 0930 to 1600 hrs. Pit was dug on 26 Jan. & new wall exposed for observations on 27 Jan.
Avg. temp., -2.5°C
Avg. density, 30 %
Ice planes: $\frac{1}{8}$" to $\frac{1}{4}$" thick, not impermeable; no apparent free water



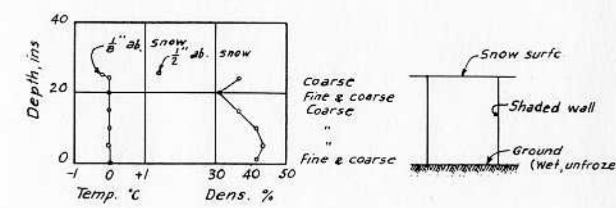
ELEVATION 5000'

Notes:
Observations taken 27 Jan. 1952, 1430 to 1500 hrs.
Weather: Clear & calm
Site: Exposed to south; snow sfc. 8% slope; full insolation all day
Avg. temp. 0°C approx.
Avg. density, 38 %
Ice planes: $\frac{1}{8}$" to $\frac{1}{4}$" thick, not impermeable; no apparent free water
percolation of melt water was not detectable)



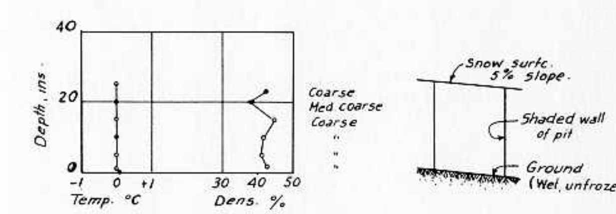
ELEVATION 4000'

Notes:
Observations taken on 27 Jan. 1952, 1150 to 1220 hrs.
Weather: Clear & calm
Site: Level, insolation on snow from 1100 to 1400 hrs.
Avg. temp. 0°C.
Avg. density 36 %. Snow is wet and appears to be at its moisture capacity
Ice planes: $\frac{1}{8}$" to $\frac{1}{4}$" thick, disintegrated



ELEVATION 3000'

Notes:
Observations taken on 27 Jan. 1952, 1055 to 1110 hrs.
Weather: Clear & calm
Site: Forested area on dirt road, shaded, level
Avg. temp. 0°C
Avg. density, 39 %. Snow is wet, and at its moisture capacity.
No visible ice planes.

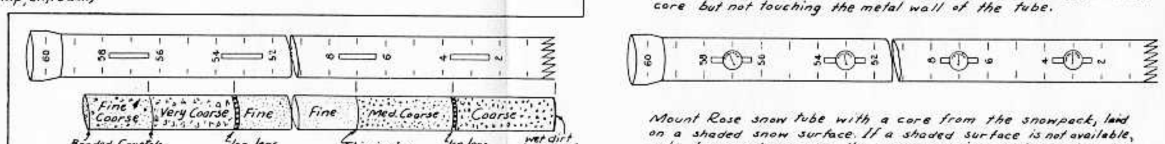


ELEVATION 3000'

Notes:
Observations taken on 27 Jan. 1952, 1025 to 1040 hrs.
Weather: Clear & calm
Site: Open, exposed to full insolation except between 1100 & 1500 hrs.
Avg. temp. 0°C
Avg. density, 42 %
No ice planes, homogeneous granular snow. Snow is wet and at its moisture capacity.

Average snow line is approximately at the 3000-foot level.

Weston bimetallic dial thermometers with stem inserted through slots in the snow tube. The sensitive portion is immersed in snow core but not touching the metal wall of the tube.



Classification of the snowpack by visual inspection of the core.

Note: Ice lenses or heavy crusts may not be as numerous or nearly as impervious in forested areas.

Mount Rose snow tube with a core from the snowpack, laid on a shaded snow surface. If a shaded surface is not available, note temperature and the corresponding depth readings as the tube is drawn from the pack and shaded by the observer. Depending on the depth, thermometers may be spaced from 4 to 24 inches apart to obtain the average temperature of the snowpack. Leave tube in snow pack long enough to come to equilibrium with the surrounding snow.

A PROPOSED METHOD OF DETERMINING TEMPERATURE AND STRUCTURAL PROFILE OF THE SNOWPACK WITHOUT DIGGING A PIT.

Note:
Observations were taken along U.S. Highway 40 between Auburn and Soda Springs, California.

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

DENSITY & TEMPERATURE PROFILES FOR EVALUATING SNOWPACK CONDITIONS

OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS U.S. ARMY

PREPARED: P.R.B./P.M.	SUBMITTED: R.N.R.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: P.R.B./P.M.	APPROVED: D.M.R.	PD-20-25/55