CHAPTER 7 - AREAL SNOW COVER

7-01. INTRODUCTION

7-01.01 General. - The area of snow cover has long been recognized as a prime variable in many applications of snow hydrology. Systematic observations of snow cover, however, have been generally lacking. Hydrologists have therefore resorted to empirically derived relationships between snow cover and runoff, assumed distributions of snowpack water equivalent by elevation zones and assumed zonal melt rates, or snow-cover indexes from ground observations of parts of a basin. Because of the lack of direct observation of snow covered area, none of these methods could be verified. As a result, the area of snow cover has been used to compensate for errors in other hydrometeorologic elements. Direct observations of snow cover are important as a forecasting tool, both for volume and rate-of-flow forecasting. In recent years there has been increasing recognition of the importance of snow cover to efficient operation of storage reservoirs, and a number of Corps of Engineers offices have begun making aerial snow-cover surveys during the spring melt season as an aid in reservoir regulation. As yet, an insufficient length of record is available to permit generalizations from snow-cover data; rather, the present use of the data has been limited to evaluating conditions at a specific time and developing observational techniques.

7-01.02 Definitions. - For the purpose of this report, the term snow cover refers to the extent of the ground area covered by snow, regardless of the depth of snow or its water equivalent. It may be expressed in units of area, such as square miles, or as a percentage of either the total basin area or an arbitrary maximum snow-covered area. The term snowpack refers to the total volume of snow on a basin. Snow-cover accretion is the increase in snow cover, while snow-cover depletion refers to a decrease in snow-covered area. Accumulation of the snowpack is the net increase in basin snowpack water equivalent, usually expressed in inches, while ablation refers to a net volumetric decrease of the snowpack water equivalent.

7-01.03 Functional use of snow-cover data. - There are two principal uses of snow-cover data in snow hydrology. One is for obtaining a measure of the areal extent of snowmelt at a given time, for the purpose of hydrograph synthesis. This may be involved in establishing procedures for streamflow reconstitutions, short-term forecasts, or design-flood computations. The second use of snow-cover data is in connection with volumetric forecasts of seasonal runoff. Snow cover may be used as a variable in establishing the volume of water stored in the snowpack, thus supplementing snowpack water-equivalent data from snow-course measurements, as was done in Research Note 22. In some mountainous regions, the area of snow cover may be used directly as an index of the water stored in the snowpack, as was done by Potts 5/ and

Croft.2/ A particularly useful application of snow-cover data is in connection with forecasting runoff for reservoir regulation after the melt season is well underway. All early-season volumetric forecasts possess a residual error, and as the melt season progresses, the magnitude of this error becomes a larger percentage of the remaining runoff. After the basin is less than, say, 50 percent covered, snow-cover data is particularly useful for verifying or adjusting earlier forecasts of runoff.

7-01.04 Requirements for hydrologic use. - In evaluating snow cover to meet the uses outlined above, there are three basic requirements to be considered: (1) the need for basic research on snow-cover accretion and depletion, and their relation to meteorologic and terrain factors which cause variation in precipitation and melt; (2) the necessity of direct observation of snow cover on project basins; and (3) the preparation of indexes or derived relationships for estimating the accretion and depletion of snow-covered area, for periods when observations are not available, or for design conditions.

7-01.05 Basic research is needed in order to improve present knowledge of the factors affecting snow cover accretion and depletion. If all basins had systematic snow-cover observations regularly taken through the accumulation and melt periods, this requirement would be much less important. Snow cover would then be simply another measured quantity. At the present time, however, observations are limited, and estimates of snow cover must be made indirectly.

7-01.06 The importance of obtaining direct observations of snow cover cannot be overemphasized. Subjective evaluations made from scanty and unrepresentative data are often misleading, because of the heterogeneity of basin areas and the complexity of the relationships between snow cover and its environment. The need for direct observations is three-fold. First, each basin has a characteristic pattern of snow-cover depletion, more or less consistent from year to year, which can be determined from direct observations of snow cover. A series of such observations over a period of years makes it possible to establish relationships for use when observations are not available. Second, such variations that do occur from year to year are so complex that they can only be determined by actual observation. Third, observations of snow-covered area, as measured quantity, are useful as a forecasting parameter for determining residual runoff volumes.

7-01.07 Primary factors affecting snow-cover accretion and depletion. - The accretion of snow cover usually begins on the higher elevations of the watershed, and continues through the accumulation period until all or a part of the watershed is covered. The depletion of snow cover begins with the exposure of the first bare ground in a completely snow-covered basin or with the date of maximum basin snowpack accumulation in a partially snow-covered basin. There are large differences between years in the length of accretion and depletion periods, depending primarily upon the meteorological regime during the accumulation and melt seasons.

7-01.08 During the accretion period, an elevation contour adequately defines the area of snow cover for small- to moderate-sized basins with relatively large ranges in elevation. This is due to the fact that the form of precipitation varies with elevation during individual storm periods, as explained in section 3-05, and the transition zone between areas of rainfall and snowfall is narrow. In addition, melt varies largely as a function of elevation during the winter period. Since solar radiation is at a minimum at this time, what little melt occurs is largely a function of air temperature, which in turn generally varies with elevation. The net result of these factors, then, is a fairly definite snowline during the accretion period.

7-01.09 Snow deposition, as related to meteorological and terrain factors, is a prime variable affecting snow-cover depletion. The variability of snow accumulation is discussed in chapter 3. During the accumulation period, the variations in the snow depths over basin areas show the combined effects of the terrain and meteorological factors. These factors include atmospheric circulation and airmass character during precipitation, opportunity for modification of airmasses, and large- and small-scale topographic influences. All of these influence the variations of snow depth from one point to another, which in turn will affect the depletion of snow cover during the melt period.

7-01.10 Snowmelt is the second prime factor affecting snow cover depletion. The meteorological and terrain factors causing variability of melt rates over a basin may act in entirely different ways from those affecting the deposition of snow. The principles involved in the variation of melt rates with respect to meteorological conditions, forest cover, and exposure to radiation are discussed in chapter 5. During winter, the melt rates over a basin are generally fairly uniform within a given elevation zone, and the amount of melt is usually small. During the spring and early summer there is wide variability to melt, due primarily to exposure; elevation effects are of lesser consequence. A definite snowline elevation does not exist during the melt period. Snow-cover depletion, therefore, reflects the variable influence of both the deposition and the melt of snow. The terrain influences on each are independent and should be considered separately.

7-01.11 In general, the seasons of heaviest snow accumulation have the longest lasting snow covers and those of lightest snowfall have the shortest. The interactions between meteorologic and topographic features determine the patterns of snow cover for individual cases. These factors are too varied and too complex to permit a practical general formula for assessment of snow cover from independent meteorological and topographic observations. Instead, a relatively simple empirical formula or chart for individual basins is needed to relate snow cover to readily observed data. Basin snow-cover depletion, snowpack ablation, and runoff are all the integrated effects of the same basic factors. Consequently, "depletion-ablation" or "depletion-runoff" curves may be constructed for a given basin if adequate and dependable data are available. The relationship may be improved by the introduction of a parameter such as the ratio of initial depth to areal snow cover, the initial basin snowpack water equivalent, or the ratio of snowpack water equivalents at low and high elevation snow courses. Using these relationships, one can determine the area of snow cover. Conversely, if a snow-cover survey is made, basin snowpack water equivalent or remaining runoff can be determined. These relationships can also provide the means for reconstructing the snow-cover depletion for years of historic floods of large magnitudes and establishing snow-cover criteria for design.

7-01.12 Organization of material and methods of approach. - The first part of this chapter deals with methods of obtaining direct observations of the snow-covered areas and summarizes generalizations on the accretion of snow cover. Then, observations of snow-cover depletion at the snow laboratories are used as a basis for discussing: (1) the relationships between snow-cover depletion, snowpack, ablation, and runoff; (2) the influences of terrain on snow cover. Finally, methods are given for using snow-cover data in forecasting residual runoff and in hydrograph synthesis.

7-02. METHODS OF OBSERVING SNOW COVER

7-02.01 General. - Systematic and complete observations of snow-covered area have been obtained only in recent years. Consequently, observational techniques for the collection of snow-cover data are not as standardized as those for many other basic hydrologic data. Also, the determination of snow-covered areas from the ground is extremely difficult, especially for rugged mountainous headwater areas, where routes of communication are generally lacking. The increasing use of aircraft for snow-cover observations has, however, made headwater areas readily accessible to both visual and photographic observations. In general, the following methods have been employed to obtain snow-cover information:

(1) Ground reconnaissance, utilizing prominent vantage points and transmountain highways to observe and map areas of snow, and also to define the elevation of the snowline when possible.

(2) Ground photography of selected sections of the drainage basin from fixed reference or vantage points.

(3) Aerial photography, either vertical or oblique.

(4) Aerial reconnaissance, from high- or low-level flight, supplemented by photographs, maps, sketches, and snowline elevation observations.

7-02.02 Ground reconnaissance. - Reliable determinations of the snow-covered area based on visual observations from the ground require considerable competence. No check or evidence exists to support the subjective opinions of the observer. The coverage cannot be as complete as coverage from aerial surveys because of obstructions, such as forest and hills, to the field of vision. In addition, the travel to satisfactory vantage points make ground observations expensive and time consuming. These limitations of ground reconnaissance surveys are more serious during the ablation than during the accumulation period. During the accumulation season, the use of ground reconnaissance is practical, since snowline elevations in mountainous areas are satisfactory indexes of snow-covered areas. In many basins, transmountain highways provide access through a range of elevations thus making possible the determination of the average snowline by automobile reconnaissance. Such observations may be made in conjunction with regular early-season snow-survey measurements. After the onset of the melt season, however, ground observations of snow cover are not recommended as a means of determining basin snow cover.

7-02.03 Simultaneous and independent observations of snow-covered areas by ground observation and aerial photographic methods were made at CSSL during the 1947 melt season. Comparison and analysis of these observations are presented in Appendix I to Research Note 16. Assuming the aerial photography analysis to give the correct snow cover, ground estimates of snow cover were found to be too high early in the season and too low later in the season. Estimates of snow cover made from high vantage points were found to be more reliable than those made from lower, inferior view points. On some of the sub-areas, the ground estimates of snow cover were as much as 50 percent less than those determined by aerial photography. For over half of the basin, however, the estimate from ground survey was within 15 percent of the value determined from the aerial photographs. From this experience, it is concluded that estimates from the ground should be made from high points whenever possible. Care should be taken not to bias the results to favor the more readily observable open areas in preference to wooded or more obscure areas. This results in overestimates early in the season and underestimates late in the season.

7-02.04 Ground photography. - Ground photographs are generally used as indexes of areal snow cover rather than measures of the total snow-covered area. Actual snow-covered area can be determined by relating these photographic indexes to actual snow-cover amounts determined by other means. Potts 5/ has utilized ground photographic methods for providing a direct index to snowmelt runoff on the middle fork of the South Platte River in Colorado, by-passing the determination of areal snow cover. Miscellaneous Report 1 describes a procedure for establishing a snowline index from horizontal ground photographs of the Sierra Nevada in the vicinity of CSSL. Panoramic photos were taken at a site at about the 5000 foot level near Emigrant Gap, California. The procedure consisted essentially of obtaining a master photograph, on which were located prominent features of the landscape with their elevations. A considerable portion of the 40 sq. mi. drainage area of the South Fork of the Yuba River is visible from this site. Between 8 March and 21 June 1948, thirteen series of panoramic photographs were taken from the site, and snowline indexes from elevation zones and exposure sectors were determined for each series. The index was used for the purpose of correlating snow cover to measurements of water equivalent of the snowpack and runoff.

7-02.05 In 1950, the U. S. Weather Bureau established a snow-cover investigations unit, for the purpose of estimating the extent of snow cover in the Columbia River basin, to be used in connection with seasonal and short-term streamflow forecasting. A report of the activities of this unit was made at the annual Cooperative Snow Investigations Conference of 1 April 1952, and at the Western Snow Conference in 1953. 1/ The principal method used by this unit to estimate snow cover has been by ground photographs from key stations. A photographic record is currently being accumulated from which indexes of snow cover may be determined. The photographs are taken periodically through the melt period by cooperative observers and using standardized photographic procedures.

7-02.06 The standardized procedure used by the snow-cover unit to photograph selected portions of a basin from fixed vantage points, for the purpose of establishing an index of snow cover, consists of:

(1) Selecting photographic stations.

(2) Preparing a master panoramic view of the watershed from each station.

(3) Dividing the master photograph into convenient exposure sectors.

(4) Identifing and determining elevation of prominent landmarks on the master photograph.

(5) Photographing the progress of snow-cover depletion from each point.

(6) Determining the average snowline in each exposure sector and assigning a snow-cover index value to each snow-line elevation.

The procedure is subject to considerable personal judgment and requires experience in taking the photographs and evaluating the snow line. A disadvantage is that some areas are obscure, and also there is great distortion with increasing distance from the camera, so that the use of a uniform grid system is not practical. An additional disadvantage of the method of ground photographs is that for routine observations a considerable time is required before the pictures are ready for analysis. Since these photographs provide only an index of snow-covered areas, if actual basin snow cover is desired, results must be correlated with simultaneous observations of the actual cover. The method does have the advantage of being inexpensive and of providing records to supplement personal judgment.

7-02.07 Aerial photography. - Aerial photography is an exact method of determining the area of snow cover. It furnishes a permanent record which can be analyzed at any time, and information which can be transferred to basin maps for evaluation of the true cover. Aerial photographs are taken both vertically or obliquely. Their use varies from a supplement to visual observations to a complete and precise delineation of the snow-covered area. The principal advantages of aerial photographs are: (1) a record is obtained which may be preserved, and from which detailed analyses may be made of true snow-covered area; (2) remote regions which are not accessible to ground surveys may be covered by air; and (3) through use of stereo-pairs, determinations of snow cover and surrounding terrain elements may be made from which the two may be correlated. Aerial photographs have been used primarily for special studies of snow cover on small basins. Their application to larger basins for operational use, however, is subject to the following limitations: (1) the large number of photographs required to cover such basins; (2) the high cost of operation of aircraft which can operate at high elevations; (3) the time required for photograph processing and evaluation; (4) the difficulty of interpretation of snow cover in forested areas; and (5) the near-ideal weather conditions required during periods when snow-cover observations are needed.

7-02.08 Aerial photographs of snow cover were obtained for UCSL and CSSL, for the years listed in table 2-6 (chapter 2). Those for UCSL were vertical photographs, taken at flight levels ranging from 13,000 to 17,500 feet and using aerial mapping cameras. For CSSL, oblique photographs were obtained primarily by light aircraft not equipped for vertical photography. Data from these flights were used for detailed studies of snow-cover relationships.

7-02.09 In the application of vertical aerial photographs for project-size basins, the most critical difficulty lies in the large number of photographs required to cover the basin. Flying at 10,000 feet above the ground surface and using a 9 x 9 inch camera with an 8.15 inch focal length, the total area covered by each picture is about 4 square miles. If only one quarter mile overlap is provided for each picture, the effective area is 2.2 square miles per picture. For a 10,000 square mile area, about 450 photographs would have to be taken, processed and interpreted. Even when photographing only the marginal zones of snow cover, a large number of pictures is required.

7-02.10 Aerial reconnaissance. - The most feasible method for obtaining timely and accurate estimates of snow cover is aerial reconnaissance. Unlike the data from aerial photographs, the reconnaissance snow-cover information is available to the hydrologist as soon as the flight is completed. The probable small increase in accuracy would not warrant taking aerial photographs, particularly when special skills for processing and interpreting them are not generally available. The cost of aerial reconnaissance using light aircraft is less than ground reconnaissance, considering the difference in time required. Its cost is far less than that for obtaining complete coverage by aerial photogrammetric methods. While suitable weather conditions are required for aerial reconnaissance, these requirements are considerably less than for aerial photos. The principal disadvantages of the method are: (1) evaluation is subjective and results cannot be verified, and (2) it is dependent to some extent upon weather conditions. Observing snow under the forest is difficult, regardless of the basic method used, whether from ground or air. Supplementing aerial reconnaissance with oblique aerial photos provides continuity between observations and aids in verifying subjective observation.

7-02.11 Various Corps of Engineers offices, including Sacramento, Portland, Seattle, Walla Walla, and Omaha districts, have made regular observations of snow cover by aerial reconnaissance for use in flood evaluation and reservoir regulation. The methods used have varied, depending upon the areas involved, aircraft available, weather, and preference of those making the flights. In general, two procedures have been used successfully. Both consist basically of observing snow-covered areas and plotting them on a topographic map. In one case, flight altitude is maintained 4000 to 5000 feet above the highest ridge lines, thus enabling the observer to obtain a fairly broad view of the basin as a whole. The other method is to fly in the canyons approximately at the elevation of the snowline. The high-level flight requires better conditions of ceiling and visibility, which often limits the time that observations may be made; however, more comprehensive definition of the snow-covered area may be made from high-level flight. Also in some cases mountain ranges may be too high to permit the use of light planes in the high-level flight procedures. Early in the season when snow generally covers a large portion of the basin, only the lower portions of the basin are exposed and there is less variability of the snowline. At such time, low-level flight may be preferred. Whenever cloud conditions prevent flying over mountain ridges, low-level flight must suffice. A hand level is sometimes used to maintain the flight level at the approximate snowline elevation so that altimeter readings can be used to measure the height of the snowline. When it is impossible to fly the entire basin, a system of sampling the elevation of snowline on various aspects and areas may be used to evaluate an average basin snowline. This in turn may be applied to an area-elevation curve to determine the snow-covered area. When viewing heavily forested areas from low-level flight, the line of sight being more or less horizontal, it is difficult to determine snow cover under trees. Viewing the area vertically gives a better opportunity to estimate snow cover under those conditions. Snow-free patches, well within the snow-covered area, often occur on steep slops. These areas appear relatively large when viewed horizontally or obliquely; actually, they may represent negligibly small areas on a horizontal projection. A detailed report on aerial recommaissance of snow cover in the Kootenai and Flathead basins by the Seattle District office is contained in Technical Bulletin 15.

7-02.12 The following general recommendations are made for conducting aerial snow-cover reconnaissance surveys:

(1) Trained personnel who know the basin hydrologic characteristics should make the survey.

(2) The observer should be familiar with landmarks throughout the basin, and ground features should be identified continually during the flight.

(3) The snowline should be identified as to elevation or location and plotted on the base topographic map.

(4) Where spotty or patchy fringe areas of snow cover exist, an average snowline should be estimated and plotted.

(5) Aerial snow-cover reconnaissance flights should be scheduled to coincide with ground snow-course surveys, insofar as possible.

(6) Aerial snow-cover surveys should not be made immediately after a new snowfall.

(7) Supplementary photographs should be taken which will show progress of snow-cover depletion in a given area from flight-to-flight. Photograph points should be established which are easily recognizable. Pictures should be taken from the same point each time, at a specific altitude. Areas photographed should show both northerly and southerly slopes.

(8) Low-level flights should be made at the snowline level and this level plotted on the topographic map.

7-02.13 The interpretation of the snow-covered area from aerial reconnaissance surveys is made by planimetering the areas of snow on the basin map. As an independent check, average snowline data may be applied to area-elevation curves, but this latter method is less reliable. Where basin coverage is not complete, area-elevation relationships must of necessity be used. For this purpose, the average snowline should be carefully weighted to reflect the various conditions of exposure throughout the basin.

7-03. SNOW-COVER ACCRETION

7-03.01 Although a simple method for quantitative evaluation of snow-cover accretion has not been developed, a few qualitative statements may be made concerning the processes involved. Broadly speaking, there are two types of areas to be considered, namely, mountainous regions and open plains. For mountainous regions, as was explained earlier, the area covered with snow during periods of accumulation varies primarily with elevation. Reference is made to section 3-04 for a discussion of elevation effects on snow accumulation. While there may be large variation in the depth of snow because of meteorological and terrain effects on snow deposition, the amount of melt during the accumulation period is small and generally is not sufficient between storms to expose the lightly covered areas. The elevation of the snowline, therefore, is primarily a function of the form of precipitation in individual storms, and accordingly is dependent upon elevation.

7-03.02 On wind-swept open plains, snow-cover accretion may be irregular because of drifting. In such areas, the elevation range is small and the effect of elevation on accretion is usually negligible. The variation in snow cover in this case is a complex function of meteorologic conditions, primarily of wind, temperature, precipitation, and the sequence of these events, superimposed on small-scale terrain irregularities. The relative magnitudes of these effects have not been determined separately.

7-03.03 In some mountainous regions, the combined effects of steep slopes, high wind, and lack of forest may result in local patches of snow-free ground in an area which is generally snow-covered during the accumulation period. Usually, the relative magnitude of these areas is small when considered with respect to the drainage basin as a whole.

7-03.04 The effect of forest on snow accretion is to cause greater uniformity of cover than would occur in bare areas. The effect of forest on snow accumulation may be considered analogous to its effect on snowmelt, in that it tends to "level out" the variability of meteorologic processes. In the case of snowmelt, forest influence permits the use of temperature to index the radiation melt process. For snow accumulation, a uniform forest stand provides a means for distributing snow more equitably with regard to the rest of the terrain features and minimizes the variability of deposition in locations of abnormally high winds or steep slopes.

7-04. SNOW-COVER DEPLETION AND ITS RELATION TO TERRAIN

7-04.01 General. - The factors affecting snow-cover depletion are extremely complex and include the interrelationships between terrain and meteorologic conditions during snow deposition, as well as during melt periods. It is not feasible to attempt evaluation of snow cover depletion by rational procedures. Rather it is necessary to derive empirical relationships with readily observed data for the purpose of determining snow cover for individual basins. Not only do these relationships vary from basin to basin but, with regard to snow-cover depletion on a particular basin, each year has its peculiarities, resulting primarily from the meteorological differences during the accumulation and melt periods. Therefore, a precise quantitative definition of snow-cover depletion applicable to all areas and to all years is not possible from the limited observations which are available. It is, rather, the intent of this section to present a qualitative evaluation of the processes of snow-cover depletion and their relation to terrain. These are based primarily on observations at the snow laboratories. Later sections of this chapter deal with snow-cover depletion as related to ablation of the snowpack and accumulated runoff.

7-04.02 Analyses of snow-cover depletion in relation to terrain have been made on the basis of snow-cover observations at CSSL and UCSL (as reported in Research Note 16). The results of the analyses contained in Research Note 16 are summarized in the following paragraphs.

7-04.03 Analysis of the 1947 season at CSSL. - A detailed analysis of snow-cover depletion during the 1947 season at CSSL was accomplished by subdividing the basin into twenty topographic units of homogeneous character, as shown on figure 2, plate 7-1. The percent snow cover was determined for each unit from analysis of aerial photographs of the entire basin which were made that year. Several flights were made from which the progress of depletion could be determined.

7-04.04 The 1946-47 season at the CSSL was deficient in snowfall; the snowpack water equivalent was less than 70 percent of normal. The melt season was warm and free of storms from 10 April until the end of May when most of the snow was gone. Consequently, the determination of snow cover during the melt period was not complicated by new-fallen snow from spring storms. The initial streamflow rise commenced on 10 April, and the snowmelt contribution of runoff terminated early in June. The peak discharge occurred on 1 May. In general, the continuous nature of the melt season made it ideal for the study of snow-cover depletion.

7-04.05 Depletion of snow cover, 1947, at CSSL. - A generalized description of the progress of depletion of snow cover during 1947 is as follows:

a. On 31 March snow cover was substantially complete over the entire basin, with minor exception of some steep slopes on Castle Peak.

b. At the middle of April, cover was still high, averaging about 92 percent over the basin; bare areas had appeared on high parts of Castle Peak and on the south side of Andesite Ridge.

c. At the end of April, cover averaged about 80 percent. Bare spots that had appeared in the middle of April were larger, and snow cover in Uhlen Valley was also partly broken up. In the other areas little change in extent of snow cover had occurred. Most of the topographic units still had more than 60 percent snow cover, and in the upper basin there was a large block of units with more than 90 percent cover.

d. At the middle of May, snow cover averaged 37 percent over the whole basin, but the dispersion was quite large. In two topographic subdivisions, mostly in the upper part of the basin on both sides of Willow Valley, snow cover exceeded 90 percent. On the other hand, eight subdivisions, chiefly south-facing slopes in both upper and lower basins, were nearly bare. Figure 7, plate 7-1, shows the areal distribution of snow cover on 30 April and 15 May, when the average basin snow cover was 79 percent and 37 percent respectively. The similarity of patterns on the two dates may be noted. The relatively stationary status of the units with above average snow and the rapid depletion of units that were initially below average in cover result in an increase of dispersion.

7-04.06 The sequence of depletion for 1947 is illustrated in figure 6, plate 7-1. This diagram shows for each topographic unit the number of days after active melt had begun before a snow cover of 60 percent was attained. It presents, therefore, a measure of the rates of snow-cover depletion for various conditions of terrain. Seven of the units reached 60 percent snow cover within 25 days, while two of the units required in excess of 50 days to reach 60 percent cover. The shortest time was 13 days for the steep, south-facing slopes of Castle Peak, while the longest time was 60 days for the sheltered north slopes of Andesite Ridge. Figure 5, plate 7-1 illustrates schematically the sequence of snow-cover depletion for an unforested area with relatively steep north- and south-facing slopes. For the CSSL, the windward slopes face south and the leeward slopes face north. As a result of local topographic influences the accumulation of snow is greater on north than on south slopes (see chapter 3). Also, since melt rates are greater on south-facing slopes, the combined depletion effect results in south slopes going bare well in advance of other areas. North slopes, with their greater accumulation and reduced melt rates, exhibit the opposite effect.

7-04.07 Topographic influences. - Watersheds differ from one another in topography and orientation with respect to exposure to the flow of airmasses and to solar radiation and other factors affecting deposition and melt. The differences cause variation in depth of snow and in the duration of the melt season between basins. Even within a watershed, local differences in topography exist which cause variability in the accumulation and melt of the snowpack, and consequently in the snowpack ablation and snow-cover depletion. In relatively flat areas, such as open meadows and valleys or in plains regions, the snow cover tends to remain in tact for a relatively long time until it becomes quite shallow. It then exhibits a rapid change as large areas of thinned snow become bare simultaneously. This tendency is characteristic of all snowpacks of uniform depth subject to uniform melting rates. In mountainous areas, on the other hand, there is wide variability in the snow-cover depletion with area. Yet, for a given area, the depletion pattern is remarkably similar from year to year. A characteristic effect of topography is manifest in the appearance and development of bare patches, which appear at the same sites and grow in nearly identical patterns each year.

7-04.08 Orientation. - The basic considerations of the effect of slope orientation on snow-cover depletion were mentioned in paragraph 7-04.06. The following tabulation, based on CSSL data for the 1947 season, shows the progress of depletion of snow cover as a function of slope orientation:

DEPLETION OF SNOW COVER WITH RESPECT TO ORIENTATION, CSSL, 1947

Orientation	Percent of area snow covered				Percent of basin area
	31 Mar	30 Apr	13 May	16 May	
N	100	83	76	57	4
NE	100	82	72	69	5
E	100	87	76	75	8
SE	98	74	37	22	18
S	99	67	32	25	27
SW	100	74	35	27	15
W	100	79	58	38	13
NW	100	83	69	56	10

The plotting of the above data in figure 3, plate 7-1, illustrates the progressive decrease in snow-covered area for the various orientations relative to one another. In extreme, the rate of change of snow-cover depletion is from two to three times greater for south slopes than for north slopes. (Actually the depletion rate tends to be least in the northeast octant, which reflects the greater deposition of snow on the lee side of local barriers during the southwesterly atmospheric circulation accompanying storms, as well as the reduced melt rates on northerly slopes.) Strictly speaking, slope orientation should not be evaluated without also considering the steepness of slope. Very flat slopes of north and south orientation would tend to be quite similar in depletion characteristics while steep north and south slopes would be markedly different. The effect of steepness will now be examined.

7-04.09 Steepness. - In general, the accumulation of snow varies inversely with the steepness of slope, as was pointed out in chapter 3. For the CSSL, the fact that most steep slopes are for southerly orientation also results in greater melt rates. The combined effect of below average snow depths and high melt rates causes snow cover to deplete at a fast rate on these steep slopes. Separate evaluation of the relationship between depletion and steepness of slope is not practical from CSSL data, because of the interrelationship between steepness and orientation.

7-04.10 Elevation. - The data from CSSL are inadequate to relate depletion with elevation, because the entire basin is within the headwaters area of the Sierra Nevada. The range in elevation is small and other topographic influences at these high elevations obscure the effect of elevation. Data from WBSL presented in chapter 3 showing the variation in slope of the snow-wedge with time reveal the nature of depletion in that type of area. As was pointed out in paragraph 3-04.06, the slope of the snow-wedge increases through the accumulation period, but after active melt is under way, there is little variation in melt with respect to elevation, resulting in a nearly uniform decrease of the snowpack water equivalent with elevation. Under these conditions, the depletion of snow cover with respect to elevation is a function almost entirely of the variation in snow accumulation, and only slightly of the variation in melt. When considered over large ranges in elevation (sea level to, say, 10,000 feet) elevation is of course the most important single topographic variable in its effect on depletion of snow cover.

7-04.11 There are several compensating factors affecting variation of melt with elevation. What melt occurs during the accumulation season is largely a function of elevation. Solar radiation melt is small, hence air temperature mainly determines the amount of melt. During the late spring melt season, however, solar radiation is the prime source of energy for melting snow.

7-04.12 Figure 4, plate 7-1 shows the snow cover-elevation relationship for various dates of observation for CSSL during 1947. This diagram illustrates the depletion of snow cover with elevation and shows that the relative magnitude of depletion in the various elevation zones was greatest in the upper and lower portions of the basin, and least in the mid-elevation zones. The effect of topographic features other than elevation obscured any quantitative evaluation of elevation effect on depletion.

7-04.13 Forest. - It is difficult to evaluate quantitatively the effect of forest on snow-cover depletion. Studies from CSSL show little relation between forest and depletion, but the results were obscured by the effect of more significant terrain parameters. Figure 1, plate 7-1 is an aerial mosaic showing the distribution of the forest at CSSL. It was shown in chapter 4 when considering the interception of snow by the forest crown that the accumulation of snow under dense forest may be less than 80 percent of that in adjacent open areas. Factors affecting melt in various-sized forest openings have been discussed in chapter 5, and in general, melt rates are highest in large clearings and decrease to a minimum in small clearings protected from sunshine by the surrounding trees. In a broad sense, the effects of forest on accumulation and melt tend to balance each other, so that the depletion rates would be similar in magnitude. It has been observed in the heavily forested WBSL that the last remaining snow patches are in the small forest clearings, which again shows the integrated effects of above-normal accumulation and reduced melt in these locations.

7.04.14 Kittredge 4/ performed an exhaustive study on the influence of forest on snow in the central Sierra Nevada using observations made over a period of seven years. Measurements included profiles of snowpack water equivalents, under various densities and species of forest, made at various times through the snow season. Those conclusions from the study directly pertinent to snow-cover depletion are quoted below:

"1. From 13 to 27 percent of the seasonal snowfall was intercepted by the forest canopies.

"2. The maximum water equivalents of the total snow on the ground or the amounts of water in storage in the snow are larger in red fir and in the cutover stand with large openings than in the clearings, and smallest in dense fir and ponderosa pine stands. The dates of maximums in the forested areas are usually later than in the open areas. Maximum water equivalents in the cutover mixed conifer and in a few other areas, for some years, vary inversely with the crown coverage within a 20-foot radius.

"3. The effect of trees on the south side of the large clearing on the water equivalents of the snow was to maintain greater storage not farther to the north than the height of the trees, as compared with the smallest amounts at greater distances where melting was more rapid.

"4. Openings between the crowns showed average maximum accumulations of 1 to 5 inches water equivalent larger than did areas under the crowns.

"5. The first exposure of bare ground varied from March 28 to May 5 between extremes in different forest types, and more than 60 days in different years in the same type.

"6. The average date of disappearance of the snow varied from April 17, in the old ponderosa pine, to June 1 in the red fir, and by about 2 months between extreme seasons.

"7. The date of disappearance of the snow varied inversely to the crown coverage within a 20-foot radius in the cutover mixed conifer area, and in some other types in certain years.

"8. The average duration of the snow cover varied from 117 days, in the ponderosa pine, to 160 days in the red fir area.

"9. The percentage of area covered by snow decreased after the first exposure of bare ground by from 4.4 percent per day, in the red fir area, to 17.2 percent in the lower meadow.

"10. The rates of melting tended to be lower under the crowns than in openings, and lower in openings than in the large clearing, per unit change in the independent variable in each case, but the influence of trees in retarding melting was quite small."

7-04.15 Snow- cover depletion, UCSL. - To illustrate the process of snow-cover depletion in an area of non-uniform deposition of snow, successive aerial photographs of the progression of depletion within the Blacktail Hills, UCSL, are shown on plate 7-3, for 1946 and 1947. The area shown in each photograph is slightly over one square mile. The growth of bare areas is apparent during successive periods of melt. The wind-swept ridge of the Blacktail Hills possesses little forest and conditions are favorable for low deposition and high melt of snow. The ridge becomes bare of snow early in the season, but on the lee side (northeast), snow remains much later in the season. These photographs illustrate the uniformity of depletion patterns between the two years (1946 and 1947) which serves to give confidence to the use of index relationships for estimating snow cover in mountainous regions. Plate 7-2 is an aerial photograph of the entire UCSL, taken on 2 May 1946, showing approximately the mid-season condition of snow-cover depletion on the basin. Also outlined on this photograph is the area of the Blacktail Hills contained in the successive photographs of plate 7-3. Notice the wide diversity of areas bare of snow for the various slopes within the basin.

7-04.16 Effect of diversity of terrain on snow-cover depletion. - The preceding paragraphs have discussed the variability of snow-cover depletion caused by each of the primary terrain factors. The integrated effect of all these factors on a basin area determines the rate of snow-cover depletion. The greater the diversity of terrain, the longer will be the time of depletion of snow cover. Areas having uniform conditions of accumulation and melt will exhibit rapid changes in snow cover from the time the first areas become bare to the condition of complete loss of snow.

7-05. SNOW-COVER DEPLETION VS. ABLATION OF THE SNOWPACK

7-05.01 General. - The preceding section described in general terms the variation of snow cover depletion with major terrain factors, in order to show the fundamental processes involved in snow-cover depletion. For the practical determination of snow-covered areas, however, it is necessary to determine average relationships between basin snow cover and commonly observed data. One such usable relationship is that with ablation of the snowpack, or as a step further, accumulated runoff.

7-05.02 Figure 1, plate 7-4 is a schematic diagram illustrating basic differences in the character of snow-cover depletion-ablation relationships of deep snowpacks. Curve A represents the conditions for heterogeneous basins, where snow accumulation and melt are affected by topographic variability. Beginning with the time the basin first begins to go bare, the area of snow cover decreases quite uniformly with ablation of the snowpack, resulting in a curve which is slightly concave downward. The reverse curvature near the bottom of the curve is caused by the few remaining deep drifts which last long after the major portion of the original snow-covered area has gone bare. Curve A is typical of mountainous areas of western United States. Curve B shows the rate of depletion on a homogeneous basin, where large amounts of snow are uniformly distributed over the area, and where melt rates are relatively uniform. Here, the snow-cover depletion with respect to ablation is slow at first and then suddenly increases. This type would be expected in the plains regions.

7-05.03 Depletion vs. ablation, CSSL. - Depletion-ablation relationships are shown in figure 2, plate 7-4 for several of the homogeneous topographic units of CSSL for the 1947 melt season. Also shown in the figure is a curve representing the basin as a whole. Curves for each of the units lie above the one for the entire basin and show that for areas of homogeneous character, there is a trend for a more pronounced "knee" in the curve as discussed in the preceding paragraph. When an area has a large variety of slope facets, as in the case of the basin as a whole, the curvature becomes less pronounced.

7-05.04 Figure 3, plate 7-4, shows the depletion-ablation relationships for four years at CSSL for the basin as a whole. Data for 1948, 1950, and 1952 are less complete than those for 1947. It is seen that the curve for 1947 lies below that of the other three years. This is accounted for by the fact that the relationship is begun on 1 April at which time the 1947 snowpack was relatively less than in the other years. Because of this fixed starting date, the curvature in the relationship is greater for years of above-normal snowpack accumulation while for years with below-normal snowpack the curvature is less than it is for normal snowpack conditions. Beginning the accumulated ablation-snowcover curves at 98 percent cover regardless of date, these curves are all similar in shape.

7-05.05 The difference between accumulated ablation of the snowpack and accumulated runoff represents the net effect of losses (evapotranspiration and soil-moisture increase) and ground-water and other basin storage. Figure 4, plate 7-4, indicates the 1947 CSSL snow-cover depletion as a function of accumulated runoff as well as accumulated ablation of the snowpack. The displacement of the runoff curve to left of the ablation curve is due to losses and storage. (In the case of CSSL, storage is relatively small in proportion to the total runoff.)

7-06. SNOW-COVER DEPLETION VS. RUNOFF

7-06.01 General. - Relating snow cover to observed runoff during the active melt period provides a convenient method for estimating snow-covered area continuously through the melt season. Snow cover may be related directly to observed data, or a mathematical function may be used to express the relationship. Data from Research Note 16, showing the relationships at the laboratories and a few miscellaneous basins, are presented to illustrate the general character of the relationships. Runoff may be accumulated commencing either from (1) the time of initial rise in streamflow, (2) the time of maximum snowpack, or (3) an arbitrary date, such as 1 April. It is also useful to accumulate historical runoff data from the end of the snowmelt runoff season, backward through the melt period, and thus relate snow cover to "future runoff." All values of accumulated runoff should be corrected for spring precipitation (either rain or snow) so that the relationships will express conditions resulting from the initial snowpack and thus will be more consistent from year to year.

7-06.02 Examples of depletion vs. runoff relationships. - Figure 5, plate 7-4 shows curves of snow-cover depletion as a function of accumulated runoff from snowmelt for the period 1 April through 31 July for the CSSL basin, Skyland Creek at UCSL, St. Louis Creek in Fraser Experimental Forest, Colorado, 3/ and for Kings River, California. These curves reflect the effects of snow-cover depletion, ground-water storage, losses, and the magnitude of the snowpack in individual years. Similar curves could be constructed on the basis of generated rather than actual runoff, and thereby eliminating the effect of storage. For the cases shown, runoff from CSSL is the least affected by storage (the curves are displaced farthest to the right). Skyland Creek at UCSL and St. Louis Creek at Fraser Experimental Forest possess longer times of storage delay to runoff, and accordingly their curves are displaced to the left.

7-06.03 Figure 6, plate 7-4 shows the snow-covered area (in percent of initial snow cover) plotted against future runoff (in inches over area initially snow covered). As would be expected, there is wide divergence in amount of future runoff associated with a given snow cover early in the season. When snow-covered area is high, the future runoff depends principally upon the water equivalent of snowpack;

as the melt season progresses, the lines converge to indicate future runoff is largely a function of remaining snow cover. Such empirical relationships suggest the possibility of forecasting from direct observation of snow cover the remaining volume of snowmelt runoff after the melt season is under way.

7-06.04 Mathematical expression for snow-cover depletion. - In the absence of observed data, snow-cover values may be obtained from a theoretical snow cover-runoff curve, (Research Note 19). The general expression used to relate snow cover to generated runoff is as follows:

$$A_s = 1.0 - (\Sigma Q_{gen})^n \qquad (7\text{-}1)$$

where A_s is the fractional portion of the basin area which is snow covered, Q_{gen} is the generated runoff relative to the total seasonal runoff from the initial snow-covered area, and n is an exponent expressing the characteristic basin snow-cover depletion with runoff. For basins which are initially 100 percent snow covered, the runoff summation begins when the basin first begins to go bare. Runoff is expressed in terms of generated flows, and hence, storage effects are not pertinent. The value of n reflects the diversity of terrain effects on snow-cover depletion. In the case of WBSL, where a snow wedge adequately defines the variation in the snowpack water equivalent with elevation, a value of n = 2 gave reasonable values of snow cover. The curve for the value of n = 2 approximates closely the condition of a uniformly ablated snow wedge for a basin with a typical S-shaped area-elevation relationship, and with snowpack water equivalent proportional to elevation above the snowline. A smaller value of n would be expected in areas of greater diversity of terrain. In plains regions with uniform deposition of snow and melt, the value for n may be 3 or more. Figure 7, plate 7-4, illustrates the rate of snow-cover depletion for various values of n in equation 7-1. It is pointed out that these mathematically expressed curves do not account for the reverse curvature which appears near the end of season in some basins, as illustrated by curve A, figure 1.

7-07. METHODS OF ESTIMATING SNOW COVER FROM INDEXES OR DERIVED RELATIONSHIPS

7-07.01 General. - In the derivation of design floods and in seasonal-runoff or rate-of-flow forecasting, it is necessary to evaluate the area of snow cover for the particular melt sequence. In some such procedures, the area of snow cover is implicitly evaluated by another variable which is related to snow cover. For example, many procedures for forecasting seasonal runoff from snow-course data do not account for the area of snow cover directly, but derived relationships between snow-course water equivalent and runoff implicitly include the average relationship between area of snow cover and snowpack water equivalent. However, since there is variability in the relationship between snowpack water equivalent and snow cover, the average relationship can at best only approximate the true volume of water stored in the snowpack.

7-07.02 The most reliable estimate of snow cover is one made from direct observation, as described in section 7-02. In many cases, however, such observations are not feasible, and estimates must be indirectly made from other observed data. Also, once a sufficient period of record of snow-cover observations have been obtained and related to other data, the frequency of making snow-cover observations can be reduced, and snow-cover estimates can be made more quickly and more economically by indirect relationships than by direct observation.

7-07.03 In estimating snow cover from other observed data, derived relationships are used in two ways. One is in obtaining a single estimate of snow cover at a specific time and the second is for estimating day-to-day changes in snow cover. Methods used for determining snow-covered areas are listed below under these two categories:

A. Methods of estimating snow cover at a specific time.

1. Index relations of snow cover to fixed ground or aerial observations, or photographs of snow cover at a point or series of points.

2. Use of snowline observations and area-elevation relationships.

3. Relation of snow cover to point measurements of snow.

a. Water equivalent measurements.
b. Snow depth measurements.

B. Methods of estimating changes in snow cover.

1. Empirical relation of snow-cover depletion to accumulated runoff.

a. Curves derived graphically from observed data.
b. Mathematical equation.

2. Relation of snow-cover depletion to temperature or some index of melt.

3. Use of current precipitation and temperature data to establish areas of new snow, within the accretion or depletion period.

4. Subdivision of basin into elevation zones or homogeneous sub-areas.

7-07.04 Indexes of snow cover. - Methods of observing snow cover, from a point, either on the ground or from the air, have been described in section 7-02. The quantitative evaluation of basin snow cover using point observations as indexes, required simultaneous observations of the index and of basin snow cover until a relationship has been established between the two. Average snowline elevations may be used with area-elevation relationships to determine snow cover in mountainous regions, particularly during the accumulation period, but care should be exercised in their use during the melt period.

7-07.05 Snow course measurements of snowpack water equivalent at one or more snow courses may be related to snow cover as a simple function. Obviously, snow courses selected for use in this relationship should be those on which snow remains for the longest possible time. The principal deficiency of the method is that such a simple correlation does not account for variation in slope of the snow wedge. In Research Note 22, the area of snow cover of the North Santiam River basin above Detroit Dam was expressed as a function of the ratio between the snowpack water equivalents of two snow courses at different elevations. Only one season's snow-cover observations were available, however, so the reliability of the method on this basin cannot be assessed. Snow-depth observations are useful primarily in defining the times that areas become bare of snow for given locations and elevations. Care should be taken in selection of the point(s) to secure representativeness of basin conditions, both with regard to snow deposition and melt. In the West, snow-course measurements are made at monthly or bimonthly intervals, so that their use is limited to the times of observations. Snow-depth measurements at weather observation stations are available daily during the period of snow cover.

7-07.06 Estimates of basin snow-cover depletion. - A knowledge of the change in snow cover between times of observation during the melt period is required for many snow-hydrology problems. The most feasible method is to assume snow cover to vary with some continuous function, such as runoff, time, or a melt index. Section 7-06 described relationships between snow-cover depletion and accumulated runoff, based on snow-laboratory observations. The procedures have been used by the Seattle District on the Kootenai and Flathead River basins, as described in Technical Bulletin 15. The available observations are insufficient, however, to derive general relationships for these areas. Empirical relationships in graphical or mathematical forms may be used to relate snow-cover depletion to runoff according to methods set forth in section 7-06. The use of a time function alone to express depletion is not too reliable because of the variations in melt (and hence depletion), with time. A simple index of melt, such as degree days, may be used to evaluate depletion, but the use of accumulated generated runoff is considered to be more practical because (1) it integrates all factors affecting melt, (2) it is simpler to use than melt indexes, and (3) it is readily available.

7-07.07 During the period of snow depletion, snow-cover estimates may be improved by use of current temperature and precipitation data. The purpose is to delineate areas of shallow new snow which contribute little to runoff. Once the areas covered by new snow are evaluated the time required to melt the new snow in order to re-establish the snow-cover depletion rate of the old snow can be determined.

7-07.08 A different approach to the determination of snow-cover depletion is that of subdividing a basin area into zones of equal elevation. Beginning with an assumed or known distribution of snowpack water equivalent with elevation, values of snowpack water equivalent are determined for each zone. By maintaining an inventory of snowpack accumulation and ablation, the depletion of snow on successive elevation zones is determined. The principal difficulty of the method is in the evaluation of precipitation distribution with elevation, particularly for heterogeneous areas. A refinement of the method is to assume a non-uniform distribution of snowpack water equivalent within a given zone.

7-08. APPLICATION OF SNOW-COVER OBSERVATIONS TO BOISE RIVER BASIN

7-08.01 General. - Of recent years, the Walla Walla District of the Corps of Engineers has determined the area of snow cover on various drainage basins within their district by means of aerial reconnaissance. Some of this information has been used by the Snow Investigations in studies of daily snowmelt and streamflow for the Boise River near Twin Springs, Idaho (D.A = 830 sq. mi.). Results of those studies are presented in chapters 6 and 9. The importance of snow cover in these studies led to a detailed analysis of snow cover on the Boise River basin during the 1954 and 1955 melt seasons. These analyses are described in this section.

7-08.02 Description of 1954 and 1955 seasons. - The snowpack on 1 April was above normal in 1954 and somewhat below normal in 1955. During April, 1954, melting conditions prevailed and light precipitation fell, principally in the form of rain. April, 1955, on the other hand, was characterized by below normal temperatures and above normal precipitation, thereby resulting in a large increase in accumulation of snow. The major portion of the snowpack ablation occurred during May of both years. In 1954 the last few days of May and the first half of June were cold and wet, thereby retarding the melt of the remnants of the snowpack.

7-08.03 Progression of snow-cover depletion. - Plate 7-5 presents the results of the aerial observations of snow cover on the Boise River basin above Twin Springs, Idaho, during the 1954 and 1955 melt seasons. Principal streams and elevation contours are shown on each of the basin maps to convey a general idea of the topography. Figure 3 on plate 7-5 shows the location of hydrometeorological stations within the basin and in the surrounding area. Plate 7-6 shows the hydrometeorological events for each of the two years, including estimated basin precipitation (both rain and snow are shown separately), mean daily temperature at Atlanta (elev. 6000 ft msl), daily discharge hydrographs for Boise River near Twin Springs, Idaho, for the period March through June, and snowpack water equivalents for snow courses within the basin or adjacent areas for those dates for which records are available. Also shown are the observed snow-cover data, plotted on the same time scale. For times between observations, the 1955 values are interpolated by means of the snow cover-generated runoff relationship (corrected for subsequent precipitation), shown in figure 3, plate 7-6. For 1954, estimates of snow cover between observations were made by drawing a smooth curve drawn through the four observed points thus defining the snow-cover depletion only in a general way. Precipitation and temperature data, between dates of observation, suggest significant deviations between the actual cover and that shown by the snow cover-time curve.

7-09. SUMMARY AND CONCLUSIONS

7-09.01 Snow-cover information is, like temperature or heat supply, an important hydrometeorological element. Snow cover is a factor in all hydrologic problems which involve basin snowmelt. At present systematic snow-cover surveys are being made in a number of basins. Despite the complexity of the variables affecting the snow-cover depletion, the hydrologist is able to approximate the snow-covered area between snow-cover surveys using available hydrometeorological data.

7-09.02 The recession of snow cover is very slow early in the melt season compared to ablation of the snowpack or runoff. Since areas of homogeneous heat supply exhibit uniform melt rates, the snow cover depletes gradually to a thin layer. A sudden increase in depletion then takes place. In years with very deep snow, a large amount of snow-depth reduction or runoff takes place before the appearance or substantial enlargement of the snow-free areas in the basin. The principal factors affecting the snow-cover depletion are the variations in snow deposition and variations in snowmelt, both of which are affected by terrain features, including orientation, steepness of slope, elevation, and forest cover. The snow-cover depletion-runoff patterns vary between basins in accordance with the difference in topography and ground-water character. Variation is also expected within each watershed from year to year on account of differences in the snowpack accumulation at the onset of the snowmelt runoff season.

7-09.03 During the winter accumulation period the determination of the snow cover is relatively simple and accurate; the snowline is well defined and coincides with an elevation contour. The area-elevation curve is used in determining the snow-covered area. In the absence of snowline or snow-cover surveys, a current snow-course survey may be used to determine snowline elevations. The water equivalent-elevation curve, even though poorly defined, will indicate the average elevation below which no snow exists on the drainage basin. The snow-covered area, as of the date of snow-course curvey, can be determined from the area-elevation curve or from the snow chart, shown in figure 1, plate 4-2 of chapter 4. The snowline elevation subsequent to the most current snowline survey can be estimated by reducing the snow wedge at the time of the survey, by an amount proportional to heat supply, or by lowering the snowline elevation if subsequent precipitation, in the form of snow, caused the snowline to advance to a lower elevation.

7-09.04 During the active melt season, the determination of an average snowline is not dependable because the snowline is not as well defined as in the accumulation period. The lower portion of the snow wedge is quite ragged or patchy for 1000 feet or more in elevation. In general, this ragged zone is higher on southerly slopes than it is on northerly slopes. It is less patchy and lower in a heavily forested area than on an open slope of same exposure. During the period of active melt season, the use of an average snowline elevation for determining the snow-covered area can be considered only a rough approximation. The most dependable basin snow-cover estimates are made from aerial reconnaissance surveys. Snow cover between surveys is determined in accordance with runoff and with the meteorological events affecting new snow cover. A characteristic of snow-cover depletion is the definite pattern in which snow depletes from year to year on a given basin. As a result of this year-to-year uniformity, only a few sites, representative of the topography of the watershed, need be observed as an index to snow cover.

7-09.05 The determination of snow-covered area by means of established "cover-runoff" or "cover-ablation" curves is accomplished from analysis of historical data. If accumulated runoff is plotted in percentage of the season's total from beginning of the appearance of the effective spring melt at the stream gaging station, the curves will tend to be close together and serve as guide for the extrapolation of the snow-cover recession for the melt season considered. Undoubtedly "cover-mass" relationships can be improved if a parameter such as the initial basin snow cover is used. The relation between snow cover and "future runoff" provides a method for estimating residual runoff. Forecasts based on those relationships are particularly useful in connection with regulation of reservoirs near the end of the filling period.

7-10. REFERENCES

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2/ CROFT, A.R., "Some factors that influence the accuracy of water-supply forecasting in the Intermountain Region," Trans. Amer. Geophys. Union, Vol. 27, No. 11, 1947, pp. 375-388.

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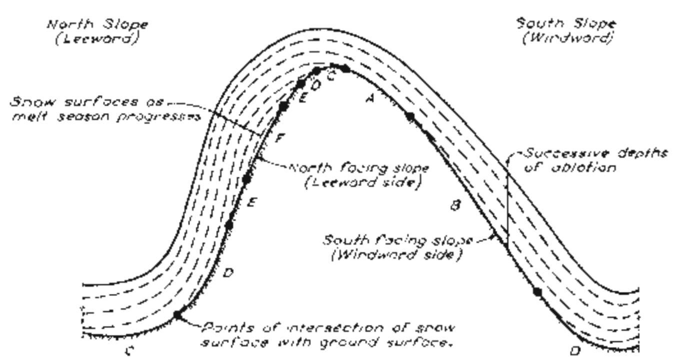
AERIAL PHOTOGRAPH, CSSL, SHOWING FOREST COVER

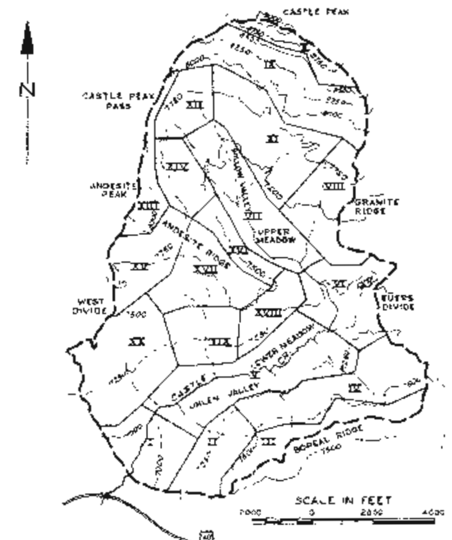
FIGURE 1



Note:
This diagram illustrates the progress of depletion of the snow cover during period of active melt. The sequence of appearance of bare ground are lettered successively beginning with the letter A. Relative melt rates are shown by the vertical distance between snow surface lines corresponding to various dates. Rate of snow cover depletion for a particular area depends chiefly on the orientation of the slope, which affects both accumulation of snow and the supply of heat for melting the snow. Note the drift effect on the accumulation of snow on windward and leeward slopes near edge of crest.

SCHEMATIC DIAGRAM OF SNOW COVER DEPLETION, UNFORESTED SLOPES, CSSL

FIGURE 5



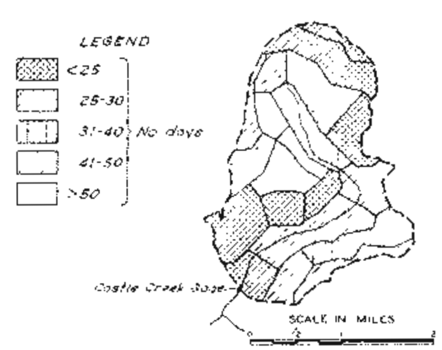
TOPOGRAPHIC UNITS, CSSL

DRAINAGE AREA 3.96 SQUARE MILES

FIGURE 2

DATE WHEN SNOW COVER IS REDUCED TO 60% OF AREA OF TOPOGRAPHIC UNIT

Topo unit	Date	Days after 10 Apr	Topo unit	Date	Days after 10 Apr
I	4 May	24	XIII	13 May	29
V	7 "	27	XIV	5 June	55
VI	7 "	27	XVI	10 "	60
II	9 "	29	VII	20 May	40
III	9 "	29	XII	7 "	27
IV	20 "	40			
XV	7 "	27	VIII	2 "	22
XVII	15 "	35	IX	28 Apr	18
XVIII	1 "	21	X	23 "	13
XIX	3 "	23	XI	1 June	50
XX	30 Apr	18			



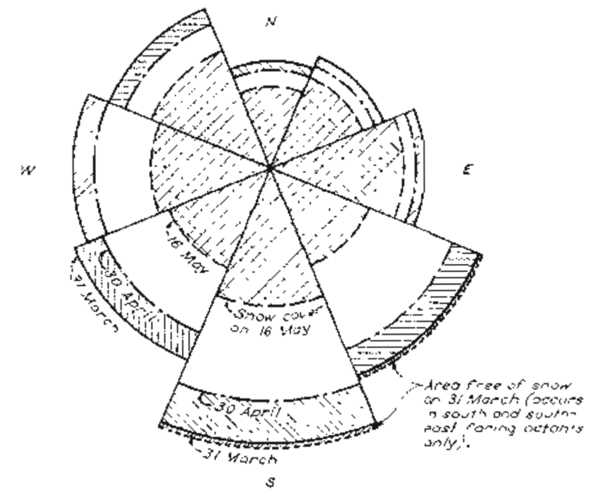
DAYS AFTER 10 APRIL 1947 WHEN 60 PERCENT OF THE AREA IN EACH UNIT WAS COVERED WITH SNOW

FIGURE 6

COVER vs ORIENTATION

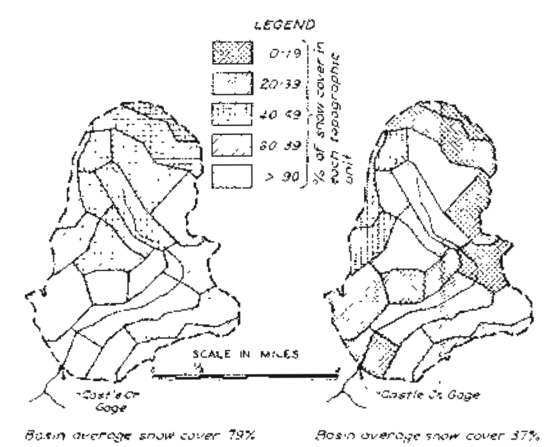
Orientation	Area in % basin	Snow cover in % basin 31 Mar	30 Apr	16 May	Median el.
N	4.0	4.0	3.3	2.3	7420
NE	5.0	5.0	4.1	3.5	7550
E	8.0	8.0	7.0	6.0	7620
SE	18.0	17.6	13.3	4.0	7410
S	27.0	26.1	18.2	6.7	7510
SW	15.0	15.0	11.1	4.1	7610
W	13.0	13.0	10.3	4.9	7530
NW	10.0	10.0	8.3	5.6	7360
Total	100.0	98.7	75.6	37.1	

Note:
Areas shown in each octant are directly proportional to snow covered areas for that octant in basin.



PROGRESS OF SNOW COVER DEPLETION WITH RESPECT TO ORIENTATION CSSL, 1947

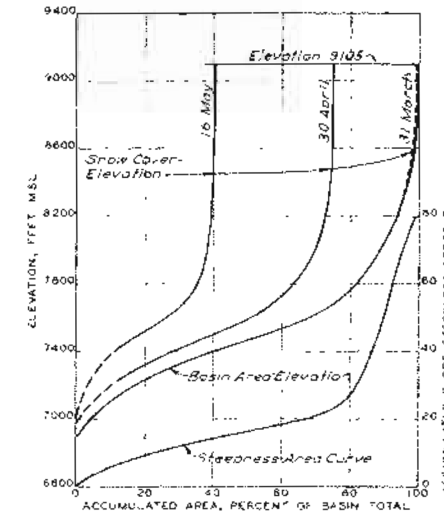
FIGURE 3



30 APRIL 1947 15 MAY 1947

AREAL DISTRIBUTION OF SNOW COVER

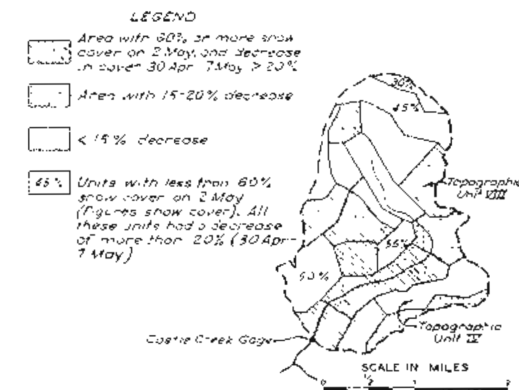
FIGURE 7



SNOW COVERED AREA-ELEVATION CURVES, CSSL, 1947

AREA-STEEPNESS CURVE, CSSL

FIGURE 4



SNOW COVER AT TIME OF PEAK FLOW ON 1 MAY 1947

FIGURE 8

Notes:

1. On 31 March snow cover was 100 percent over all topographic units, except on a few very steep slopes of high elevations.
2. The basin snow water equivalent depth reached its maximum value on about 10 Apr. when snow melt runoff began to appear at the gaging station in Castle Creek.
3. On 15 April approximately 92 percent of the basin was covered with snow.

SNOW INVESTIGATIONS SUMMARY REPORT

SNOW HYDROLOGY

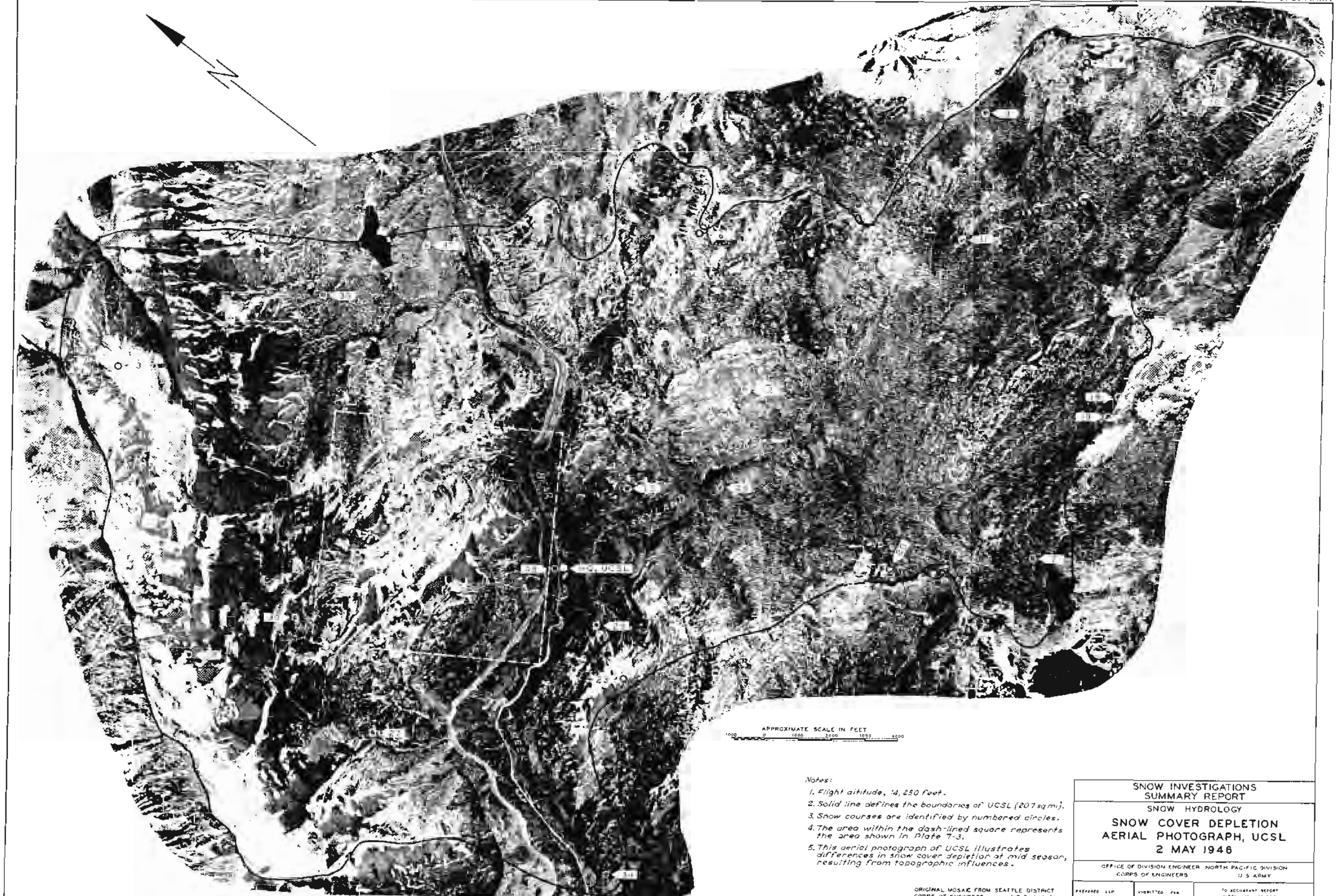
SNOW COVER DEPLETION CSSL, 1947

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

TO ACCOMPANY REPORT DATED 30 JUNE 1956

PD-20-25/40

PLATE 7-1



Notes:

1. Flight altitude, 14,250 feet.
2. Solid line defines the boundaries of UCSL (207 sq mi).
3. Snow courses are identified by numbered circles.
4. The area within the dash-lined square represents the area shown in Plate 7-3.
5. This aerial photograph of UCSL illustrates differences in snow cover depletion at mid season, resulting from topographic influences.

ORIGINAL MOSAIC FROM SEATTLE DISTRICT CORPS OF ENGINEERS NO D-6-7-61

SNOW INVESTIGATIONS SUMMARY REPORT

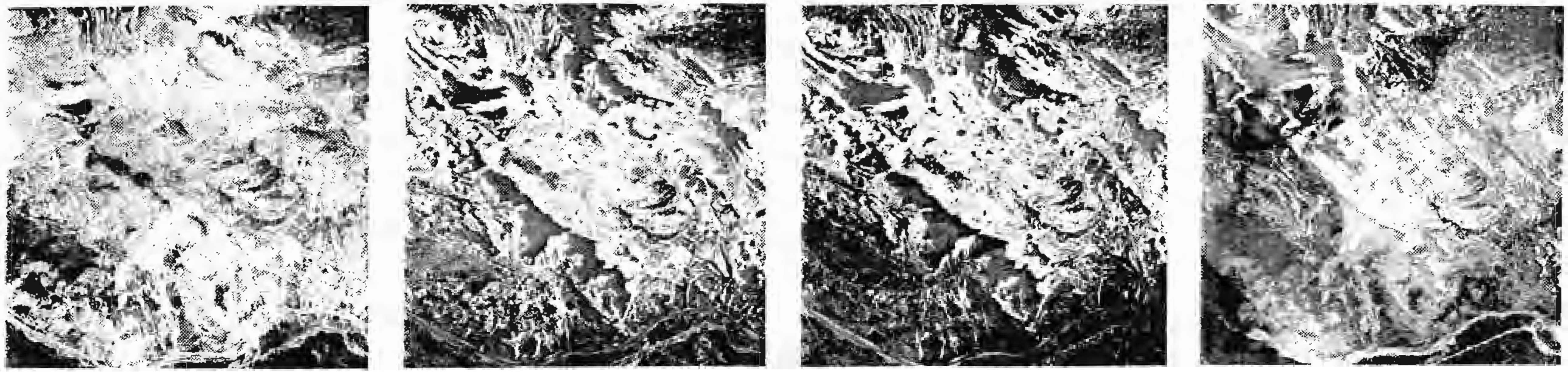
SNOW HYDROLOGY

SNOW COVER DEPLETION AERIAL PHOTOGRAPH, UCSL 2 MAY 1946

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

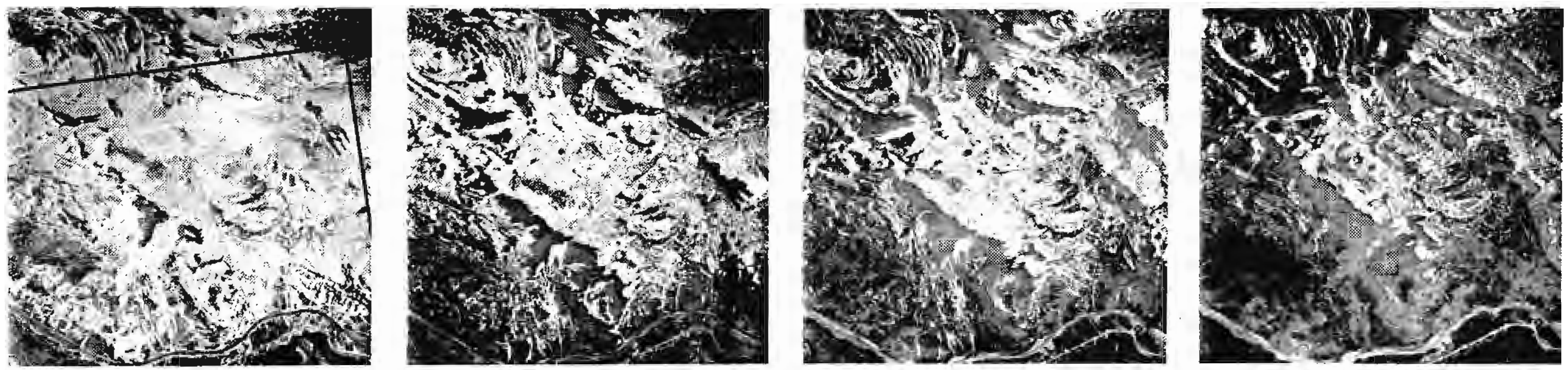
PD-20-25/41

PLATE 7-2



7 APRIL 24 APRIL 2 MAY 17 MAY

FIGURE 1 — 1946 AERIAL PHOTOGRAPHS



16 APRIL 3 MAY 8 MAY 20 MAY

FIGURE 2 — 1947 AERIAL PHOTOGRAPHS

Note:
The photographs illustrate that each year the sequence of areas going bare is the same. The pattern of growth of bare patches is similar each year if the forest cover is unchanged. The area encompassed in each photograph of this series is approximately one square mile. See Plate 7-2 for general location and orientation of area.

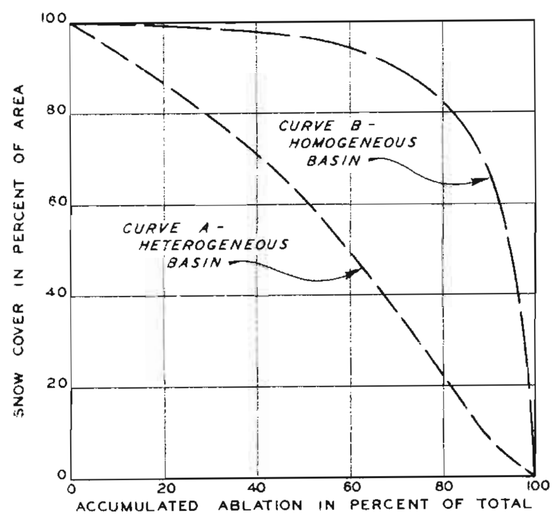
SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

PROGRESS OF SNOW-COVER DEPLETION
UCSL, 1946 AND 1947

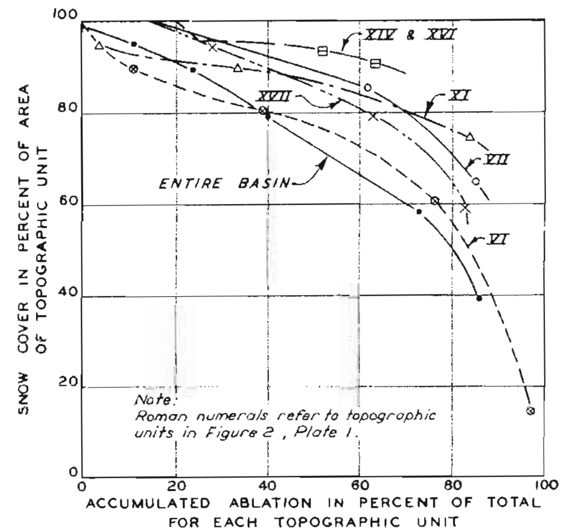
OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS U.S. ARMY

PREP:	SUBM:	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN:	APPR:	PD-20-25/42



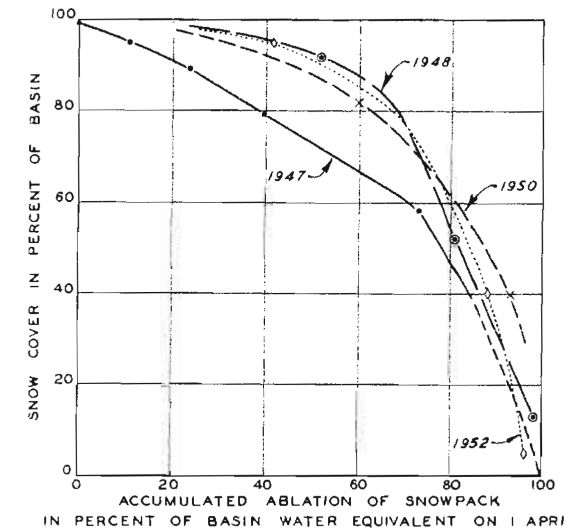
SCHEMATIC DIAGRAM OF SNOW COVER DEPLETION - ABLATION RELATIONSHIP

FIGURE 1



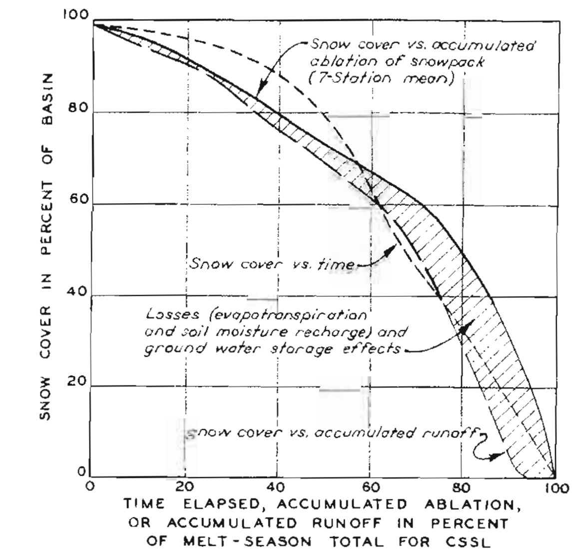
SNOW COVER DEPLETION - ABLATION RELATIONSHIP, CSSL, 1947

FIGURE 2



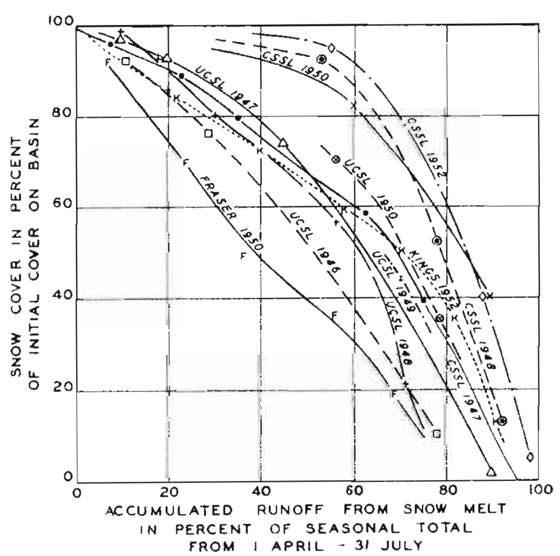
SNOW COVER DEPLETION - ABLATION RELATIONSHIP, CSSL

FIGURE 3



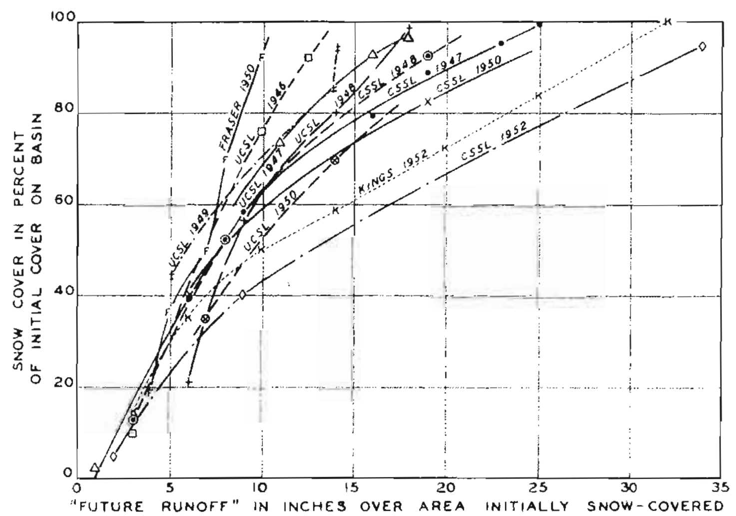
SNOW COVER DEPLETION, ABLATION AND ACCUMULATED RUNOFF, CSSL, 1947

FIGURE 4



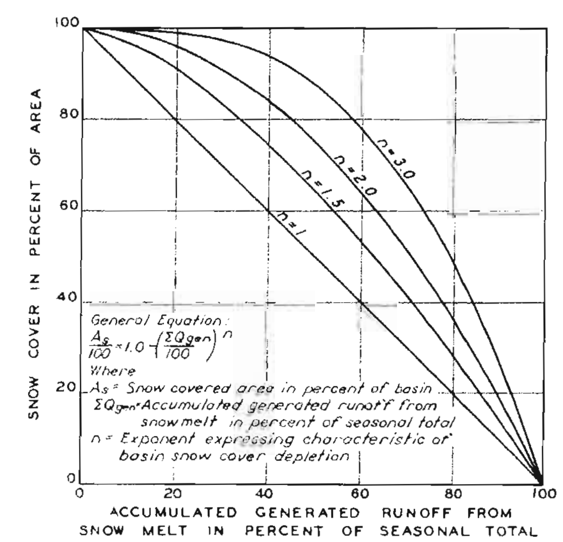
SNOW COVER DEPLETION - RUNOFF RELATIONSHIPS

FIGURE 5



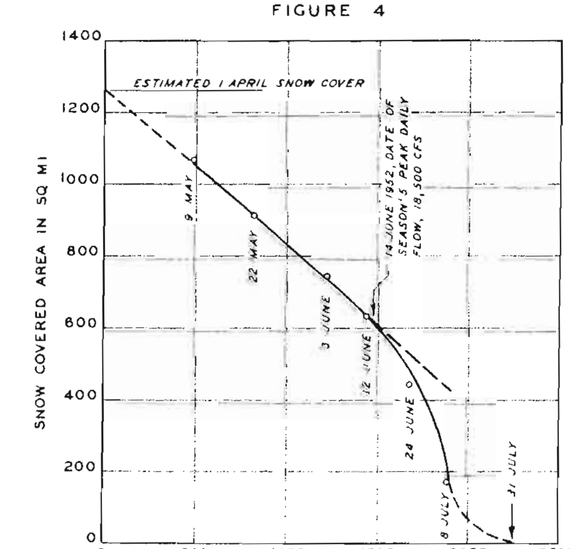
SNOW COVER - "FUTURE RUNOFF" RELATIONSHIPS

FIGURE 6



MATHEMATICAL EXPRESSIONS FOR SNOW COVER DEPLETION

FIGURE 7



ACCUMULATED RUNOFF IN 1,000 AC FT (1 DAY LAG)
(DAILY OBSERVED INFLOW TO PINE FLAT RESERVOIR, SACRAMENTO DISTRICT, CALIFORNIA, 1 APRIL - 31 JULY 1952)

SNOW COVER - RUNOFF RELATIONSHIP KINGS RIVER, CALIFORNIA

FIGURE 8

Notes for Figures 2, 3, 4, 5 and 6:

1. Accumulated runoff from 1 April - 31 July is corrected for rainfall between snow cover surveys but not adjusted for ground water recession flow.
2. Initial snow cover is the snow covered area as of 1 April.
3. In Figure 3, if the accumulation for 1948, 1950 and 1952 began at 98 percent snow cover the curves would fall close to 1947 curve.

SNOW INVESTIGATIONS SUMMARY REPORT

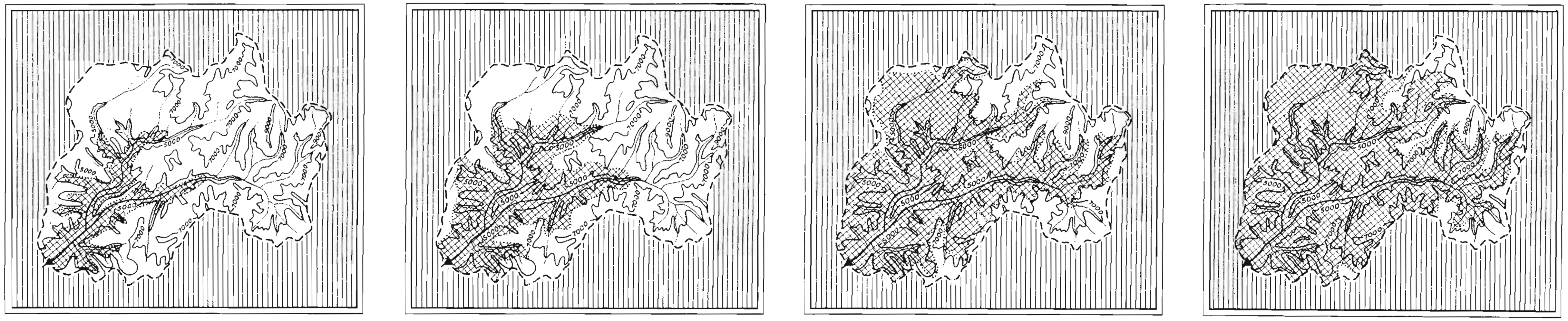
SNOW HYDROLOGY

SNOW COVER DEPLETION, ABLATION OF THE SNOWPACK, AND RUNOFF

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

PREPARED P.B.B. SUBMITTED P.B.B.
DRAWN H.E.S. APPROVED D.M.R.

PD-20-25/43



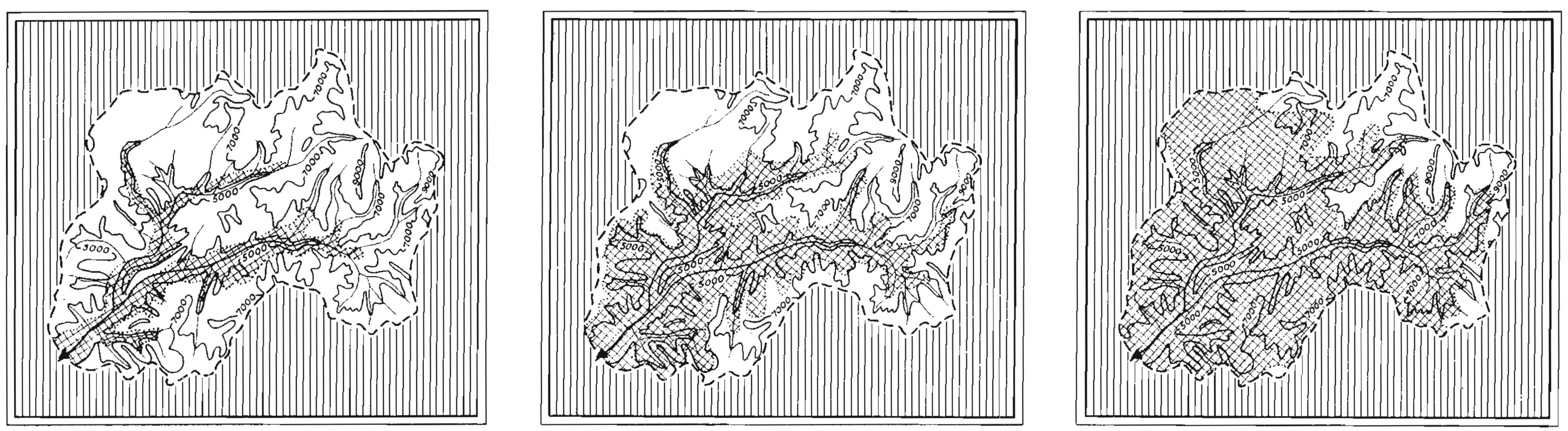
31 MARCH 1954 - 86 % SNOW COVER

22 APRIL 1954 - 69 % SNOW COVER

6 MAY 1954 - 38 % SNOW COVER

20 MAY 1954 - 18 % SNOW COVER

FIGURE 1 - 1954 AERIAL RECONNAISSANCE



5 MAY 1955 - 86 % SNOW COVER

22 MAY 1955 - 59 % SNOW COVER

8-9 JUNE 1955 - 22 % SNOW COVER

FIGURE 2 - 1955 AERIAL RECONNAISSANCE

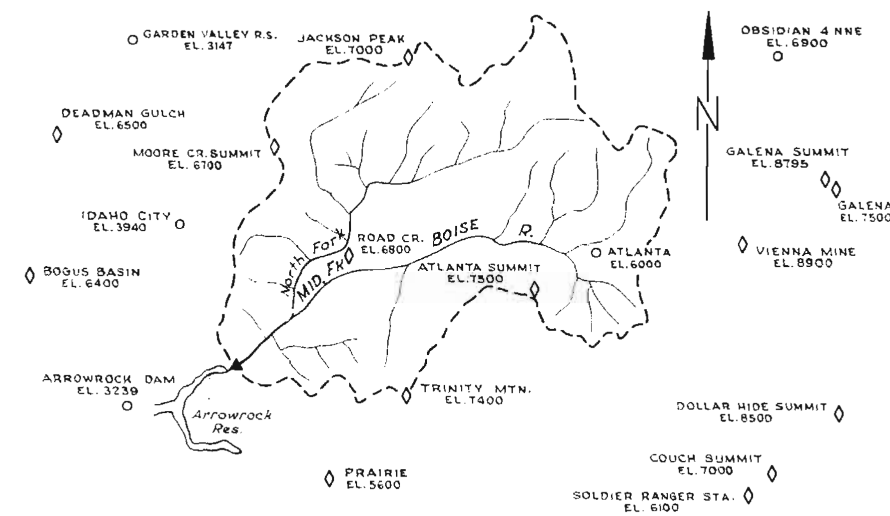


FIGURE 3 - HYDROMETEOROLOGICAL STATIONS

LEGEND

Snow-free Area } From aerial snow line reconnaissance on dates shown.
Snow Covered Area
○ Meteorological Station
◊ Snow Course
▲ Stream Gage

SUMMARY OF WEATHER				
YEAR	MARCH	APRIL	MAY	JUNE
1954	Temperature slightly below normal. Precipitation 80% of normal. Periods of major storms: 8-12, 7-21, 24-28. Snowfall at lowest elevation on 20th.	Temperature and precipitation slightly above normal. Maximum snow accumulation during first week. Storms: 3-7, 9-10, 13-15, 18-19, 20-21, 27-28, 30. Effective snow-melt runoff began on 10th.	Above normal temperatures. Peak stream flow on May 21st. Storms: 1, 16, 21-23, 25-31	Subnormal temperature. Storms: 1-2, 5-8, 8-13, 15-17, 26-29.
1955	Temperature considerably below normal. Precipitation near normal with snow at low levels. Storms: 1-5, 9-16, 22-24, 28-31.	Temperature below normal. Precipitation above normal. Storms: 1-4, 10-30. Effective snow-melt runoff began on 28th.	Temperature below normal. Precipitation above normal. Maximum snow accumulation during first week. Storms: 1-4, 14-17, 21-22, 25-28.	Temperature below normal. Precipitation near normal. Peak stream flow on 10th. Storms: 2-3, 12-15, 24, 26, 28-29.

Note: Snow cover observations by aerial reconnaissance obtained from Walla Walla District, U. S. Corps of Engineers.

SCALE IN MILES

10 0 10 20

SNOW INVESTIGATIONS
SUMMARY REPORT

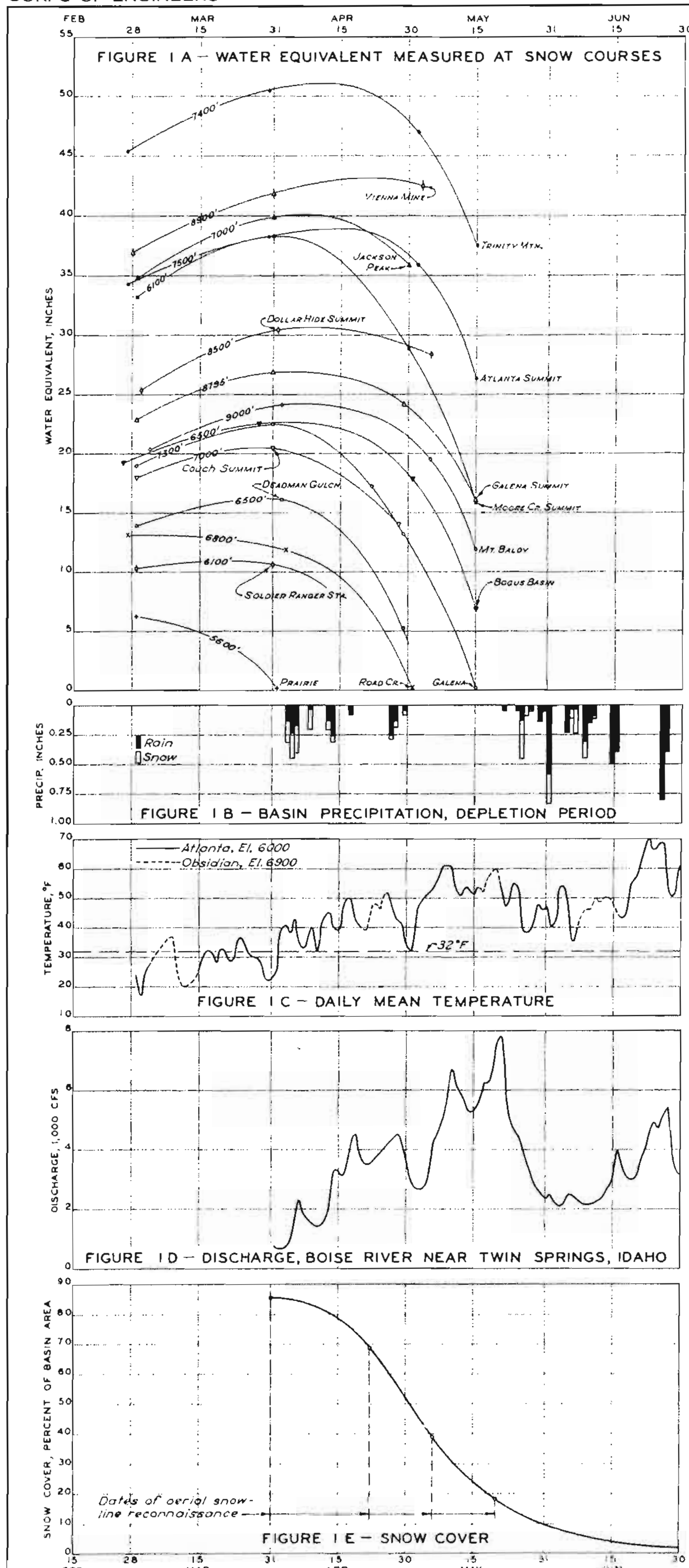
SNOW HYDROLOGY

SNOW COVER OBSERVATIONS
1954 - 55

BOISE RIVER ABOVE TWIN SPRINGS, IDAHO
DRAINAGE AREA 830 SQ. MI.

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

PREPARED: PM	SUBMITTED: PBB	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: NJM	APPROVED: DMR	PD-20-25/44



1954

NOTES for FIGURES 1A and 2A:

1. Lines between points are primarily for identification of snow courses and show only the general trend of the water equivalent variation between measurements. Actually the accumulation and depletion of the snowpack is very irregular.
2. Location of snow courses is shown in Figure 3, Plate 7-5.

NOTE for FIGURES 1B and 2B:

Basin precipitation computed from 4-Station average, adjusted to represent basin amounts on basis of normal annual precipitation.

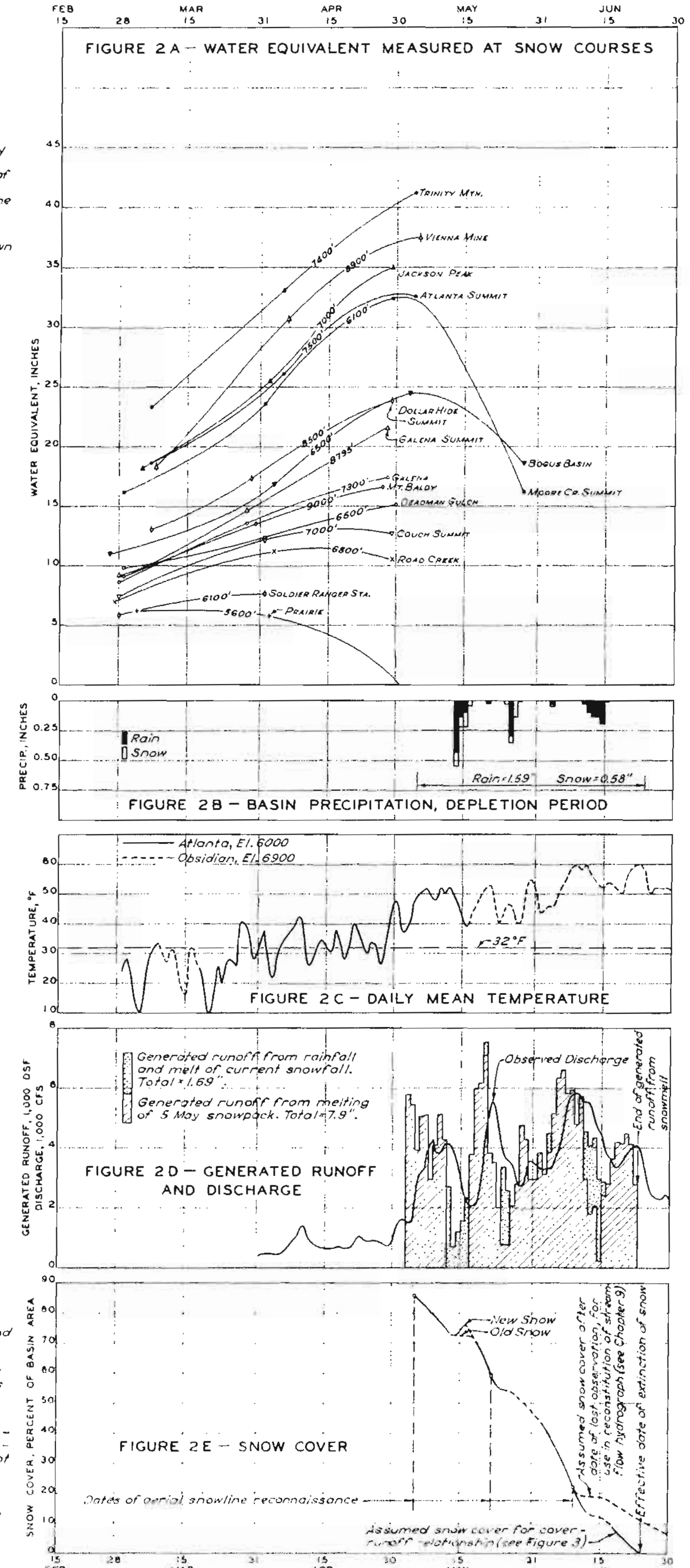
NOTES:

FIGURE 1E

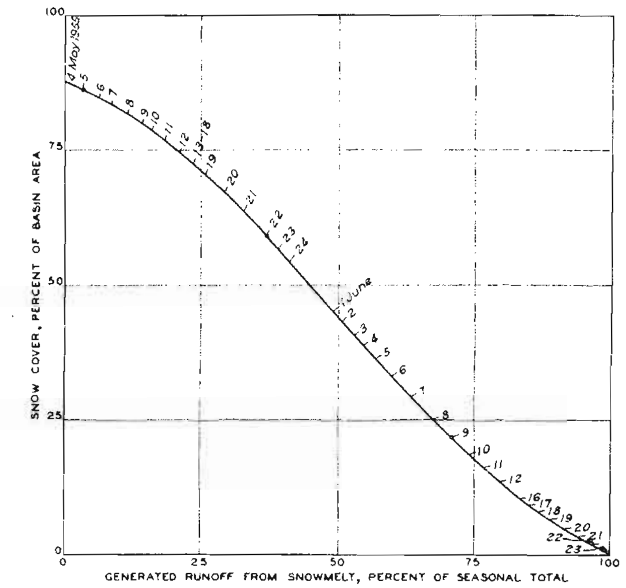
Curve shows only the general trend between observations of snow cover. No attempt was made to estimate the probable values between observation dates as was done for 1955, Figure 2E.

FIGURE 2E

1. Snow cover during periods of precipitation (---), estimated by considering temperature and percent of basin above estimated snow isotherm.
2. Snow cover between storms and observations interpolated with aid of Figure 3, upper right.



1955



NOTE:

This curve is derived from data found in Figures 2D and 2E. The effect of new snow and rain (coverage and runoff) was estimated and the curve adjusted accordingly to represent the cover-runoff relationship for the basin snow as observed on 5 May 1955. This is the date when appreciable snowmelt rise in the discharge hydrograph began. Season's total runoff from the melt of the 5 May snowpack (with 86% cover) was 7.9 inches.

FIGURE 3 – SNOW COVER, GENERATED RUNOFF RELATIONSHIP – 1955

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

SNOW COVER DEPLETION
1954 AND 1955

BOISE RIVER ABOVE TWIN SPRINGS, IDAHO
DRAINAGE AREA 830 SQUARE MILES

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

PREPARED: C.W.P.M.	SUBMITTED: P.B.B.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: S.W.	APPROVED: OMK	PD-20-25/45

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°C due to outgoing longwave radiation; the liquid water will freeze, but below this surface layer, the snow remains at 0°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 $0^{o}C$, 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

$$P = 1 - \frac{\rho}{0.92} = 1 - 1.09\,\rho \tag{8-1}$$

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°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°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°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 Movement of water in snow. - 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 $0^{\circ}C$ 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	Trans-mission rate*	Liquid water content**			Duration of observation
				Initial	Peak	End	
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 D is the depth of penetration in inches; i_r and m are the rain and melt intensities in inches per hour; t is the duration in hours; ρ is the density of snow in g/cc; T_s is the temperature of the snow in $^{\circ}C$ below freezing; and f_p'' is the liquid-water-holding capacity of the snow in percent. For a moist snow, $T_s = 0^{\circ}C$, and if the liquid-water deficiency is 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 $\underline{E}$ is equivalent energy to condition the snowpack in percent of melt energy, $\underline{T_s}$ is the average snow temperature below zero, in $^{\circ}$C, and $\underline{f_p''}$ is the liquid-water-holding capacity of the snowpack in percent. Thus, with an average snowpack temperature of -5°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 Formulas for computing runoff delay. - 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 $0^{\circ}C$, 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 $0^{\circ}C$ 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

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

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

$$t_t = \frac{D}{v_t} \tag{8-11}$$

so that

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

and, since $D = W_o/\rho$

$$t_t = \frac{W_o}{\rho \, v_t} \tag{8-13}$$

Total storage of liquid water before appreciable runoff occurs is

$$S = W_c + S_f + S_t \tag{8-14}$$

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

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

The time required to produce runoff is

$$t = t_c + t_f + t_t \tag{8-16}$$

or

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

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°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°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°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

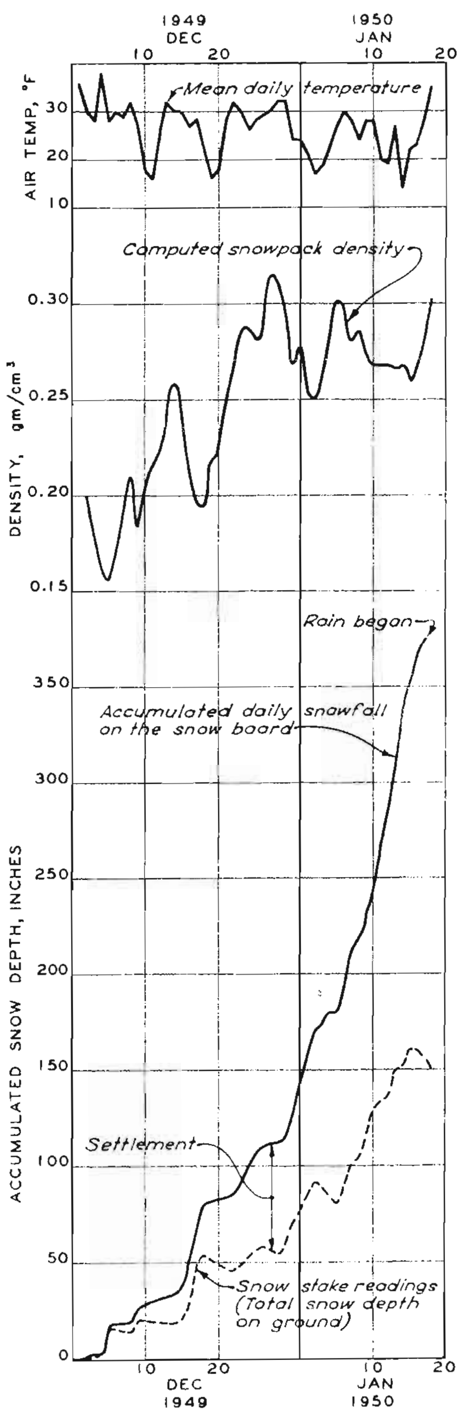
LINE	ITEM	ELEVATION					UNIT	SYMBOL	EQUIVALENT	REMARKS
		6900	6000	5000	4000	3000				
1	Initial snow depth	172	161	98	58	25	in.	D		Observed
2	Initial snow density	0.28	0.30	0.38	0.36	0.40	g/cc	ρ		Observed
3	Initial snowpack water equivalent	48.5	48.3	37.2	20.9	10.0	in.	W_o	ρD	
4	Initial snow temperature	-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	$-W_oT_s/160$	
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.

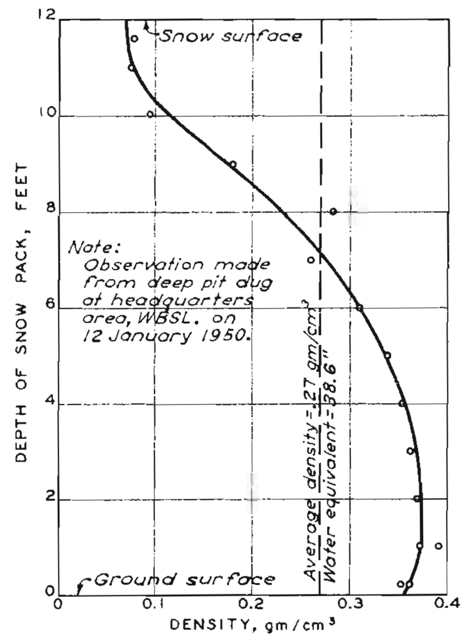


COMPACTION OF WINTER SNOW

FIGURE 1

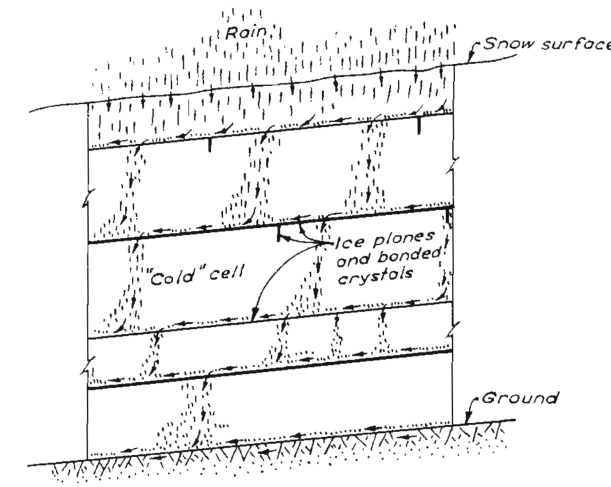
NOTES for FIGURE 1:

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 of 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.



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

FIGURE 2

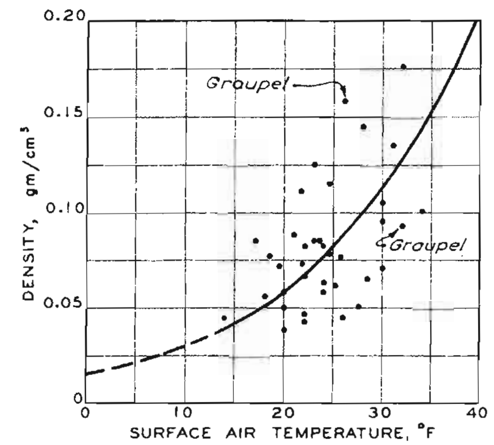


SCHEMATIC DIAGRAM ILLUSTRATING THE FLOW OF WATER WITHIN THE SNOW PACK

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

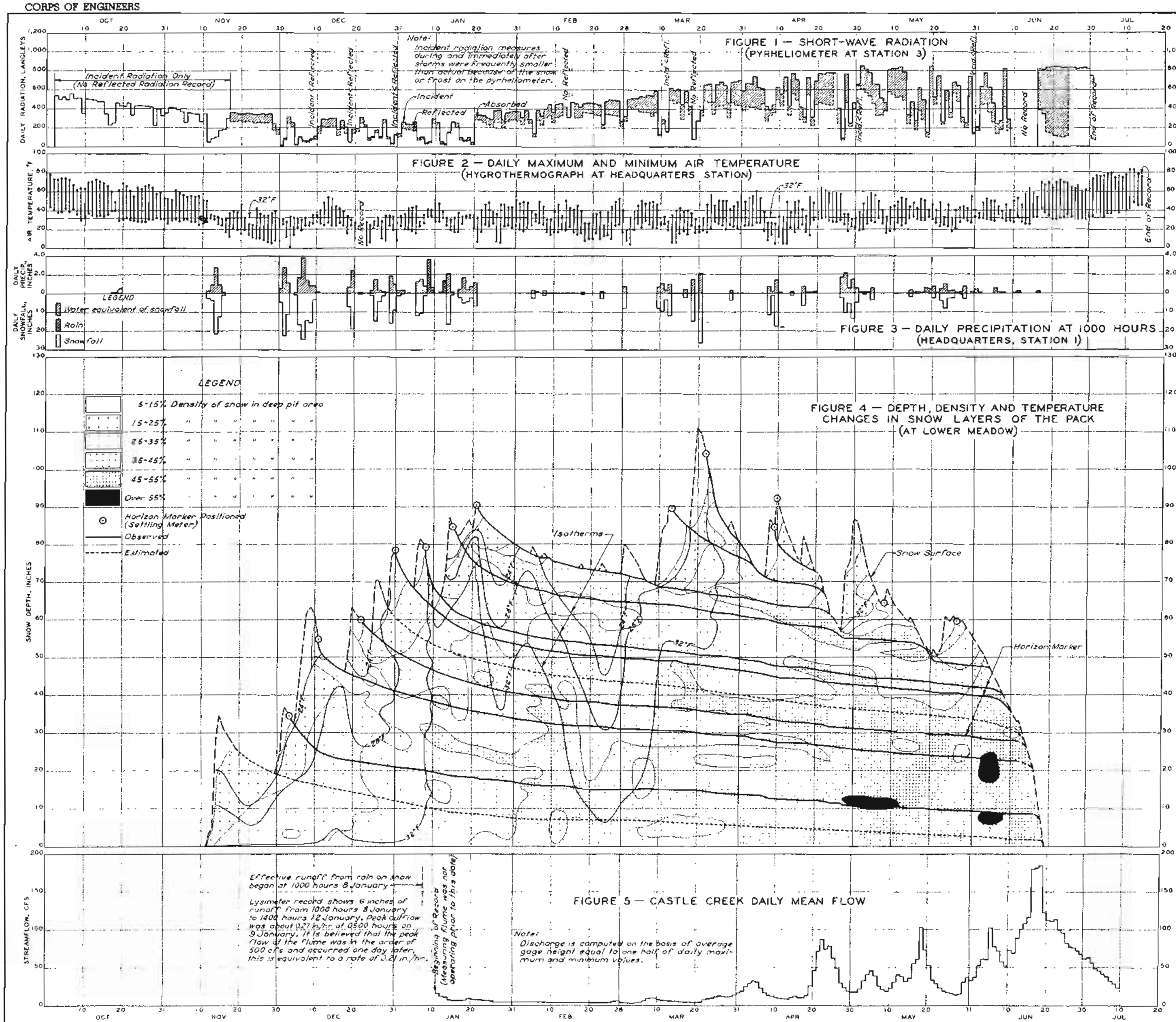
SNOW HYDROLOGY

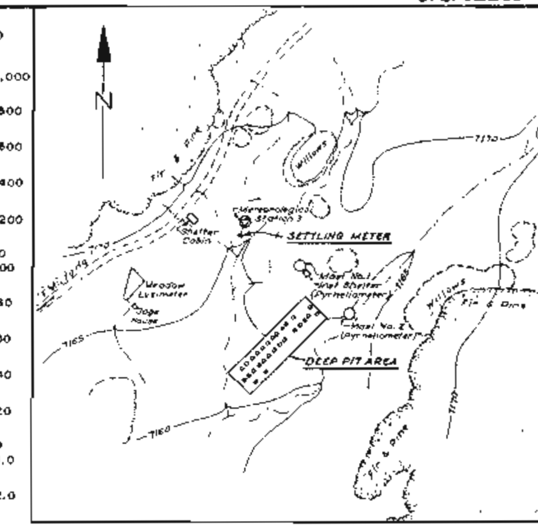
DENSITY AND STRUCTURE OF WINTER SNOWPACK

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

PREPARED: C.B.B. SUBMITTED: R.B.B. TO ACCOMPANY REPORT DATED 30 JUNE 1955
DRAWN: B.J.L. APPROVED: D.M.R.

PD-20-25/46





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 1¼ 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.S.S. R.W.	SUBMITTED: R.G.B.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: A.V.	APPROVED: A.N.R.	PD-20-25/47

PLATE 8-2

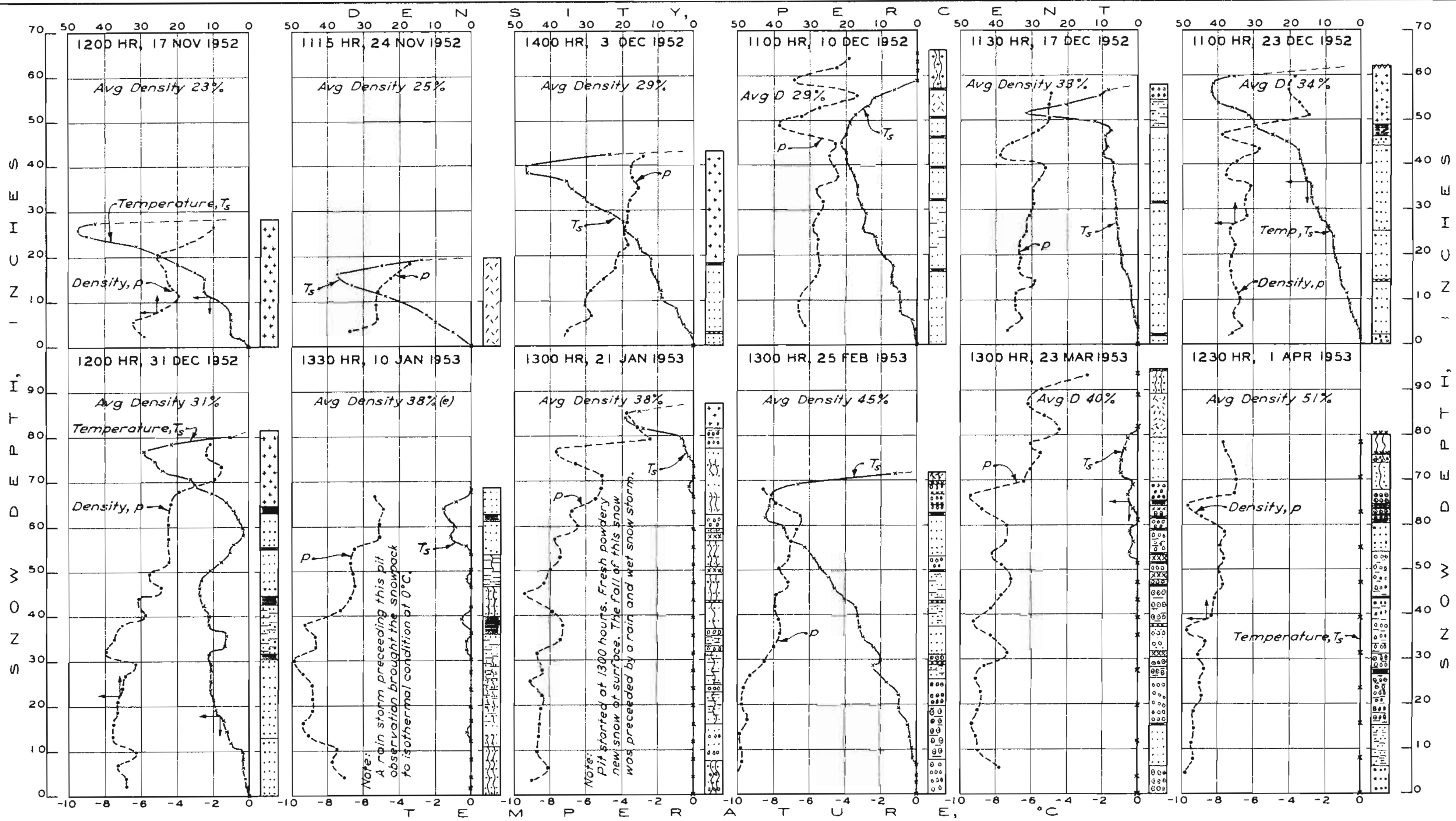


FIGURE 1 — DEEP PIT OBSERVATIONS, CSSL, 1952-53 WATER YEAR

LEGEND

- FEATHERY (DENDRITIC) — "New Snow", "Powder Snow"
- FELTLIKE (INTRANSFORMATION) — "Settling Snow"
- "Old Snow", "Settled Snow" "Firn"
- GRANULAR (ISOMETRIC) — 0 - 1.5 mm Diameter; 1.5 - 3.0 mm Diameter; Over 3.0 mm Diameter; Hoar Frost
- ICE — Compact; Granular
- SURFACE — Wind Erosion; Crust
- WET SNOW — Contains Free Water

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 bimatellic 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.*

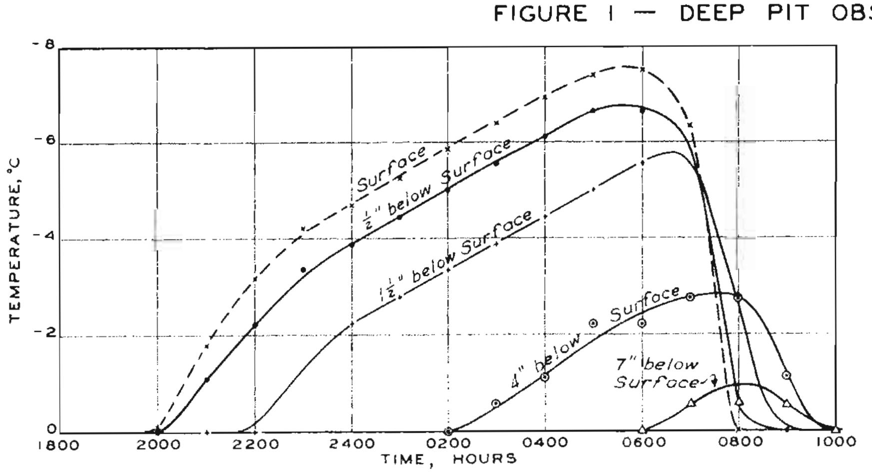


FIGURE 2 — NIGHTTIME COOLING IN SURFACE LAYER OF INITIALLY MOIST SNOW, 12-13 MAY 1954

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.*

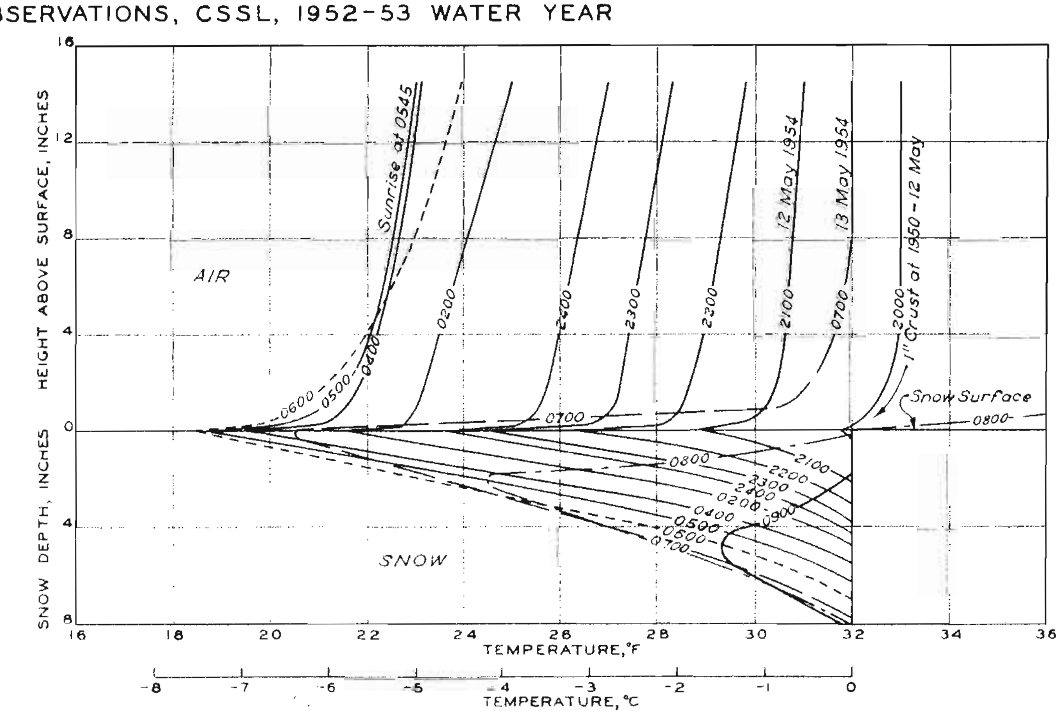


FIGURE 3 — TEMPERATURE PROFILES NEAR SNOW SURFACE DURING NIGHT OF 12-13 MAY 1954

SNOW INVESTIGATIONS SUMMARY REPORT

SNOW HYDROLOGY

SNOWPACK CHARACTERISTICS CSSL

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

PREPARED: DMJ/RB. SUBMITTED: RHB. TO ACCOMPANY REPORT DATED 30 JUNE 1955

DRAWN: AK. APPROVED: ILMR.

PD-20-25/48

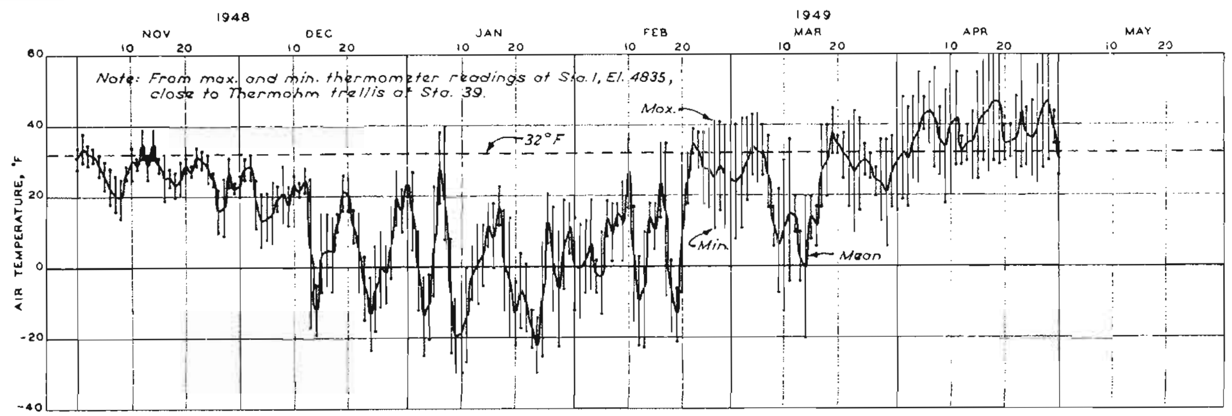


FIG. 1 - AIR TEMPERATURE, UCSL

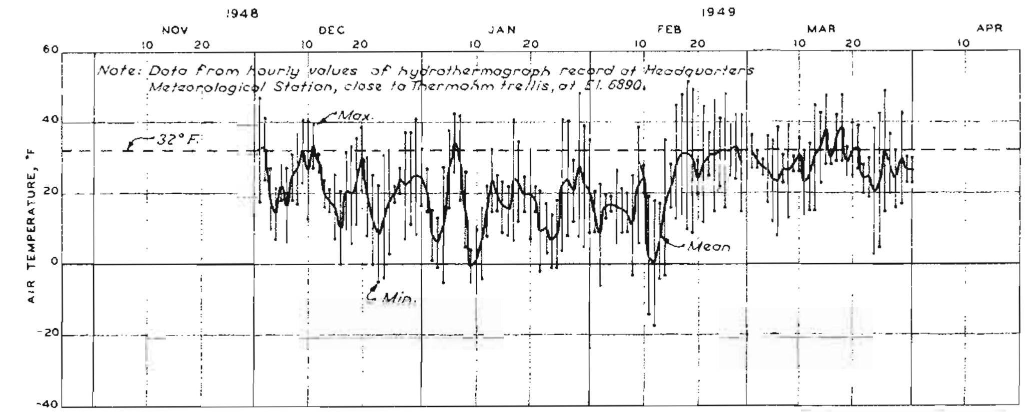


FIG. 3 - AIR TEMPERATURE, CSSL

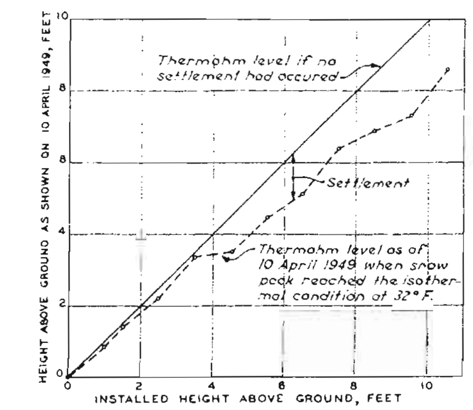


FIG. 5 - POSITION OF THERMOHMS, CSSL

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.

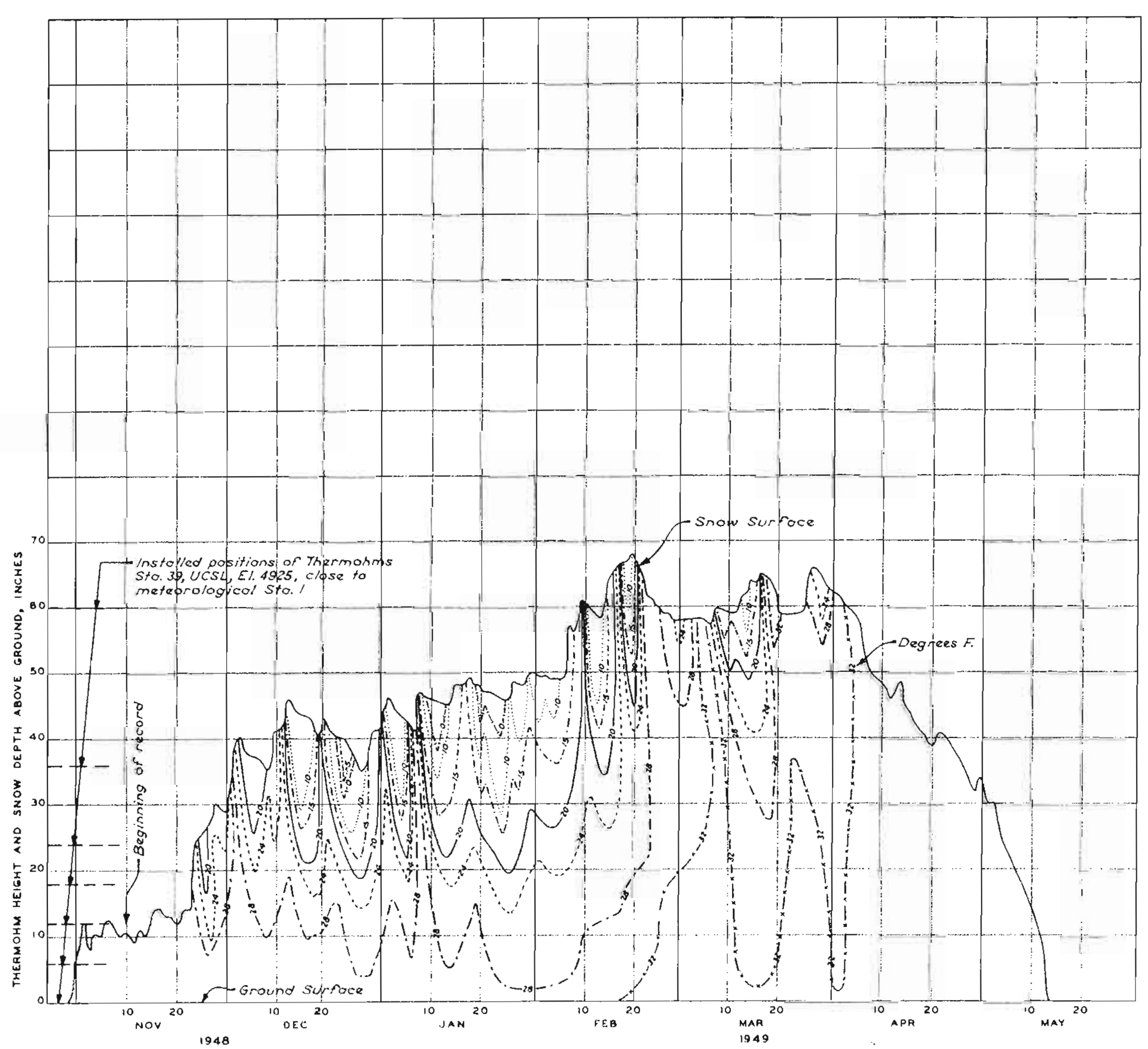


FIG. 2 - ISOTHERMS IN SNOW PACK, UCSL

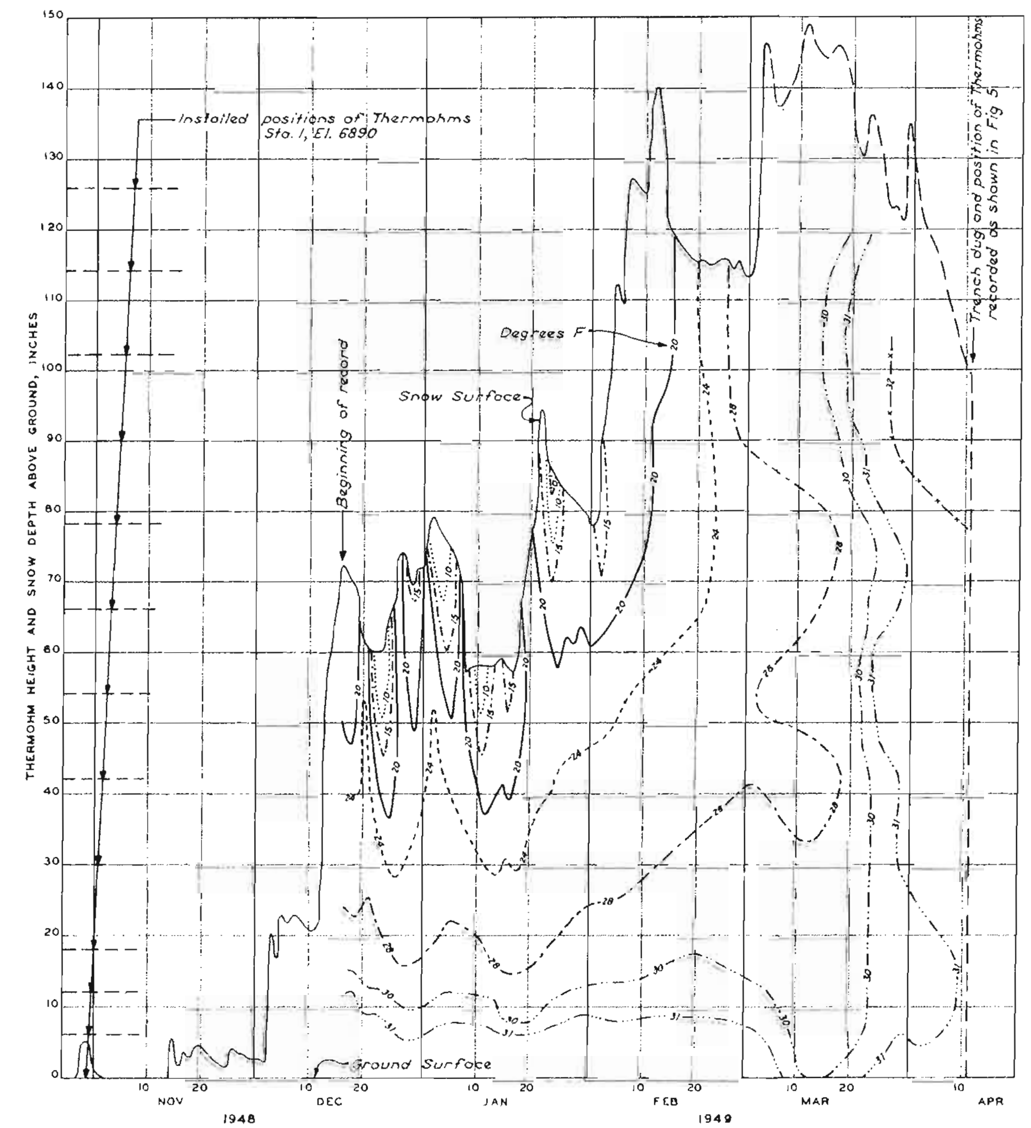


FIG. 4 - ISOTHERMS IN SNOW PACK, CSSL

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 TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: WJM APPROVED: DMR

PD-20-25/49

PLATE 8-4

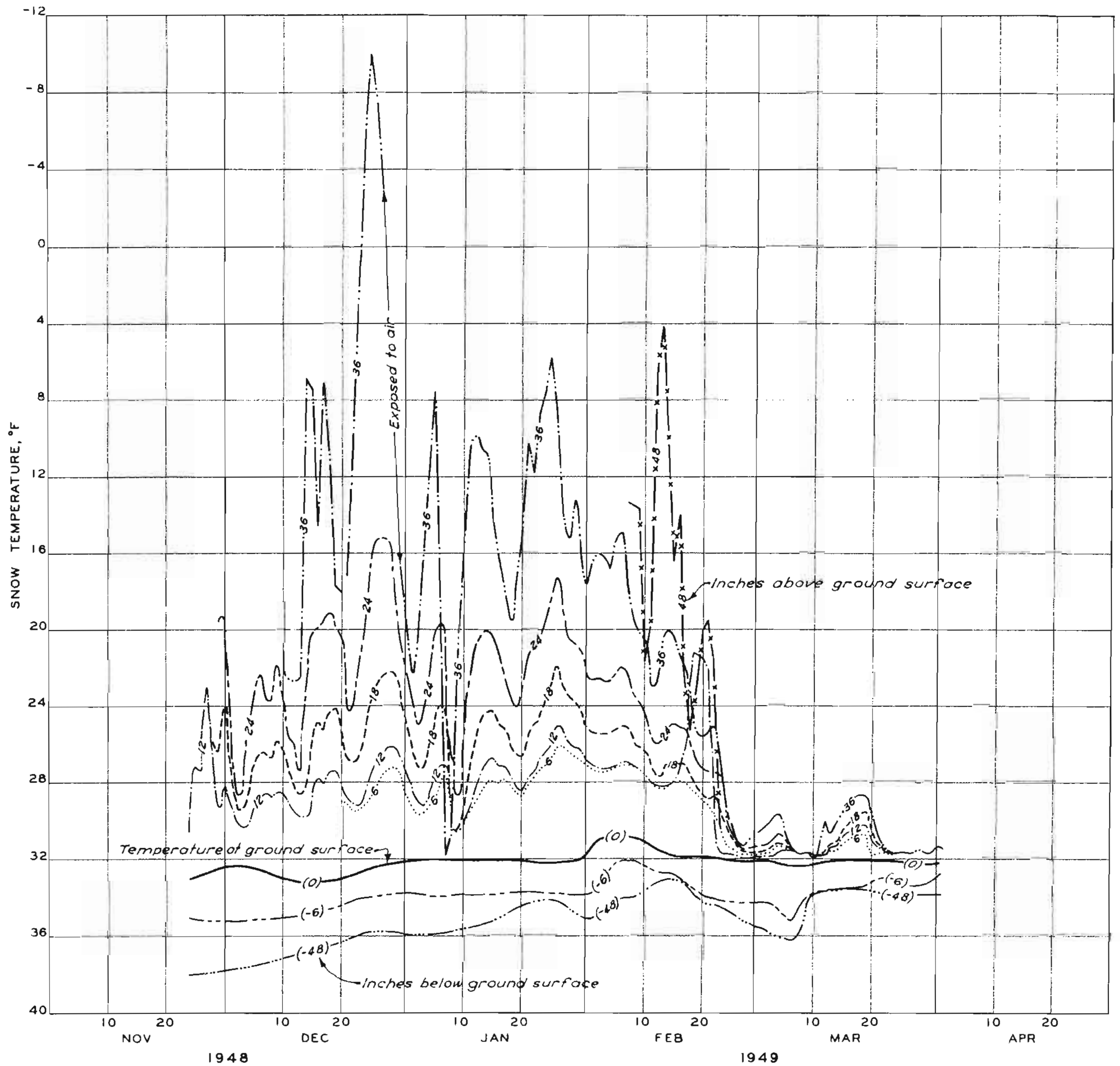


FIGURE 1 — SNOW AND GROUND TEMPERATURES, UCSL

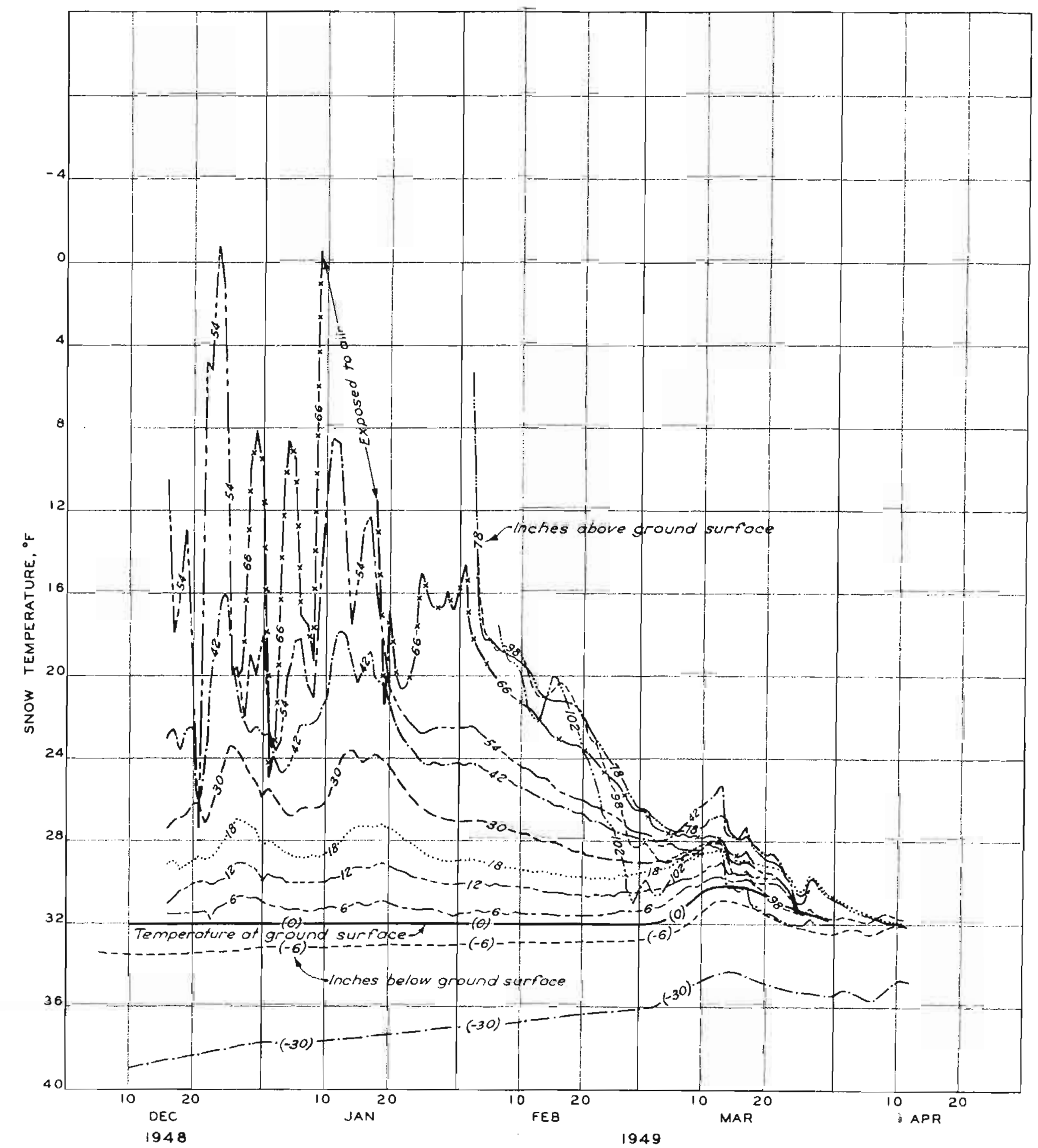


FIGURE 2 — SNOW AND GROUND TEMPERATURES, CSSL

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 of 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.*

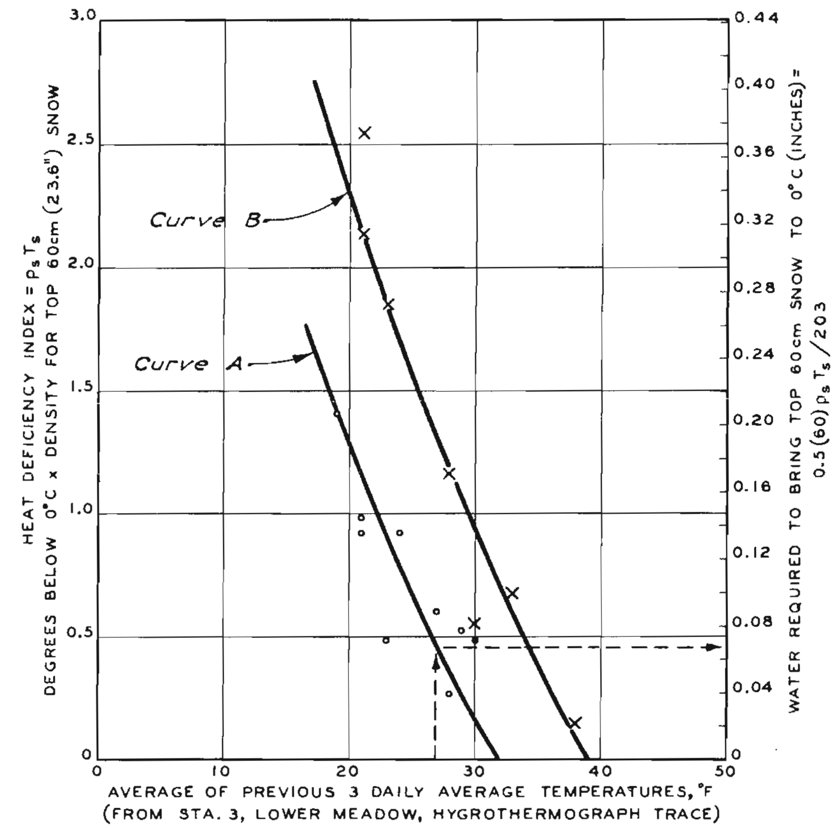
SNOW INVESTIGATIONS
SUMMARY REPORT
SNOW HYDROLOGY

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.	TO ACCOMPANY REPORT DATED 30 JUNE [illegible]
DRAWN: B.V.	APPROVED: D.M.R.	PD-20-25/50

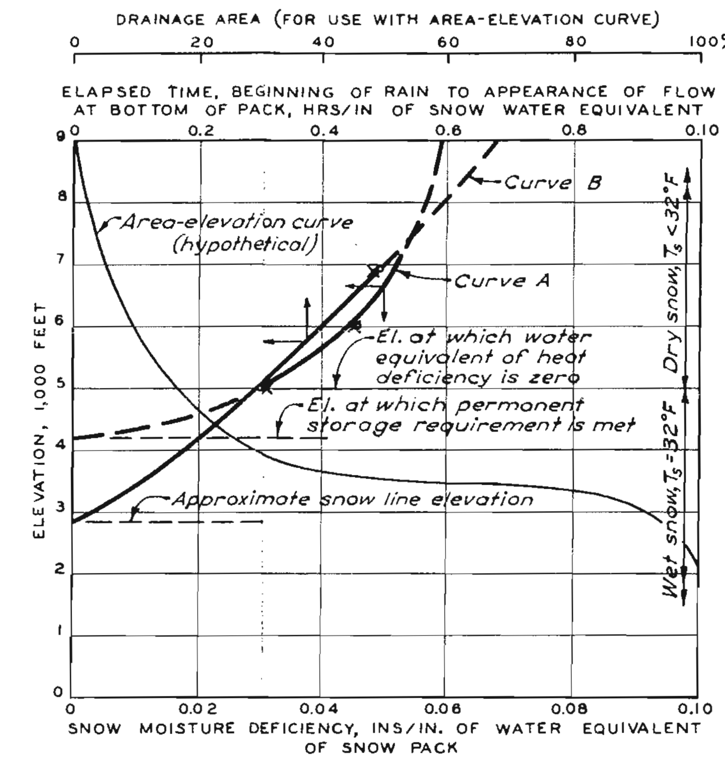


COLD CONTENT AND MOISTURE DEFICIENCY
(TOP 60 CM OF SNOW)

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 (= 60 x 0.32 x 0.5 x 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.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: B.V.	APPR.: D.M.R.	PD-20-25/51

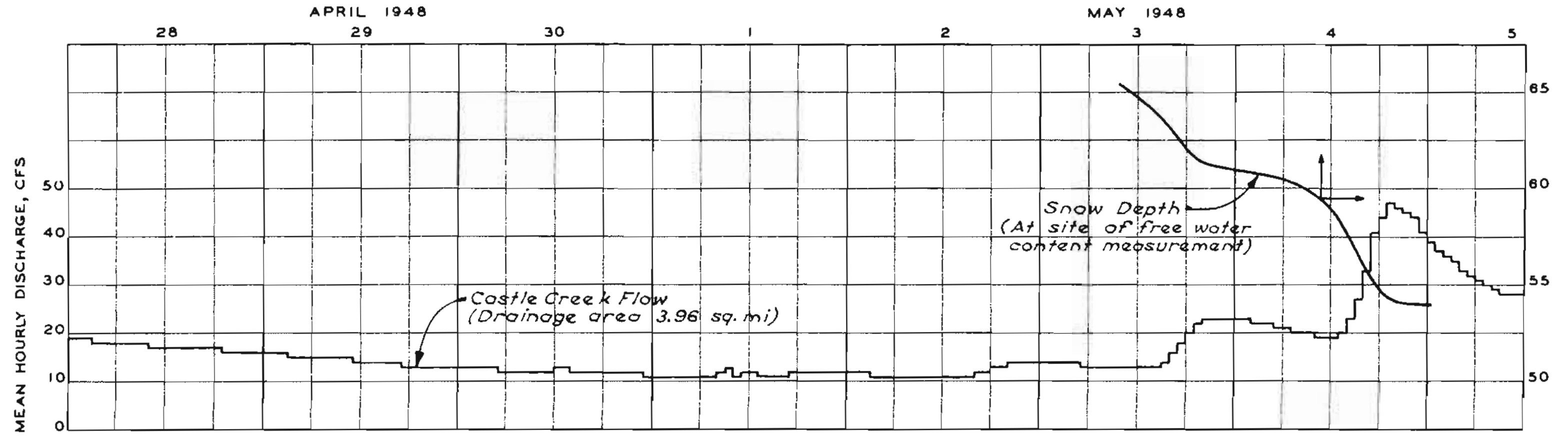


FIGURE 1 - DISCHARGE & SNOW DEPTH

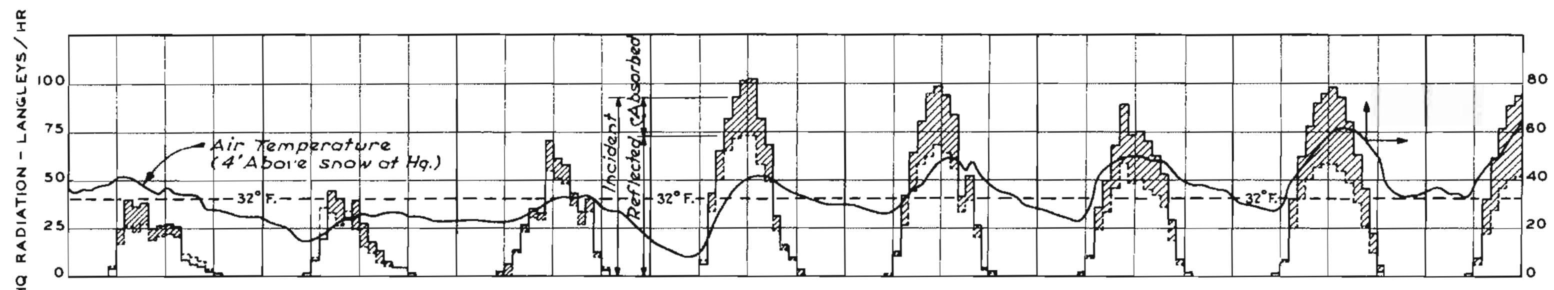


FIGURE 2 - SOLAR RADIATION & TEMPERATURE

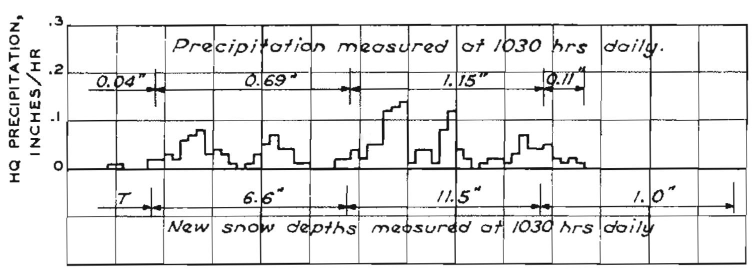
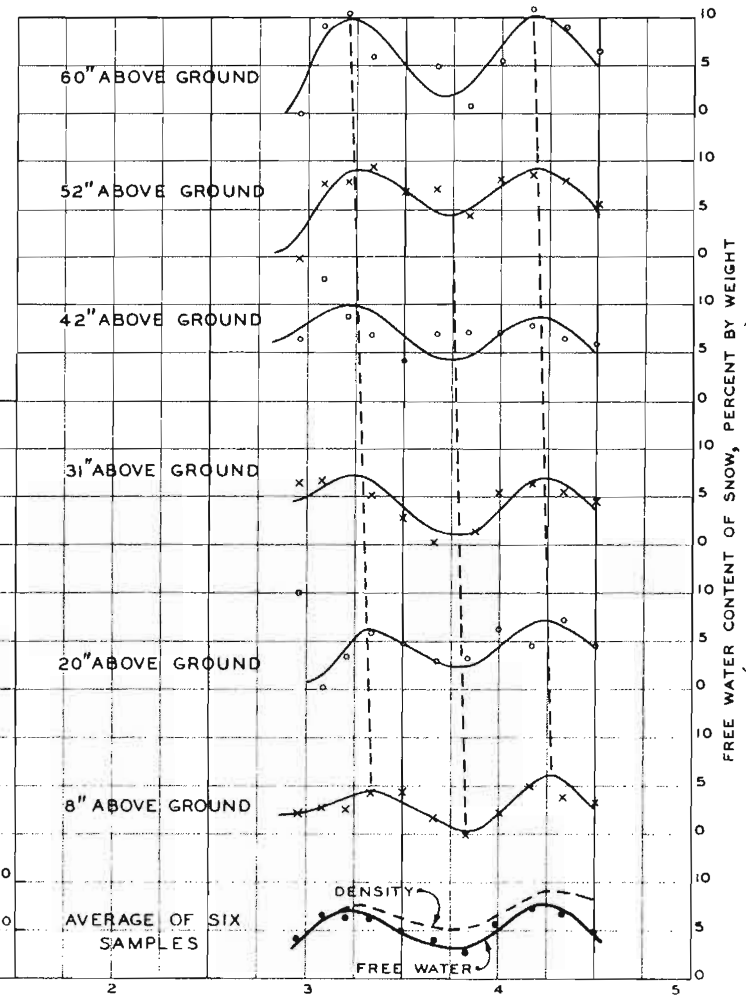


FIGURE 3 - PRECIPITATION

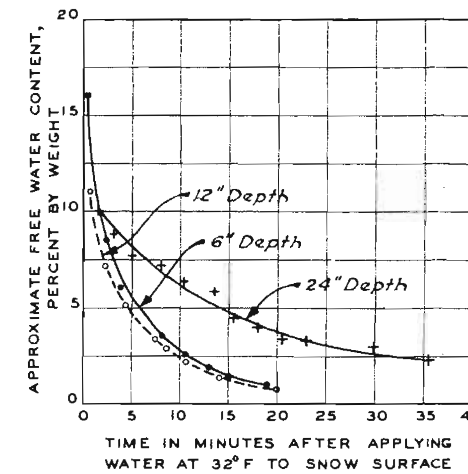


Note:
The measurements shown in Fig. 4 were made at a level site near headquarters building, CSSL, elevation 6900 ft. The snow pack consisted of six distinct layers, separated by ice planes. Calorimeter measurements were made on horizontal snow core samples from each layer.

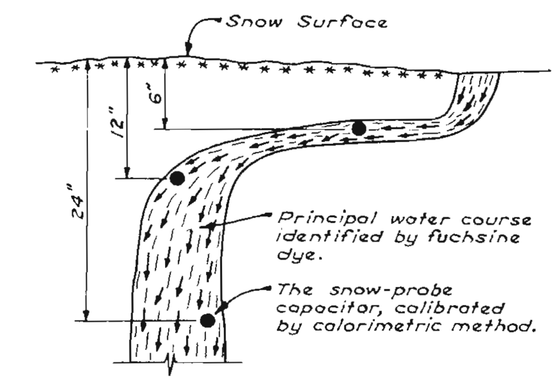
Free water draining through a snow pack is rarely of uniform distribution, except perhaps in the surface layer. A measurement at a particular point indicates conditions at that point or at another identical sample elsewhere.

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



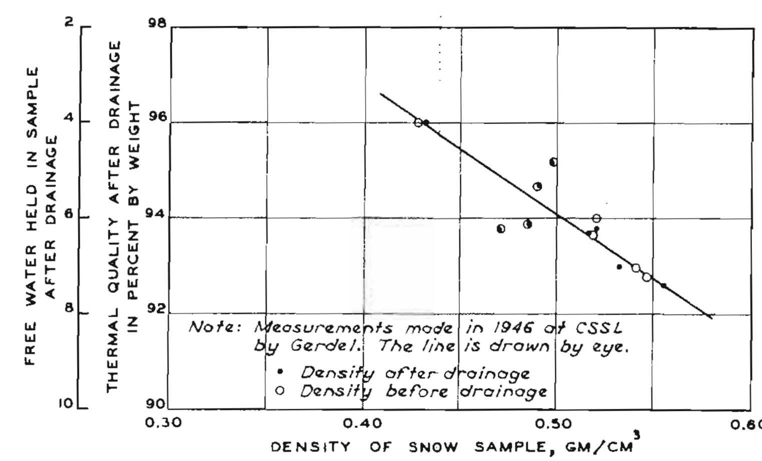
WATER MOVEMENT THROUGH SNOW DETERMINED BY CAPACITANCE METER



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

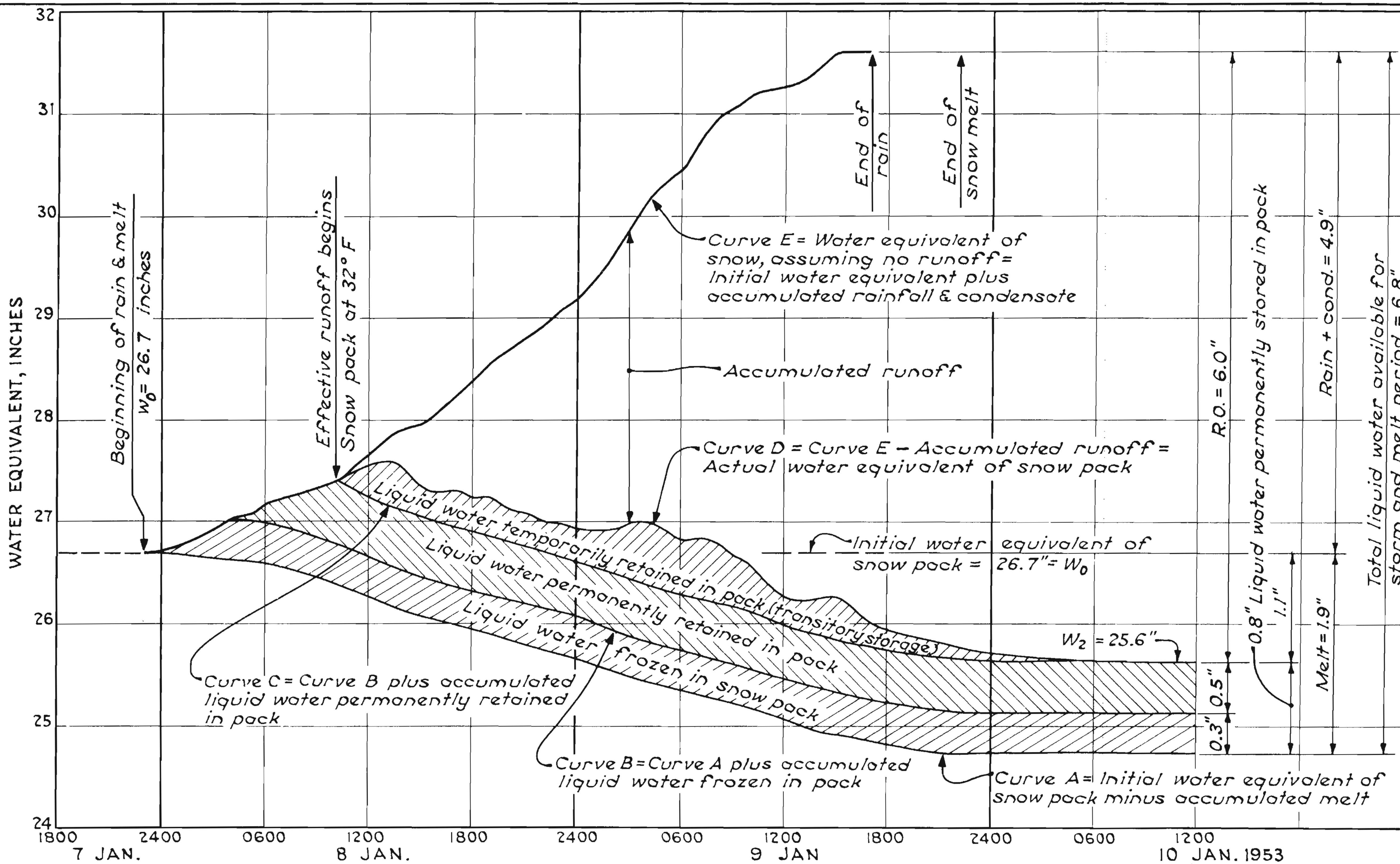
Note:
Snow densities in gm/cm³ on this plate are equivalent to commonly used densities in percent, divided by 100.

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	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: WJM	APPROVED: DMR	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

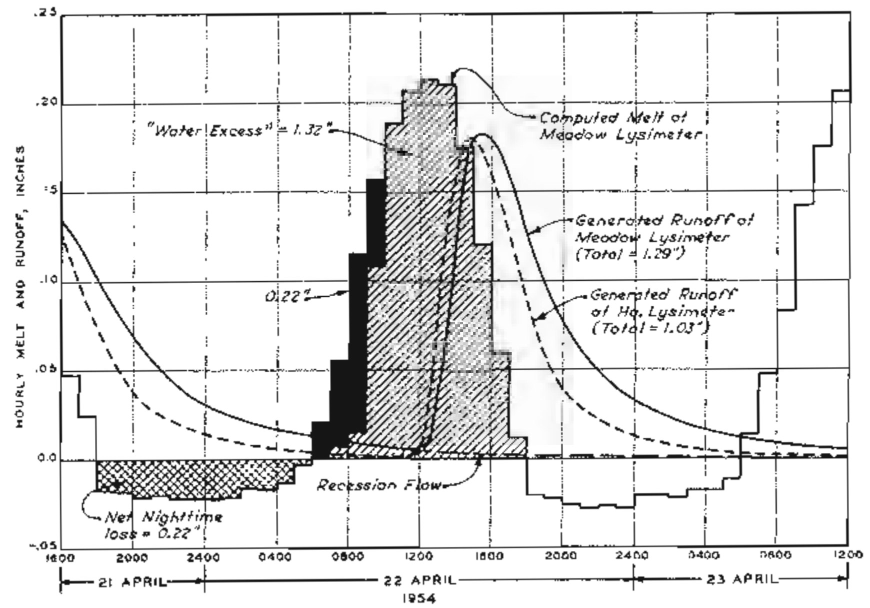


FIGURE 1 - CLOUDLESS DAY

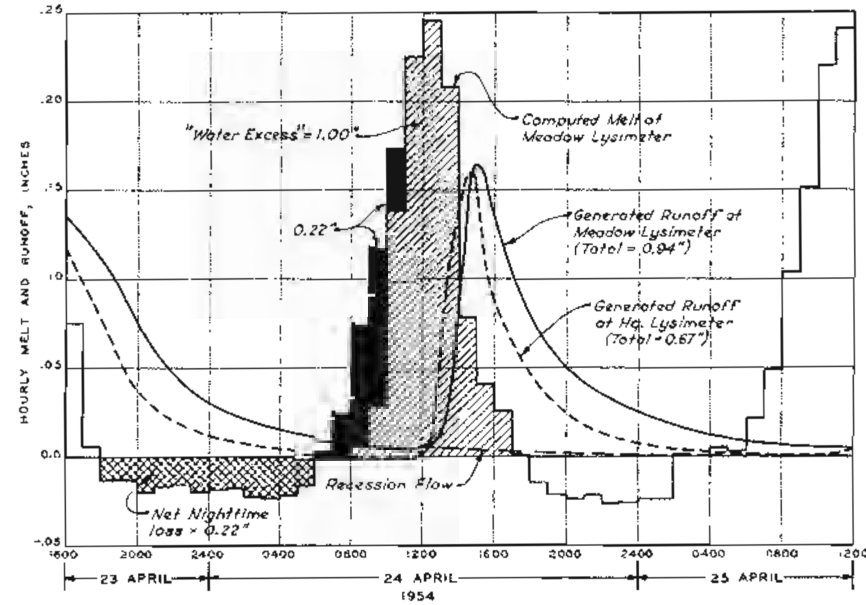


FIGURE 2 - PARTLY CLOUDY DAY

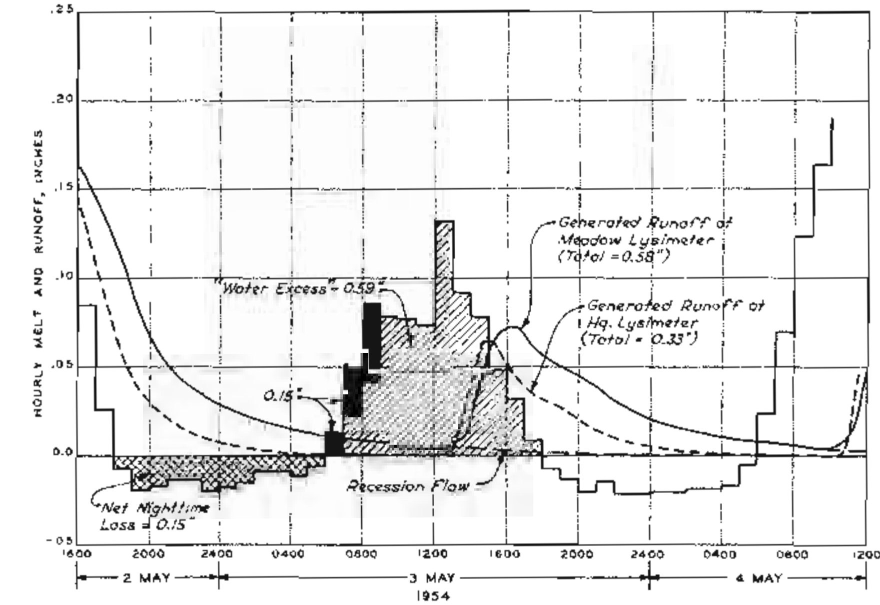


FIGURE 3 - CLOUDY DAY

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 of 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.

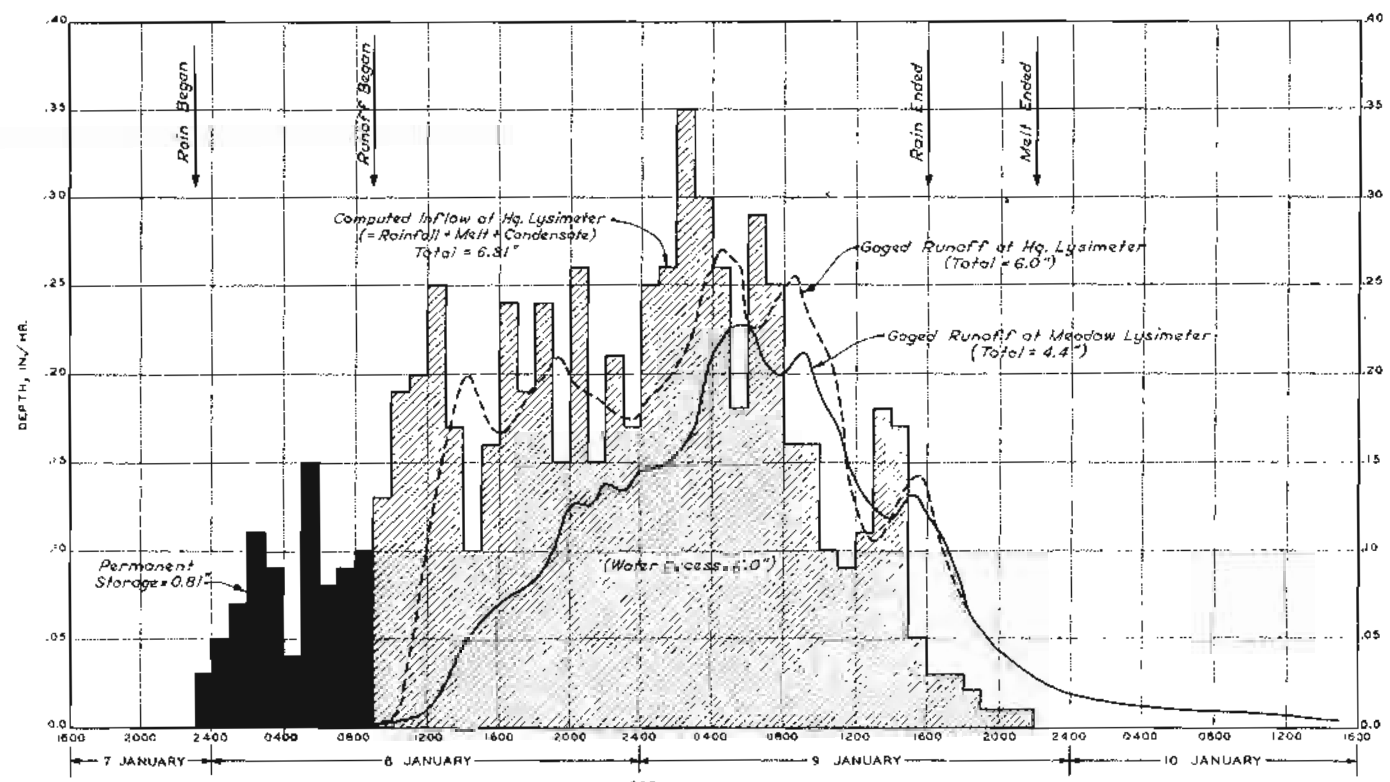


FIGURE 4 - RAIN ON SNOW

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

- (cross-hatched) Water equivalent of night-time heat loss from snow
- (solid black) 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.
- (hatched) "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

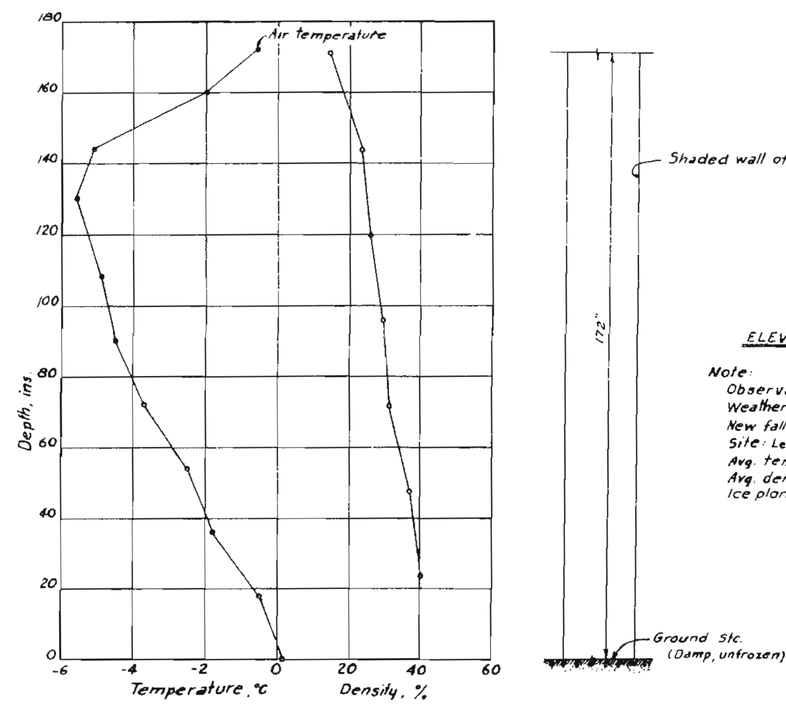
SNOW HYDROLOGY

LYSIMETER RUNOFF HYDROGRAPHS

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

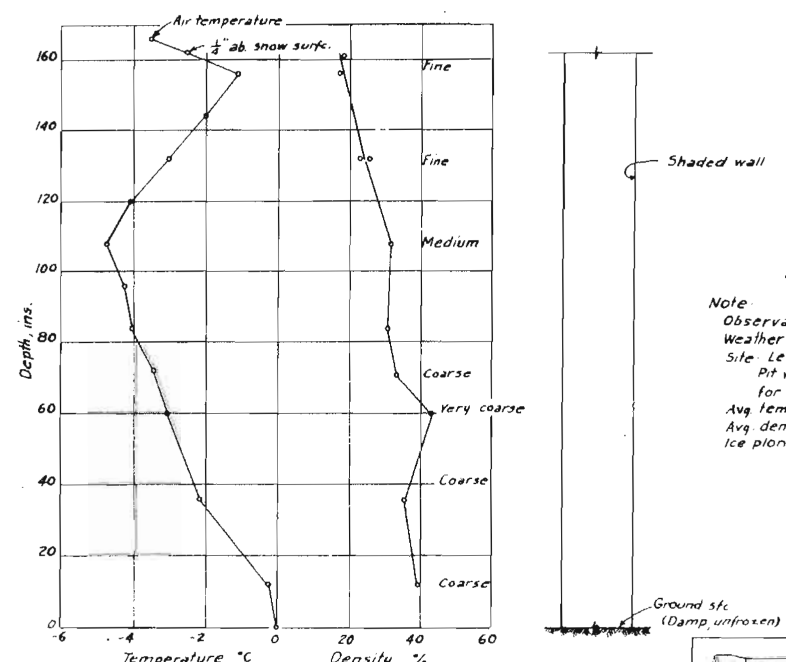
PREPARED PSS	SUBMITTED PSB	TO ACCOMPANY REPORT DATED 30 JUNE 1954
DRAWN MJM	APPROVED SMR	PD-20-25/54

PLATE 8-9



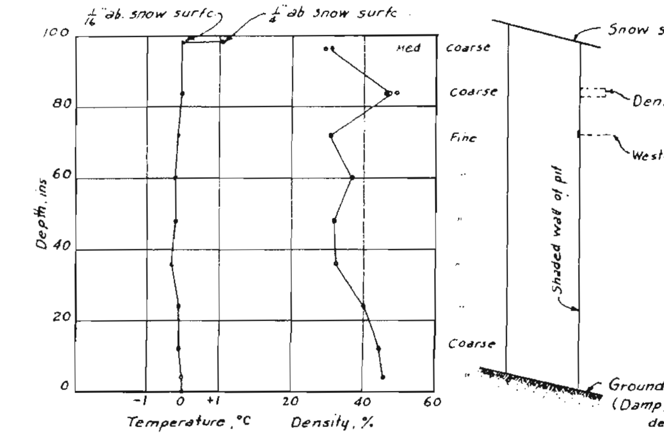
ELEVATION 6900'

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: ⅛" to ¼" thick, not impermeable; no apparent free water



ELEVATION 6000'

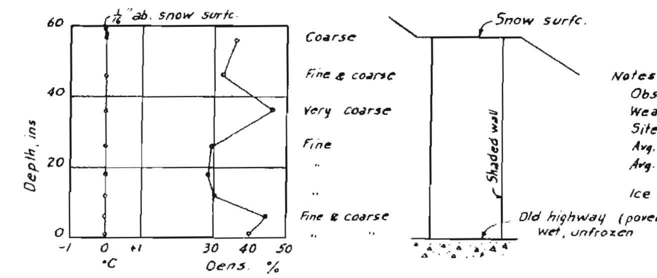
Note:
Observations taken 27 Jan. 1952, 1530 to 1700 hrs.
Weather: Clear & calm
Site: Level, exposed to full insolation 0930 to 1600 hrs. Pit was dug on 26 Jan. & new wall exposed for observations on 27 Jan.
Avg. temp., -2.5°C
Avg. density, 30 %
Ice planes: ⅛" to ¼" thick, not impermeable; no apparent free water



ELEVATION 5000'

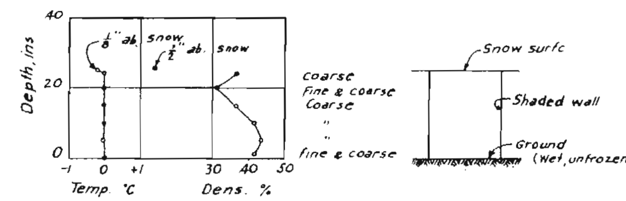
Notes:
Observations taken 27 Jan. 1952, 1430 to 1500 hrs
Weather: Clear & calm
Site: Exposed to south; snow sfc. 8% slope; full insolation all day
Avg. temp. 0°C approx.
Avg. density, 38 %
Ice planes: ⅛" to ¼" thick, not impermeable; no apparent free water

(Damp, unfrozen percolation of melt water was not detectable)



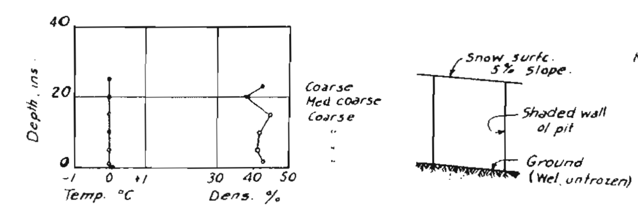
ELEVATION 4000'

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: ⅛" to ½" 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'

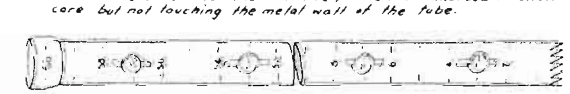
Notes:
Observations taken on 27 Jan. 1952, 1025 to 1040 hrs.
Weather: Clear & calm
Site: Open, exposed to full insolation except between 1100 & 1500 hrs.
Avg temp. 0°C
Avg density, 42 %
No ice planes, homogeneous granular snow.
Snow is wet and at its moisture capacity.

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

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.

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.



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

PLATE 8-10

CHAPTER 9 - HYDROGRAPH SYNTHESIS

9-01. INTRODUCTION

9-01.01 General. The foregoing chapters of this report have been concerned with several specialized aspects of snow: the deposition and distribution of the snowpack and methods by which it is measured; the role of snow in the hydrologic cycle; the physical causes and practical indexes of snowmelt; variations in snow cover and methods by which it can be estimated; and the effect of the snowpack on the storage and routing of water. This report is not, however, concerned primarily with the study of snow itself; rather, it is interested in the hydrologic aspects of snow, and the effect snow has on the runoff from basins where snow exists. Consequently, it is only when the separate findings of the previous chapters are considered in relation to their effects upon streamflow that the purpose of this report is realized. There are two aspects to be considered in the problem of determining runoff from snow-covered areas: one is concerned only with the total volume of snowmelt runoff; the other requires that the time distribution of the runoff also be determined. It is the latter aspect that is of concern in this chapter. The problem of forecasting the volume of runoff will be considered separately in chapter 11. In the determination of the time distribution of runoff from snow-covered areas there are, furthermore, two distinct types of hydrograph synthesis involved. One requires that the flow be determined only a few days in advance, current conditions of snow cover and streamflow being known. This type is used in river forecasting and in the operation of reservoirs (see chapter 12). The other requires that the discharge hydrograph for an entire rain-on-snow event or the hydrograph for an entire snowmelt season be determined, with only the initial conditions of streamflow and snow cover being given. This type of hydrograph synthesis is most often used in the development of design floods (see chapter 10). Both types will be dealt with here. Moreover, flood hydrographs resulting both from rain-on-snow events and from snowmelt alone will be considered. These same problems have previously been considered in a report by Snyder 19/ which briefly summarizes much of the work of the Snow Investigations with respect to hydrograph analysis and synthesis. Before examining these specialized aspects of runoff from snow-covered areas, some basic considerations common to all shall first be examined.

9-01.02 Basic considerations. - In any system devised for the synthesis of discharge hydrographs, whether for snow-covered or non-snow-covered areas, there is one paramount consideration: the system must be internally consistent. That is to say, each component of the synthesis must be determined in relation to all the other components. For example, in the determination of losses, the methods by which rainfall and snowmelt were determined play a most important part. An overestimation of either of these must result in a compensating overestimate of losses. While the deliberate use of such compensating errors is not advocated, it must be realized that in a field such as hydrology, where measurements are somewhat inexact to begin with and areal variations in the measured elements make accurate determination impossible, such errors are inherent in the basic data. Recognizing their existence, systems can be worked out to mitigate these effects. Many systems of hydrograph reconstitution currently in use give adequate results even though the magnitudes of some of the factors involved are obviously incorrect. Precipitation amounts may be uncorrected for gage deficiencies and for areal variation, resulting in much too low a total figure. Yet losses, determined as the difference between precipitation and runoff, may here be underestimated, bringing the system into balance. Likewise snowmelt amounts are often underestimated and compensated by an overestimate of the areal extent of the snow cover, the latter being the derived factor which makes agreement between snowmelt and runoff quantities. On the other hand, the fact that such systems can give suitable reconstitutions is not to argue that care should not be taken in determining the variables. The chief danger in any system in which the basic data are not a true representation of the physical facts is that the system may be applied to data outside the range for which it was developed. This extrapolation may produce results which are no longer rational: negative losses or greater than 100 percent snow cover, for example, may be required to bring the system into balance. Thus, while any system of hydrograph synthesis should be consistent within itself, it should at the same time be rational. All variables should be estimated as closely as possible and in a manner such that a balance is possible without undue juggling of the data.

9-01.03 There are two general situations in which snow has an important effect upon streamflow. One is the discharge hydrograph that results from snowmelt alone or from snowmelt abetted by small and scattered amounts of rainfall. The snowmelt may extend over a period of several months, as it does in the mountainous drainage basins of the western United States, melting at moderate rates with only part of the total drainage basin contributing at any one time, or it may last for only a few days, as is generally the case in the Great Plains area, and be characterized by more intense rates and basinwide melt. The other general situation where snow plays an important role is where an intense rain storm falls on a snow-covered area. Here the rain may be abetted by melting snow, thereby increasing its effect, or, on the other hand, it may be partially stored or detained by the snow cover, mitigating its effect. Both situations will be considered in this chapter.

9-02. GENERAL APPROACH

9-02.01 Elevation effects. - The synthesis of hydrographs which result from snowmelt or from rain-on-snow differ in several respects from those resulting from rain alone. For one thing, a drainage basin cannot be considered simply as a homogeneous unit; the areal extent of the snow cover is involved. In snowmelt floods this limits the contributing area; in rain-on-snow floods, loss rates may differ markedly between the snow-free and snow-covered areas. Because the snowpack exhibits its principal variation with elevation (see chapter 3), it becomes necessary to include, in some manner or another, elevation effects in any system of hydrograph synthesis for basins in which snow is a factor and which have a sufficient range in elevation to warrant it. This consideration of elevation is also pertinent in the determination of form and intensity of precipitation--a problem not limited to snow-covered areas but frequently involved in rain floods in general. As was shown in chapter 3, the intensity of precipitation generally increases with increasing elevation, and it is more frequently in the form of snow at higher elevations that it is at lower elevations. Then too, snowmelt rates tend to decrease with increasing elevation as is subsequently discussed. In view of all this, the importance of elevation effects in the synthesis of runoff hydrographs may readily be seen.

9-02.02 There are two general approaches to the problem of computing the runoff from snow-covered areas. They differ in the manner in which elevation effects are handled. The first method to be considered consists simply of dividing the drainage basin into bands of equal elevation and computing the snowmelt, rainfall, and losses for each such elevation band separately; the net runoff from all bands is then combined to arrive at the net basin runoff. Such a method was used in the synthesis of discharge hydrographs for the Columbia River basin above McNary Dam. 8/ Sufficient bands should be selected so as to smooth any incremental changes, as no finer sub-division is made than the elevation band as a whole. The entire band is considered to be snow-covered or not, the entire band to be effectively melting or not, etc. Bands may be determined either on the basis of equal increments of elevation or on the basis of equal areas. The former method is advantageous from the standpoint of melt and form-of-precipitation computations, since the temperature decrease with elevation may then be assumed to be uniform between bands. For this reason it is the more commonly used method; however, the use of equal areas is superior in almost all other respects. With the exception of the highest and lowest bands, however, both methods are generally similar due to the usual approximate linear relationship between area and elevation for intermediate elevations.

9-02.03 The other general approach to determining runoff from snow-covered areas is to treat the basin as a unit, making corrections for the non-snow-covered area and other non-contributing areas (e.g., areas of no snowmelt and areas having precipitation in the form of snow during rain-on-snow storms). In this approach the assumption is usually made that the basin snow cover is depleted in a regular manner with elevation: the lowest portions of the basin are the first to become bare and the snow-cover depletion with time progresses regularly upwards. In the situation where low-elevation melt is taking place but no melt occurs at the higher elevations within the basin, even though they are snow-covered, only the area in the band between the "snowline" (average elevation of the lower limit of the snow-covered area) and the "melt line" (average elevation of the upper limit of snowmelt) contributes to to snowmelt runoff. In the case of rain-on-snow, the contributing area for rainfall runoff has an upper limit at the elevation where the rain becomes snow. There may be three distinct elevation bands marked by different situations in rain-on-snow events: (1) an upper band where snow falls on a snowpack; (2) an intermediate band where rain falls on the snowpack; and (3) a lower band where rain falls on bare ground. The deviations of these bands may change with time making for a complex situation. This situation will be considered further in section 9-03.

9-02.04 Areal effects. - In the foregoing the basin has been considered as a unit in an areal sense. Even when broken up into elevation bands, portions of the basin having similar elevations were considered to have the same snowmelt, precipitation, snow cover, and losses. This is not always a good approximation, especially in the case of large basins covering a range of climatic factors. Temperatures may be considerably warmer, the snowline higher and the precipitation less for a given elevation in one part of such a large basin than in another. In such basins it sometimes becomes necessary to consider separately the several sub-areas having different characteristics. Separate hydrograph reconstitutions may be made for each sub-area and these combined by proper streamflow routing techniques. Such was the approach used in the design flood determinations for the Gila River basin above Painted Rock Damsite in Arizona, an area of some 50,000 square miles. 3/ On the other hand, it is sometimes possible to treat such large basins as a unit, as was done for the entire Columbia River drainage above McNary Dam. 8/ By using average values of the several variables which include an areal sampling it is possible to arrive at mean runoff values which are adequate. This is possible since the large basin itself effectively averages out its extremes.

9-02.05 Melt period. - Another important general consideration in the reconstitution of streamflow hydrographs for snow-covered areas is the melt period, and hence the routing interval, selected. Since snowmelt is diurnal in character, daily melt amounts are customarily computed for all but the smallest, flashiest basins. However, as has been domonstrated in chapter 5, the daily snowmelt quantity is usually generated in something less than one-half day, the remainder of the day being a period of heat loss. In large basins where the runoff is relatively sluggish and no regular diurnal pattern is discernible in the discharge hydrograph, this fact is of small consequence. Daily melts may be routed using a daily time interval to get the resulting discharge hydrograph. For smaller, hydrologically-faster basins having a regular diurnal snowmelt runoff pattern, such an approach is not always adequate. Yet even here if it is not desired to reconstitute the diurnal fluctuation but only to reconstitute mean daily flows, a daily routing interval is adequate. On the other hand, where it is desired to reconstitute the diurnal rise and fall of the stream, routing intervals of twelve or eight hours may be used. All the melt is attributed to one of the periods, the other(s) contributing nothing to runoff except during periods of rainfall. In the case of rainfall, the shorter routing intervals (less than one day) are generally better suited to the reconstitution of hydrographs because of the possible extreme variation in precipitation rates with time. Such data are not always available, however. For large basins daily rainfall amounts are usually adequate.

9-03. RAIN-ON-SNOW FLOOD HYDROGRAPHS

9-03.01 General. - The methods used in the synthesis of flood hydrographs which are predominantly the result of rain-on-snow are similar to those which are used for rain floods in general. In consequence of the high rates of rainfall encountered in these situations, only direct runoff is explicitly considered; base flow rates are usually estimates since they contribute relatively little to the flow at or near the time of peak flow. Also, the relatively high rate of rainfall makes it the primary variable in the analysis; the added increment of snowmelt is considered more as an additive factor than as a primary variable. In rain-on-snow situations, the effects of the snowpack are twofold: (1) to add an increment of melt water to the rainfall and (2) to store and detain, in varying degrees, the melt and rain water generated. It is the latter effect that makes the reconstitution of rain-on-snow floods most complex. Rain falling on a snowpack may be stored by the pack or pass through without depletion, depending upon the condition of the pack. A considerable quantity of rain water may be stored by a dry, sub-freezing, snowpack. Moreover, a deep snowpack that has previously experienced little or no melt or rainfall of consequence may add an additional increment of storage by virtue of its delaying effect upon runoff. Impenetrable ice planes within the snowpack may give a large horizontal component to the flow of water through the pack itself (along the ice planes seeking a pervious area). Then too, water may be perched above such impenetrable layers. In addition, such a snowpack effectively chokes or dams the natural surface drainage channels to high rates of flow. Thus a sudden occurrence of heavy rainfall on such a pack is quite effectively retarded. Delays as long as two days have been noted in situations where rain fell on such a snowpack. (This storage action of the snowpack is discussed in detail in chapter 8.) On the other hand, the snowpack may be quite pervious to the high rates of rainfall. Prior rains or melt may have caused it to become isothermal at 32°F, may have satisfied its liquid-water-holding capacity, may have established percolation paths through the pack, and may have melted and scoured out adequate surface drainage channels beneath the snowpack. If such be the case, not only is there practically no delay in runoff as a result of the snowpack, but the snowpack may abet runoff by adding an increment of melt water. Even more important, its melt may have maintained the soil moisture and depression storage so that even those usual losses are reduced. Between the two extreme conditions cited above range an indefinite number of intermediate conditions. From the foregoing discussion, one important fact stands out: the condition of the snowpack has a dominant effect upon the initial basin discharge of a rain-on-snow event. Because of this, rain-on-snow floods are difficult to synthesize; some knowledge of the initial condition of the snowpack is mandatory.

9-03.02 Because of the general similarity of methods employed in the synthesis of rain-on-snow floods and rain floods in general, no actual synthesis of a rain-on-snow event will be made. Examples of some outstanding occurrences will be given, followed by a discussion of the principal factors involved in such events. Some problems pertinent to rain floods in general will be considered as well as those peculiar to rain-on-snow flood events.

9-03.03 Examples. - Two outstanding examples of rain-on-snow floods occurred during the period of operation of CSSL, affording an excellent opportunity for study. One, actually a series of separate flood events, occurred in November-December 1950. Intense rains falling on a relatively shallow snowpack were abetted by melting snow. A record peak discharge estimated at 1200 cfs was observed from this small, 4-square mile basin. Except for two of the flood waves (in the series of five) which were preceded by new-fallen snow, little of the rain or melt water was stored by the snowpack; its action was rather to add to runoff by melt and by decreasing basin losses. Data on this flood series may be found in the Hydrometeorological Log for the 1950-1951 water year at CSSL. Analyses of the event at CSSL were made in Technical Bulletin 14 and in Snow Investigations Miscellaneous Report 3. A reconstitution of this same flood event in the American River basin, California (adjacent to the CSSL area), is contained in the previously cited report by Snyder 19/. The other outstanding rain-on-snow flood at CSSL occurred in January 1953; it is described in Research Note 18. Here a considerable amount of rain fell on a moderately deep and cold snowpack. About 12 percent of the water supply was lost to runoff as a result of the snowpack and the runoff was delayed due to the damming and channel-choking action of the snowpack. Unfortunately, the flume used to gage runoff from the CSSL basin area was also choked by snow and no discharge record was available for the basin. A detailed analysis of the runoff from the headquarters lysimeter was made (see Research Note 18) to investigate the storing and delaying action of the snowpack. The results of this analysis are given in chapter 8.

9-03.04 WBSL was established primarily for the express purpose of obtaining data on rain-on-snow events; however, many of the storms for that laboratory involved both (1) rain and snow falling simultaneously at different elevations, and (2) partial basin snow covers, adding sufficient complications to make most cases not readily amenable to analysis. During February of 1951, however, a sequence of storms occurred in which the precipitation was almost entirely in the form of rain; moreover, the basin was virtually 100 percent snow covered. An analysis was made of this sequence in Research Note 24; the results of this analysis are presented in plates 9-1 and 9-2. No actual reconstitution of the discharge hydrograph was made; rather a recession analysis was made of the hydrograph, separating periods of significant change and determining the water generated during the periods. Ten periods were thus defined (see Fig. 1, plate 9-1). Estimates of the water generated during each period were made by the techniques subsequently discussed in this section, and these amounts were compared with those from the recession analyses (see fig. 3, plate 9-2).

9-03.05 Rainfall. - It is not the purpose of this paragraph to describe methods by which basinwide rainfall amounts may be computed. That has been done elsewhere in this report (see chapter 4). The principal concern here is in the manner in which rainfall amounts, once computed may be fitted into a comprehensive scheme for determining the resulting runoff. A few remarks regarding the determination of basin rainfall are fitting, however. It is often the case that inadequate consideration is given to the form of the precipitation; in many storms where rain is falling at the observation sites, the precipitation at the higher elevations is in the form of snow. This fact is often ignored and all precipitation is considered to be of the same form observed at the precipitation stations. A study has been made relating the form of precipitation to surface air temperature (see 3-02.03), and the data are presented diagrammatically in figure 1 of plate 3-1. It will be noted that with a surface air temperature of 34°F, the frequency of occurrence of snow is greater than is the frequency of rain; with an air temperature of 35°F the frequency of rain is greater than that of snow. Using this dividing line between rain and snow and a standard lapse rate of 3°F per 1000 feet (or, better, the pseudo-adiabatic lapse rate, since precipitation is occurring), it is possible to estimate surface air temperatures and hence form of precipitation at different elevations within the basin from the temperature stations usually found at the lower elevations. If the basin is sub-divided into elevation bands, it is a simple matter to estimate the temperature at the mean elevation of each band and hence the form of precipitation for the band. If the basin is being treated as a unit, corrections must be made for the portion of the precipitation that occurs in the form of snow.

9-03.06 A correction for the variation of precipitation with elevation is a refinement that is seldom made in studies of rainfall runoff for snow-covered areas or otherwise. This is mainly because its inclusion in any scheme of hydrograph synthesis complicates it greatly while making little difference in the results. Usually basin rainfall may be determined by using a fixed ratio between it and the rainfall at some index station(s). However, when the precipitation changes from one form to another over large portions of the drainage basin and deficiencies in loss rates between snow-covered and snow-free ground also are important in the synthesis, (also an elevation function since snow cover varies with elevation), it may be that some consideration should be given to the variation of precipitation with elevation. The only practical method of accomplishing this is to use the elevation-band method and to relate normal precipitation in each band to the normal basin precipitation or directly to the normal for the precipitation index stations, thus determining a factor which then may be used to determine storm precipitation amounts in each band.

9-03.07 Snowmelt. - The computation of snowmelt during periods of significant rainfall is a problem quite different from the computation of melt during non-rain periods. Because of the generally overcast conditions, solar radiation has but a minor role in the melt scheme; longwave radiation losses are small, and at times there is even a net heat gain from this source. Because of the turbulent conditions which usually accompany rainstorms, convection and condensation melts are relatively large. In addition, fairly high vapor pressures result from the high relative humidities encountered in this situation, tending further to increase condensation melt. This problem was considered at some length in chapter 6 and an equation was developed for the computation of snowmelt during periods of rainfall. It is repeated here.

$$M = (T_a - 32)(0.029 + 0.0084kv + 0.007P_r) + 0.09 \qquad (9\text{-}1)$$

where M is the total daily snowmelt in inches for open or partly-forested basins, T_a is the mean daily air temperature at the 10-foot level in degrees F, v is the mean daily wind speed at the 50-foot level in mph, P_r is the total daily rainfall in inches, and k is the basin constant expressing its exposure to wind (see par 6-04.13). In application, this equation may be further simplified by several assumptions. For one, the variation of melt with wind speed may be ignored by considering the wind to be constant. This assumption is especially suited to areas of heavy forest cover where the 50-foot level wind is relatively light and constant. Assuming, for example, as in chapter 6, a mean wind speed of about 5 mph, the foregoing equation becomes:

$$M = (T_a - 32)(0.074 + 0.007\,P_r) + 0.05 \qquad (9\text{-}2)$$

the convection-condensation term being combined with the term representing long-wave radiation.

9-03.08 Snowmelt, of course, occurs only over the snow-covered portions of the drainage basin. Moreover, it is possible that no melt may be occurring at the higher elevations within the basin at the same time the pack is melting at lower elevations. The resulting intermediate contributing area varies in time with both snow cover and temperature. As with rainfall, melt may be computed by elevation bands or by considering the basin as a unit and making corrections for non-contributing areas. A simple assumption which may be used in the synthesis of rain-on-snow events is to consider the melt as being uniform over the entire snow-covered area on which rain is falling (area having temperatures in excess of 34°F) and to assume no melt in areas over which snow is falling. Further refinement than this is seldom warranted in rain-on-snow situations since snowmelt is usually a relatively small contribution to the total storm runoff, particularly for design floods.

9-03.09 Losses. - Losses in rain-on-snow situations consist not only of water permanently lost to runoff by evapotranspiration, deep percolation, etc., but also of water that is detained both by the snowpack and by the basin itself. This is the more usual connotation of the term losses as used in rain storms in general, where the term losses implies water lost to direct runoff. It is distinct from the use of the term in the synthesis or reconstitution of hydrographs from snowmelt alone, where only water that is permanently lost to runoff is included in the term (as will be discussed subsequently). Since in the synthesis of rain-on-snow flood hydrographs, as with all rain flood hydrographs, the high rates of water generated result in high peak flows from direct runoff, the water discharged more slowly over a longer period by base flow is of little concern in the hydrograph synthesis, even though a considerable volume of water may be included in the base flow. Hence the water which goes to make up the base flow is considered to be a part of the losses.

9-03.10 Of primary importance in rain-on-snow events are the initial losses; that is, non-recurrent losses that need be satisfied only once at the start of a given rain-on-snow event. These losses may be further categorized as those which result from the basin itself. The former includes water which may be frozen within a sub-freezing snowpack, water which may be permanently held by capillarity and absorption within the pack, and water perched above impermeable ice planes or otherwise dammed by the snowpack. As was previously mentioned, it is the extreme variability of this loss that makes the reconstitution of rain-on-snow flood hydrographs most difficult. Such a loss may be non-existent in the case of saturated snowpack, isothermal at 32°F, or may amount to several inches of water in the case of a deep and cold snowpack. Moreover, this snowpack loss may be compounded by basin losses. Once snowpack losses are satisfied, in the case of a sub-freezing snowpack, it still may be necessary to supply water to soil moisture and depression storage before appreciable direct runoff occurs. Beneath a melting snowpack, on the other hand, soil moisture and despression storage losses are generally satisfied, so that rain falling on such a pack not only suffers no losses within the snowpack but losses that usually exist even in snow-free areas are non-existent. It is because of this possible extreme variation in initial losses that a knowledge of pre-existing conditions of the snowpack and the basin is required in the synthesis or reconstitution of discharge hydrographs resulting from rain-on-snow. Methods of determining losses within the snowpack were discussed in chapter 8; other initial basin losses are considered in chapter 4. (Reference is made to Research Notes 4, 18, and 24 and to Technical Bulletin 17 for further and more detailed discussion of the storage effect of the snow cover.)

9-03.11 After the initial basin losses are satisfied, still other losses to direct runoff continue; however, these losses are relatively constant in time and easy to evaluate. Evapotranspiration removes some water from the soil, thus allowing further soil moisture loss. Some water percolates downward through the soil to the ground-water level to be discharged very slowly, for the most part subsequent to the period of interest. Some water merely takes devious routes through the ground (inter-flow) not reaching the stream channel until after the period of interest. Yet all these are considered losses in the sense in which the term is applied to rain-flood hydrograph reconstitutions. It is to be pointed out that there is a difference between the losses previously enumerated and the ultimate disposition of the water involved. Water initially lost in the snowpack is released with the melting of the snow; water initially lost to depression storage may subsequently add to the soil moisture and to the ground-water storage, other water taking its place in filling the depressions; water held in soil moisture is, in turn, evaporated and transpired, mostly after the cessation of the storm event; and water which percolates to the ground-water table is discharged slowly over a long period. Methods of determining basin losses are many and varied and shall not be gone into here. Reference is made to an article by Snyder 17/ and to standard hydrology text books (e.g., Applied Hydrology 15/ and Hydrology Handbook 1/) for a discussion of those losses and methods by which they are included in the over-all routing procedure. When losses are deducted from the total water generated (rainfall plus snowmelt) the residual is termed water excess. Methods by which this water excess is distributed to determine the resulting discharge hydrograph will now be considered.

9-03.12 Time distribution of runoff. - The incremental quantities of water excess (water generated minus losses), determined as explained in the preceding paragraphs of this section, are translated into the resultant discharge hydrograph by any of the standard methods used in conjunction with rain floods in general. Unit hydrographs (or distribution graphs) and methods of storage routing are used. It is to be emphasized that here, as with all rain floods, the water excess routed consists only of that water that reaches the stream channels by the more direct routes and results in the high peak flow characteristic of rain floods. Water travelling by indirect routes is included in a base flow curve which is generally estimated. This approach is familiar to hydrologists and will not be considered further here. Reference is made to the manual, "Flood Control" 12/ and to chapter 5 (Flood-hydrograph analyses and computations 4/) and chapter 8 (Routing of floods through river channels 5/) of the Engineering Manual for Civil Works Construction for descriptions of standard methods of flood-hydrograph determination.

9-03.13 A few general remarks regarding the routing interval to be used in determining rain-on-snow flood hydrographs follow. Since it is the rainfall that is of primary concern here, and not the snowmelt, the availability of rainfall data should determine the time periods selected. Thus if 6-hourly rainfall data are available from Weather Bureau stations, the routing interval should be made to correspond to these times of measurement. If only daily data are available from cooperative observers and these readings are made during the morning or evening, as is customary, then the routing period must agree with these measurements. Only where hourly precipitation data are available may the routing interval be selected as desired. Here it is usually advantageous to subdivide the day into a fixed number of even periods beginning at midnight (e.g., 00-08, 08-16, 16-24 hours). The length of the periods selected should be short enough to adequately define the rapid rise and fall of the hydrograph yet should not be so short as to require unnecessarily detailed computations. Computations of snowmelt are made to agree with the periods selected for the rainfall determinations.

9-03.14 A good example of the synthesis of a rain-on-snow event is contained in Design Memorandum No. 2 for Cougar Dam and Reservoir in Oregon 9/. The syntheses of standard project and maximum probable floods given therein make use of elevation bands and maintain inventories of snowpack water equivalent in each band to determine the areal extent of the snow cover. Snowmelt computations are based upon the equation given in this section. Plate 10-1 gives the results of the Standard Project Flood derivation; it is discussed further in chapter 10.

9-04. SPRING SNOWMELT FLOOD HYDROGRAPHS

9-04.01 General. - So far this chapter has been concerned with the synthesis and reconstitution of floods that result from rain falling on snow. As was previously pointed out, these flood events are for the most part like any other rain floods with only the added effects of the storage and the melt of the snowpack. In this section the synthesis of springtime snowmelt floods is to be considered. The methods used in the synthesis of these floods are markedly different from those used in rain-on-snow floods. Special techniques quite different from those used in rain or rain-on-snow flood synthesis are required in their synthesis. The Boise River basin above Twin Springs, Idaho will be used as an example to illustrate the points raised herein. This basin was selected as being typical of areas in which springtime snowmelt is of major importance. In chapter 6 snowmelt indexes were determined for this basin, one of which will be used to compute snowmelt for the sample presented here. In chapter 7 basin snow-cover relationships for the Boise River basin were determined which will also be used here. Reference is made to two other studies of snowmelt runoff for this same general area, by Summersett 20/ and Zimmerman 21/ and to the Definite Project Report on Lucky Peak Dam, on the Boise River, Idaho, 11/ which are of interest to what follows. The 1955 melt season as a whole will be reconstituted on the basis of mean daily flows; also forecasts of mean daily snowmelt runoff, one, two, and three days in advance will be made throughout the season. In addition, reconstitutions will be made showing the diurnal variation of the snowmelt runoff for a portion of the season.

9-04.02 In the mountainous areas of the western United States, the annual spring snowmelt flood results more from the sustained melting of deep snow packs over a long period of time than it does from high rates of generation of water. Continued melting over a period of a month or two results in a piling up of runoff as a result of slow recession until relatively high flood flows result even from the moderate

rate at which snow melts. For example, during the 1952 spring snowmelt season at CSSL, a peak discharge of 306 cfs was attained, which amounts to a flow of 77 cfs/sq.mi., for this small, 4-square-mile basin. Reference is made to Technical Bulletins 4, 8, 9, and 10 for some early studies of the synthesis of mountain snowmelt hydrographs at CSSL. In most areas rain usually adds an additional increment to the basin discharge; however, it is of secondary importance to the snowmelt in these situations. While what follows in this section is concerned mainly with the spring snowmelt floods which result from the deep snow packs of the mountainous areas of the western United States, it is also generally applicable to other areas and other flood situations which are primarily the result of snowmelt, providing allowance is made for characteristics peculiar to the area. The northern Great Plains area, for example, often experiences large floods early in the spring from the comparatively rapid and simultaneous melting of the extensive but relatively shallow snow cover of that area. Elevation effects are nonexistent here, as are forest cover effects. Runoff from the area is also frequently affected by frozen soil. These characteristics of snowmelt in the plains area will be considered later in this section.

9-04.03 Three approaches to the problem of synthesizing springtime snowmelt hydrographs from deep mountain snowpacks will be considered: (1) a rational approach wherein snowmelt, rainfall, snow cover, losses, etc., are evaluated separately and combined to arrive at the resulting discharge hydrograph; (2) the elevation-band method where separate computations of all elements are repeated for each band; and (3) a one-step method whereby snowmelt runoff is computed directly from a single diagram relating a temperature index and areal snow cover to snowmelt runoff. Other approaches using different combinations are of course also possible. Before considering these approaches, however, a discussion of some of the components involved is in order.

9-04.04 Snowmelt. - Basic to the synthesis of snowmelt hydrographs is the computation of snowmelt itself. Snowmelt may be computed by any of the methods previously discussed in chapters 5 and 6. For design floods the thermal-budget approach may best be used, while for operational forecasting some index method is probably better suited to the purpose. In chapter 6 analyses were made of snowmelt in the Boise River basin and thermal-budget indexes were developed relating snowmelt runoff to the parameters of air temperature, vapor pressure and radiation. One of these relationships is used in a reconstitution to be made later in this chapter. It is repeated below:

$$M = 0.0267T_{max} + 0.00227G - 2.00 \qquad (9\text{-}3)$$

where M is the snowmelt runoff for Boise River above Twin Springs, Idaho, in in./day, T_{max} is the daily maximum temperature at Idaho City, and G is the net radiation absorbed by the snowpack (including both absorbed shortwave radiation and net longwave radiation loss). Temperature indexes are the most widely used method of computing snowmelt and snowmelt runoff. They are used in the elevation-band and the one-step methods described herein. A few remarks concerning them follow.

9-04.05 In the computation of basinwide snowmelt or snowmelt runoff by temperature indexes, the temperature is usually adjusted to the mean elevation of the contributing area (see chapter 6). This presupposes a direct variation in melt rate with temperature and hence with elevation within a given basin. Now, from the thermal budget considerations of chapter 5, it would seem this implied decrease in melt rate with elevation is not strictly valid. While it is true air temperature and vapor pressure tend to decrease with increasing elevation, thus tending to reduce convection-condensation melt with increasing elevation, these melt components are but a part of the total melt. Solar radiation, the single most important source of heat in melting snow, tends to increase with increasing elevation due to the lesser scattering and absorption by the air at higher elevations. Yet a comparison of snowmelt rates at different elevations over a period of time indicates generally less melt at the higher elevations, especially early in the melt season. A partial explanation of these apparently contradictory statements may be had when the variation of albedo with elevation is taken into account. As a result of the greater frequency of new snowfalls at higher elevations of a basin, there is an increase in the mean albedo with elevation; it is primarily in consequence of this higher albedo at high elevations that the melt is reduced rather than as a direct result of the decreased air temperature. (Over extreme ranges, air temperature itself certainly also has an effect. Very little melt occurs with marked sub-freezing temperatures.) Thus for periods having no new snowfall and late enough in the melt season to assure a ripe snowpack of uniform albedo throughout a drainage basin, melt is largely independent of elevation. Practically, however, for the melt season as a whole, the delay in ripening, the higher albedo of the higher-level snow, and the decrease in air temperature and vapor pressure with elevation all result in decreasing melt rates with increasing elevation. This is allowed for in temperature-index melt computations by the lapse rate correction which thus represents average climatic characteristics more than an actual physical relationship between air temperature and snowmelt.

9-04.06 In the computation of snowmelt and snowmelt runoff for use in hydrograph synthesis and in short-term forecasts of runoff, a high degree of accuracy is not ordinarily essential. Random errors which result from the imperfect relationship between various indexes and snowmelt are of small consequence. Since, in hydrograph synthesis, a given day's observed runoff is the integrated result of several days' snowmelt, these random errors tend to compensate one another. It is important, however, that no consistent errors or errors of bias occur in the computation of melt amounts. Melt amounts consistently too high or consistently too low cannot be self compensating. While adjustments in loss rates or areal snow-cover amounts can correct for incorrect melt rates (as was previously discussed) such a procedure is not recommended. It is better that each factor in a snowmelt snythesis be a rational approximation of the actual event as it occurs in nature. Still more important, the relationship between snowmelt and the snowmelt index used should be consistent for all ranges of melt. An index that gives, say, too high estimates of melt at low rates of melt and too low estimates at high rates of melt is not satisfactory. Assuming no such errors of bias to exist, random errors do not seriously affect either seasonal hydrograph synthesis or short-term forecasts.

9-04.07 Units. - Snowmelt may be expressed in units of acre-feet, day-second-feet, inches or other measure of volume. If expressed in inches, it may be given in terms of either inches over the basin or inches over the snow-covered area. Because of the variation in snow-covered area, melt rates are usually given in terms of the latter; however, the computation of the discharge hydrograph requires that inches of melt be given for the basin as a whole. The use of inches over the basin is convenient in that it makes it possible to readily combine snowmelt and rainfall amounts (which are ordinarily given in those units) and to deduct losses. In addition, this unit is easy to visualize and to compare even for basins of markedly different size. For these reasons, it is used here and elsewhere in this report. The use of day-second-feet, while convenient in routing the generated runoff, is not amenable to the several other steps in the reconstitution.

9-04.08 Snow-cover depletion. - The actual areal extent of the snow cover is often omitted in calculations of snowmelt runoff, the effects of varying cover being integrated with other factors in establishing the relationship between melt rates and snowmelt runoff. In other cases it is included as a derived factor relating point melts to basinwide snowmelt or snowmelt runoff. Such practices are undesirable; in keeping with the objectives of this report--that only indexes which logically explain the physical phenomena be used--the effect of each important factor should be evaluated rationally wherever possible. In chapter 7, methods whereby the areal extent of the snow cover could be estimated were given. In addition, the depletion of the snow cover was related to other variables so that the areal cover could be estimated throughout the season. Two distinct problems exist in the determination of areal snow cover as a result of the different requirements of seasonal hydrograph reconstitutions and short-term forecasts of runoff. Seasonal reconstitutions require that, starting with a known initial snow cover (and depth-elevation characteristics), the increase and decrease in extent of cover for the remainder of the season be obtainable from regularly available hydrologic data. Short-term forecasts generally require only few determinations of areal snow cover from observed data and require little, if any, interpolation of snow-cover data. When the elevation-band approach to hydrograph synthesis is used, it is possible to maintain an inventory of the mean snowpack water equivalent in each band, thereby determining when the band becomes bare of snow. All new accretions of snow are added as well as melt amounts subtracted. This approach is especially amenable to design flood computations; it will be discussed further in a subsequent paragraph.

9-04.09 Rainfall. - Since there are few areas that do not have some rain during the spring snowmelt season, the inclusion of rainfall in spring snowmelt flood hydrograph synthesis is usually necessary. The special problems encountered in the determination of basinwide rainfall amounts in mountainous areas have already been discussed previously (see paragraph 9-03.05) and little need be added here. Differences in the form of the precipitation (rain or snow) must be considered here also. In addition, rainfall on bare ground and rainfall on the snowpack must be treated separately. In the case of springtime snowmelt, it is likely that a considerable portion of the basin (at the lower elevations) will be snow free, the portion increasing as the melt season progresses. In general, only the zone having rain-on-snow contributes appreciably to runoff, with both snowmelt and rainfall runoff occurring in this zone. Assuming, as is explained in the following paragraph, that all rain that falls on bare ground is lost, there is no contribution to runoff from the lowest zone. Moreover, since little or no melt occurs at elevations where snow is falling, the contribution from the top zone is practically nil.

9-04.10 Losses. - The term losses, as used here, means permanent losses, that is, water which will never show up at the gaging station. This differs from the use of the term with respect to rainfall hydrograph studies where losses are usually considered to consist of all water that does not show up directly as runoff. The reason for this difference is that in the analysis of rainfall flood hydrographs much of the runoff is found to be direct runoff. This runoff, being quickly discharged from the drainage basin, produces the sudden rise and sharp peak characteristic of most rain floods. While a considerable portion of the total rainfall runoff is also discharged by more indirect routes, this flow is relatively sluggish and is hence distributed over a long time interval. As a result, these rates of flow are very low compared to those of the direct runoff and, consequently, the "base flow" is merely estimated in rain-flood hydrograph analysis. Since at the time of peak flow, the base flow component is usually less than 10 percent of the total discharge, it is evident that even large errors in its estimation have little effect on the final result. No strict accounting is kept of the rainfall that goes into losses and the water that is subsequently discharged as base flow. In the analysis of snowmelt flood hydrographs, on the other hand, such an approach is not applicable. As a result of the comparatively low rates of snowmelt(as compared to rainfall), almost all of the snowmelt would go into losses should such a rain-flood hydrograph procedure be used. Little or no direct runoff would remain to produce a hydrograph peak; there would be only a base flow curve to be estimated. Obviously, snowmelt hydrograph syntheses require a different approach from those used for rain floods.

9-04.11 Since sub-surface flow is more important in snowmelt flood hydrographs than in rain-flood hydrographs, all water not permanently lost to runoff must be routed. Permanent losses consist basically of evapotranspiration and deep percolation. In addition, however, some melt water is lost to soil moisture recharge and depression storage; it is eventually disposed of by evapotranspiration and deep percolation occurring subsequent to the melt season; hence it too is a permanent loss. The losses due to soil-moisture recharge and depression storage are not ordinarily recurring losses but constitute an initial loss at the beginning of the melt season only. After the initial loss is satisfied, only losses due to evapotranspiration and deep percolation remain. For this reason snowmelt losses are relatively simple to estimate when compared to losses from rain storms. Once the initial loss is satisfied at the start of the snowmelt season--soil moisture recharge and depressions filled--an equilibrium is reached between water available and losses. This condition prevails throughout the melt season. Since evapotranspiration is somewhat proportional to heat supply and deep percolation to available water (see chapter 4), losses may conveniently be included in the snowmelt index. When an index of snowmelt runoff is computed, it is assumed that losses are a fixed percentage of the heat supply and hence of the snowmelt. One fault in assuming a fixed percentage loss for snowmelt floods becomes apparent from a consideration of extreme melt rates. At extremely low melt rates all melt may be lost; on the other hand, it is unreasonable to suppose losses to keep increasing directly with melt rates up to their highest possible values. An alternative method (to a fixed percentage loss) has been to use a constant loss rate for all ranges of melt. Here some critical snowmelt rate is required before any snowmelt runoff is realized and the greater the melt rate the higher is the percentage runoff. Still more logical than either of the foregoing is use of a curve combining the best features of the two: A fixed loss rate that must be exceeded by supply before any direct runoff results, with losses then increasing with increasing water generated until maximum loss rate is attained, beyond which losses are constant regardless of increasing water generated.

9-04.12 Generated runoff. - Many different approaches have been used by hydrologists concerned with snowmelt runoff for determining the combined effect of snowmelt, snow cover, rainfall, losses etc., on runoff. As previously mentioned, these may be grouped into three general methods for determination of generated runoff: (1) Method A - a rational method wherein the basin is considered as a unit and adjustments are made for variations in melt rates, snow cover, form of precipitation, and losses; (2) Method B - the elevation-band method where the basin is subdivided into elevation bands, each band being considered to have a uniform melt rate, be entirely snow covered or bare, have the same form and intensity of precipitation throughout, and have uniform losses; and (3) Method C - a one-step method whereby generated runoff is determined directly from temperature index and snow-cover data. Each of these methods have something to recommend it; they will be discussed in detail in what follows. To illustrate the methods, the drainage basin of the Boise River basin above Twin Springs, Idaho is used as an example. Particulars regarding each of these methods follow.

9-04.13 Method A. - In this method the basin is treated as a unit; melt is computed in inches over the snow-covered area, to which is added the mean basin precipitation in inches. The sum is then multiplied by the contributing area (the percentage of snow-covered area below the freezing level) to arrive at the total water generated in inches over the basin. Losses are then deducted to arrive at the water excess. The device of combining snowmelt and rainfall before multiplying by the percentage contributing area presupposes that all rain falling on bare ground is lost and that the dividing line between rain and snow is at the freezing level. Both of these are approximations that are sufficiently accurate for most areas of spring snowmelt providing no considerable amount of rain is involved. While this method is essentially simple, there are a few complicating factors which should be pointed out. The temperature index is ordinarily corrected to the median elevation of the contributing area. This may be done handily with the aid of figure 3 of plate 9-3 where standard lapse rate curves of 3°F per thousand feet are superimposed on an area-elevation curve of the Boise River basin (see figure 1, plate 9-3). From the temperature index, it is possible to determine the elevation of the freezing level. By assuming all of the snow-covered area to be above all of the snow-free area, it is possible to determine the mean lower limit of the snow cover, or the snowline from the basin snow-cover data. By bisecting the contributing area (area between freezing level and snowline), the median elevation of the contributing area is found. An example, using this method to reconstitute the spring 1955 snowmelt hydrograph for the Boise River above Twin Springs, Idaho, is given later in the chapter.

9-04.14 Method B. - In this method the basin is subdivided into equal-elevation bands and snowmelt, rainfall, and losses are computed separately for each band. An example of such a subdivision is given in figure 2 of plate 9-3. Melt and rain are considered to be uniform throughout the band and the entire band is considered to be either snow covered or bare. For simplicity, temperature indexes are generally used to compute snowmelt, although other indexes could be used. Two variations of this method have been used. In one, rain and melt amounts are computed in terms of inches over the elevation band, the melts then being combined as a weighted average for the basin as a whole, the weighting being in accord with the proportionate share of the basin being contained within each band. In this method, a separate inventory may be kept of the snowpack in each band. In the other variation, melt is computed from curves which automatically give melt in terms of inches over the basin as a whole. Whether or not the band is snow covered must be determined, in this case, from a separate snow-cover index. Such curves expressing snowmelt in the various bands in terms of inches over the basin are shown in figure 4 of plate 9-3 for the Boise River basin above Twin Springs, Idaho. These curves reflect both the area included in the particular band and the elevation of the band with respect to the temperature index station. They are based on an assumed melt rate of 0.1 inch per degree-day and must be multiplied by an appropriate conversion factor. This variation of the basic method was originally used by the Office, Chief of Engineers, in computing the spillway design flood for McNary Dam on the Columbia River. 8/ The other variation whereby the melt in each elevation band is weighted and averaged and an inventory of snowpack water equivalent in each band is maintained has been used in the synthesis of the maximum probable flood for the Painted Rock Reservoir on the Gila River, Arizona. 3/

9-04.15 Method C. - This method makes use of a diagram which gives snowmelt as a function of temperature index and mean elevation of the snow line. Such a diagram for the Boise River basin above Twin Springs, Idaho is included as figure 5 of plate 9-3. (A similar diagram for computing monthly melt on the North Santiam River in Oregon is shown in figure 3, plate 11-4.) The diagram takes into account the contributing area, assuming no melt from areas having temperatures below freezing and from snow-free areas. The method may be used to compute either snowmelt or snowmelt runoff. In the appendix to the Definite Project Report on McNary Dam, it is used in the former sense, while Linsley, in a discussion of the method, 14/ makes use of it to compute snowmelt runoff. Moreover, since Linsley relates it directly to observed (rather than generated) runoff, he found it necessary to include an auxiliary diagram to explain the apparent increase in melt rate through the melt season. In the example given in figure 5, a melt rate of 0.1 inch per degree-day was adopted as a convenience. Hence the results from this diagram must be multiplied by an appropriate factor. As a rule, this method is more amenable to day-to-day forecasting than it is to computation of design floods although it may be used for either.

9-04.16 Time distribution of runoff. - In the preceding paragraph, methods were presented whereby the water generated within a drainage basin during a given time interval could be computed. In order to determine the resultant discharge hydrograph, some method of distributing these amounts of water with time must be employed. For snowmelt runoff hydrographs, the techniques employed in making time distributions of runoff are quite different from those used for rain-flood hydrographs, although the general principles are the same. Those techniques are described in what follows, along with a general discussion of the effect of the snowpack on the time distribution of runoff.

9-04.17 The delay in runoff caused by the snowpack in areas of snow cover has been discussed in some detail in chapter 8. Methods whereby snowmelt or rainwater could be routed from the snow surface to the snow-ground interface were presented. It was shown that most of the rain falling on a subfreezing pack of low density would be absorbed within the pack and the time for the remainder to pass through the pack could be large. This same effect was also shown to apply to early season snowmelt, occurring before the pack was thoroughly ripened and drainage channels had been established. Once the initial losses were satisfied--the pack isothermal at 32°F and liquid-water-holding requirements met--the time delay to runoff caused by the snowpack became relatively small and constant. The time required for melt (or rain) water to percolate through the snowpack varies, of course, with the depth of the pack. Thus even thoroughly ripe packs show some variation with time in the time delay to runoff. This effect, which reduces the time delay as the melt season progresses, tends to be offset by the fact that, as the melt season progresses, the remaining snow cover becomes more and more remote from the basin outlet. Only in very small basins (the size of the laboratory areas) does the time delay becomes shorter as the melt season progresses. In larger basins no such change is discernible. In very large basins, it would seem the reverse should be true: the time delay should increase as the melt season progresses and the remaining snow cover becomes more and more remote from the basin outlet. It has been found, however, that in large basins where the travel time is large compared to time required for melt water to percolate through the snowpack, there is no need to make allowances for variations in basin storage once the spring melt season is actively progressing.

9-04.18 Two methods have been employed in reconstituting discharge hydrographs from given amounts of water excess for snow-covered areas. One employs the method of storage routing; the other makes use of the unit-hydrograph approach. Both methods give satisfactory reconstitutions; however, the latter is generally preferred because of its greater simplicity of computation. (Examples of reconstitutions made by both methods are given in the paragraphs which follow.) For large basins where no regular diurnal hydrograph rise as a result of snowmelt is discernible, or even for smaller basins where only mean daily flows are to be determined, the time distribution of melt is relatively simple and either of the foregoing methods may be employed. If, on the other hand, it is desired that the diurnal rise as a result of snowmelt also be shown, the unit-hydrograph method is definitely superior to that of storage routing. Considering first the situation where only mean daily flows are desired in the reconstitution, standard storage routing and unit hydrograph techniques may be used with a few modifications.

9-04.19 The time distribution of snowmelt runoff by the storage routing method requires that the total runoff be separated into two components: surface runoff and ground-water discharge. (Interflow is included in these two to varying degrees depending upon the method of separation used.) Each component is then routed separately and the two added to determine the resultant streamflow. The surface component has a relatively short storage time while the time of storage for the subsurface component is very long for most basins. If the unit-hydrograph approach is used, on the other hand, it is not necessary to separate the runoff into two components. The unit hydrograph used has an exceptionally long recession limb which effectually represents the slow subsurface and ground-water flows. The special techniques necessary in the derivation and application of such snowmelt unit hydrographs are discussed in section 9-05. Also contained in this section is a further discussion of the storage routing techniques in the synthesis of snowmelt hydrographs.

9-04.20 This section has so far been concerned exclusively with snowmelt and snowmelt runoff in mountainous areas. Because of the effect of elevation on both snowmelt and snow cover, only rarely do mountainous drainage basins contribute melt from all levels simultaneously. A more limited contributing area is usually found which decreases in areal extent and retreats to higher elevations as the melt season progresses. Moreover, these mountainous areas are generally forested to varying degrees, a fact that is of importance in the computation of snowmelt (see chapter 6). While the mountainous areas of the western United States were the particular concern of what has gone before, the relationships presented are also generally applicable to any mountainous area where snow accumulates in deep and lasting snowpacks. Such is not the case with the northern Great Plains area of the United States.

9-04.21 Snowmelt in the Great Plains. - While snowmelt floods are of great importance in this area, they present a problem distinct in many respects from what has so far been considered. The snow cover is relatively shallow; snowmelt floods last but a few days. Due to the flat terrain and lack of forest cover, melting occurs practically simultaneously over entire drainage basins and melt rates are higher than those ordinarily found in mountainous areas. Both these factors tend to produce high, sharp flood waves of the type characteristic of rain floods. In addition the ground beneath the snowpack is often frozen, which encourages surface runoff. The flat terrain and shallow stream gradients allow melt water to be dammed up for some time before being released with a rush.

9-04.22 An extreme example of such a flood was the spring 1950 flood on the Cannonball River near New Leipzig, North Dakota which is illustrated in figure 3 of plate 9-6. The general situation which produces these floods is described in the following excerpt from an unpublished report by K. A. Johnson (see Appendix II, No. 44):

"The plains area of the Missouri River basin may be described as predominantly rolling country with relatively few trees. The temperature range is large with hot dry summers and cold winters. The snow accumulation season generally begins in December and extends through March. Although some melting generally occurs as a result of short warming periods during the winter months, the major portion of the snowmelt occurs in a period of 10 days or less during late March or early April. Flooding as a result of snowmelt does not occur every year, but it is the most prevalent type of flood for the western tributaries of the Missouri River down to the Nebraska-South Dakota State line.

"When a flood potential does exist as the result of snow accumulation the following conditions are frequently found at the beginning of the melt period: (1) moderate to severe drifting, (2) frozen ground with top few inches likely to be quite moist, (3) layer of solid ice and/or granular ice crystals next to ground. Items (1) and (2) are almost always present but the existence of item (3) is likely to be quite spotty even though fairly widespread. As the temperature rises and melt begins, the snowpack increases in density and bare ground becomes evident in numerous cases. A layer of slush is likely to be found at the bottom of the remaining snow. Appreciable runoff into the streams is not likely to occur before these conditions are noted. Then, as warm temperatures continue, the ground becomes progressively free of snow cover, and runoff into the streams increases rapidly, continuing until the area is free of snow, with the exception of that part which is covered by deep drifts or protected from the melting factors."

Meteorological conditions antecedent to and during this flood are given in figure 1 of plate 9-6. Concerning this flood occurrence is the following quotation from an unpublished report by C. W. Timberman (see Appendix II, No. 38):

"Description of Basin. The Cannonball River basin is located in southwestern North Dakota and drains an area of approximately 4300 square miles. The river flows in an easterly direction to enter the Missouri River about 45 miles downstream from Bismarck, North Dakota. The D. A. of the sub-basin above New Leipzig is approximately 1180 square miles and is of predominantly rolling topography. Elevations range from about 2250 feet at the New Leipzig gage to over 3000 feet along the rim of the basin with scattered buttes extending up to 3300 feet. Characteristic low bluffs occur along the stream channels. Very few trees grow in the area even along the main stream channels.

"Climate. The climate is sub-humid. Average annual precipitation is slightly over 15 inches, of which about 11 inches occur from April to September, inclusive. General rains with average depths of over two inches are rare. Amounts vary greatly from the normal. Snow accumulation during the winter is usually moderate. The mean annual temperature at Mott, North Dakota, is 41.7°F; normal mean for January is 10.2°F. Extreme temperatures vary between 114 and minus 47°F.

"Floods. Spring floods, caused by the melting of the winter snow accumulation, are the most frequent type and occasionally cause extensive damage. Summer rains causing extensive floods are rare. Average discharge over a nine-year period of record is 107 cfs at New Leipzig. The 1950 flood, the reconstitution of which is the object of this report, is by far the largest of record throughout the basin except possibly in some of the small headwater areas above the heavy 1950 snowfall area. The preceding winter was one of the coldest of record while precipitation was considerably above normal. No appreciable runoff occurred from first week in December through the end of March because of the low temperatures. The melt that did occur during the winter is believed to have infiltrated into and saturated the upper layer of ground which subsequently was frozen into an impervious layer. From 23 to 27 March a severe blizzard occurred, with precipitation amounts ranging to over 3 inches of water content. From 7 to 10 April approximately one additional inch (water content) fell. Warm temperatures during the first week of April over the lower portion of the basin resulted in approximately 100,000 acre feet of runoff passing the gaging station at Breien; however, no appreciable flow was evidenced at the New Leipzig or the Pretty Rock gaging stations, above which lay the heaviest accumulation of snow. At the end of the second week in April much warmer temperatures occurred (with maximums approaching 70°F on 17 April) causing rapid melting of the entire snow cover, except the deeper drifts."

9-04.23 Another basin in this area that has been extensively investigated is that of Spring Creek near Zap, North Dakota. It also experienced a severe flood in 1950 and again in 1952. These flood events, along with the pertinent hydrometeorological data, are illustrated in figures 1, 2, and 4 of plate 9-6 and discussed in the following excerpt from an unpublished report by C. A. Burgtorf (see Appendix II, No. 42):

"Description - Spring Creek lies in west central North Dokata and is a tributary of Knife River which it enters about 40 miles above its mouth. Zap, North Dakota lies on Spring Creek about 11 miles upstream from its confluence with Knife River. The drainage area above Zap is 545 square miles. The topography is predominantly rolling with very few trees and elevations ranging from about 1750 to 3000 feet.

"Climate - The climate is relatively dry with a large temperature range. The average annual precipitation is about 16 inches of which about 60 percent falls during the summer months. Snow usually accumulates through the winter months and melts off in March or early April. The major portion of the melt usually occurs during a period of less than ten days and often results in some flooding. Rainfall floods in the area are rare.

"1950 and 1952 Floods - The two largest floods of record for Spring Creek at Zap occurred in 1950 and 1952. From snow surveys it was estimated that the water content of the 1950 snow cover at the beginning of the melt period was 2.5 inches and for 1952 was 3.4 inches. Discharge records show that the runoff from the principal melt period was 1.05 inches in 1950 and 2.08 inches in 1952. The crest discharge in 1950 was, 4580 cfs and in 1952 was 6130 cfs...."

9-04.24 The reconstitution of such plains area floods is a difficult procedure. For one thing, the lack of forest cover makes temperature and temperature-vapor pressure indexes of snowmelt generally unsatisfactory. As a result of rapid changes in albedo of the snowpack during such a flood event and the difficulty inherent in the estimating of albedo, the inclusion of radiation in a thermal-budget index is of questionable value. The initial condition of the snowpack and the underlying soil have most important, yet difficult to assess, effect upon the resulting runoff. Akin to rain-on-snow events, the runoff is largely dependent upon snow and ground conditions, and because of the rapid rise in both these types of floods, this initial condition must be known. Unlike spring snowmelt floods from the deep mountain packs where the pack is ripened and initial losses satisfied long before peak flows are reached, the rapid rise immediately follows satisfaction of these losses. Rapid variation in the areal extent of the shallow snow cover serves to further confound the problem. The problem will not be dwelt on further here; no ready solution is known. Reference is made to the Definite Project Reports for Garrison, and Oahe and Fort Randall Reservoirs for attempts at practical solution. 6/ 7/

9-05. TIME DISTRIBUTION OF RUNOFF

9-05.01 General. - The time distribution of runoff from rain-on-snow events is customarily made using the methods applicable to rain floods in general: the unit-hydrograph method is commonly employed to distribute the water excess, the base flow being estimated. Because these methods are common to hydrology in general, they will not be examined here. Of concern to this report are methods whereby the runoff from melting snow may be distributed into a discharge hydrograph. This problem is peculiar to the field of snow hydrology and little is said concerning it in the general literature of hydrology. For this reason, it shall be treated here in some detail.

9-05.02 One thing that makes the time distribution of snowmelt water different from that of rain floods is the difference in the rates of generation. In rain-flood control problems, since only relatively high rates of runoff are usually considered, it has been customary to deal only with the direct runoff in the unit hydrograph application, that is, the water that reaches the stream channels by the most direct routes. The other runoff--that which is more delayed in reaching the stream channels--is considered only as base flow, its time distribution being merely estimated. While a considerable volume of water may eventually be discharged as base flow (even exceeding the volume of the direct runoff), because of the relatively sluggish flow, compared to the direct runoff, it adds relatively little to the rate of flow at the time of peak flow. Thus even a large error in estimating the base flow component has relatively little effect upon the peak discharge. The total water generated, in the case of rain floods, is separated into water excess (direct runoff) and "losses" usually by means of an infiltration curve which gives infiltration rates corresponding to different accumulations of water generated. "Losses," so defined, thus include much of the water ultimately discharged by the base flow curve. Usually no strict accounting is kept between the "losses" and the water discharged by the base flow curve. The unit hydrograph approach may be used for snowmelt runoff hydrographs by routing separately the subsurface and surface runoff components. Also, storage routing techniques are applicable to the time distribution of runoff from snowmelt. Both of these approaches will be considered.

9-05.03 Storage routing. - Storage routing, while most commonly associated with the routing of flood waves through river reaches or through reservoirs, may also be applied to the determination of discharge hydrographs from drainage basins. The rainfall and snowmelt water generated within the basin is the inflow to be routed; the hydrologic characteristics of the basin are reflected in the time of storage used in the routing procedure. The following paragraphs will describe briefly the methods employed. No detailed discussion of storage routing in general will be given here, it being assumed the reader is familiar with the basic principles.

9-05.04 In the solution of the general storage equation, two assumptions are commonly made: (1) that the storage is directly proportional to the outflow, $S = t_s(O)$; and (2) that the storage is a function of both inflow and outflow, $S = K\,(xI + (1-x)\,O\,)$. The former is termed reservoir-type storage, the assumption being that outflow and storage vary together. The latter assumption is the basis for the Muskingum system of flood routing; here it is assumed that the storage varies directly with a weighted inflow and outflow. (As x approaches zero, the conditions of reservoir-type storage are approached.) Simple reservoir-type storage is limited in application, since no allowance can be made for time of travel through a river reach or in a drainage basin. Inherent in the method is the fact that the peak of the outflow discharge hydrograph always occurs at the time at which the outflow graph crosses the recession limb of the inflow hydrograph. This follows from the fact that subsequent to this time outflow exceeds inflow and hence the amount of storage (and hence the outflow also) must decrease. This restriction does not hold for the Muskingum method of routing since here storage is also, partially, a function of inflow. This makes this method somewhat more flexible, allowing for a possible travel time for the flood wave.

9-05.05 The storage routing approach has been used by the U. S. Weather Bureau River Forecast Center at Portland, Oregon for reconstitutions of spring snowmelt floods. Flood hydrographs for the Payette River basin, Idaho, have been determined by this method as reported on by Zimmerman. 21/ Briefly the method consists of separating the total water excess into two components: surface runoff and ground water. Each is then routed separately using different times of storage. These times of storage are empirically determined to give the best fit to historical data. The time of storage for the ground-water component is, of course, quite long compared to that for surface runoff. To facilitate storage routing in general, the U. S. Weather Bureau has developed an electronic routing analogue which solves the Muskingum routing equation. 13/ It is especially useful in reconstituting an entire season's snowmelt flood hydrographs. Basically the method is simple. Practically, the division of the runoff into the two components, the determination of the best storage times, and the relative weighting of inflow and outflow in determining the storage time for the two components, are more difficult.

9-05.06 Another method of storage routing, based on the reservoir-type storage equation, may also be used to determine outflow-hydrographs from drainage basins. This method consists of multiple-stage reservoir-type storage routing. That is, the inflow hydrograph is successively routed through two or more stages of reservoir-type storage. An example of this type of routing is given in figure 4, plate 9-7, which shows a rectangular inflow hydrograph routed through one, two, and three 6-hour stages of reservoir-type storage. Also shown is the same inflow hydrograph routed through one 18-hour stage of reservoir-type storage. As may be seen, a unit-hydrograph-shaped outflow wave results from the square inflow wave. By this method any desired time of travel delay may be had by the proper selection of number of stages and times of storage for each stage. Moreover, by varying the times of storage between stages, an extremely flexible system of time distribution of runoff is obtained, capable of reconstituting discharge hydrographs from basins of widely differing hydrologic characteristics. The disadvantage of such a procedure is that the computations involved are laborious. Even one stage of reservoir-type storage requires a considerable amount of computation; multiple stages make the computations even more formidable. Recently, however, an electronic analog has been developed which solves this type of storage routing (see Tech.Bull. 18). The analog permits the use of as many stages as desired with different times of storage in each stage if desired. In addition, this device makes it possible to vary the time of storage during the routing operation, a feature that further increases its flexibility. Multiple-stage routing is, of course, also possible for the Muskingum type of storage routing, and an electronic analog to solve this type of routing appears feasible. This type of routing is discussed by Clark 2/ who also points out the expedient of translating the inflow hydrograph in time and then routing it through a single stage of reservoir-type storage in order to simplify the computations involved. The use of multiple-stage routing in conjunction with the Muskingum method seems hardly warranted in view of the adequacy of the alternative approach of multiple stage storage-type routing.

9-05.07 Unit hydrographs. - The unit-hydrograph approach to the time distribution of runoff has been the method most extensively used in connection with runoff from snowmelt. However, as was previously pointed out, unit hydrographs developed for snowmelt are not applicable to rainfall and vice versa. Yet the difference between a rainfall unit hydrograph and one for snowmelt for a given area is one of degree only. Base flow curves can be eliminated for snowmelt runoff as for rainfall runoff; however, in the former case, the rate used to separate the two components of flow must be considerably less than in the case of rainfall. No absolute division exists between water excess and losses. As a greater percentage of the total water available is considered to be water excess, the recession limb on the unit hydrograph increases in length and rate of flow and the base flow curve decreases its contribution to runoff. On the other hand, as a greater quantity of water is considered to be losses and less as water excess in the infiltration curve separation, the unit-hydrograph tail shortens, and the unit hydrograph approaches that used for rain-flood synthesis. At the same time the base-flow curve increases in magnitude, becoming progressively more difficult to estimate. It is because of this that the method given herein was devised: all water not permanently lost to runoff is distributed by means of the snowmelt unit hydrograph. This assumes a fixed and constant quantitative relation between direct and base flow, which also has certain weaknesses. No base-flow curve need be estimated; only the recession from the existing streamflow at the start of the reconstitution is added to the computed hydrograph. The exceptionally long recession limb of the resulting unit hydrograph poses a special problem in its application. This and other problems involved in the derivation and application of unit hydrographs will now be considered.

9-05.08 Rainfall unit hydrographs may best be derived from a brief, isolated period of intense rainfall, falling at a uniform rate on a surface which has previously has its initial loss capacity satisfied so that the water excess rate is high and uniform. For snowmelt runoff, where the rate of water excess is low and is more or less continuous, the use of the S-hydrograph approach to the derivation of unit hydrographs for snowmelt runoff is appropriate.

9-05.09 The S-hydrograph approach to the derivation of unit hydrographs 16/ is useful in many respects: (1) it provides a method of adjusting the derived unit hydrograph for non-uniform rates of generation of water during the period used in computing the unit hydrograph; (2) it provides a means of adjusting the observed period to the period desired for the derived unit hydrograph; (3) it provides a convenient method of adjusting the area under the unit hydrograph to unit volume; (4) it allows several unit hydrographs to be averaged in order to arrive at a mean unit hydrograph; and (5) it provides a method of seperating a given unit hydrograph into two unit hydrographs of unequal periods of generation. It is this last aspect that makes the S-hydrograph approach especially valuable to snowmelt runoff. The aspects enumerated above are considered in detail in Technical Bulletin 14; they shall be discussed only briefly here.

9-05.10 Figure 1 of plate 9-7 shows an example of the use of an S-hydrograph in adjusting the unit hydrograph for non-uniform rates of generation of water excess. Suppose the hydrograph given by the solid curve results from the 6-hour period of non-uniform water excess illustrated. If this pattern of water excess is repeated every six hours, the resulting hydrograph is likewise repeated, the total flow being given by the wavy solid curve. This curve was determined by repeating the observed hydrograph every six hours and summing its ordinates. A smooth curve drawn through the wavy one represents an S-hydrograph which results from a constant rate of water excess equivalent to the mean rate during the 6-hour period (0.2 in./hr.). Expressing the ordinates of this curve in percent of its equilibrum rate, a percentage S-hydrograph results which is independent of the rate of water excess and reflects only the basin characteristics. From the percentage S-hydrograph, unit hydrographs of any period may be derived as illustrated in figure 2 of plate 9-7. The equilibrim rate corresponding to the rate of water excess for the period selected is determined, and the ordinates of the S-hydrograph expressed relative to this rate. Differences in ordinates, (e.g., bc, b'c', b"c") separated by the desired unit-hydrograph period (ab, a'b, a"b") define the unit hydrograph.

9-05.11 In the application of the unit hydrographs of snow-melt runoff, the selection of the best unit-hydrograph period becomes a problem. The early portion of the unit hydrograph with its comparatively rapid changes requires a relatively short period in order that it be adequately defined, while with the long recession limb this would result in unnecessarily detailed computations. Here a longer period is better suited to the job. It is possible, for a single S-hydrograph, to define two unit hydrographs of unequal periods, a shorter period being used for the earlier, more rapidly changing portion and a longer period for the long, more slowly changing recession limb. This may be seen by reference to figure 3 of plate 9-7. Supposing it is desired to separate the S-hydrograph CDE at time D. If a horizontal line AB is drawn to intersect the curve CDE at point D, two S-hydrographs are thus defined: CDB and ADE. By taking incremental differences on these two S-hydrographs, it is possible to determine unit hydrographs of any desired period. For example, supposing a 3-hour unit hydrograph is desired for the portion to time D and a 6-hour unit hydrograph thereafter. Three-hour incremental differences are thus determined for the first portion and 6-hour incremental differences for the latter, each being multiplied by the proper conversion factor. Such unit hydrographs are illustrated in figure 3 of plate 9-7 along with the S-hydrographs from which they were derived. This example, however, is not representative of the actual situation, where a greater contrast in time periods would exist as well as a longer recession limb on the S-hydrograph. The example was chosen for clarity in illustrating the method of diversion rather than its representativeness of an actual situation. It is to be pointed out that the same water generated is distributed by both these unit hydrographs. No separation into two components, as was the case in the storage-routing approach, is necessary. In combining the two flow components resulting from the time distributions by the two unit hydrographs, flows corresponding to the finer time increment are determined from the coarser by interpolation.

9-05.12 By rainfall unit-hydrograph standards, the two unit hydrographs above are both predominantly for base flow. If it is also desired to distribute rainfall-type water excess, still another surface runoff unit hydrograph is required; however, the detailed base flow analysis just discussed is hardly warranted in this case. The method of rainfall unit hydrographs (with estimated base flow) is generally used. Finally, it is pointed out that the separation of water generated into two components is quite arbitrary; the important thing is that the unit hydrograph used to distribute the water excess and the method used to estimate the base flow be consistent with the method of separation--a precaution that was previously discussed in connection with the synthesis of discharge hydrographs in general.

9-06. BOISE RIVER HYDROGRAPH RECONSTITUTIONS

9-06.01 General. - To illustrate some of the methods of snowmelt hydrograph synthesis previously discussed, the example of the 1955 spring snowmelt hydrograph rise on the Boise River near Twin Springs, Idaho is used. Melts for the period were computed by the thermal-budget index discussed in paragraph 9-04.04. They are shown diagramatically in figure 1 of plate 9-4 which also shows the pertinent meteorological data. One-, two-, and three-day forecasts of mean daily flow were made from these melt data (and gaged rainfall amounts), as well as reconstitutions of virtually the entire melt season. The reconstitutions and forecasts are discussed in the paragraphs which follow.

9-06.02 Seasonal reconstitutions. - In figure 2 of plate 9-5 the actual discharge hydrograph for the 1955 spring snowmelt season on the Boise River above Twin Springs, Idaho is given in terms of mean daily flows. Also shown on the same figure are reconstitutions made using the unit hydrograph of figure 3, plate 9-4 and by storage routing. The storage-routing reconstitution was accomplished by separating the total water excess into two components: 70 percent to direct runoff and 30 percent to ground-water discharge. Both components were routed using multiple-stage reservoir-type storage routing, the direct runoff being routed by two 36-hour stages and the ground-water discharge by three 10-day stages. Prior to the beginning of the reconstitutions on 1 May, several weeks of melt had occurred. Thus the pack was thoroughly ripe so that a constant melt factor could be used, and also all initial losses, both in the snowpack and in the basin, were satisfied. Recession flows, from the flow at the start of the reconstitution, were added to the flows determined by unit-hydrograph and storage-routing methods. (The recession flow curve for the Boise River basin is shown in figure 2, plate 9-4.) In making the foregoing reconstitutions, it is assumed that the actual temperature sequence, basin snow cover, and precipitation are known throughout the season. The agreement between the actual discharge hydrograph and the reconstitutions is actually a test of how well the discharge hydrograph can be reconstituted from known hydrometeorological conditions. This is what is pertinent in the synthesis of design floods. It is not a test of ability in forecasting meteorological conditions.

9-06.03 In figure 4 of plate 9-5, a portion of the 1955 spring snowmelt hydrograph for the Boise River basin is snown in expanded time scale. Hourly flows are plotted and the diurnal variation in flow is apparent. This diurnal variation in flow was reconstituted using the 8-hour unit hydrograph of figure 3, plate 9-4. All snowmelt was assumed to have occurred during one 8-hour interval (1000 - 1800 hours), the other two such intervals having no water generated except in the instances where rain occurred during these times. While such a reconstitution is seldom required, except possibly for very small drainage basins, it is included here to demonstrate that such reconstitutions are possible.

9-06.04 Short-term forecasts. - The reconstitution of an entire melt season, or portion thereof, as in the preceding paragraphs, is usually made only in connection with design-flood determinations. More usual are short-term forecasts of runoff made for the operation of reservoirs and other purposes. Such forecasts are generally more accurate than are the predicted flows for the same days taken from a reconstitution of an entire season's runoff hydrograph. The chief reason for the better accuracy of short-term forecasts is that when short-term forecasts are made, the current streamflow is known and only the increment of flow above the recession from the known flow need be estimated. When an entire snowmelt season's hydrograph is reconstituted, all water generated from the beginning of the season through the day in question has an effect upon the discharge for a given day. Presented in figure 1 of plate 9-5 are the results of one-, two-, and three-day forecasts of runoff for the 1955 spring snowmelt season on the Boise River. These forecasts were made using the same basic data, and a distribution graph derived from the same S-hydrograph was used to make the seasonal reconstitutions. Actual values of temperature, vapor pressure, precipitation and snow cover were used in the examples given; however, these data would not be available for actual runoff forecasts, and forecast values would have to be used, introducing another possible source of error. Thus figures 1a, 1b, and 1c represent what could be done in the way of one- to three-day forecasts, providing the forecasts of the meteorological conditions were correct. In making such short-term forecasts of runoff, the long recession flow of the unit hydrograph need not be run out; only as many days flow need be used as the length of the forecast. Thus there is a considerable saving in computation over that required to reconstitute an entire season.

9-07. SUMMARY

9-07.01 Two kinds of syntheses of runoff hydrographs are encountered in snow hydrology: (1) short-term forecasts and (2) the synthesis of an entire melt season or rain-on-snow event. The former is ordinarily used in the operation of reservoirs and in the making of streamflow forecasts, while the latter is ordinarily involved in the determination of design floods. With respect to the first kind of hydrograph synthesis, current conditions of streamflow, snow cover, etc., are known; only the increment of flow above the recession from the current flow need be estimated, and that only a few days in advance. Forecast values of meteorological parameters are required if the forecast period exceeds the lag time for the basin. With respect to the second kind of hydrograph synthesis, an entire flood hydrograph must be determined with only the initial conditions of streamflow and snow cover known. The actual values of the meteorological parameters necessary to the computation are known in the case of the reconstitution of a historical flood, and the assumed parameters in the case of a design flood synthesis.

9-07.02 Elevation has an important effect upon both snowmelt and precipitation excesses. Snowmelt rates vary inversely with elevation as a result of the general decrease in net heat supply with increasing elevation. The form of the precipitation (rain or snow) is a function of air temperature and hence also of elevation, while the total quantity of precipitation also increases with elevation, due to the orographic effect. Snow cover ordinarily exhibits a marked increase with elevation, in consequence of the precipitation increase with elevation, the greater likelihood of it occurring in the form of snow with increasing elevation, and the greater melt rates at lower elevations. Consequently, basinwide snowmelt must first increase with increasing elevation as the snowline is approached and the areal extent of the cover increases, and then must decrease with the decreasing melt rates at the highest elevations over the virtually 100 percent snow-covered areas. Moreover, snow cover has an important effect upon the runoff which results from rainfall. Generally speaking, very little runoff results from the usually light to moderate rains which fall on the snow-free portions of the basin, during the spring snowmelt season, while the percentage runoff is quite high for the snow-covered portions. During the winter season, however, this effect may be reversed, with the more intense winter rains producing considerable runoff from the snow-free areas, at the same time being stored to a greater degree over the snow-covered areas. In consequence of all these things, it becomes apparent that elevation must be considered in any general scheme of hydrograph synthesis for snow-covered areas.

9-07.03 There are two general methods by which elevation effects may be incorporated in a scheme of hydrograph synthesis. One is simply to divide the drainage basin into elevation bands and compute the water excess for each band separately--snow cover, precipitation, snowment and losses to be uniform over each band. The other method is to treat the basin as a unit, making corrections for variations in the form of precipitation, snow-covered area, melt rates, etc., with elevation.

9-07.04 The basic components of any method of hydrograph synthesis are: (1) snowmelt, (2) rainfall, (3) losses, and (4) time distribution of runoff. Pertinent comments on each of these follow:

(1) Snowmelt. - In general, the thermal-budget method of snowmelt computation is more amenable to design floods and the index method to the forecasting of streamflow. Because of the different meteorological conditions, different methods are necessary for the computation of melt during spring snowmelt periods and winter rain-on-snow events. (See sections 6-04 and 6-07.)

(2) Rainfall. - In determining basin rainfall from precipitation gage data, corrections must be made for gage deficiencies and form of precipitation. In separating out snowfall amounts, it should be remembered that gage deficiencies are commonly large in areas of snowfall.

(3) Losses. - The concept of losses is different for synthesizing rain-on-snow hydrographs and predominantly snowmelt hydrographs. Rain-on-snow synthesis uses the conventional rainfall-loss concept, wherein all water is considered "lost" (to direct runoff) which is delayed in reaching the gaging station through varying degrees of subsurface flow, so that it contributes little to the hydrograph peak. Snowmelt snythesis considers only that water to be a "loss" which is permanently stored in the snowpack (as free or refrozen water) or is permanently lost to runoff (by evapotranspiration and deep percolation).

(4) Time distribution. - Either unit hydrographs (including distribution graphs) or storage routing methods may be used in the time distribution of runoff from snow-covered areas. Conventional rainfall-type unit hydrographs may be used for rain-on-snow events; special "long-tailed" unit graphs are used to distribute spring snowmelt excess. Storage routing is most amenable to spring snowmelt hydrograph synthesis where the total water excess is divided into two (or more) components and routed separately using relatively short times of storage for the more direct component and relatively long times of storage for that water which is more delayed in reaching the basin outlet.

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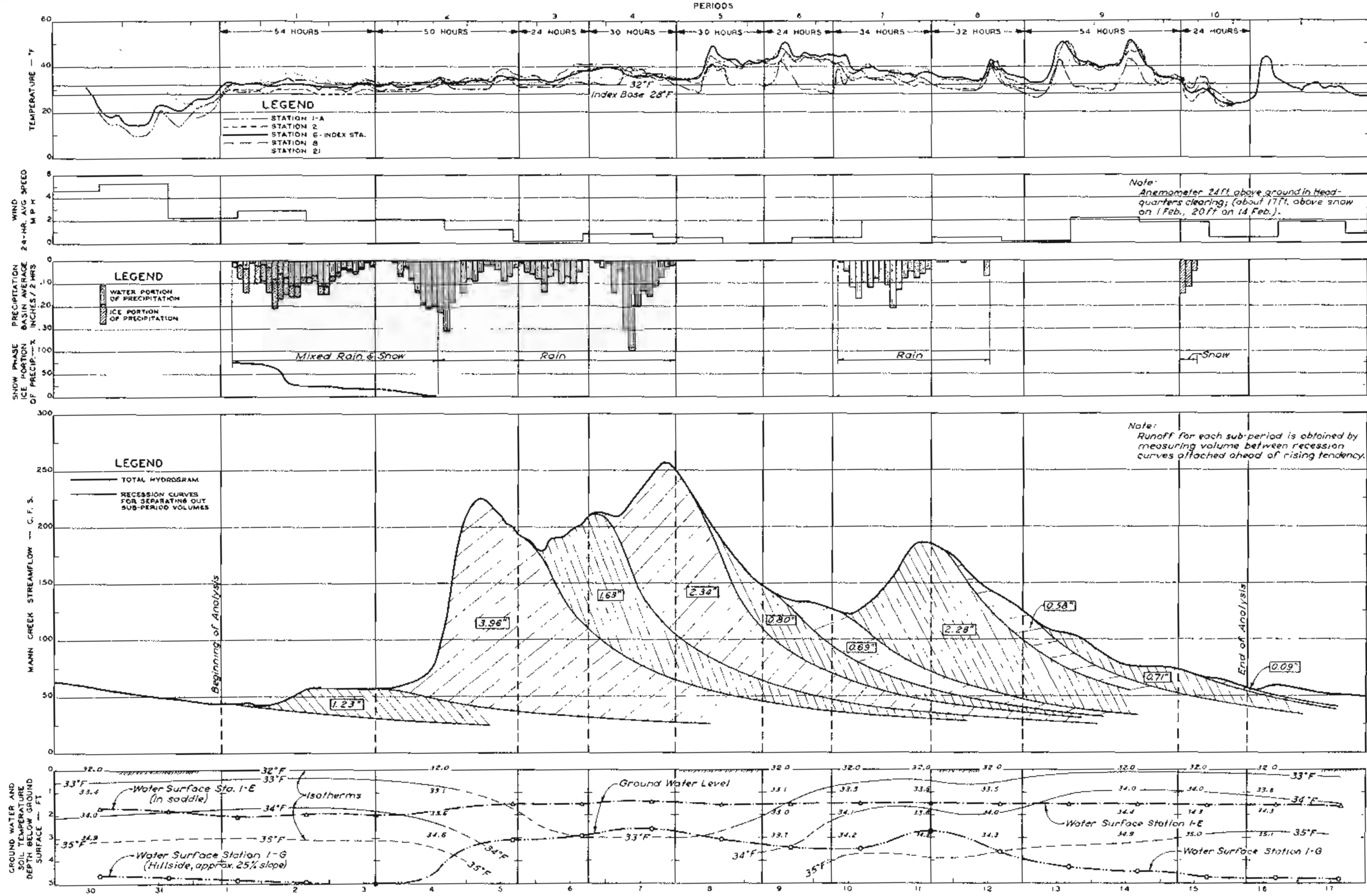


FIGURE 1 — HYDROLOGICAL AND METEOROLOGICAL LOG — JAN.-FEB. 1951

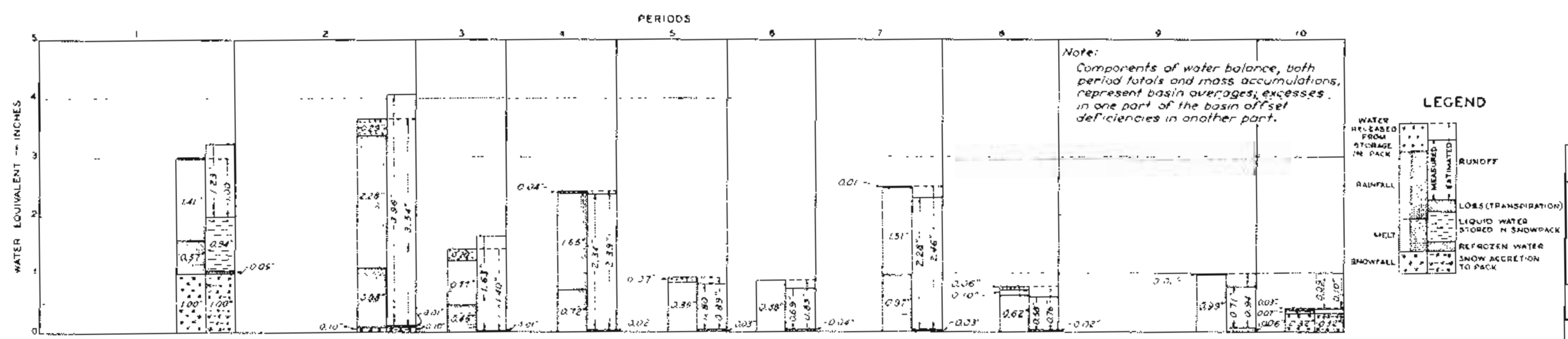
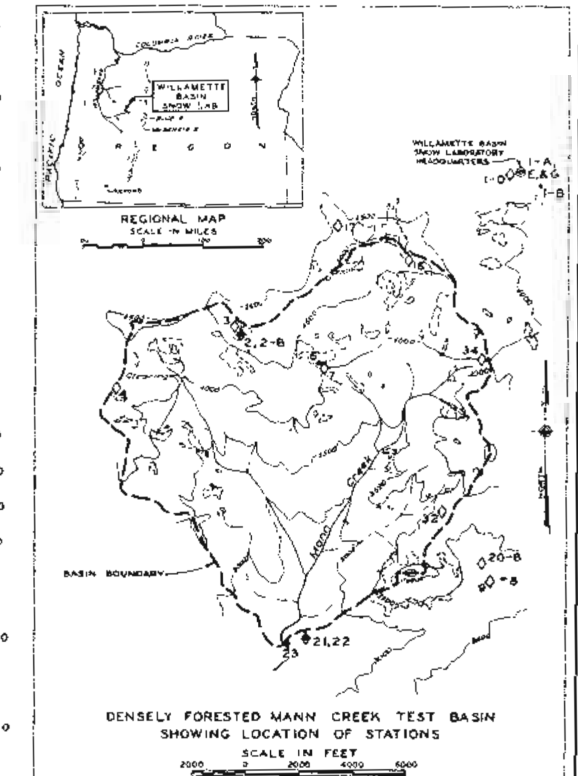


FIGURE 2 — COMPONENTS OF WATER BALANCE FOR EACH PERIOD



OBSERVATIONS		
DATA ELEMENTS	STATIONS	SYMBOL
PRECIPITATION (RECORDERS)	1-B, 2, 6*, 8, 21	•
AIR TEMPERATURE AND RELATIVE HUMIDITY	1-A, 2, 6*, 8, 21	-o-
SOIL AND SNOW TEMPERATURE, WIND MOVEMENT, AND TWO GROUND WATER WELLS	HEADQUARTERS (1-A, E, & G)	◎
STREAM FLOW	23	▲
SNOW DEPTH AND WATER EQUIVALENT	1-0, 2-B, 3, 4, 7, 9, 16, 17, 20-B, 22, 32, 34	◇

*STATION 6 IS THE TEMPERATURE INDEX STATION AS IT IS IN RESEARCH NOTE NUMBER 19.

FIGURE 3

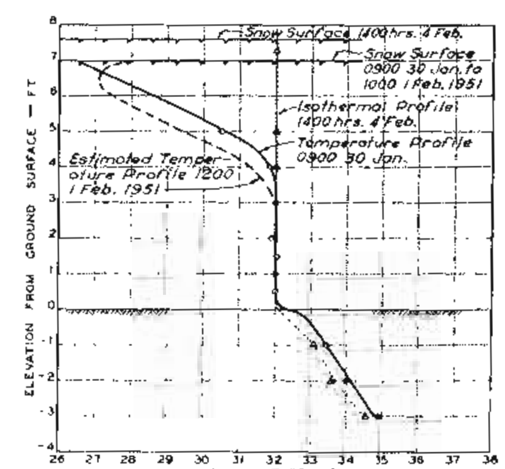


FIGURE 4 — GROUND AND SNOW-PACK TEMPERATURE PROFILES — HEADQUARTERS

SNOW INVESTIGATIONS SUMMARY REPORT

SNOW HYDROLOGY

RAIN ON SNOW ANALYSIS

FEBRUARY 1951 WILLAMETTE BASIN SNOW LABORATORY
MANN CREEK DRAINAGE AREA 5.2 SQUARE MILES

SHEET 1 OF 2

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

TO ACCOMPANY REPORT DATED 30 JUNE 1956

PD-20-25/56

PLATE 9-1

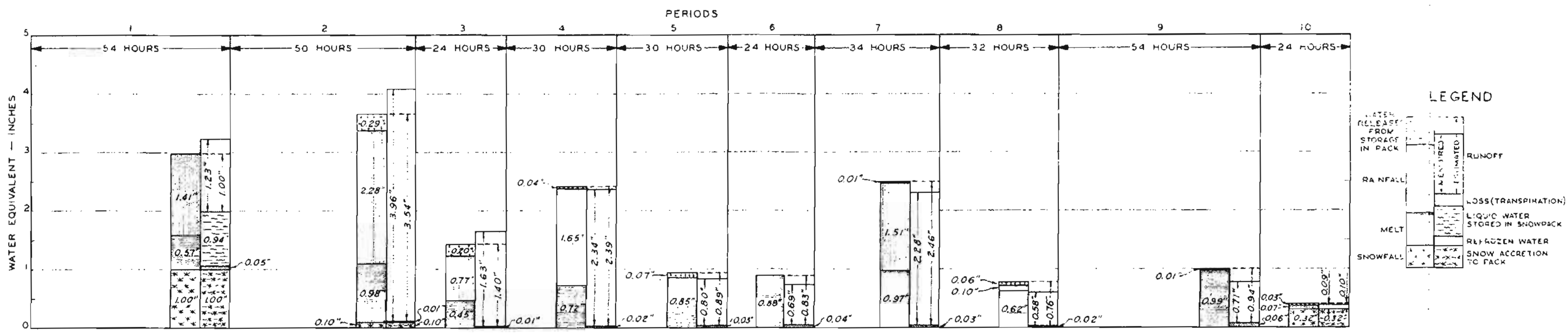


FIGURE 1 — COMPONENTS OF WATER BALANCE FOR EACH PERIOD①

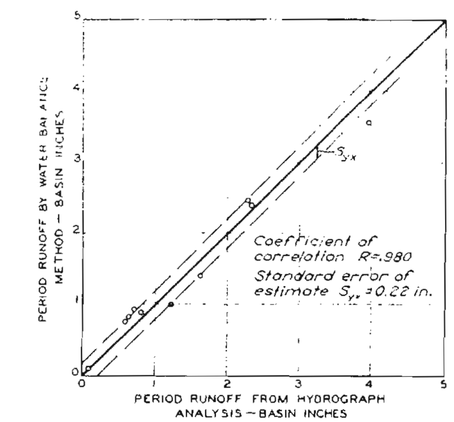


FIGURE 3 — RUNOFF COMPUTED BY WATER BALANCE METHOD COMPARED WITH THAT DERIVED FROM HYDROGRAPH ANALYSIS

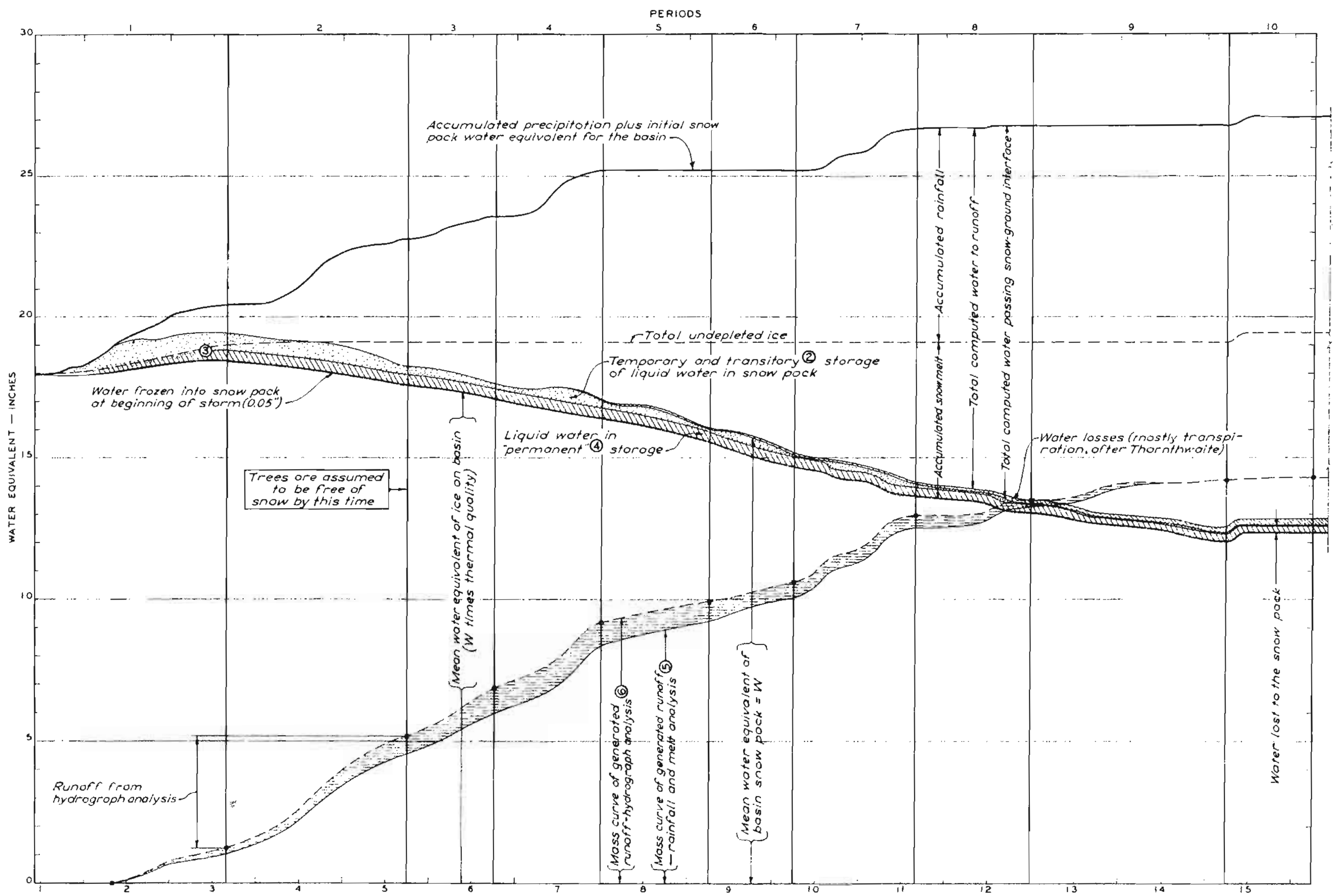


FIGURE 2 — ACCUMULATION AND DEPLETION OF HYDROLOGIC ELEMENTS (MASS CURVES)①

Notes:

① *Components of water balance, both period totals and mass accumulations, represent basin averages; excesses in one part of the basin offset deficiencies in another part.*

② *Transitory storage is computed by regarding the snow cover as a channel and routing the rain plus melt through it to the ground surface by the Muskingum method with $x=0.3$ and $t=2.5$ hours, while the water equivalent of the snow cover depletes from 19 to 15 inches; and with $x=0.3$ and $t=1.5$ hours as the snow water equivalent decreases from 15 to 12 inches.*

③ *Distinction between temporary and permanent storage during first sub-period is not significant and therefore not shown.*

④ *Basin snow pack is assumed to have the potential of holding 2% by weight as liquid water adsorbed to the snow crystals. This water that resists gravitational drainage is designated as "permanent" storage, although it becomes available for runoff when the ice matrix to which it is adsorbed is melted.*

⑤ *Curve ⑤ was drawn from the 2-hourly values of generated runoff at snow-ground interface, computed from precipitation, melt, and storage in the snow pack. Sta. 6 temperatures were used for melt.*

⑥ *Curve ⑥ was drawn to plotted points (o's) computed from hydrograph analysis, but between points was patterned in accordance with curve ⑤.*

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

RAIN ON SNOW ANALYSIS

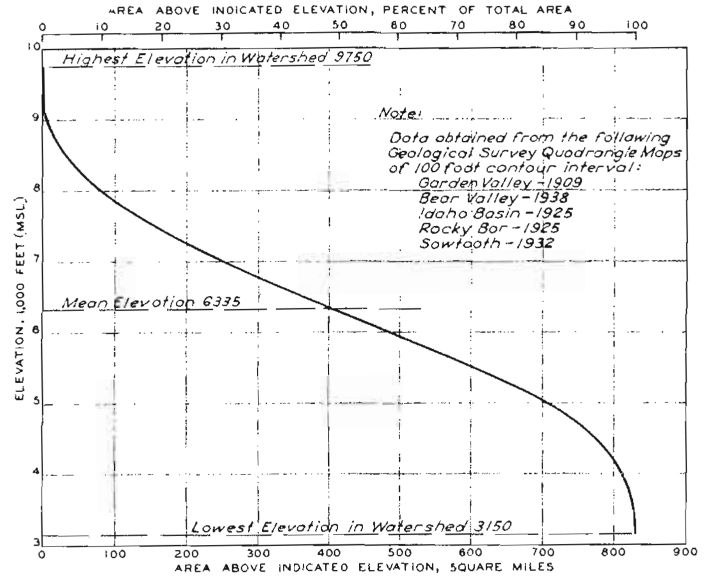
FEBRUARY 1951 WILLAMETTE BASIN SNOW LABORATORY
MANN CREEK DRAINAGE AREA 5.2 SQUARE MILES

SHEET 2 OF 2

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

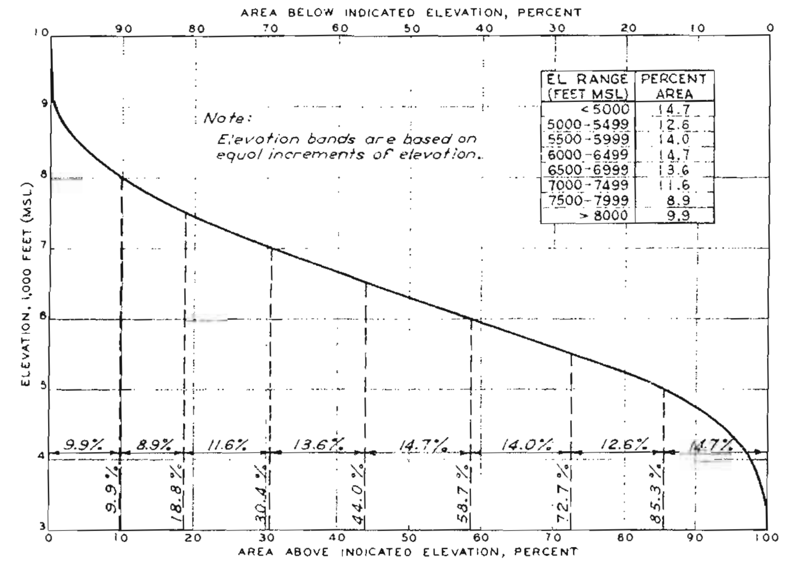
PREPARED: C.E.J. SUBMITTED: [illegible] TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: D.V. APPROVED: D.M.R.

PD-20-25/57



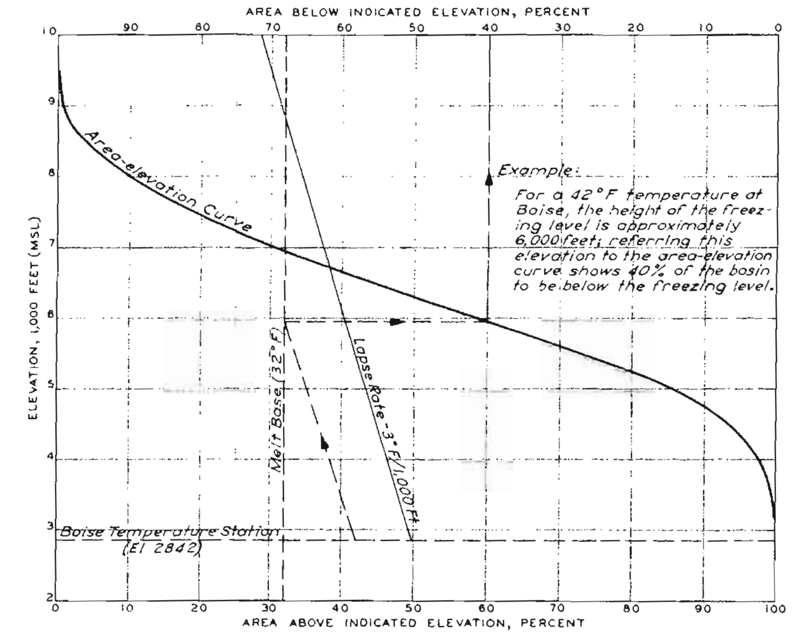
AREA-ELEVATION CURVE

FIGURE I



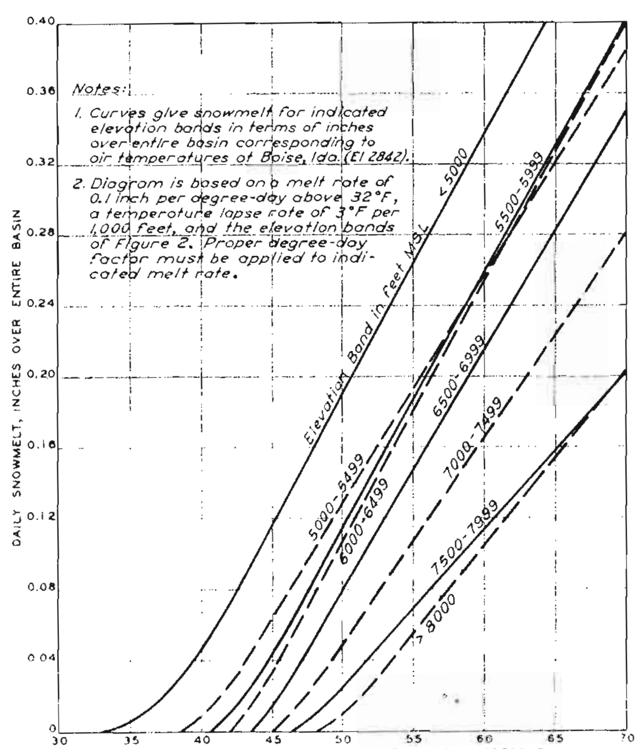
BASIN SUB-DIVISION INTO ELEVATION BANDS

FIGURE 2



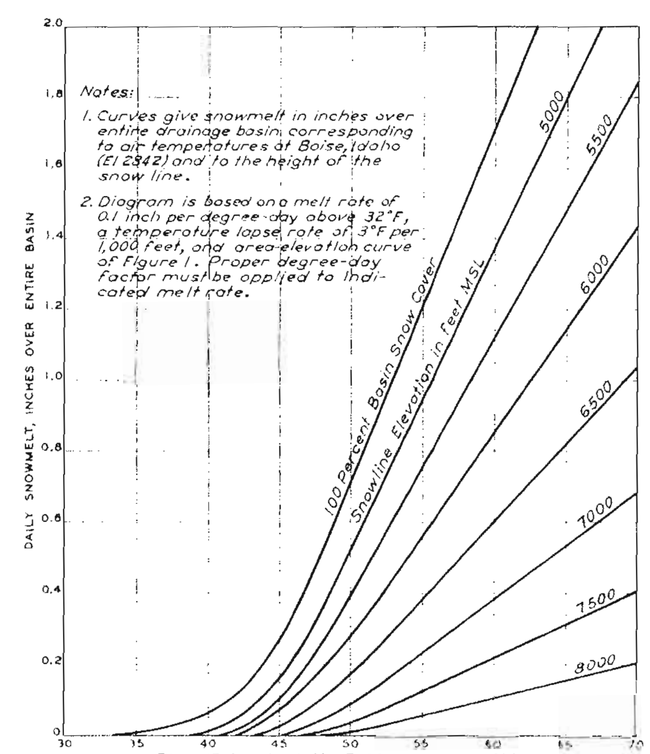
CONTRIBUTING AREA DIAGRAM

FIGURE 3



TEMPERATURE-SNOWMELT CURVES
FOR INDIVIDUAL ELEVATION BANDS

FIGURE 4



TEMPERATURE-SNOWMELT CURVES
FOR BASINWIDE SNOWMELT

FIGURE 5

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

TEMPERATURE-INDEX COMPUTATION
OF SNOWMELT

BOISE RIVER BASIN ABOVE TWIN SPRINGS, IDAHO
DRAINAGE AREA 830 SQUARE MILES

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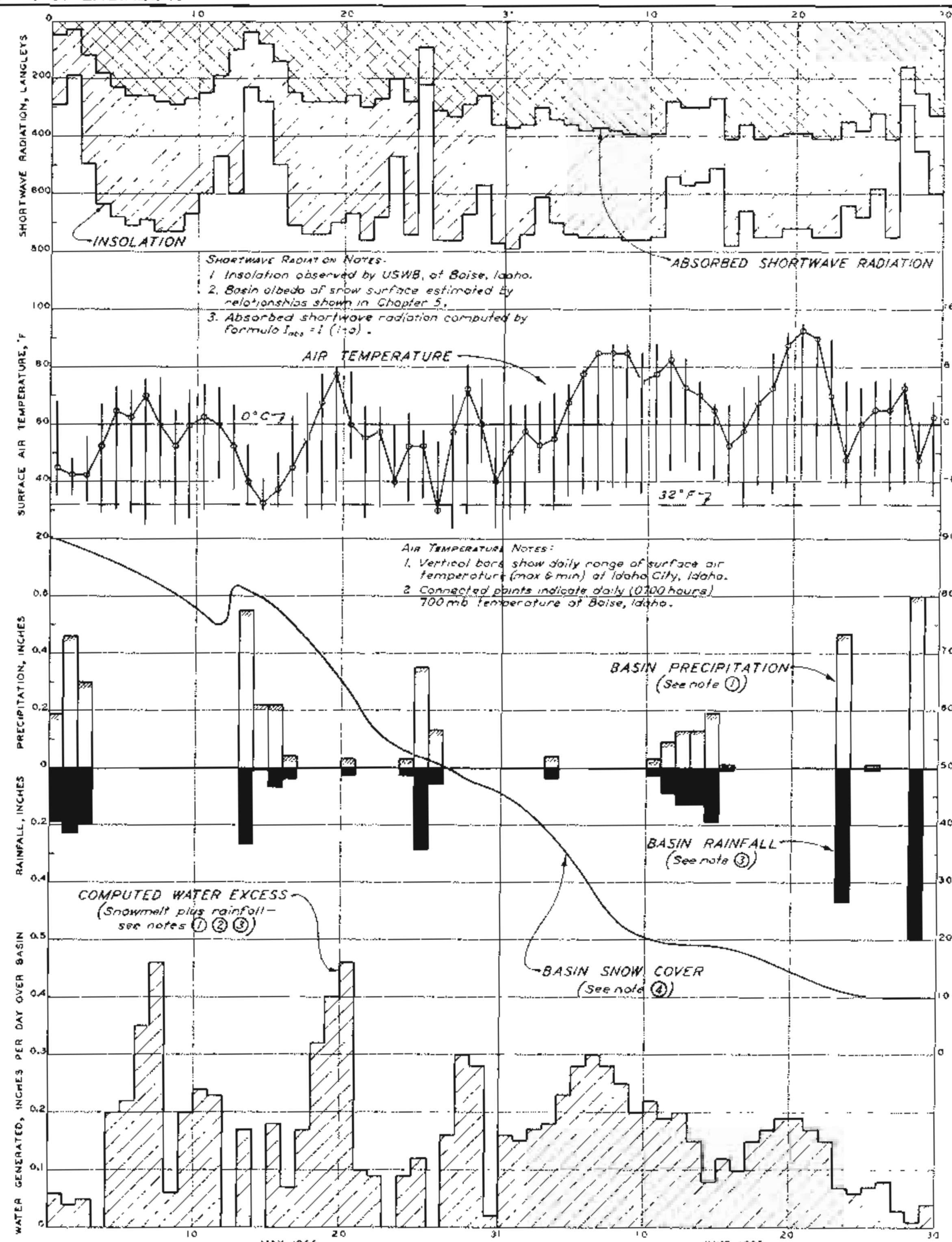
PLATE 9-3



HYDROMETEOROLOGICAL DATA AND COMPUTATION OF WATER GENERATED

FIGURE 1

NOTES for FIGURE 1.—

① Basin precipitation computed as follows: precipitation index equals sum of Arrowrock Dam, Idaho City, Obsidian (4 NNE), and two times Atlanta (1E) precipitations. Normal annual precipitation (NAP) for basin equals 33.3 inches, while precipitation index for station NAP equals 113.0 inches hence,

$$\text{Basin Precip} = \frac{13.0}{113.0}\ \text{Precip Index}$$

$$= 0.30 \times \text{Precip Index}$$

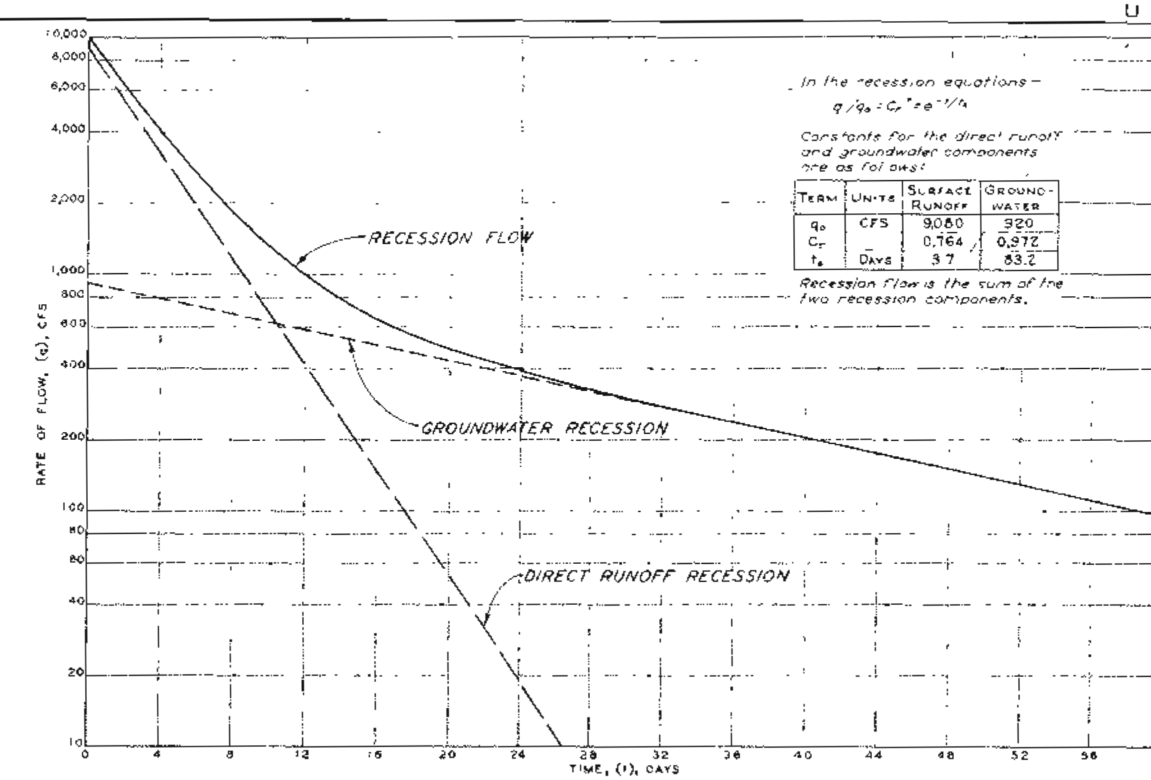
② Snowmelt excess computed from equation,

$$M = 0.0267\ T_{max} + 0.00227G - 2.00$$

where M is the snowmelt in inches over the basin, T_{max} is the daily maximum temperature of Idaho City, in degrees F, and G is a radiation parameter in langleys (equals absorbed shortwave radiation plus estimated longwave loss—longwave loss estimated from Boise 700 mb temperature and Idaho City minimum temperature using diagram of (Figure 2, Plate 6-3).

③ Rainfall computed from basin precipitation assuming lapse rate of 3 degrees F per 1,000 feet and using Idaho City mean daily temperature. (Precipitation in form of snow at temperatures less than 35 degrees F). Rainfall excess assumes all rain falling on bare ground is lost while 100 percent runoff results from snow-covered area.

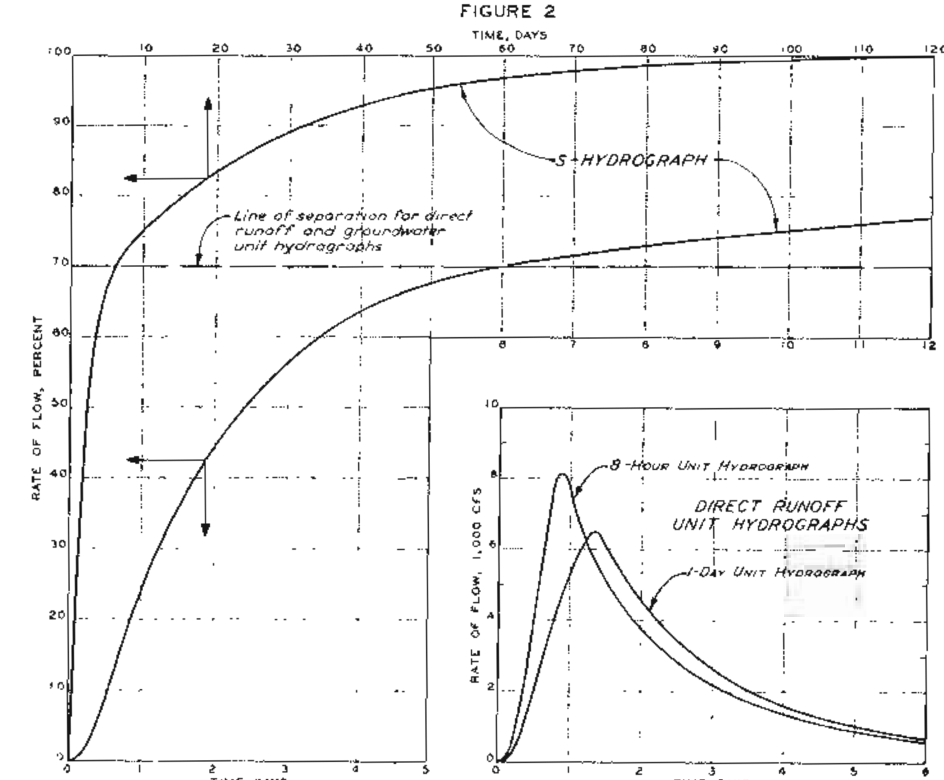
④ Basin snow cover obtained from observations by aerial reconnaissance, Walla Walla District Office. See Plates 7-5 and 7-6.



TERM	UNITS	SURFACE RUNOFF	GROUND-WATER
q_0	CFS	9,080	920
C_r	—	0.764	0.972
t_s	DAYS	3.7	83.2

RECESSION CURVES

FIGURE 2



S-HYDROGRAPH AND UNIT HYDROGRAPHS

FIGURE 3

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

FLOW FORECASTS AND RECONSTITUTION

BOISE RIVER NEAR TWIN SPRINGS, IDAHO
1955 SPRING SNOWMELT SEASON
DRAINAGE AREA 830 SQUARE MILES
SHEET 1 OF 2

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PREPARED C.E.M.	SUBMITTED C.E.H.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
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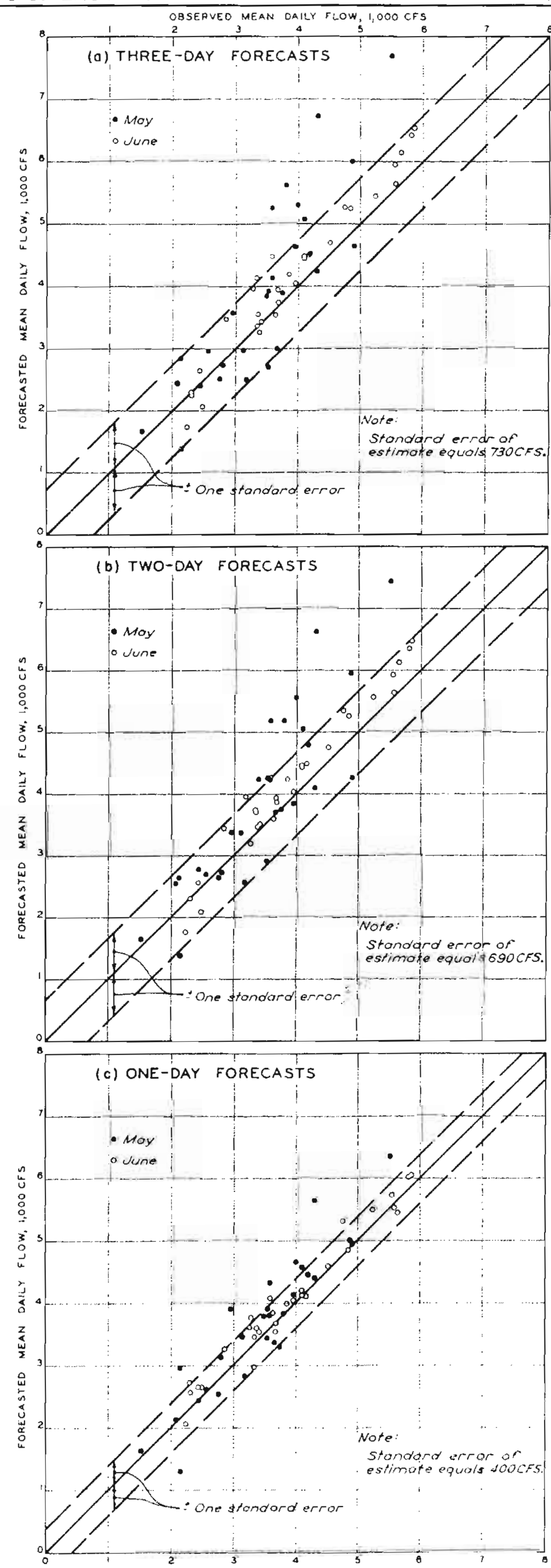
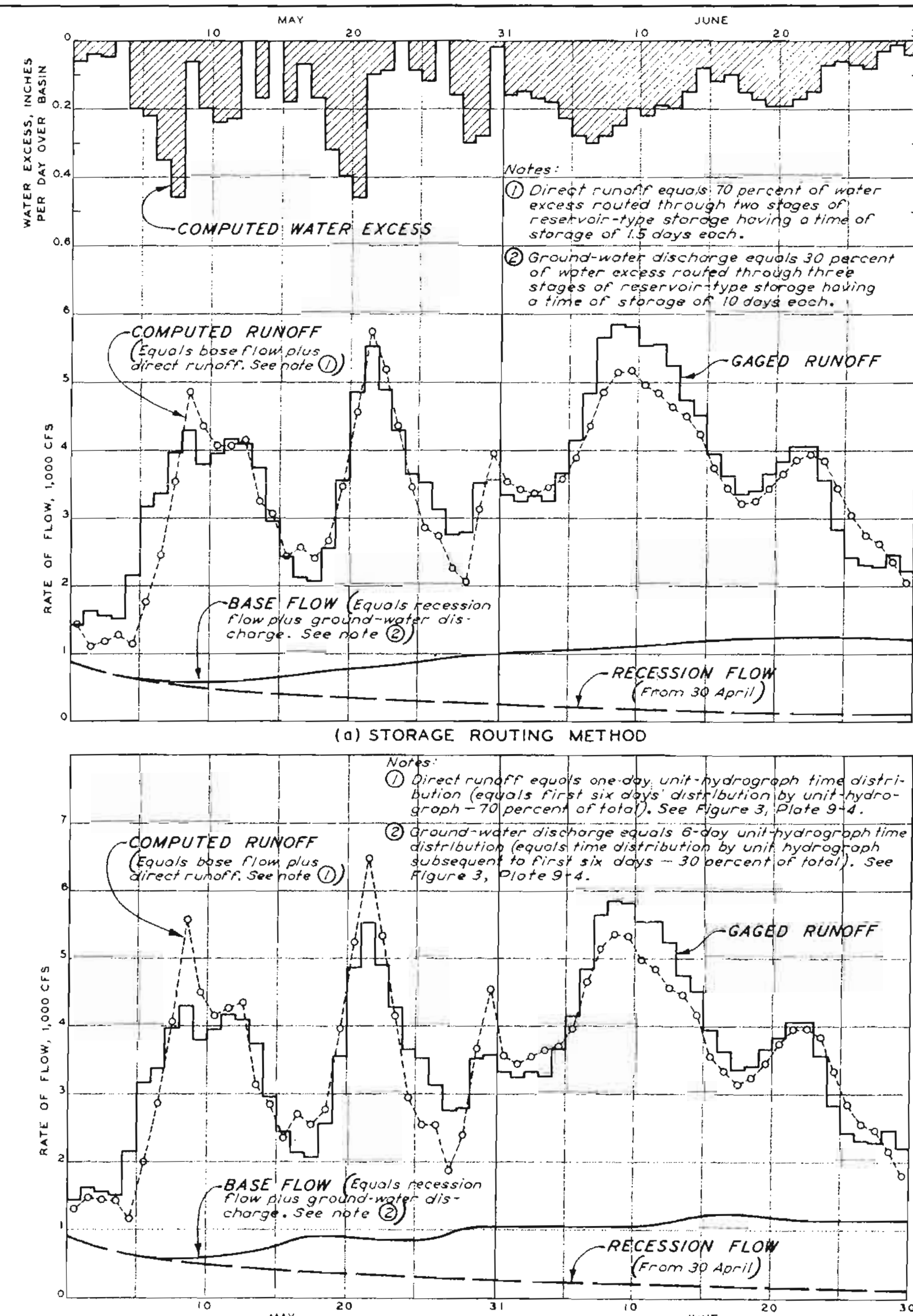


MEAN DAILY FLOW FORECASTS

FIGURE 1

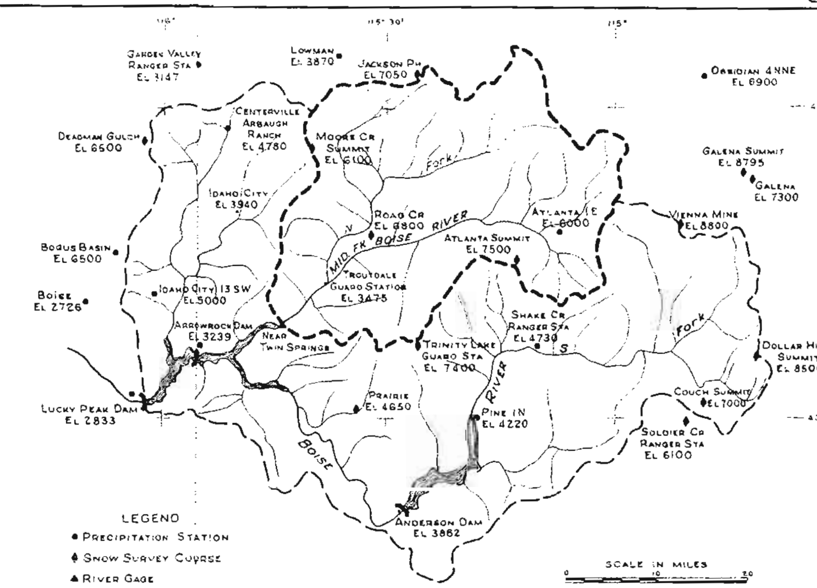
NOTE for FIGURE 1:
One-, two-, and three-day forecasts computed from values of snowmelt and rainfall described on Figure 1, Plate 9-4, utilizing distribution graph derived from S-hydrograph shown on Figure 3, Plate 9-4, and total recession flow from date of forecast based on recession curve shown on Figure 2, Plate 9-4. Actual observed melt parameters and rainfall were used in melt equation.



(b) UNIT-HYDROGRAPH METHOD

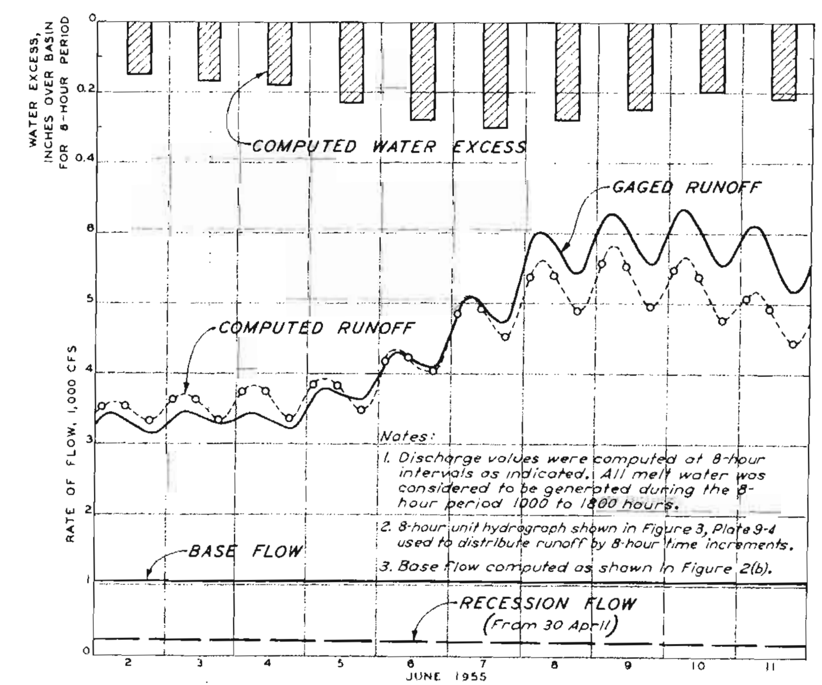
RECONSTITUTION OF SEASONAL HYDROGRAPH OF MEAN DAILY FLOWS

FIGURE 2



HYDROMETEOROLOGICAL STATIONS

FIGURE 3



RECONSTITUTION OF HYDROGRAPH SHOWING DIURNAL FLOW VARIATION

FIGURE 4

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

FLOW FORECASTS AND RECONSTITUTION

BOISE RIVER NEAR TWIN SPRINGS, IDAHO
1955 SPRING SNOWMELT SEASON
DRAINAGE AREA 830 SQUARE MILES
SHEET 2 OF 2

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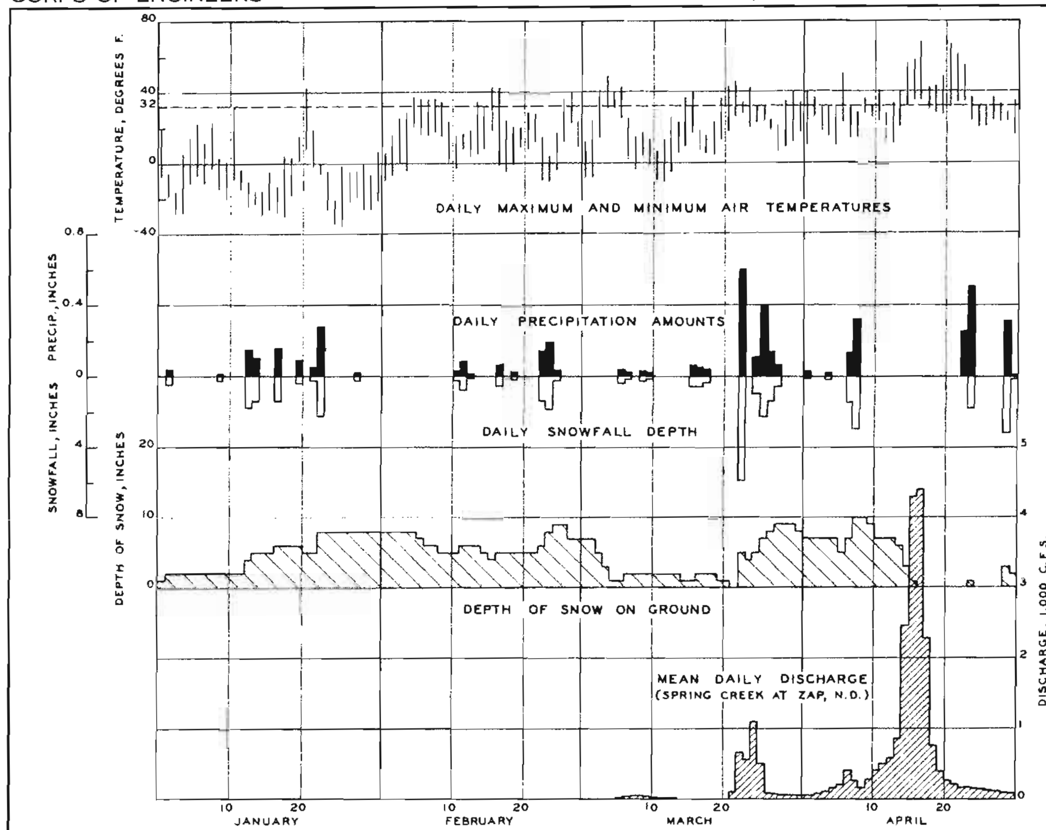
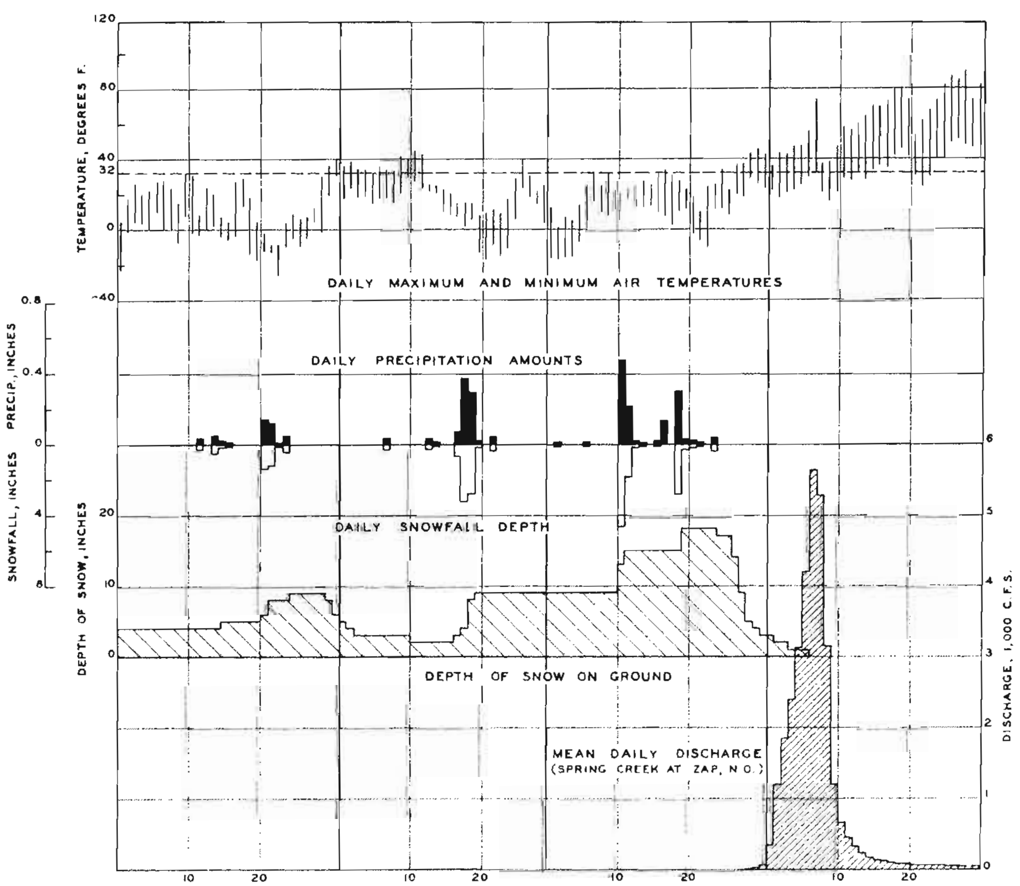


1950 DATA

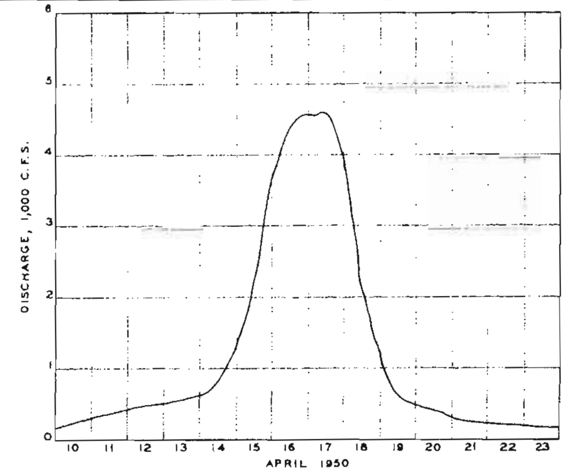


1952 DATA

HYDROMETEOROLOGICAL DATA

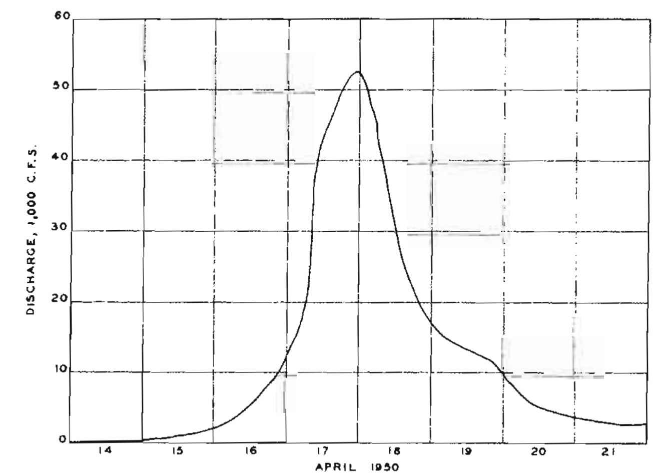
FIGURE 1

NOTE
METEOROLOGICAL DATA IN FIGURES ARE FOR DICKINSON CAA AIRPORT STATION (EL 2587)



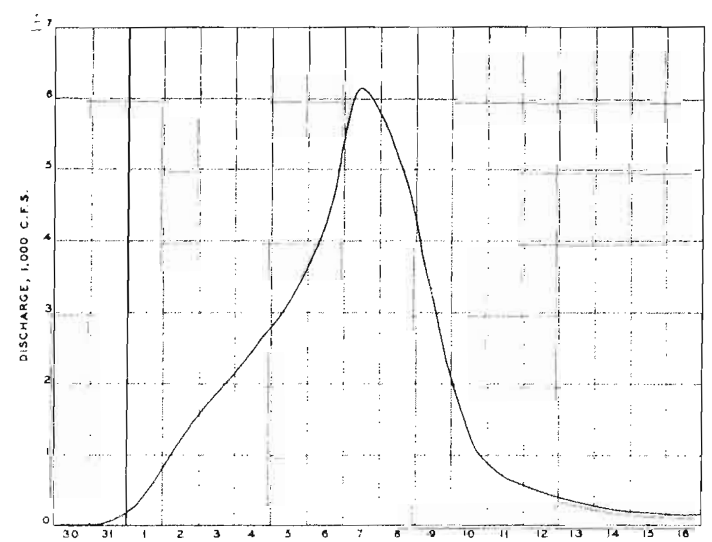
SPRING 1950 FLOOD HYDROGRAPH
FOR SPRING CREEK AT ZAP, N.D.
DRAINAGE AREA, 545 SQ. MI.

FIGURE 2



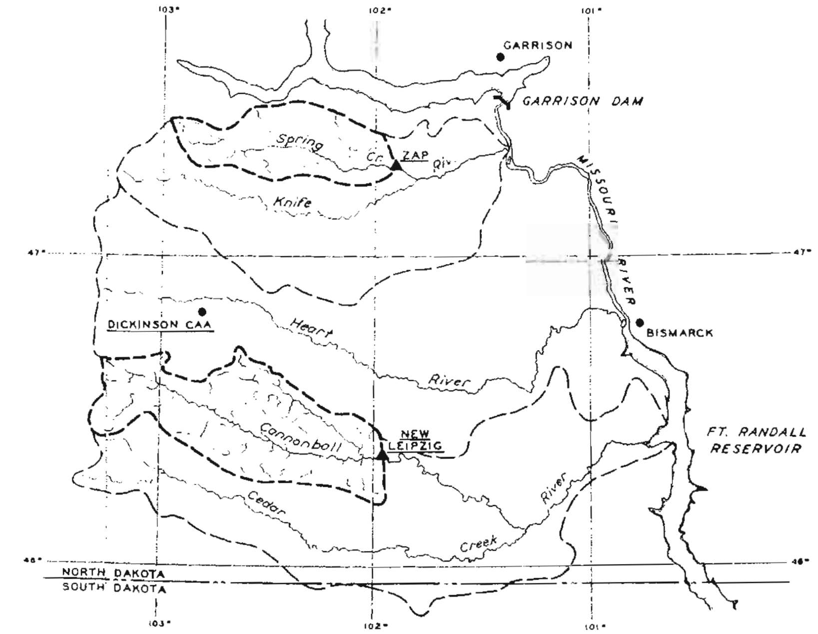
SPRING 1950 FLOOD HYDROGRAPH
FOR CANNONBALL RIVER NEAR NEW LEIPZIG, N.D.
DRAINAGE AREA, 1,160 SQ. MI., APPROXIMATELY

FIGURE 3



SPRING 1952 FLOOD HYDROGRAPH
FOR SPRING CREEK AT ZAP, N.D.
DRAINAGE AREA, 545 SQ. MI.

FIGURE 4



LOCATION MAP
SCALE IN MILES

SNOW INVESTIGATIONS
SUMMARY REPORT
SNOW HYDROLOGY

SNOWMELT FLOODS IN
GREAT PLAINS AREA

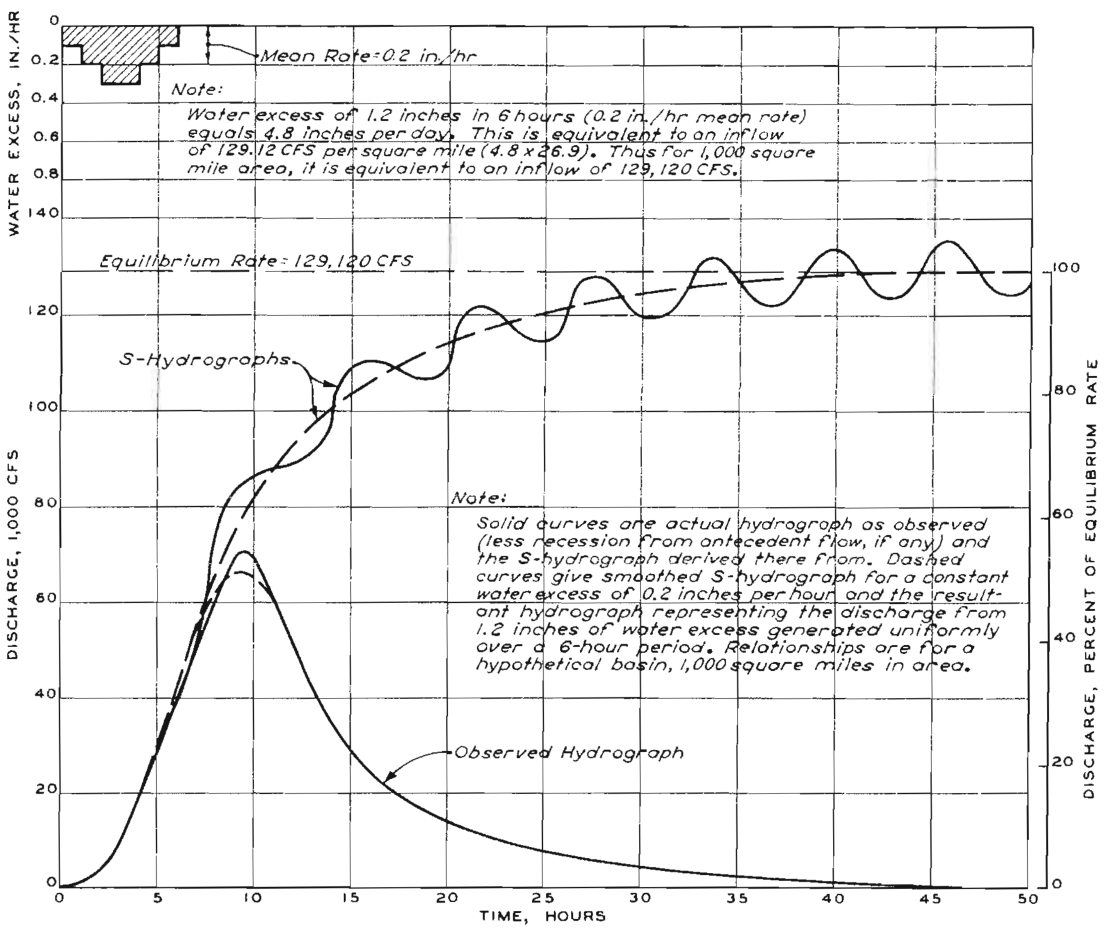
OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS U. S. ARMY

PREPARED C.E.H. SUBMITTED C.E.H.
DRAWN H.E.B. APPROVED D.M.R.

TO ACCOMPANY REPORT DATED 30 JUNE 1956

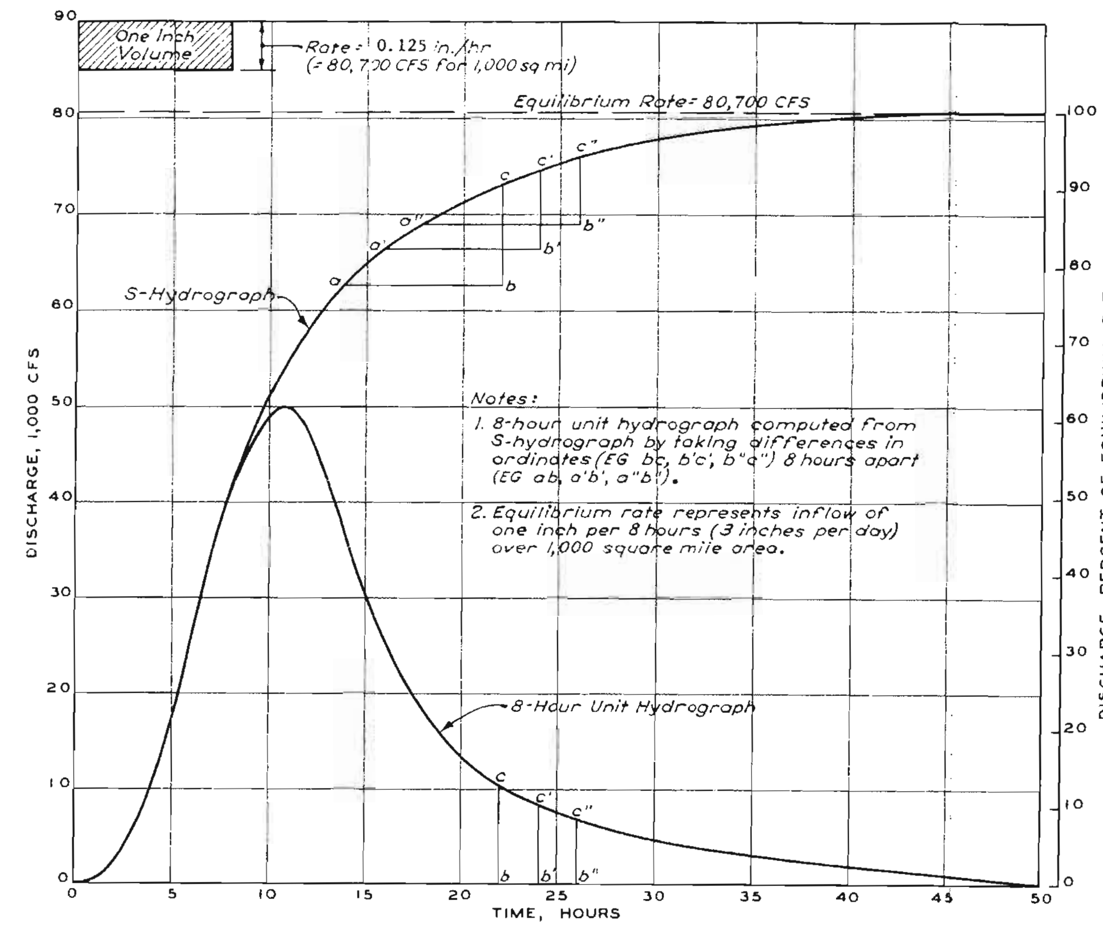
PD-20-25/61

PLATE 9-6



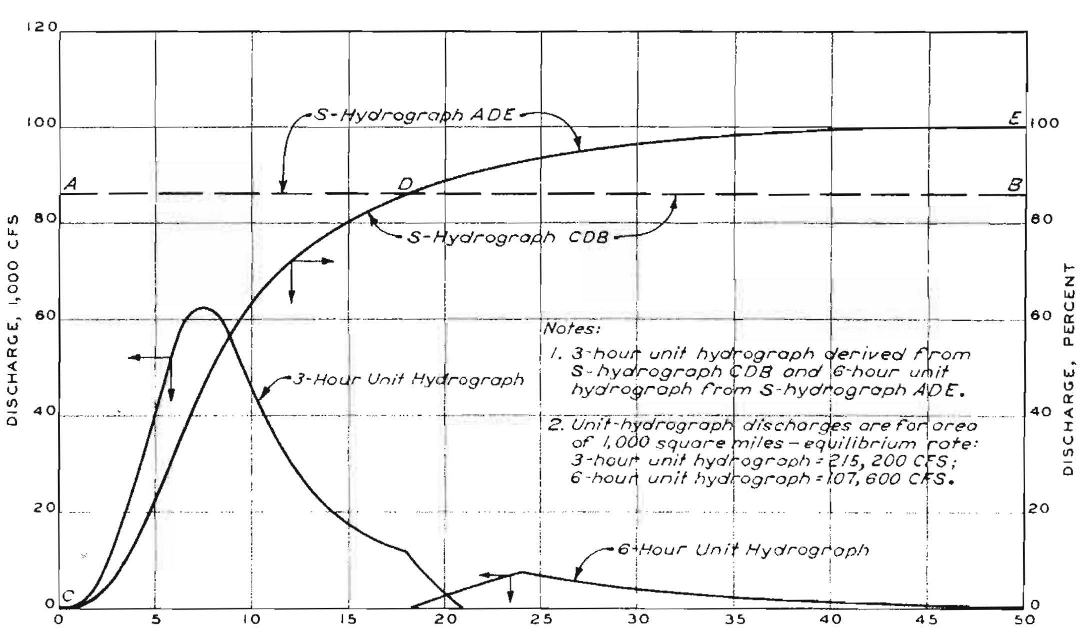
S-HYDROGRAPH — UNIT-HYDROGRAPH RELATIONSHIPS

FIGURE 1



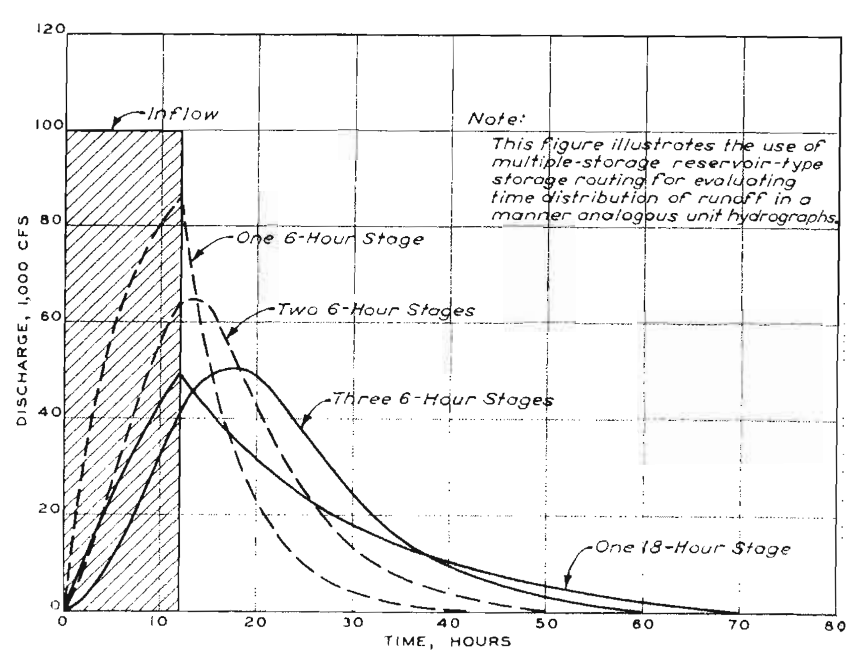
DERIVATION OF UNIT HYDROGRAPH FROM S-HYDROGRAPH

FIGURE 2



DERIVATION OF UNIT HYDROGRAPHS HAVING DIFFERENT PERIODS FROM A DIVIDED S-HYDROGRAPH

FIGURE 3



EXAMPLE OF MULTIPLE-STAGE RESERVOIR-TYPE STORAGE ROUTING

FIGURE 4

SNOW INVESTIGATIONS SUMMARY REPORT

SNOW HYDROLOGY

ILLUSTRATIVE DIAGRAMS OF TIME DISTRIBUTION OF RUNOFF

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

PREPARED: G.E.H. SUBMITTED: G.E.H.
DRAWN: B.V. APPROVED: D.M.R.

TO ACCOMPANY REPORT DATED 30 JUNE 1956

PD-20-25/62

CHAPTER 10 - DESIGN FLOOD DETERMINATION

10-01. INTRODUCTION

10-01.01 General. - No general all-inclusive rules of universal applicability can be given for use in hydrologic design. Every basin, every stream, is an individual and separate problem unique in its flood-producing characteristics. Each requires careful study to establish hydrometeorological relationships by which estimates of probable optimum conditions can be translated into the rates of streamflow (or volume of runoff) for the several different design requirements. Optimum conditions of weather, ground, and snowpack must be considered in combination to arrive at estimates of the basic flood magnitudes which form the basis of design of projects. Observed floods usually reflect compensating variations in the several factors affecting flood runoff, so that the runoff rates and volumes are far below those that would result from more critical combinations of the factors. Statistical studies provide a means of estimating the magnitude of flood potential and average flood frequencies for streams having relatively long periods of record, particularly where records of flow for many streams in a region of reasonably comparable hydrologic and meteorologic influences can be analyzed. However, because of the number and range of variation in independent variables involved in floods, and the wide range between flood magnitudes that would result from optimum combinations of critical flood-producing factors as compared with combinations generally observed, statistical analyses of actual stream flow records seldom, if ever, provide a reliable indication of extraordinary flood potentialities of a specific drainage basin.

10-01.02 Basic flood estimates. - In Corps of Engineers practice, there are two classes of floods for which hydrographs are usually synthesized: (1) maximum probable flood, which is used primarily for the design of spillways and appurtenant structures for virtually complete security of major projects against structural failure, and is defined as the flood discharge that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the region; and (2) standard project flood, which represents a "standard" against which the degree of protection finally selected for a project may be judged and which thus will serve as a basis for comparison with protection provided at similar projects in other localities. The standard project flood is defined as the flood discharge that may be expected from the most severe combination of meteorologic and hydrologic conditions that are considered reasonably characteristic of the geographical region involved, excluding extremely rare combinations. The standard project flood is based on less severe conditions than the maximum probable flood; in practice it has been found to be generally equal to 40 to 60 percent of the maximum probable flood for the same basins.

10-01.03 Design Flood. - The term design flood has been applied to the flood volume or peak discharge finally adopted for which full protection is being provided in a particular project or section thereof. It may be either greater or less than the basic flood estimate, depending to an important extent upon flood characteristics, frequencies, and potentialities, and upon economic factors and other practical considerations. The preceding definitions of basic and design floods have been summarized from Civil Engineer Bulletin No. 52-8. 2/ More complete listings and definitions of design criteria for these floods may be found therein.

10-01.04 The rational procedure. - The principal factors to be considered in determining the magnitude of design floods are discussed in chapter 5, "Flood-hydrograph analyses and computations," of Part CXIV of the Engineering Manual for Civil Works Construction. 3/ The rational procedure involves consideration of the optimum meteorologic and hydrologic conditions which are likely to occur simultaneously to produce maximum runoff. Rational determinations of design floods involving snow require knowledge and use of the combined effect of snow accumulation, snowmelt, and effect of the snowpack on runoff, as described in the preceding chapters. In general, the limited period of record of snow accumulation data precludes their use for application to design floods. The estimate of snow accumulation for a given design condition may, however, be based on a function of normal annual precipitation for cases where winter precipitation is nearly all in the form of snow. Extrapolation of precipitation to design condition amounts is possible because of the many years of record of storm experience which are usually available. Snowmelt is determinable from thermal-budget indexes appropriate to the type of area and the specific flood condition. The melt coefficients may be derived from historical data or from generalized melt equations as presented in chapter 6. Since snowmelt is a direct function of thermal energy input to a basin, there are definite upper limits to the amount of heat exchange that may be experienced by radiative processes or by advection of heat by airmasses. The effect of the snowpack on runoff varies through a wide range of conditions; the pack may be initially "primed" or "ripe" (conditioned to produce runoff); or it may be initially "cold" and dry. In addition to the effects of snow in the development of rationally derived design floods, other hydrologic factors must be evaluated, including rainfall, soil moisture recharge, ground water condition, and evapotranspiration loss. Also, the natural storage time of the basin as expressed by such standard routing techniques as unit graphs or storage-routing procedures must be determined. Having determined the basin hydro-meteorological characteristics, it is then possible to maximize each variable on the basis of optimum runoff-producing conditions, combined with the optimum meteorological sequence, for the specified condition of design.

10-01.05 Simplified design-flood estimates. - In some cases preliminary estimates of design floods or flood estimates may be required for minor engineering works which do not warrant a complete flood analysis by the rational procedure outlined in the preceding paragraph. For such determinations, the judgment and experience of the hydrologist is relied upon; short cuts and subjective analysis of the factors affecting runoff are used. Previously derived floods for areas of similar hydrologic character may be used as guides, as for example charts 1 and 2 contained in Appendix "M", Columbia River and Tributaries, 6/ which show curves for estimating spillway-design-flood peak discharges resulting from snowmelt in the Columbia River basin on the basis of drainage area and normal annual precipitation. Many factors affecting runoff are not directly evaluated by these curves. For this reason, it is especially important that the hydrologist have a full understanding of the basin to which they are applied, in order to account for differences in conditions from those for which the curves were derived. Estimates so derived should be considered to be preliminary and/or approximate, subject to revision when and if more complete analysis is warranted. The use of historical streamflow data alone should not be considered as a basis of derivation for design-flood determinations (e.g., the arbitrary use of a multiplication factor applied to the maximum flood of record). For the short period of streamflow records normally available, there is little likelihood that a constant relationship between the maximum flood of record and a specific design condition exists.

10-01.06 Design floods involving snow. - There are two general types of design floods involving snow: (1) winter rain-on-snow floods, which are of relatively short duration and for which snowmelt usually constitutes the minor contribution to runoff; and (2) spring snowmelt floods, which are the result of the melting of the accumulated snowpack, are usually several months in duration, and for which rainfall is usually of lesser consequence. For both types of floods, the snowpack accumulation, snowpack condition, and snowmelt rates must be evaluated, plus all other factors affecting runoff.

10-01.07 Factors in design flood derivation. - In the rational derivation of design floods involving snow, certain general procedures should be outlined and certain basic factors evaluated before detailed studies are begun. They are summarized as follows:

I. Review of general hydrologic features

A. Location of drainage area with respect to major topographic features, airmass types, and general airmass circulation during storms and periods of melt.

B. Physical characteristics of the watershed.

1. Drainage area.
2. Area-elevation relationship.
3. Normal annual basin precipitation.
4. Normal annual runoff.
5. Normal annual loss.
6. Normal snowpack accumulation and seasonal distribution.
7. Soil conditions and seasonal change in soil moisture.
8. Ground water geology and ground water storage.
9. Vegetative cover.
10. Artificial regulation of streamflow.
11. Streamflow characteristics from analysis of past record.
12. Natural basin storage time, with or without snow cover, expressed by unit hydrograph or storage-routing constants.

II. Evaluation of specific conditions pertinent to winter rain-on-snow design floods, according to established design criteria.

A. Initial snowpack characteristics.

1. Snow-covered area.
2. Snowpack depth and water equivalent and distribution with respect to elevation (slope of snow wedge).
3. Snowpack condition with respect to temperature, free water, and density-elevation variation.

B. Determination of sequence of meteorological factors affecting melt.

C. Selection of snowmelt rates (snowmelt indexes or generalized snowmelt equations appropriate to area and rain-on-snow conditions).

D. Determination of rainfall.

1. Time distribution.
2. Total amount.

E. Determination of loss and runoff conditions.

F. Synthesis of all factors affecting runoff into a design flood hydrograph.

III. Evaluation of specific conditions pertinent to spring snowmelt design floods, according to established design criteria.

A. Initial snowpack characteristics.

1. Snow-covered area.
2. Snowpack water equivalent and distribution with respect to elevation (slope of snow wedge).
3. Albedo of snow surface (for areas with significant open areas).

B. Determination of critical sequence of meteorological factors affecting melt.

C. Selection of snowmelt rates utilizing thermal-budget indexes or generalized snowmelt equations appropriate to area.

D. Evaluation of effects of rainfall at time of maximum snowmelt flood, considering changes in snowmelt conditions during rain.

E. Determination of loss and runoff conditions.

F. Synthesis of all factors affecting runoff into a design flood hydrograph.

10-02. OPTIMUM CONDITIONS FOR DESIGN FLOODS

10-02.01 General. - In the derivation of design floods it is necessary to consider the optimum runoff-producing conditions, with regard to: (1) the snowpack; (2) the meteorological sequence affecting melt and rainfall; (3) the effect of losses to soil moisture and evapotranspiration; (4) changes in ground-water storage; and (5) time delay to runoff. The following paragraphs describe the derivation of optimum runoff conditions for maximum probable and standard project floods, in connection with both winter- and spring-type floods.

10-02.02 Optimum snowpack conditions. - The three basic considerations of optimum snowpack condition are (1) water equivalent and its distribution, (2) areal cover, and (3) structural character. For spring snowmelt design-flood hydrographs, the structural character of the snowpack is unimportant (it is assumed the snowpack is isothermal at 32°F and saturated with free water). Generally, only the total water equivalent of the snowpack and its distribution with elevation and area must be considered; for basins with significant open areas, snow-surface albedo must also be evaluated. For winter rain-on-snow floods, however, the stage of metamorphism of the snowpack must be taken into account as set forth in chapter 8. For winter floods, the total water equivalent of the snowpack may not be critical. The principal consideration for winter rain-on-snow floods is that possible storage of liquid water in the snowpack must be satisfied before runoff occurs.

10-02.03 For spring snowmelt design floods, the maximum possible snowpack water equivalent is generally based upon detailed studies of the potential total winter-season precipitation, with assumed percentages of total winter precipitation falling in the form of snow. The studies may relate maximum winter-season precipitation to size of drainage area and normal annual precipitation, as was done for the Columbia River basin by the Hydrometeorological Section of the U. S. Weather Bureau. 7/ From such studies the maximum winter snowfall for specific basins may be derived. The increase of the snowpack with elevation is determined on the basis of normal increase of precipitation with elevation. The snow wedge so derived represents the maximum possible flood-producing snowpack. For standard project flood conditions, the snowpack water equivalent determination is based on less severe conditions than that for the maximum possible and conforms to the maximum which is reasonably characteristic of the region involved.

10-02.04 The initial snowpack condition for winter rain-on-snow floods is important both from the consideration of snowmelt and for storage and delay of liquid water in the snowpack. For maximum probable rain-on-snow flood conditions, in some cases it may be assumed that sufficient water equivalent exists to provide snowmelt continuously through the storm period throughout the entire range of elevation. In other cases, a derived maximum snow wedge is required. Also for the maximum probable flood, it may be assumed in most cases that the preceding melt or rainfall has provided drainage channels through the snowpack and has conditioned it to produce runoff without significant delay, so that water excesses from rain and snowmelt during the storm period are immediately available for runoff. In unusual circumstances, however, especially where a significant portion of the basin is at high elevations, it may be necessary to ascribe snowpack storage and delay to a portion of the water excess (see discussion of liquid-water-holding capacities of the snowpack in section 8-05.). Evaluation of this snowpack condition may be established on the basis of meteorological events preceding the design storm. For standard project flood determinations, the storage and delay of liquid water in the snowpack should be evaluated for all ranges in elevation, based on preceding meteorological events. The maximum-runoff condition in this case is one where there is (1) sufficient snow on the basin initially to provide melt contribution to runoff over the entire area for the storm period, and yet (2) a minimum depth of snow, especially at high elevations, to provide the least possible storage required in conditioning the snowpack to produce runoff. Thus the flattest possible snow wedge having sufficient snow to just equal the total melt at the lowest elevation in the basin, is the optimum condition for winter rain-on-snow floods.

10-02.05 Optimum meteorological conditions. - Meteorological conditions during both the pre-flood and flood periods affect design floods involving snow. Pre-flood conditions determine the snowpack soil-moisture and ground water conditions, as well as the recession flow. Rates of snowmelt and rates of rainfall during the flood period are governed by meteorological conditions. For spring snowmelt floods, the optimum condition is that in which winter snowpack accumulation occurs with no significant melt, followed by a cold spring with minimum snowmelt and continued increase in the snowpack, and finally by a sudden change to a sustained high heat input to the basin at a time when the seasonal energy input may be near maximum. Rainfall occurring near the snowmelt peak may be superimposed upon the critical snowmelt sequence to augment the maximum probable flood peak discharge. For standard project flood conditions, a similar but less severe sequence of snowmelt conditions may be assumed, which would be reasonably characteristic of the maximum for the region involved.

10-02.06 During winter rain-on-snow design floods, the optimum meteorological sequence for the maximum probable flood requires sufficient water equivalent accumulation in the pre-flood period to provide active snowmelt for the entire flood period accompanied by heat supply and rainfall sufficient to condition the pack for runoff prior to the occurrence of the design storm. During the design storm period, maximum possible snowmelt rates commensurate with the meteorological conditions accompanying the rainfall are assumed. For standard project floods, the pre-flood meteorological sequence must be carefully analyzed, to determine the initial snowpack condition. Air temperatures may be such that part of the precipitation falling during this period will be in the form of snow in the higher elevations, and part in the form of rain in the lower areas. Separation of these effects must be made in order to arrive at a reasonable snowpack condition for the basin as a whole. During the period of the design storm, snowmelt rates are assumed which are reasonably near maximum for the region considering the meteorological conditions accompanying the rainfall.

10-02.07 Meteorological factors which are pertinent to the computation of snowmelt for design floods are subdivided as follows:

Type of area	Spring snowmelt design flood	Winter rain-on-snow design flood
Open	Incident radiation Air temperature Dewpoint temperature Wind speed Cloud cover	Air temperature* Wind speed Rainfall
Partly forested	Incident radiation Air temperature Dewpoint temperature Wind speed	Air temperature* Wind speed Rainfall
Heavily forested	Air temperature Dewpoint temperature	Air temperature* Rainfall

* Air temperature function accounts for condensation melt under a saturated air condition.

The meteorological factors shown in the above tabulation appropriate to the type of area and design flood should be considered in setting up optimum meteorological conditions for determining snowmelt for design flood synthesis.

10-02.08 Optimum ground conditions. - Evaluation of loss through the processes of soil-moisture and ground-water recharge must be made for design-flood determinations. For spring snowmelt floods, the soil-moisture deficit from the preceding summer season must be assumed at the beginning of the accumulation of winter precipitation. Usually this amount is assumed to be equal to the difference between the wilting point and field moisture capacity for the average basin soil mantle. Part or all of this deficit will be satisfied by fall rains and minor melting of the snowpack during the winter. For winter rain-on-snow floods, soil-moisture deficits are usually assumed to be satisfied by snowmelt or rainfall prior to the occurrence of the design storm. In the case of standard project floods, a less severe runoff assumption as to loss by soil-moisture requirements is made, depending upon conditions which may reasonably prevail over the basin area. For cases where shallow snow depths and low temperatures prevail prior to the design storm, it is possible to have solidly frozen ground which would prevent any loss of water to the soil and also provide less delay to water in transit than occurs with unfrozen ground. With a deep snowpack, however, there is generally sufficient flow of ground heat to keep the soil unfrozen, regardless of the air temperature above the snow.

10-02.09 Ground-water recharge may be accounted for by the separation of flows through streamflow recession analysis as explained in chapter 4. Transitory storage in the soil and ground results in time delay to runoff, which may be accounted for by unit graph or storage routing techniques, as explained in chapter 9. For design flood computations, minimum time delay to runoff commensurate with the design criteria and basin characteristics is assumed, thereby maximizing peak flow conditions.

10-02.10 Evapotranspiration and interception loss. - Spring snowmelt design floods must account for loss of water by evapotranspiration to the atmosphere. During the snow accumulation season, there is a small loss by evaporation from the snow surface and transpiration from the forest. Under assumptions of maximum snow accumulation, however, air temperatures would be low, and these amounts would be negligibly small. Loss by interception can be estimated as a constant percentage of the precipitation. During the snowmelt season, the energy consumed in the evapotranspiration process is directly proportional to the energy used in melting the snowpack; therefore, the loss by evapotranspiration can be considered as a fixed percentage of the snowmelt for the snow-covered portions of the basin. For winter rain-on-snow floods, evapotranspiration loss is negligible during the storm period.

10-03. COMPUTATION OF SNOWMELT FOR DESIGN FLOODS

10-03.01 General. - Synthesis of design floods requires (1) the determination of the optimum meteorological flood-producing sequence, and (2) the use of snowmelt equations to compute the snowmelt runoff (as outlined in chaps. 5 and 6). The meteorological factors pertinent to such design-flood snowmelt computations differ according to varying forest cover, and are listed in paragraph 10-02.07. The necessary snowmelt equations may be derived from a rational analysis of historical records of the particular basin under consideration by use of the thermal-budget index technique (as explained in chap. 6) and tested by reconstitution of historical flood hydrographs (as shown in chap. 9). For cases where it is impossible or impractical to derive particular basin melt coefficients, the generalized snowmelt equations listed in section 6-07 may be applied. As indicated in section 9-02, there are two general procedures for computing runoff from snow-covered areas, depending upon the manner in which elevation effects are handled. The basin may be either (1) subdivided into elevation bands or (2) treated as a whole, making corrections for non-snow-covered areas and other non-contributing areas. For the computation of snowmelt, the first method requires the application of appropriate generalized snowmelt equations, while for the second, either generalized snowmelt equations or particular basin melt coefficients derived from historical record may be used.

10-03.02 Snowmelt during winter rain-on-snow design floods. - Having adopted the optimum weather and basin conditions for design and the method of subdividing the watershed, the snowmelt portion of winter rain-on-snow design floods may be determined from the following general equations described previously in chapter 6:

Open or partly forested area:

$$M = (0.029 + 0.0084kv + 0.007P_r)\ (T_a - 32) + 0.09 \qquad (10\text{-}1)$$

Heavily forested area:

$$M = (0.074 + 0.007P_r)\ (T_a - 32) + 0.05 \qquad (10\text{-}2)$$

where $\underline{M}$ is the total daily snowmelt in inches per day, $\underline{T_a}$ is the temperature of air (assumed to be saturated) at the 10-foot level in $^{\circ}F$, $\underline{P_r}$ is the daily rainfall in inches, $\underline{v}$ is the wind speed at the 50-foot level in miles per hour, $\underline{k}$ is the basin convection-condensation melt factor expressing the relative exposure of the area to wind and is affected principally by forest cover. The value of $\underline{k}$ is 1.0 for plains areas with no forest cover. It may be slightly greater than 1.0 for exposed ridges and mountain passes, and for heavily forested areas it approaches a minimum value of about 0.2. The 50-foot level wind value for forested areas is assumed as the average wind in an open area resulting from the general airmass circulation prevailing at the time. The constants 0.09 and 0.05 represent average maximum daily melt under rain-on-snow conditions, which would result from absorbed shortwave radiation and ground heat. For heavily forested areas such as WBSL, it has been shown that wind is damped out to a great extent and that heat transfer by convection and condensation may be expressed by an average constant wind, so that wind variation need not be considered. The melt equation for rain-on-snow conditions in heavily forested areas involves only air temperature and rainfall intensity. The above equations are for saturated air conditions, and assume linear variation between dewpoint temperature and saturation vapor pressure.

10-03.03 Design-flood snowmelt during rain-free periods. - Computation of snowmelt for design floods during rain-free periods, which is generally required for spring snowmelt-type floods, is somewhat more complex than that for rain-on-snow type floods. Because of the variation in dewpoint, radiation exchange, and cloud cover, clear-weather melt cannot always be expressed by the simple temperature functions used during rain periods, especially for open or partly forested areas. Reference is again made to chapter 6, for a discussion of the generalized snowmelt equations applicable to clear-weather (rain-free) melt periods, and the equations are repeated below for use in design-flood derivation.

Heavily forested area:

$$M = 0.074\ (0.53T_a' + 0.47T_d') \qquad (10\text{-}3)$$

Forested area:

$$M = k(0.0084v)\ (0.22T_a' + 0.78T_d') + 0.029T_a' \qquad (10\text{-}4)$$

Partly forested area:

$$M = k'(1 - F)(0.0040\ I_i)\ (1 - a) + k(0.0084v)(0.22T_a' + 0.78T_d') + F(0.029T_a') \qquad (10\text{-}5)$$

Open area:

$$M = k'(0.00508\ I_i)\ (1 - a) + (1-N)(0.0212T_a' - 0.84) + N(0.029T_c') + k(0.0084v)\ (0.22T_a' + 0.78T_d') \qquad (10\text{-}6)$$

where:

M is the snowmelt rate in inches per day.

T_a' is the difference between the air temperature measured at 10 feet and the snow surface temperature, in $^{\circ}F$.

T_d' is the difference between the dewpoint temperature measured at 10 feet and the snow surface temperature, in $^{\circ}F$.

v is the wind speed at 50 feet above the snow, in miles per hour.

I_i is the observed or estimatod insolation (solar radiation on horizontal surface) in langleys. (See plates 5-1 and 6-1)

a is the observed or estimated average snow surface albedo. (See figures 3-4, plate 5-2 for estimating albedo of the snow.)

k' is the basin shortwave radiation melt factor. It depends upon the average exposure of the open areas to shortwave radiation in comparison with an unshielded horizontal surface. (See figure 6, plate 5-1, for seasonal variation of k' for North and South 25° slopes).

F is an estimated average basin forest canopy cover, effective in shading the area from solar radiation, expressed as a decimal fraction.

T'_c is the difference between the cloud base temperature and snow surface temperature, in $^{\circ}$F. It is estimated from upper air temperatures or by lapse rates from surface station, preferably on a snow-free site.

N is the estimated cloud cover, expressed as a decimal fraction.

k is the basin convection-condensation melt factor, as defined in paragraph 10-03.02. It depends on the relative exposure of the area to wind.

The melt coefficients given in the above equations express melt rates in inches per day. For those equations where wind is included in the convection-condensation term, it may be necessary to subdivide the day into smaller time increments, especially if there is marked variation in both wind and temperature or dewpoint. The coefficients also express melt for ripe snowpacks (isothermal at 0°C and with 3 percent initial free water content — see chap. 8). Except for loss by transpiration from forested areas, the melt determined by the above equations represents the actual melt of the snowpack averaged over a basin area (or zone), expressed as ablation of the snowpack in inches of water equivalent. The equations are based on linear approximations between saturation air-vapor pressure and dewpoint, and between longwave radiation and the temperature of the radiating surface for the ranges ordinarily experienced (see chap. 6). Substitution of values for design conditions is made in accordance with the optimum meteorological sequence for each of the meteorological factors, either on the basis of the average for the whole snow-covered area of the basin, or of varying values for increments of elevation. For cases where elevation zones are evaluated separately, it is necessary to describe the meteorological sequence and melt factors characteristic of each zone. This requires lapsing air temperature, dewpoint, and wind to the specified elevation level. An additional consideration, when applying any design-flood snowmelt equations to forested or partly forested areas, should be given to the possibility of change in forest condition by subsequent timber removal and consequent change in the basin convection-condensation melt factor, k.

10-03.04 Basin clear-weather snowmelt coefficients. - For those basins with adequate hydrometeorological records for synthesizing historical streamflow data, basin melt coefficients using appropriate thermal budget indexes may be derived as outlined in chapter 6. It is necessary, of course, to treat the basin or component sub-basins as a whole rather than a series of elevation bands. The derived basin snowmelt coefficients integrate the basin characteristics with regard to factors affecting snowmelt, and relate the snowmelt to a fixed condition of observation. It is then necessary to relate the meteorological factors to the conditions of measurement for which the coefficients have been derived.

10-03.05 Elevation variation of snowmelt. - The use of elevation zones for snowmelt computations leads to consideration of the variation of snowmelt with elevation. It is a generally held opinion that snowmelt decreases with elevation because of the normal decrease of temperature with height. It has been shown for WBSL that, during active melt periods, the decrease of snowmelt with elevation is very slight, considering average basin characteristics in mountainous regions. Although the average snow surface albedo tends to increase with height, there is normally less dense forest cover at higher elevations, so that there is likelihood of greater energy input to the snowpack directly by solar radiation. Wind speeds, also, are generally greater at high elevation areas. These factors tend to balance the normal air temperature decrease with elevation, as it affects snowmelt. It is emphasized that this situation prevails only during clear weather periods in the active melt season; limited studies of water equivalent ablation under these conditions tend to verify nearly uniform melt rates with respect to elevation. In the derivation of design floods, the separation of the basin into elevation zones is important from the standpoint of defining the snow wedge and subsequent depletion of the snow cover. If a simple temperature index is used to evaluate melt for spring snowmelt design floods, an increase in the melt factor with elevation, which would partially compensate for the normal decrease in temperature with elevation, is appropriate.

10-04. DESIGN FLOOD HYDROGRAPH SYNTHESIS

10-04.01 The derivation of design flood hydrographs requires combining the effects of snowmelt, rainfall, losses by evapotranspiration and soil-moisture recharge, and total time delay to runoff by storage in the snowpack, ground, and channel. All must be evaluated on a time-rate basis over the effective runoff-producing areas. The methods of hydrograph synthesis presented in chapter 9 apply directly to design flood analysis, and accordingly the information presented there will not be repeated. Wherever possible, the method of hydrograph synthesis should be checked against historical data by the reconstitution of major floods of record.

10-04.02 The extension of the hydrologic variables to design-flood conditions can be accomplished as set forth in section 10-02. Having arrived at the optimum meteorological sequence, rational snowmelt rates may be determined (section 10-03.) and water excesses from rain and snowmelt may be routed through the optimum basin storage condition consistent with the design condition to produce the maximum peak discharge. The principles outlined above apply to both winter and spring floods. The storage effect of the snowpack must be taken into account for winter floods. For spring floods, it is usually assumed that the snowpack is primed prior to the flood event.

10-05. EXAMPLES OF DESIGN FLOODS INVOLVING SNOWMELT

10-05.01 General. - Under Project CW-171, the Snow Investigations Unit has assisted participating district offices in the derivation of a number of the design floods involving snowmelt for a number of reservoir projects. The following paragraphs contain brief descriptions of some of the design floods so derived by district offices. Also shown are excerpts from the plates prepared for illustrating the procedures.

10-05.02 Painted Rock maximum probable flood. - The maximum probable flood for the design of the spillway at Painted Rock Reservoir was derived by hydrologists in the Los Angeles district office. The details of design are reported in Design Memorandum No. 1 for the project. 1/ This flood is an example of a winter rain-on-snow type, in which the major contribution to runoff is from rainfall, but snowmelt significantly augments the runoff volume as well as peak discharge. The project is located on Gila River, near Gila Bend, Arizona. The drainage area of

50,800 square miles was divided into 12 sub-areas, each of which were further divided into 8 elevation zones. The initial snowpack condition was determined from analysis of climatological records involving snow depths, to which were applied an assumed density consistent with the time of year. A snow wedge, based on an enveloping line of water equivalent vs. elevation, was determined for each sub-basin. Snowmelt was computed for each sub-area and elevation zone by six-hour increments, utilizing the methods outlined in section 10-03. The values of snowmelt were added to the six-hour rainfall increments for the maximum probable storm. Losses to direct runoff were computed on the basis of assumed infiltration rates by zones and sub-areas, and water excesses contributing to direct runoff were routed by synthetic unit hydrographs. The hydrograph for each watershed was in turn routed through upstream channel and reservoir storage to the Painted Rock reservoir site, and a composite design flood hydrograph was derived for the project. The snowline was initially at 3000 feet and receded to 5000 feet by the end of the storm period.

10-05.03 Cougar standard project flood. - The standard project flood for Cougar Dam site on the South Fork, McKenzie River, Oregon, is an example of a winter rain-on-snow standard project flood and was derived in the Portland District office, as reported in Design Memorandum No. 2, Cougar Dam and Reservoir. 4/ Plate 10-1, which is extracted without change from the design memorandum, illustrates the pertinent information used in the derivation of the standard project flood. The 210-square-mile drainage area was divided into 5 elevation bands which varied from 4 to 35 percent of the basin area. Figure 1 illustrates the components of the hydrologic balance for the standard project storm. Values of rainfall, snowmelt, water stored in the snowpack, surface losses, and water excesses are given, together with the assumed temperature distribution. Figure 2 shows the snow-wedge condition before and after the design storm. The initial snow wedge was derived from analysis of water-equivalent data for snow courses in the surrounding regions. Figure 3 is the standard project flood series, showing the inflow and outflow hydrographs derived from the assumed pre-flood storm and the standard project storm. Figures 4, 5, and 6 are depth-duration curves, a six-hour unit hydrograph, and loss curves, respectively. In the derivation of this flood, snowmelt was computed by zones, using a melt rate of 0.08 inch per degree-day above 32°F applied to appropriate air temperatures for each zone. The melt rate conforms to that previously described for the condition of rain-on-snow in heavily forested areas. Melt from rain itself was added separately. Storage in liquid water in the snowpack during the pre-flood storm was computed in accordance with the liquid-water-holding capacities of the snowpack presented in chapter 8. Reference is made to the previously referenced design memorandum for a more complete description of the standard-project-flood analysis for this site.

10-05.04 Libby spillway design flood. - The derivation of a maximum probable flood for the design of the spillway for Libby project was completed by the Seattle District office and reported on in the Design Memo No. 2 for that project. 5/ This flood is the spring snowmelt type, augmented by rainfall assumed to occur near the crest of the flood. Evaluation of the basin runoff characteristics and empirical snowmelt rates was first accomplished by reconstitution of flood season hydrographs for five years of historical record. The procedures were then applied to the optimum flood-producing sequence as determined from a study of the maximum flood producing meteorological conditions in the Columbia River Basin, by the Hydrometeorological Section of the U. S. Weather Bureau. 7/ The Kootenai River, upon which the project is located, drains 10,240 square miles at the gaging station at Libby, Montana. In the derivation of the maximum probable flood, the basin was treated as a whole, rather than subdividing the area into zones of elevation or homogeneous units. Corrections for snow-covered area were made progressively through the melt season. Snowmelt rates were computed using degree-day indexes, the degree-day factors being varied according to season. Runoff excesses were routed to the project site by a single unit hydrograph. As an independent check upon results, snowmelt by the thermal-budget method was computed, and a separately derived inflow hydrograph was obtained. Plate 10-2 shows the spillway design flood inflows computed by each method, as well as pertinent data used in the flood derivation.

10-06. SUMMARY

10-06.01 The technique of determining either a maximum probable or a standard project flood is essentially the same for both snow-free and snow-covered areas. The existence of snow merely introduces additional complicating factors. Two principal types of floods occur: (1) winter floods resulting from rain-on-snow events where the air temperature is relatively low and the snowmelt contribution to flood is relatively small; and (2) spring floods from melting of the accumulated winter snowpack. Rain falling on snow at a time when the streams and melt rates are high may also contribute to a spring snowmelt flood. Winter floods are generally of short duration and exhibit a rapid rise and fall in the runoff hydrograph, because of the relatively intense rates of rainfall compared to those of snowmelt. In contrast, spring snowmelt floods are of long duration and the runoff hydrograph is generally flat-crested.

10-06.02 Hydrologic design requirements for reservoir projects include the control of a selected design flood and the ability to pass safely the maximum probable flood inflow. A design flood of maximum volume does not necessarily produce a maximum peak discharge. Both volume and peak discharge are evaluated from a certain optimum combination of weather, snow and soil moisture conditions. In evaluating the factors for design conditions, the selected values must be compatible with the other factors affecting runoff or peak discharge.

10-06.03 Assurance of economical and safe design can be best obtained through use of a rational approach to the problem, based on known physical laws concerning the processes affecting streamflow and runoff, and extension of those relationships to given conditions of design. The use of simplified or short-cut methods is warranted only for preliminary use or for projects whose safety and economic justification do not require detailed flood analyses. For such cases, the judgement of the engineer responsible for selection of design floods is relied upon to evaluate the flood potential properly. His background and experience in applied hydrology should include such a knowledge of hydrograph analysis and synthesis as is indicated in this chapter.

10-07. REFERENCES

1/ CORPS OF ENGINEERS, Los Angeles District, "Hydrology for Painted Rock Reservoir, Gila River, Arizona," Design Memo. No. 1, 1 August 1954.

2/ CORPS OF ENGINEERS, Office of the Chief of Engineers, "Standard project flood determinations," Civil Engineer Bulletin No. 52-8, Washington, D. C., 26 March 1952.

3/ CORPS OF ENGINEERS, Office of the Chief of Engineers, "Flood-hydrograph analyses and computations," Part CXIV, Chap. 5, Engineering Manual, Civil Works Construction

4/ CORPS OF ENGINEERS, Portland District, "Hydrology and meteorology, Cougar Dam and Reservoir, South Fork McKenzie River, Oregon," Design Memo. No. 2, 15 December 1955.

5/ CORPS OF ENGINEERS, Seattle District, "Derivation of spillway design flood inflow, and Appendix A, Libby Project, Kootenai River, Montana," Design Memo. No. 2, 29 July 1952.

6/ CORPS OF ENGINEERS, U. S. Army "Columbia River and tributaries, northwestern United States," House Doc. 531, 81st Cong., 2nd sess., (8 vols.), Government Printing Office, Washington, D. C., 1952.

7/ U. S. WEATHER BUREAU, Hydrometeorological Section, "Tentative estimate of maximum-possible flood-producing meteorological conditions in the Columbia River basin," 25 January 1945.

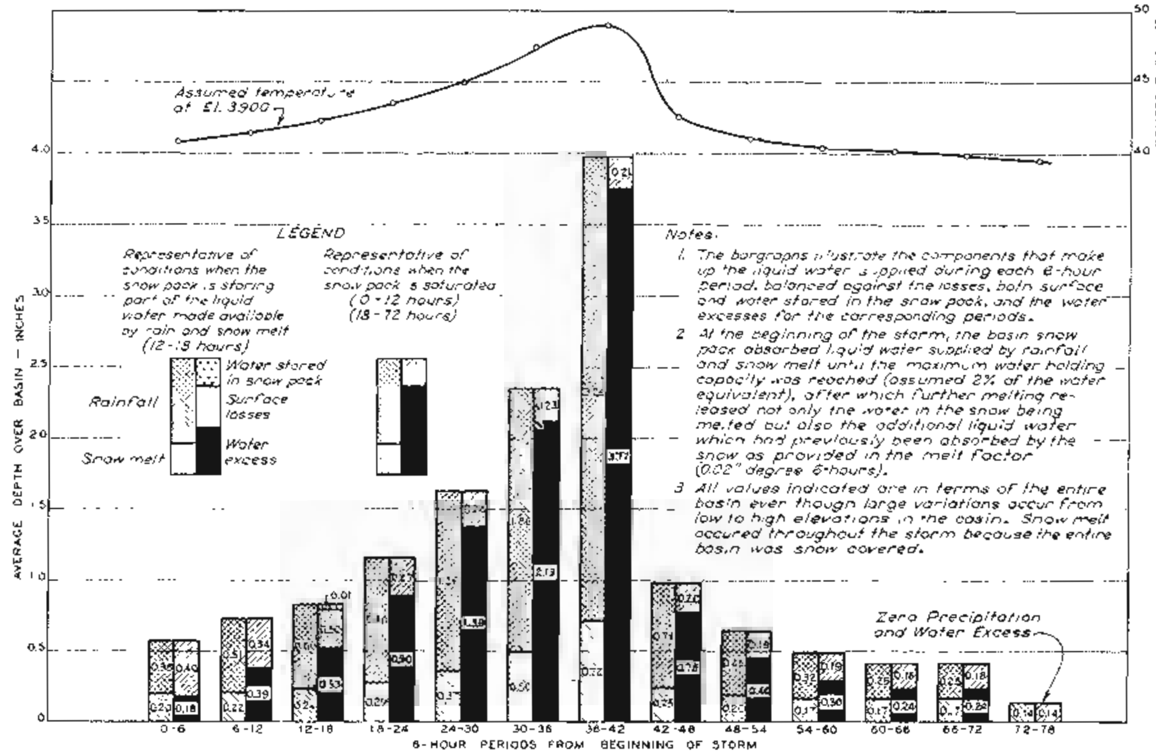


FIGURE 1
STANDARD PROJECT STORM HYDROLOGIC BALANCE

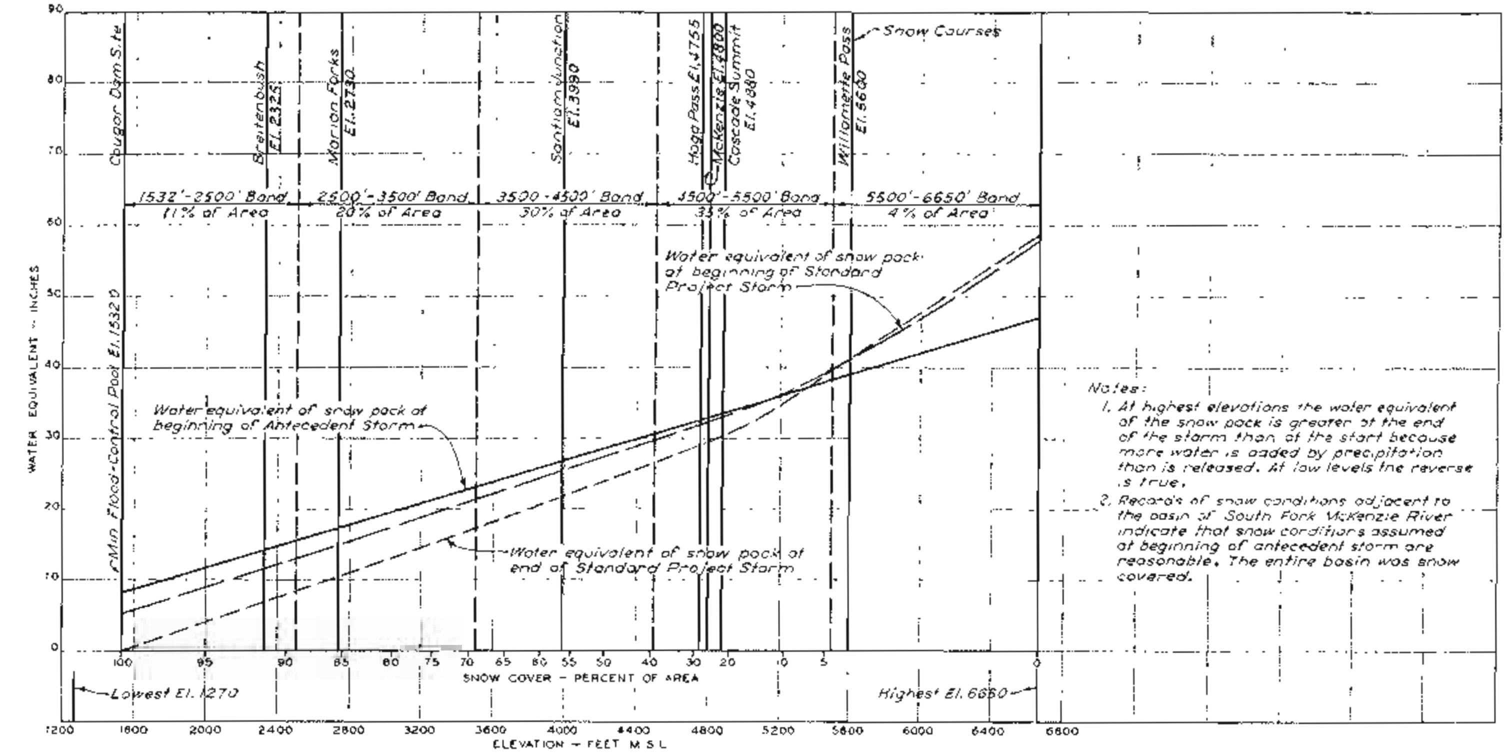


FIGURE 2
SNOW COVER DISTRIBUTION

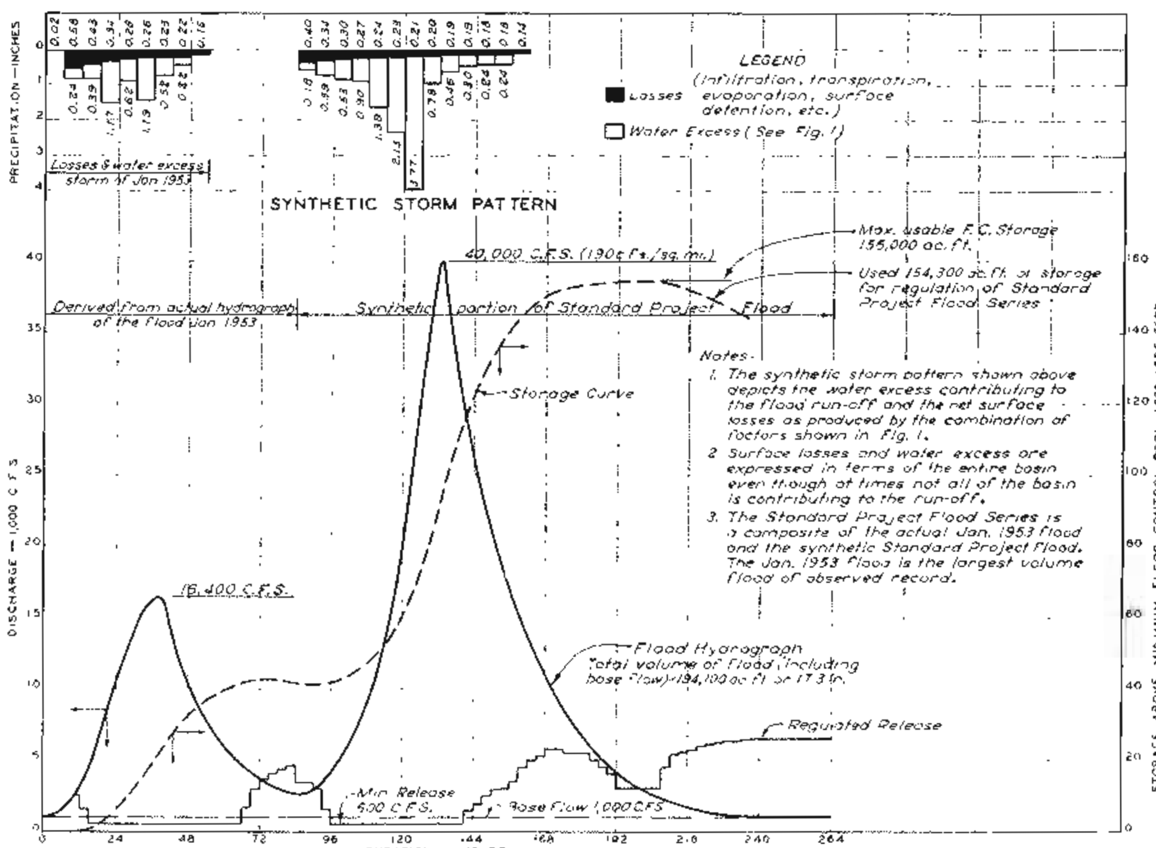


FIGURE 3
STANDARD PROJECT FLOOD SERIES

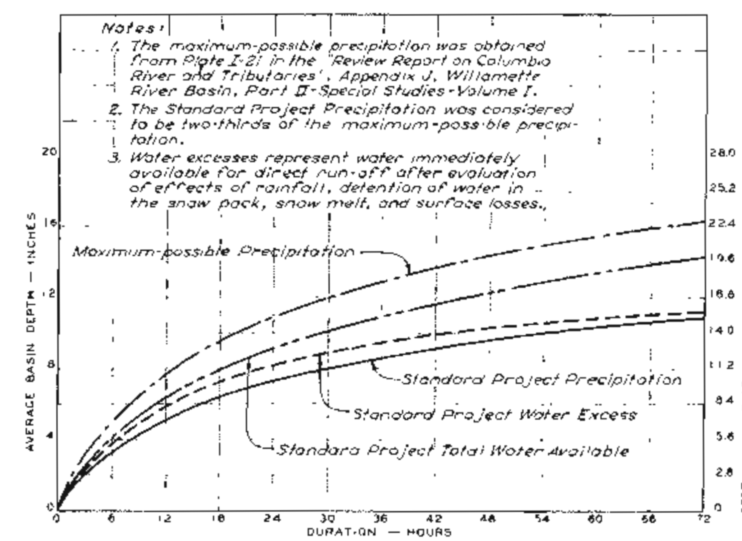
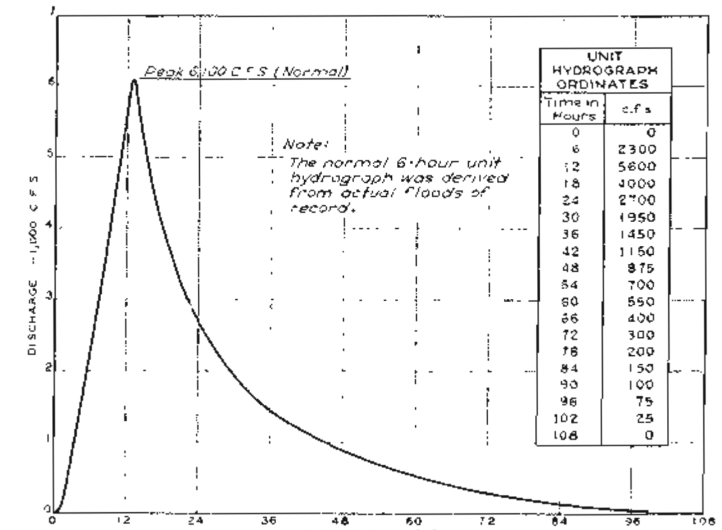


FIGURE 4
DEPTH-DURATION CURVES



UNIT HYDROGRAPH ORDINATES	
Time in Hours	c.f.s.
0	0
6	2300
12	5600
18	4000
24	2700
30	1950
36	1450
42	1150
48	875
54	700
60	550
66	400
72	300
78	200
84	150
90	100
96	75
102	25
108	0

FIGURE 5
6-HOUR UNIT HYDROGRAPH

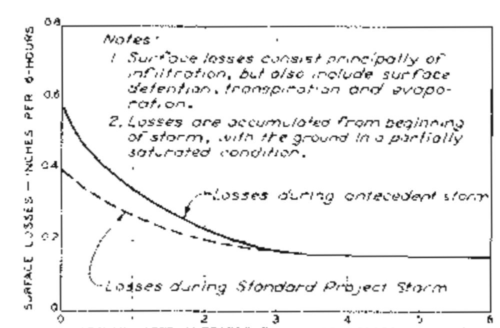


FIGURE 6
SURFACE LOSSES

WILLAMETTE RIVER BASIN, OREGON
SOUTH FORK McKENZIE RIVER
COUGAR DAM

STANDARD PROJECT FLOOD

SCALES AS SHOWN
PORTLAND DISTRICT, CORPS OF ENGINEERS NOV. 15, 1955

SUPERVISED: CHIEF, HYDROLOGY & METEOROLOGY SECTION
SUBMITTED: CHIEF, PLANNING BRANCH
RECOMMENDED: CHIEF, ENGINEERING DIVISION
APPROVED: COLONEL, CORPS OF ENGINEERS, DISTRICT ENGINEER
TRANSMITTED WITH REPORT DATED NOV. 15, 1955

CU-20-2/12

PLATE 10-1

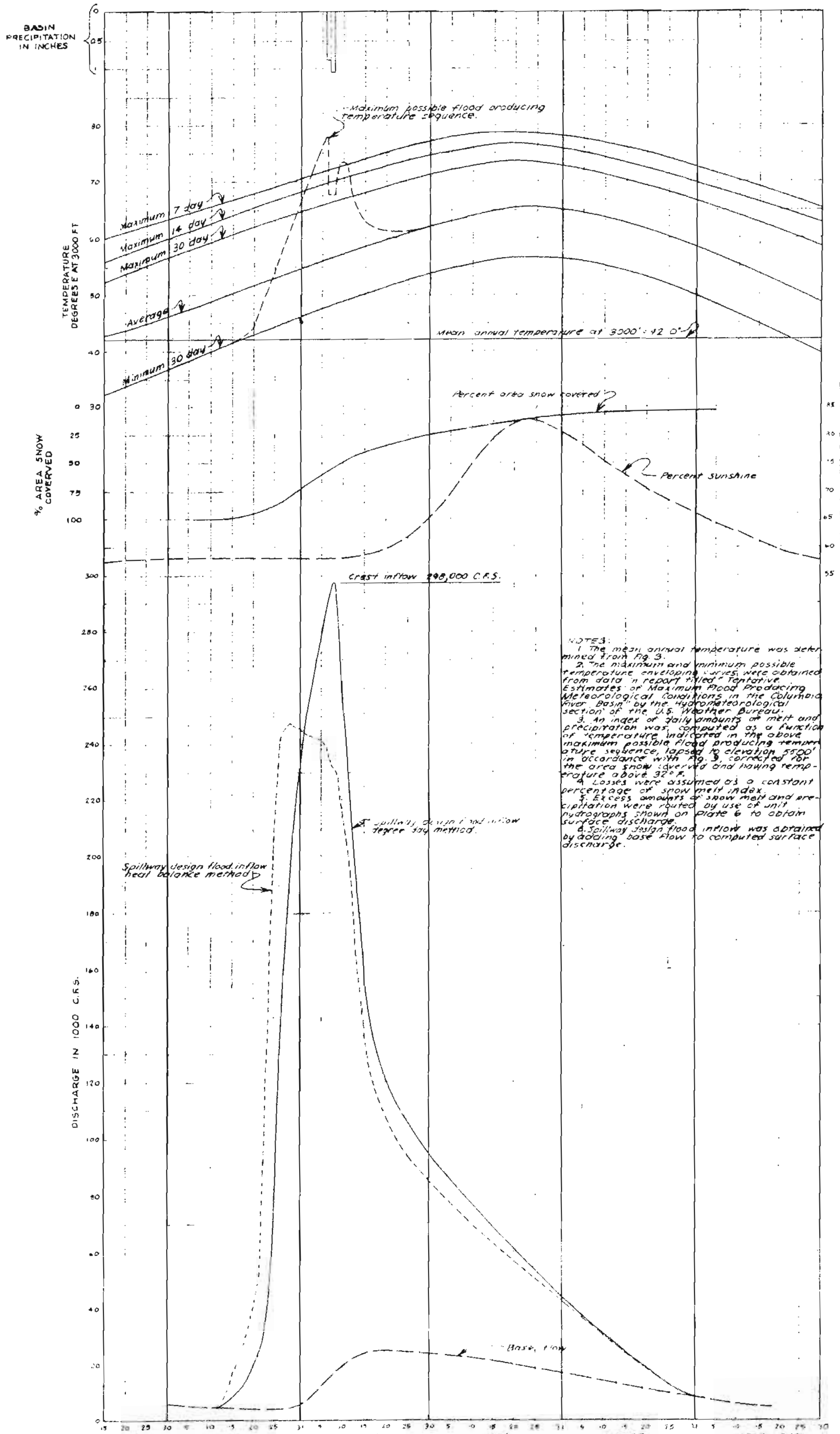


FIG. 1 SPILLWAY DESIGN FLOOD INFLOW TO LIBBY RESERVOIR

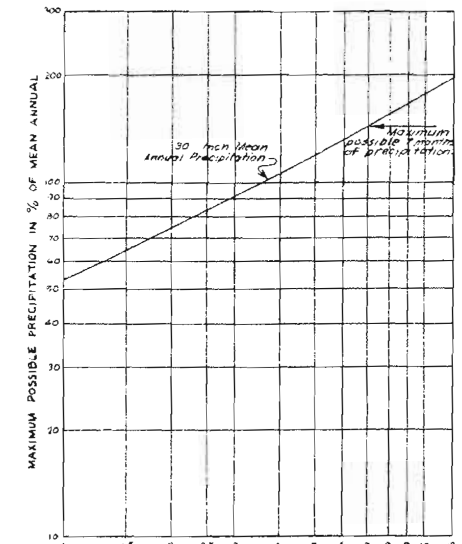


FIG. 2 PRECIPITATION DURATION CURVE

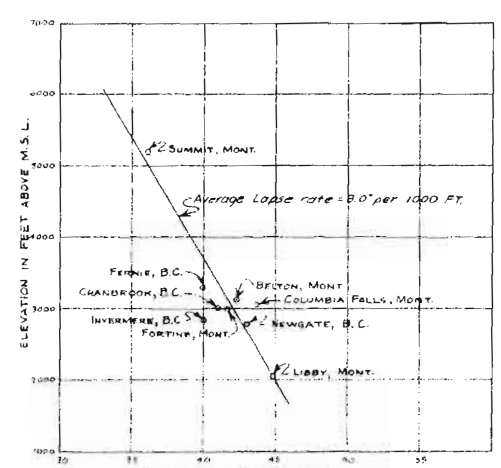


FIG. 3 TEMPERATURE-ELEVATION CURVE

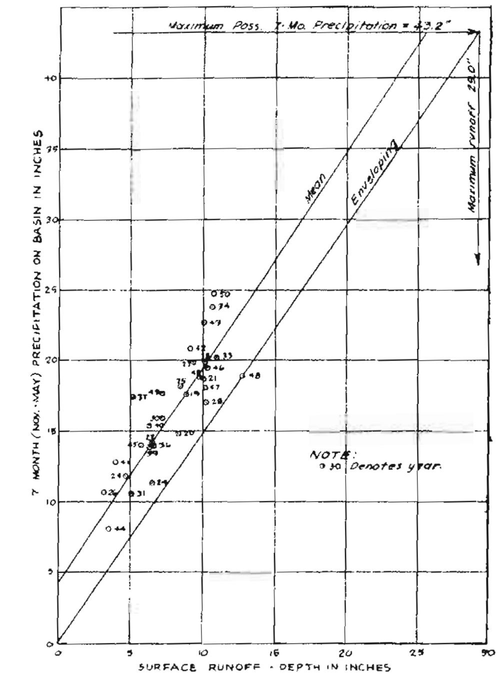


FIG. 4 PRECIPITATION RUN-OFF CURVE

KOOTENAI RIVER, MONTANA
LIBBY PROJECT

SPILLWAY DESIGN FLOOD INFLOW

In 1 Sheet Sheet No. 1 Scale: As Shown
Seattle District, Seattle, Washington 29 July 1952
Prepared: Submitted:
Recommended: Approved:
Chief, Planning and Reports Branch Chief, Engineering Division
Drawn by: M.E.T. File No.
Traced by: W.E.L. Transmitted with report dated 29 July 1952 E-53-3-8
Checked by: M.E.T.

CHAPTER 11 - SEASONAL RUNOFF FORECASTING

11-01. INTRODUCTION

11-01.01 General. - The continued expansion in the use of water resources has emphasized the need for reliable seasonal runoff forecasts. These forecasts are useful for operational planning both in areas in which the streamflow is regulated by reservoirs and in areas where no such controls exist. In the case of uncontrolled flows, an advance knowledge of the anticipated volume of runoff is most useful in making advance plans for irrigation diversions, power generation, flood protection, etc. Where storage reservoirs exist, optimum use of the storage space for such conservation uses as power production, irrigation, navigation, industrial and domestic needs, preservation of fish and wildlife, pollution abatement, and recreation requires an advance knowledge of runoff volume. The flood-control operation of reservoirs is also benefited by volume-of-runoff forecasts. The most important need for such forecasts is to be found, however, in the operation of multiple-purpose reservoirs, where the contradictory requirements of flood control and conservation require accurate forecasts of seasonal runoff volume. As demands for additional water and additional flood protection continue to increase, the need for greater efficiency in the control of water, and thus for reliable seasonal runoff forecasts, becomes increasingly important.

11-01.02 Limitations. - The accuracy of seasonal runoff forecasts from snowmelt basins is limited by a number of factors. As was emphasized in chapter 3, the problem of evaluating the actual amounts of precipitation and basin snowpack water equivalent is a complex one, particularly for areas where hydrologic stations are sparse. As pointed out in chapter 4, the problem of evaluating other factors such as soil moisture, evapotranspiration loss, and ground water supply is also a difficult one. Even with a knowledge of conditions throughout the forecast period, forecasts are subject to error resulting from improper evaluation of the important factors affecting runoff.

11-01.03 Also contributing toward inaccuracy of seasonal runoff forecasts are those hydrologic events which occur after the initial date of forecast, the most important of these being spring precipitation. Their importance is largely due to the fact that they cannot be forecast accurately by presently available techniques. Seasonal runoff forecasting is particularly difficult in areas where significant proportion of the runoff results from widely varying amounts of spring precipitation from year to year. Factors such as loss by evapotranspiration and variations in soil moisture retention are generally of lesser importance. These factors may increase the error in runoff forecast significantly if their effects are additive to errors resulting from improper evaluation of other factors. On the other hand their effects may cause an apparent increase in accuracy of a given forecast by compensating for errors in other factors. Such random improvement cannot be depended upon to produce forecasts of equal reliability in the future.

11-01.04 Unfortunately, on many project basins, runoff resulting from conditions occurring after the date of forecast is of such magnitude and variation that forecasts of an acceptable degree of accuracy are not presently possible. At some future date the accuracy of seasonal runoff forecasts may be improved by use of long-range weather forecasts. Meanwhile, special consideration must be given to effects of conditions occurring subsequent to the date of forecast. It is often necessary to revise the forecast in keeping with conditions which occur after the initial forecast is made. Such a situation emphasizes the need for developing forecast procedures that permit easy and logical revision of a given forecast where necessitated by the occurrence of unusual weather conditions.

11-01.05 Feasibility. - Despite the difficulties encountered in forecasting seasonal runoff, forecasts of acceptable accuracy can be made if due consideration is given to all important factors affecting runoff. On most snowmelt basins, a large proportion of the spring snowmelt runoff can be evaluated at the time the forecast is made. This is particularly true on basins where the snowpack water equivalent on the date of forecast represents a large percentage of the seasonal runoff. Accurate evaluation of factors existent on the date of the forecast restricts errors in the forecast to those caused by occurrence of subsequent unusual weather conditions. On basins where conditions subsequent to the forecast date account for only a small proportion of the runoff and do not vary greatly from year to year, errors may be quite small. Under such circumstances seasonal runoff forecasting may be accomplished with reasonable assurance that the deviation of the forecasted amount from the true amount will be confined within certain prescribed limits. Such prescribed limits, of course, vary in accordance with the use for which the forecast is intended; a forecast acceptable for one purpose may be entirely inadequate for other purposes.

11-01.06 <u>Factors affecting runoff</u>. - Factors affecting runoff may be logically classified under the two categories, supply and loss. Supply for a given season is comprised largely of precipitation, minor sources being condensation and carry-over of water from preceding seasons in various forms such as ground water, channel and lake storage, and snow. A possible additional source of supply is underground flow from adjacent basins. Soil moisture is not considered a source of supply because it is not available for runoff.

11-01.07 Loss occurs in a number of ways, the importance of each varying in accordance with meteorological and basin characteristics. Generally, the greatest proportion of loss on a basin results from evapotranspiration, comprised of evaporation from the ground and snow surfaces and transpiration from leaves of vegetation. Considerable loss also occurs through evaporation of intercepted snow and liquid water from the external surfaces of vegetation. Such losses occur before the precipitation reaches the ground and is generally called interception loss, since its occurrence is dependent upon interception of precipitation by vegetation. The remaining sources of loss on a basin during a given season are deep percolation, retention as soil moisture, and carryover of moisture into the next season in various forms, such as ground water, channel and lake storage, and snow. Loss by deep percolation is difficult to evaluate. It is generally assumed that such loss is either negligible, a constant amount, or a fixed percentage of the total loss, and its effect upon runoff is integrated into one or more of the other factors affecting runoff.

11-01.08 Factors affecting the quantity of precipitation were discussed in chapter 3, and, since the relationship of quantity of precipitation to runoff is clearly defined, further discussion is deemed unnecessary. Supply resulting from condensation is dependent upon the vapor pressure gradient between the surface and the air; the gradient, in turn, is dependent upon the vapor pressure of the air and of the snow surface. Although the addition of condensation to the quantity of runoff is negligible, the resultant heat of condensation has a significant effect upon rate of snowmelt and, consequently, upon the distribution of runoff. Supply through underground flow from adjoining basins cannot be precisely determined, but qualitative evaluation can be made from detailed geologic and hydrologic investigations. Factors affecting carryover from preceding seasons are those which determine the supply and loss during the antecedent seasons. Direct evaluation of ground water is impractical because of general unrepresentativeness of ground water well observations and great variability of ground water conditions over basin areas. Indirect evaluation based on recession analysis is generally satisfactory as a method for estimating changes in ground water storage. Carryover between years in the form of snow, channel, ground or lake storage may be computed where necessary. Factors affecting the amount of runoff as a result of variation in loss are interrelated with factors associated with supply of moisture. Since evaporation and transpiration losses vary largely in accordance with temperature, the latter is considered an important factor affecting runoff. A related factor affecting loss by evapotranspiration is supply of water during periods when evapotranspiration is occurring.

11-01.09 High rates of rainfall are conducive to high runoff per unit volume of precipitation. On the other hand, precipitation is less effective in producing runoff if it occurs in light storms, particularly if it is associated with high temperatures during or between storms. Precipitation falling in the form of rain on bare ground is subject to greater loss than that falling on snow. For light rainfall intensities, precipitation falling on bare ground during the spring melt season may be considered to be lost to runoff, while precipitation falling on snow-covered areas may be considered to be 100 percent effective in producing runoff. Thus the areal extent of snow cover during periods of spring precipitation and during periods of high evaporation rates has an effect upon seasonal runoff.

11-01.10 The soil moisture content is affected by the climatic regime of a given area. Where autumn or winter rains are sufficient to provide full field capacity of the soil, the year-to-year variation in soil moisture at the beginning of the spring snowmelt runoff season is negligible. However, lesser amounts of precipitation will result in corresponding deficits in soil moisture, up to full field capacity of the soil. Such deficits must be made up by melt or rainfall contribution during the melt season, resulting in a corresponding loss to runoff.

11-01.11 Soil moisture deficits may be accounted for in a number of ways, as will be explained later in connection with runoff indexes. Consideration should be given to the probable condition of soil moisture at the time of the forecast. After the melt season is well underway and the soil has attained field moisture capacity throughout the entire range of elevation within the basin, no further consideration need be given to losses due to soil moisture deficiency. Once the soil reaches field moisture capacity as the result of fall or winter rains, soil beneath the snowpack will remain saturated throughout the period of snow cover, because any loss by transpiration will be supplied by melt. When soil moisture deficits exist, however, they vary widely with elevation within a basin.

11-01.12 Methods. - Methods of forecasting seasonal runoff may be broadly classified as two main types, water-balance and index. A third type consists of a combination of the two main types. The index method assumes a fixed relationship between volume of runoff and causative indexes representing factors. In the index method, no implication is made that the factors are quantitatively evaluated. The water-balance method, on the other hand, implies that each factor is quantitatively measured, the algebraic sum of all the factors being equal to the runoff. In water-balance procedures the factors determining runoff are referred to as components since they are actually the component parts of runoff.

11-01.13 Regardless of the method, the factors used should be selected on the basis of the hydrologic balance of the area involved. The water balances shown in chapter 4 for each snow laboratory provide a guide for selecting pertinent factors. The forecasting procedure should utilize all important variables affecting runoff. The effects of the variables before and after the date of forecast should be evaluated separately, to insure proper weighting of each variable and provide a means of revising forecasts to suit conditions subsequent to the date of forecast. Direct correlations of early-season precipitation or snow accumulation with total seasonal runoff should be avoided, because of the likelihood of unrepresentative weightings of the variables caused by unaccounted random variance in late-season precipitation and losses.

11-02. INDEX PROCEDURES FOR FORECASTING SEASONAL RUNOFF

11-02.01 General. - Procedures for forecasting runoff by the index method basically involve correlations of historical records of runoff with indexes of important determinants of runoff for the area. Forecasting procedures may be based on either mathematical or graphical correlations, or a combination of the two. The regression functions so derived effectively weight the variables corresponding to their effect on runoff. An adequate period of record is essential to proper evaluations of runoff coefficients, and in general, the greater the number of variables involved, the longer is the period of record required. The use of statistical procedures for deriving mathematical relationships has been widely used by hydrologists for obtaining the best fit of historical data. Statistical procedures provide standard methods for evaluating effectiveness of runoff parameters and for comparing relative reliability of forecasting methods. The use of statistical methods, however, should not be attempted on a casual basis without full knowledge of the hydrologic factors involved, the statistical techniques, and the limitations of the methods.

11-02.02 The simplest mathematical procedure for estimating seasonal runoff is by means of a simple linear regression,

$$Y = a + bX,$$

where $\underline{Y}$ is the dependent variable, runoff; $\underline{X}$ is an index representing the principle determinant of runoff, and $\underline{a}$ and $\underline{b}$ are the derived constants. A comparable graphic procedure consists of simply plotting the values of each of the variables on rectangular graph paper and drawing a linear regression line of best fit by eye through the plotted points. However, numerous factors usually affect the volume of runoff, necessitating the introduction of additional parameters into the forecast procedure. Thus, mathematical relationships may involve equations varying from simple two-variable regressions to multi-variable linear and curvilinear regressions. In some instances variables used in the basic forecast equation are derived by correlating component parts of a given independent variable with the dependent variable. As an example, monthly precipitation values are often correlated with runoff in a multiple regression equation to aid in determining the weight to be assigned to monthly values to obtain the best possible precipitation index for inclusion in the basic forecast equation. Likewise graphic procedures may vary from simple single straightline relationships to complex coaxial graphs involving numerous variables, with relationships of variables represented by curves of varied shapes.

11-02.03 Indexes used in runoff forecasting. - A given factor can often be represented by more than one index. The supply of water stored in a snowpack on a given date, for example, may be represented by an index of either precipitation or snowpack water equivalent.

11-02.04 Water supply index. - Since the supply of water in a snowpack is the most important factor affecting runoff in areas of snow accumulation, the selection of an index to represent this factor has been given much attention. The relative reliability of precipitation and snow course measurements has been discussed in chapter 3, where it was shown that both types of measurements include errors due to the method of sampling as well as errors due to non-representativeness of point measurements. It was also pointed out (in chap. 3) that measurements of precipitation are generally more suited to early-season forecasts, while snow accumulation measurements are generally more reliable for late-season forecasts. In either case, the availability of historical record is a vital factor in the selection of indexes of water supply. If the period of record of both types of data are approximately equal, each should be tested to determine which yields the best results for historical data. In addition to the foregoing indexes, measurements of quantities such as low-elevation winter runoff, atmospheric moisture inflow, or heat supply-runoff relationships, may be used.

11-02.05 Hydrologic network. - When considering the development or expansion of a network of hydrologic stations in snowmelt basins, the choice of whether to establish precipitation stations or snow survey courses depends on varying needs. For proper evaluation of rainfall effects, especially during the fall or spring, precipitation stations are necessary. They are more economical from the standpoint of cost and time where the services of an observer are available. On the other hand, if taking the observations necessitates field trips, the economy is no greater than that of making snow surveys, and involves, moreover, the particular data complications at unattended sites arising from the variability in gage catch due to the deficiencies discussed in chapter 3. Snow surveys, while subject to disadvantages of their own, have the advantage of providing a direct estimate of actual snowpack conditions at a given date, and consequently they provide a measure of the residual water supply which remains in storage in the snowpack. Precipitation gages which are attended daily can provide data for evaluation of incremental changes in moisture supply from the time of a comprehensive snow survey of a basin, by which short-term changes in forecasts may be made. Whichever source of water-supply data is used (precipitation gages or snow courses), emphasis should be placed on proper site selection, in accordance with the requirements outlined in chapter 3, in order to provide reliable and representative basic data. Since the adequacy of a newly-established network cannot be fully appraised until a number of years have elapsed, it may be desirable to establish both precipitation-gage and snow-course networks, and maintain both until it becomes conclusive that one or the other provides the data most suitable for an index. The final appraisal of the indexes is largely determined by the results obtained from their use in the development and testing of forecast procedures.

11-02.06 Precipitation index. - A simple type of precipitation index is the average of measurements at a number of stations considered representative of the basin. Such an index assumes that the data at all stations have equal weight in determining the volume of runoff. Often, however, the distribution of stations is such that weighting of station values is necessary to obtain proper results. Furthermore, the method of computing the index is dependent upon whether or not loss is treated in a separate index; if loss is not treated separately, its effect upon runoff is generally included in the precipitation index.

11-02.07 A method developed by Kohler and Linsley 6/ and used by the U. S. Weather Bureau consists of performing a multiple correlation, using annual basin runoff as the dependent variable and annual precipitation at representative stations as independent variables. Resultant regression coefficients are used as guides in establishing station weights. Stations having high negative values are considered unrepresentative and are excluded. A weighted basin value for each month is determined by summing the products of station weight and respective monthly precipitations. This weighted basin value is often referred to as effective precipitation; however, it is not a quantitative evaluation but an index of the precipitation effective in producing runoff. Since precipitation occurring in various months is not equally effective in producing runoff, further weighting is necessary if greater refinement is desired in establishing the effective precipitation index. This phase of weighting consists of performing a multiple correlation, with annual runoff as the dependent variable and the preliminary effective precipitation index by months as the independent variables. Resultant coefficients are used as guides in establishing weights to be assigned to the various months, the procedure being similar to that used for determining station weights. Final adjustment of the values is facilitated by plotting the monthly values as a function of time and drawing a curve through the plotted points.

11-02.08 Another method of weighting precipitation stations consists of qualitatively assigning weights, using graphs of station precipitation versus runoff as a guide. Preparation of the graphs consists simply of plotting water-year precipitation at individual stations versus water-year runoff and drawing a curve of best fit through the plotted points. The process is performed for each station considered representative of the basin. Deviations of the plotted points from the curves are indicative of the correlation of precipitation values with runoff. Weighting of stations consists of assigning high weights to stations showing the best correlation with runoff, and assigning progressively lower weights to stations for which the deviations of the points from the curve are progressively greater. No set rule can be established regarding the magnitude of the weights, but it is customary to make the sum of the station weights equal to unity. Normally the highest weighting factors are not greater than 3 times the smallest factors, though in some cases, the Weather Bureau has assigned weights as high as 5 times the smallest weight for stations on a given basin. Further refinement can be made by assigning weights to monthly values. These weights are based largely on loss rates; highest weights are generally assigned to coldest months when losses are at a minimum, with decreasing weights being assigned to months with increasing mean temperatures. Months are omitted in which the runoff resulting from precipitation is insignificant. As in the case of station weights, it is customary to make the sum of the weights equal to unity.

11-02.09 Basin precipitation amounts determined by the method described in paragraph 3-06.03 may be used as an index. In this connection, the index is one of basin precipitation as distinguished from effective basin precipitation. Accordingly, such an index should be used only if the loss factor is treated separately.

11-02.10 Snowpack water equivalent index. - A snowpack water-equivalent index of water supply can be derived in a number of ways. In general, methods for determining the effective precipitation index are applicable to the water-equivalent index; however, monthly weightings are not necessary. Since the basin snowpack water equivalent is a measure of the snow accumulation on a given date rather than of the amount occurring during a given period of time, the time of occurrence is unimportant. Because of the limited period of record of snow-course data on most basins, statistical procedures have not been generally used in weighting snow courses. The most commonly used index for expressing water supply in the snowpack is the average of water-equivalent measurements at a number of courses representative of the basin. The method is highly favored because of its simplicity. However, on many project basins snow courses are not representatively distributed, particularly with regard to elevation. Because of the pronounced effect of elevation upon depth of snow it is often advantageous to segregate snow courses by elevation zones, weighting each group in accordance with the percentage of basin area represented by each zone.

11-02.11 The snow chart described in paragraph 3-08.04 is a useful tool for computing indexes of snowpack water equivalent. Other means of weighting snow course measurements to obtain a basin index include assigning of weights in accordance with the area represented by each snow course or assigning weights in accordance with the hydrologist's subjective estimate of the representativeness of each snow course with respect to the basin snowpack water equivalent. Estimation of weights to be assigned to snow courses may be facilitated by plotting runoff versus snowpack water equivalent at individual snow courses, and comparing the degree of scatter of plotted points for each snow course.

11-02.12 Indirect indexes of water supply. - Other indexes of water supply exist, which represent less directly than precipitation or snowpack water equivalent the amount of stored water on a given area. Among these are (1) area of snow cover, (2) accumulated heat supply and runoff relationships, and (3) low-elevation winter streamflow. The area covered by snow can be determined in several ways, as described in chapter 7. It was pointed out that the usefulness of this index lies in evaluation of late-season residual runoff, when basin snow cover is less than, say, 50 percent of the initial snow-covered area. The error of the forecast represents a correspondingly smaller percentage of the total runoff than that of forecasts made earlier in the season (e.g., April first forecast). Photographic indexes of snow cover for forecasting runoff volumes have also been developed.8 / However, early season forecasts of runoff based solely on observations of snow-covered areas are usually unreliable because of the varying slope of the snow wedge from year to year. Relationships between heat supply and runoff have been tested for various basins, the form of the relationship usually being expressed in terms of an accumulated temperature melt index and accumulated runoff. Such relationships are based primarily on the relation between water supply and area of snow cover, as indicated by the runoff produced for a given condition of seasonal heat supply. Such relationships also integrate a variety of other effects of water supply, runoff, and loss. Koelzer 5 / devised such a procedure for the Seminoe River, Wyoming, and a somewhat similar procedure was developed for the Columbia River near The Dalles, Oregon under project CW 171. The usefulness of the method is that it provides an independent check upon forecasts made by other methods. Also, it evaluates runoff potential through the melt period. Its application, however, is limited to periods after the melt season is underway. The use of low-elevation winter runoff as an index of snowpack water equivalent is confined to situations where the area on which the runoff index is measured is in the path of the airflow carrying the moisture to the high-elevation areas where the snowpack forms. This method has been applied to the Columbia River near The Dalles, Oregon, as is reported on in Research Note 23. It is discussed in paragraph 11-03.09.

11-02.13 Soil moisture indexes. - Soil moisture can be represented by a variety of indexes. Correlations between precipitation indexes and runoff implicitly evaluate soil moisture conditions, since a relatively constant soil moisture deficit from the previous summer period must be satisfied before significant runoff occurs. Procedures involving water equivalent of the snowpack, on the other hand, must consider possible variations in soil moisture deficits. One of the most commonly used indexes of soil moisture is fall precipitation. An index of soil moisture deficit based exclusively on fall precipitation, however, is not entirely realistic, because of the variation in form of precipitation that may occur in the fall, and the possibility that winter rains or snowmelt may penetrate through the snowpack. Varying amounts of snowpack melt from ground heat may also affect the condition of soil moisture. Also, the effect of elevation variation of soil moisture should be taken into account, since an index at one elevation level may not be representative of other levels. Another commonly used index of soil moisture is winter runoff, since greater winter flows are generally associated with higher soil moisture content. However, this is more directly an index of ground water.. Actual measurements of moisture content of soil samples may be used as indexes of soil moisture. They are obtained by direct measurement of the moisture in soil samples by laboratory techniques, or by electrical resistance methods, using either Bouyoucos or Colman blocks. At present, electrical resistance methods are unreliable because of the difficulties in calibration (see chapter 4).

11-02.14 Ground water indexes. - Various indexes may be employed to represent the amount of ground-water storage on a given date. A commonly used index is volume of runoff occurring during a given period, higher runoff volumes generally being associated with higher ground water storage. Properly located wells provide data for a useful index of ground-water storage. Another highly useful index of ground water is base flow; however, inability to separate base flow from total flow sometimes imposes a limitation on the use of the base flow index.

11-02.15 Evapotranspiration indexes. - A separate index of evapotranspiration loss is seldom used in index forecasting procedures. Because the meteorological factors affecting evapotranspiration are generally the same as those causing snowmelt, the loss tends to be a direct function of melt for the snow-covered portions of the basin. Light spring precipitation falling on bare areas may usually be considered to be lost. Therefore, evaluation of evapotranspiration in a procedure involving primarily the water equivalent of the snowpack is not warranted. Methods based on an index of total precipitation throughout the period of snow accumulation and melt could logically include an index of evapotranspiration to account for variation in water loss during the fall and winter season. A temperature index function, based on mean monthly air temperature at a station representative of the basin area, could most easily serve this purpose.

11-02.16 Statistical methods. - Statistical techniques may be used to determine the effect of each index upon runoff and its relative importance in explaining the variance of runoff. Various indexes for a particular variable may be tried independently, to determine from historical record the ones which provide the best correlation. It is emphasized that the use of either graphical or mathematical methods of statistical analysis, whether they be used for simple linear two-variable correlations or complex multivariable relationships, should be considered simply as a tool to aid the hydrologist in evaluating indexes. The selection of variables used in the statistical analyses should be based on sound and thorough reasoning with regard to the conditions affecting runoff on the particular basin involved. Statistical methods may easily lead to a false sense of knowledge if results are used blindly without regard to hydrologic significance. This is particularly true in the case of procedures for forecasting seasonal runoff volumes, where historical data usually limit the number of observations in the sample to less than 20. Little confidence can be placed in a statistically derived forecasting procedure if the cause and effect relationships are either unknown or poorly understood.

11-02.17 Graphical methods. - Details pertinent to development of graphic correlations are given in various standard texts on hydrology and statistical methods; only a brief discussion of the principal methods of graphic analysis is presented here for the purpose of general appraisal of the method. One of the simplest methods of determining graphically the effects of a number of factors upon a given dependent variable is the method of deviations described by Ezekiel.4/ The first step consists of plotting scatter diagrams relating each independent variable to each of the remaining ones, and eliminating one of any pair of variables that show a high degree of correlation; such a correlation indicates that the variables are so closely related that their effects upon the dependent variable are inseparable. Of the remaining independent variables, the one considered most important (labeled X), is plotted against the dependent variable (Y), and a line of best fit is drawn through the plotted points. The deviations, $Y-Y'$ (where Y' is the ordinate of the line of best fit corresponding to a given value of X.) of each point are then plotted against the next most important independent variable (X_2), and a curve of best fit is drawn through the plotted points. Deviations of each point from this curve are then plotted against a third variable (X_3). The process is repeated for each factor considered to have an effect upon the dependent variable. The completed curves are first-approximations, subject to revision inasmuch as each curve is drawn without consideration of the factors treated in subsequent curves. Having completed the first-approximation curves, the deviations in the last curve drawn are plotted as deviations from the initial first-approximation curve, $Y=f'(X_1)$. A revised curve, $Y = f''(X_1)$, is drawn through the plotted points. The deviations from the new curve are then plotted as deviations from the first-approximation to $Y = f'(X_2)$ and a revised curve is drawn through the plotted points. The process is repeated for each of the first approximation curves. Third-approximation curves are generally unnecessary, but if they are considered desirable, they may be made by the procedure used for the second-approximation curves. Although this method is relatively simple, its usefulness is limited by its lack of consideration of joint relationships between variables. As an example, the method implies that runoff resulting from a given amount of spring precipitation would be the same regardless of the extent of basin snow cover. Water-balance computations, as well as actual observations, indicate that such an implication is erroneous.

11-02.18 Another graphic method of determining the effect of variables upon runoff is the coaxial method (described in Applied Hydrology 7/). While more complex than the method of deviations, it is better adapted to the representation of joint functions. In one of the common variations of the method, the first step consists of plotting runoff, Y, along the ordinate versus the most important independent variable, X, along the abscissa in the first of four quadrants on a graph. The indexes representing a second important variable, X_2, are shown at each plotted point and a family of curves representing the index values is drawn. Runoffs determined from the curves in the first quadrant are then plotted on the ordinate of the second quadrant versus the observed runoff along the abscissa. Each of the plotted points is labeled with an index representing a third independent variable, X_3, and a family of curves is constructed to fit the plotted points. Similarly, additional variables are introduced in the third and fourth quadrants. Another graph of four additional quadrants may be utilized if necessary to consider all the important variables. As in the method of deviations, the first-approximation curves are subject to revision. Deviations of observed runoff values from the curves in the final quadrant are plotted against the first independent variable, X_1, and a curve of best fit is drawn through the plotted points. Deviations of this curve from the zero axis at given values of the variable X_1 denote the change to be made in the curves of the first quadrant at corresponding values of X_1. Following revision of the curves in the first quadrant, the curves in all successive quadrants must be revised before proceeding with refinements in the second quadrant. The revised deviations in the final quadrant are plotted against the second independent variable, X_2, and a line of best fit is drawn through the plotted points. Deviations of this line from the zero axis are used for adjusting the curves in the second quadrant, using the procedure described for the first quadrant. The process is repeated until all variables have been considered. Although generally unnecessary, a third approximation may be made, using the procedure described for the second approximation.

11-02.19 Numerical statistical methods. - It is not within the scope of this report to present a discussion of statistical techniques. Reference is made to standard textbooks or references on statistical analysis for detailed presentations of the methods commonly used. (e.g., Ezekiel 4/, Snedecor 9/, Brooks and Carruthers 3/, Arkin and Colton 1/, and Wilm 11/) Full understanding of the capabilities and limitations of least squares techniques, familiarity with the statistical nomenclature and significance of the concepts involved in statistical analysis, are requirements for intelligent application of statistical methods to forecasting procedures. In establishing a forecasting procedure for a given area, indexes of all variables known to have a significant effect on runoff during the forecast period should be incorporated in the multiple correlations, in order to determine the reliability of the method as a whole. The least significant variables may then be dropped, depending upon requirements, and incremental effects of variables may be determined. Data for regression analysis may be transformed logarithmically or exponentially to provide curvilinear rather than linear relationships. Such transformation is not recommended, however, unless curvature is known to exist from physical considerations of the variables involved. Computations performed in connection with multiple regression analysis involving extensive hydrologic data are laborious and time consuming. With the advent of high-speed electronic computing machines, however, the time and labor involved in performing the computations may be reduced to a small fraction of that required using desk calculators. Special programs for electronic computers are available which may be used to perform automatically all computations involved in the solution of the normal regression equations.

11-03. EXAMPLES OF INDEX METHODS

11-03.01 General. - Index methods for forecasting seasonal snowmelt runoff have been developed for a wide variety of conditions. Many of the procedures have been reported on in various technical journals dealing with hydrologic problems, while others, although in operational use, have not been generally disseminated. A complete review of all such forecasting procedures is not practical here. Reference is made to examples of graphical correlations for forecasting seasonal runoff for California drainages, as described by Strauss 10/. A brief discussion of a report on procedures for forecasting seasonal runoff for Columbia River near

The Dalles, Oregon, issued by the Water Management Subcommittee, Columbia Basin Inter-Agency Committee,13/is presented to illustrate some of the basic techniques involved. A total of four procedures prepared by various federal agencies were reviewed in connection with this report.

11-03.02 The Columbia River basin (D.A. = 237,000 sq. mi.) is characterized by wide variations in both meteorological and topographical features. A large proportion of the winter precipitation is in the form of snow, with the maximum accumulation of snow occuring on about April 1st of each year. A high proportion of the runoff occurs during the late spring and early summer months, largely as a result of snowmelt. Basic hydrologic data used in the development of forecast procedures are comprised of runoff, precipitation, and snowpack water equivalent data. Adequate precipitation records are available as far back as 1927; in addition there are a number of stations in the Columbia Basin whose records extend back before the turn of the century. A complete record of discharge, as gaged near The Dalles, Oregon, is available from 1879 to date. Adequate records of snowpack water equivalent are generally confined to years subsequent to 1938.

11-03.03 U. S. Weather Bureau procedure. - A procedure which uses a precipitation index as the principal parameter has been developed by the U. S. Weather Bureau for forecasting seasonal runoff on the Columbia River near The Dalles, Oregon. The procedure consists essentially of forecasting the runoff on each of 22 sub-basins and equating the runoff from the sub-basins to runoff at successive downstream points. Procedures for sub-basins consist generally of establishing a relationship between water-year runoff and precipitation for the period September through June. The precipitation period is longer for some sub-basins, the objective being to include all months having significant amounts of precipitation for any area. A total of 78 precipitation stations are used for the basin as a whole, the number per square mile for each sub-basin varying widely as a result of over-all variation in density of stations having adequate records. Precipitation values are weighted with regard to both station and month, multiple correlations of runoff and precipitation being used as guides in assigning the weights for various stations and months. Weighting of precipitation by months serves as an indirect means of accounting for losses, less weight being assigned to months in which greater losses are normally incurred.

11-03.04 In most of the sub-basin forecasts, effects of conditions occuring in previous years are accounted for either by a carry-over factor incorporated in the precipitation index or by a carry-over adjustment to the forecasted runoff, the latter generally being used when consideration is given to the conditions occuring in several antecedent years. A carryover factor in the precipitation index is normally used when carryover effects are considered for only the preceding year. The value of the factor is determined by multiple correlation and usually varies from one-tenth to two-tenths of the previous year's partial precipitation index. that is, the index exclusive of carryover effects. Although the runoff for the full water year is used in the statistical correlations, forecasts of seasonal runoff can be made by simply deducting the flow prior to the date of forecast from the amount forecast for the water year as a whole. Observed precipitation values are used for months prior to the date of forecast; assumed, forecast, or normal values are used for subsequent months.

11-03.05 An outstanding characteristic of the Weather Bureau procedure is the extensive use of statistical analyses. In conjunction with statistical derivations, it has been noted that in some instances stations located outside of a given sub-basin are used in preference to a station located within the sub-basin, the latter, however, being used for another sub-basin. Although forecast results were improved by use of the carry-over adjustment, it is believed that an adjustment based on the flow at the end of the preceding water-year would yield results comparable to those obtained by the laborious statistical procedure used by the Weather Bureau.

11-03.06 Corps of Engineers (Portland District) procedure. - An example of an index method using snowpack water equivalent as the independent variable is that derived by the Corps of Engineers, Portland District, for forecasting seasonal volume of runoff on the Columbia River near The Dalles, Oregon. As in the Weather Bureau method, forecasts were prepared for sub-basins. Because of the relatively large size of the Columbia River basin, some difficulty is experienced in selecting stations that properly represent the basin as a whole. The general form of the forecast equation used is

$$y = a\ (x_1 + x_2 \ \ldots\ldots \ x_9) + b$$

where the x values are forecasts for the sub-basins. The equations for the sub-basins are of the form

$$y = a\,x + b$$

where x is now an index representing the April 1st snowpack water equivalent. All relationships for the sub-basin forecasts are derived by graphical correlations. The period 1938 through 1953 was used for verification of the Columbia River forecast, this being the longest period for which adequate water equivalent data were available. Although the procedure was primarily developed for preparation of a forecast on April 1st, earlier forecasts can be made by extrapolating existing conditions to April 1st. The effects of spring precipitation or other factors were not directly included as parameters in the forecast procedure. Accordingly, forecasts made after April 1st do not directly take into account the effects of abnormal spring precipitation. Since the derivation of the procedure does not differentiate between effects of spring precipitation and effects of other factors, only subjective adjustments for abnormal spring precipitation can be made. The outstanding feature of the forecast method is its simplicity. Results could probably be improved by inclusion of other parameters which would evaluate spring precipitation and soil moisture deficits. However, such refinements would detract from its simplicity. The graphical derivation of the relationship between water equivalent and runoff permits subjective visual evaluation of the data, by which allowances may be made for unrepresentative conditions of precipitation or known deficiencies in the data.

11-03.07 Soil Conservation Service procedure. - A method utilizing both snowpack water equivalent and precipitation indexes has been developed by the Soil Conservation Service for forecasting seasonal runoff on the Columbia River near The Dalles, Oregon. Indexes used in this method are measures of the amount of water in storage in the snowpack on the date of forecast, usually April 1st, and the amount of water stored in the soil as the result of autumn precipitation. Basically, the forecast procedure consists of correlating April-through-June runoff with these indexes of water supply. Selection of the April-through-June runoff period was made with the objective of correlating volume of runoff with peak flow (see chapter 12). The forecast equation, developed from data for the period 1937 through 1950, is of the general form

$$Y = aX_1 + bX_2 + c$$

where X_1 is the snowpack water equivalent index and X_2 is the autumn precipitation index. For the May 1st forecast the equation is expanded to include an April precipitation index, X_3. A similar equation for forecasts issued on May 15th, uses an April 1st-to-May 15 precipitation index instead of the April index. The Y value in all cases is the April-through-June runoff. Snowpack water equivalent and spring precipitation indexes are determined for each of 8 sub-basins and then weighted in accordance with the average runoff contribution of each sub-basin to obtain the index for the Columbia River basin. Spring precipitation indexes are based on departures from normal published in USWB Climatological

Bulletins, the index being the average of the departures at stations representative of the sub-basin. It is noted that the effect of spring precipitation upon the seasonal runoff was not considered when correlating runoff with water supply in the derivation of the equation for the April 1st forecast. On the other hand, spring precipitation was considered important enough to warrant its inclusion as a variable in deriving the equations for the May 1st and May 15th forecasts. The omission of the spring precipitation parameter in the development of the equation may have a significant effect upon the coefficients of the $\underline{X_1}$ and $\underline{X_2}$ terms, thus significantly affecting the runoff values computed by the equation. The usefulness of a runoff forecast for the period April through June for the Columbia River near The Dalles, Oregon, is limited because of the variability of distribution of runoff in individual years. The average April-June runoff is 61 percent of the April-September runoff, but values for individual years range from 47 to 70 percent, depending upon the meteorologic sequences during the melt season. Since the sequence cannot be forecast on a long range basis, an additional variable which cannot be evaluated is introduced when forecasting for the April-through-June period.

11-03.08 Soil Conservation Service-Geological Survey procedure. - A method developed jointly by the Soil Conservation Service and Geological Survey incorporates the use of base flow as an index of the soil-moisture content. The method is similar to that described in the previous paragraph, the principal difference being the use of base flow instead of autumn precipitation for the soil-moisture index. Base flow is generally considered to be a good index of soil-moisture content because it integrates conditions over the entire basin. A disadvantage of using base flow is that it cannot always be accurately determined, particularly when it is necessary to separate base flow from that resulting from recent rain and/or snowmelt. Regardless of whether autumn precipitation or November 1st base flow is used as an index of soil moisture, it is assumed in these methods that no significant change in soil moisture occurs during the period from November 1st to the date of forecast. It should be recognized that a soil-moisture index which accounts for varying soil moisture deficits as of 1 November of each year does not necessarily represent the deficit which would occur on April 1st, the effective date of the forecast for which snow survey data are generally available. Also, there is some ambiguity as to whether a base-flow index is representing soil moisture or ground water deficits, or a combination of the two.

11-03.09 Coastal winter-flow index method. - An index method based primarily upon the relationship between winter runoff of low-elevation drainages in western Washington and Oregon, and the spring snowmelt runoff of the Columbia River was reported in Research Note 23. Indexes of winter temperature and spring precipitation are included in the forecast procedure as secondary parameters. The use of low-elevation winter flow as an index is confined to regions where the low-elevation and high-elevation areas have a common source of moisture. Such a situation exists in the region comprised of the Columbia River basin and western Washington and Oregon, the entire region being well centered in the belt of prevailing westerlies. Moisture is carried in a generally eastward direction from the Pacific Ocean, the amount being largely dependent upon the rate of the flow and precipitable water content of the air. The amount of moisture deposited over the region is a function of the moisture supply in the atmosphere and is reflected by both winter streamflow at low elevations and accumulation of snow at high elevations. If it is assumed that a given supply of moisture results in a fixed winter precipitation pattern over the entire region, precipitation at lower coastal mountains may be correlated with that at higher levels in inland mountain ranges. However, winter streamflow and accumulation of snow, as well as transpiration losses vary with temperature, necessitating the introduction of a temperature parameter. Likewise, amounts of seasonal runoff associated with given amounts of snow accumulation, vary with amounts of spring precipitation occurring over the high-elevation area, necessitating the introduction of a spring precipitation parameter. Indexes used in the forecast procedure were averages of observations for several representative stations. The relationship of the parameters to the runoff of the Columbia River was determined graphically, using a coaxial method similar to the one described in paragraph 11-02.18. A comparison of the reliability of various index procedures developed for forecasting seasonal runoff for the Columbia River shows that the low-elevation winter-flow index method is as accurate with regard to historical data as those which use precipitation and snow-course data for the principal index.

11-03.10 Plate 11-1 is a map of the Columbia River basin, and shows the location of the index streams and the spring precipitation station used in the winter-flow index method. Plate 11-2 shows the forecasting diagrams and scatter diagrams illustrating the relative reliability of forecasts made as of 1 March and continuing through 1 July. The procedure was developed by utilizing all known hydrologic data for the water year, as of 1 July. Forecasts made for earlier dates were derived by assuming average conditions of precipitation for the period subsequent to the date of forecast.

11-04. EXAMPLES OF WATER-BALANCE METHODS

11-04.01 General. - Procedures for forecasting runoff by the water-balance method consist of evaluating each of the water-balance components and summing them algebraically to determine runoff. In using historical records to develop the procedure, hydrologic events occurring both previous and subsequent to the date of forecast are evaluated. Application of the water-balance method, as well as any other method of seasonal runoff forecasting, necessitates the use of normal, forecast, or assumed values for events which occur after the date of forecast. The distinguishing feature of the water-balance procedure is that the effect of each factor upon runoff is in accordance with its actual value. It will be remembered that index procedures involve use of coefficients by which the index is multiplied to obtain the effect of a given factor upon runoff, the coefficients being evaluated in accordance with the integrated effect of all factors collectively.

11-04.02 Basically, all water-balance procedures for forecasting runoff are similar, differences being largely confined to the number of components considered and the method of their evaluation. The simplest type of water-balance procedure is one in which only the principal component is evaluated separately, the remaining components being evaluated collectively. In more complex procedures, more than one component is evaluated, and collective evaluations are confined to minor components only. A highly developed procedure is one in which all the significant components are evaluated separately by the best available means. An example of such a procedure is the development of the water balance for each of the snow laboratory areas, as described in chapter 4.

11-04.03 Example of simple water-balance procedure. - A simple water-balance procedure is that developed by Bean and Thomas 2/ primarily for forecasting minimum volume of runoff on the Androscoggin River basin in Maine (D.A. = 3430 sq. mi.). A computed volume of snowpack water equivalent was used as the primary determinant of volume of seasonal runoff. A relatively high density network of snow courses (approx. one per 50 sq. mi.) located through a wide range of elevation was used in computing basin snowpack water equivalent. The basin area was divided into elevation zones bounded by 500-ft. contours and mean water equivalent depths within each zone were determined. For high elevations where snow course data were lacking, values were extrapolated. Total basin values were obtained by summing the products of water-equivalent depth and the area of each zone. Losses were estimated to be 25 percent of the total amount of water contained in the snowpack. Thus, 75 percent of the snowpack water equivalent was considered to be a firm source of water supply. Although precipitation that occurs subsequent to the date of forecast cannot be accurately forecast, the additional runoff from this source can be estimated on the basis of past records. The feature of this method is that snowpack water equivalent, the component of prime importance, is computed with a relatively high degree of accuracy, whereas those of lesser importance are estimated.

11-04.04 Combination water balance-index procedures. - In cases where the use of index procedures is limited by a combination of short record and many variables, the number of variables may be reduced by introduction of water-balance evaluations. A typical example of such a procedure is that developed by the Walla Walla District, Corps of Engineers in 1953 for Boise River at Lucky Peak Dam (D.A. = 2650 sq. mi.).12/ A preliminary study indicated that the important variables to be considered were winter precipitation, April 1st snowpack water equivalent, and spring precipitation. Water stored in the snowpack was evaluated in accordance with methods described in chapter 3, using a snow chart constructed for the basin. Because of the limited number of years with adequate snow course records, it was believed that results could be improved by reducing the number of independent variables in the statistical correlation to two. Variables selected for inclusion in the regression equation were winter precipitation and April 1st snowpack water equivalent. The contribution of spring precipitation to runoff was found to be dependent to a great extent upon percent of area covered by snow. It was noted that precipitation falling on bare ground during the spring months did not produce significant rises in streamflow; it was therefore assumed that this precipitation was lost by evapotranspiration. Precipitation falling on snow was considered to be fully effective in producing runoff; that is, losses normally incurred by the snowpack are not increased as a result of precipitation falling on the snow. The contribution of effective spring precipitation to runoff was, therefore, considered to be the amount falling on the snow field. The dependent variable used in the correlation was observed generated runoff minus runoff from effective spring precipitation.

11-04.05 A feature of this method is that the independent variables (April 1st water equivalent and winter precipitation) in the regression equation are indexes whose values are known on the date of the forecast. Thus, revisions necessitated by occurrences of unexpected conditions during the forecast period may be made as conditions warrant. The amount of runoff expected from spring precipitation is computed separately, based upon occurrence of normal, assumed, or forecast spring precipitation and temperature. Separate computation of runoff resulting from factors effective during the forecast period permits easy revision of the runoff forecast where necessitated by the occurrence of unexpected conditions. Furthermore, the weighting of the prime variables in the regression equation is not affected by occurrences of unusual spring precipitation.

11-04.06 Forecasts for partial season. - Forecast procedures discussed thus far are for seasons ending after the snowpack water equivalent remaining on the ground is negligible. However, it is sometimes necessary to have a runoff forecast for a period ending prior to the end of the snowmelt season. Such a forecast, of course, necessitates determination of the runoff resulting from snowmelt during the forecast period. It is apparent that the accuracy of runoff forecasts for periods ending before all snow is depleted is largely dependent upon ability to forecast weather conditions subsequent to the date of forecast. With presently available means of forecasting weather, forecasts for periods of more than a few days are not sufficiently reliable to warrant their general use for forecasting seasonal runoff. Runoff resulting from conditions occurring after the date of forecast is best determined on the basis of normal or assumed weather conditions.

11-04.07 Because of limited accuracy of forecasts of weather for extended periods, direct computation of resultant runoff for periods ending before all snow is depleted is not justified. Equally good results can be obtained by preparing the forecast for the full melt season and subtracting the flow expected to occur after the termination of the period for which the forecast is desired. Such subsequent flow may be determined on the basis of past records. It is generally expressed in terms of percentage of total seasonal flow remaining after a given date. Obviously, such percentages will vary in accordance with conditions occurring during the melt season, and selection of the percentage used in the forecast is usually the normal percentage.

11-04.08 Application of water balance method to Detroit Project basin. - The most refined water-balance procedure for forecasting runoff is that in which each component is evaluated by the best available means. The water-balance derivations for the laboratory areas, described in chapter 4, are illustrative of such refined methods. However, instrumentation and observational facilities on the laboratory areas are far better than those on the average project basin. The water-balance procedure for forecasting seasonal runoff on the North Santiam River above Detroit Reservoir, Oregon, reported in Research Note 22, is considered representative of a method adaptable to an average project basin. Although the method is basically the same as that used on the small laboratory areas, deviations from these procedures are significant enough to warrant some explanation. For example, it will be noted that in the development of the procedure for Detroit Reservoir no mention is made of losses by interception. It will also be noted that no direct calculations of gage-catch deficiency due to wind were made in computing the basin precipitation. Omission of these items from the water-balance computations is not to be interpreted as failure to recognize their importance; their effects were considered in the computation of the net precipitation occurring over the basin. Wind records applicable to the precipitation gages were lacking, necessitating computation of net basin precipitation by indirect means. Net precipitation on the laboratory areas was obtained by subtracting interception loss from total basin precipitation, the latter having been computed by the isopercentual method, utilizing station values adjusted for gage-catch deficiency due to wind effect. For the Detroit Reservoir area, net precipitation for each water year was obtained by summing the generated runoff and evapotranspiration loss. Month-to-month variation in gage catch was accounted for by varying the ratio of basin to station precipitation, the ratios being derived from water-balance studies. Since no differentiation was made between total and net precipitation, the sum of runoff and evapotranspiration loss was designated simply as basin precipitation, a term comparable to net precipitation as used in the laboratory studies. Likewise, since interception loss was not computed as a separate component, the term loss refers to that resulting from evapotranspiration and change in soil moisture; that is, it does not include interception loss, as in the laboratory studies.

11-04.09 Description of area. - The North Santiam River basin above Detroit Reservoir (D.A. = 438 sq. mi.), is located on the west slope of the Cascade Mountains about 60 miles southeast of Portland, Oregon. Elevations range from 1200 feet at the damsite to 10,495 feet at the top of Mount Jefferson, the mean basin elevation being 3718 feet. A location map and area-elevation curve for the basin is shown on plate 11-3. A large percentage of the area is comprised of valleys and ridges with steep slopes, and a heavy stand of coniferous timber covers most of the area. In general, the area is underlain with rock of basalt formation which outcrops on many of the steep slopes, particularly at higher elevations. Soil cover is relatively thin, but there is considerable duff and litter under the heavy forest canopy.

11-04.10 Because of its location on the windward slope of the Cascade Range, the climate of the area is dominated by maritime influences during the entire year, except during short periods of continental airmass control. The climate is characterized by wet, moderately cold winters and dry, warm summers. Snow accumulates to great depths at higher levels during the winter months, temperatures being near freezing at these levels during most of the winter. Normal annual precipitation over the basin is estimated at 82 inches and ranges from less than 70 inches near Detroit to over 100 inches near Mount Jefferson. Records at Detroit indicate that about 60 percent of the annual precipitation occurs during the November-through-February period, largely in conjunction with the widespread storm activity. Precipitation during the June-through-September period comprises only about 10 percent of the annual amount, much of it occurring in convective-type storms. The percentage of precipitation occurring as snow is small at Detroit, but increases with elevation to approximately 75 percent at the 7000-foot level. The accumulation of snow over the basin as a whole generally increases from the beginning of the water year until April. At low levels, periods of depletion as well as accumulation occur throughout the snowfall season. Reference is made to the water balance for WBSL as presented in chapter 4, for a hydrologic summary of an area similar in character to that of the North Santiam River basin above Detroit Dam.

11-04.11 Hydrologic data available. - Precipitation, snowfall, streamflow, air-temperature, and snowpack water-equivalent data are available for varying periods. The streamflow record for North Santiam River above Mayflower Creek is directly applicable to the area above Detroit Reservoir, the drainage areas being nearly identical. The only adequate temperature record available is that at Detroit, necessitating use of lapse rates to obtain estimated temperatures at higher levels. Precipitation data are available for five stations of which one, Detroit, has a virtually continuous record since 1909. The remaining four stations, Santiam Pass, Santiam Junction, Marion Forks, and Breitenbush have short records with significant periods of missing data. Water equivalent is measured at four snow courses having records since 1941. Depth of snow on the ground is measured at Detroit, and supplementary snow surveys have been obtained since 1950 at two low-level stations, Detroit and Whitewater Bridge. Because of regulation of streamflow during the construction phase of Detroit Dam, the streamflow record subsequent to 1951 is not considered usable for study, thus limiting the hydrologic study to prior years. Since adequate snow-course data are not available for years prior to 1941, the period of record suitable for study is confined to the water years 1940-41 through 1950-51. Locations of hydrologic stations are shown on plate 11-3.

11-04.12 Analysis for forecast period ending August 31. - This phase of the analysis is applied to forecast periods ending on

August 31 at which time the snowpack remaining on the basin is negligible. The forecast procedure was developed for three periods: February through August, March through August, and April through August. The basic equation used for all periods is as follows:

$$Q_{gen} = P + (W_1 - W_2) - L \qquad (11\text{-}1)$$

in which Q_{gen} is generated runoff, P is precipitation, W_1 and W_2 are the initial and final snowpack water equivalents respectively, and L is loss. The final snowpack water equivalent, W_2, is equal to zero in this case. Methods of evaluation of the terms of the equation are discussed in subsequent paragraphs.

11-04.13 The basin snowpack water equivalent was computed by use of a snow chart. Figure 1, plate 11-4 shows the snow chart and a sample determination of the snowpack water equivalent on February 1, 1954. Using the three key stations, Santiam Junction, Marion Forks, and Hogg Pass, a line was drawn representing the unadjusted mean depth of water equivalent over the basin. The line is drawn through points A and B, representing the mean depths and elevations of Marion Forks and Santiam Junction, and Santiam Junction and Hogg Pass, respectively. The unadjusted basin water equivalent is obtained by summing the zonal depths and dividing by 10. The values are shown in the tabulation accompanying the figure.

11-04.14 The factor by which the unadjusted value is multiplied to obtain the actual basin water equivalent, is derived from computed 11-year averages of precipitation, loss and runoff for the period September through December. These data are shown in the following tabulation:

Precipitation (P)	37.8 inches
Loss (L)	7.1 "
Generated Runoff (Q_{gen})	23.6 "

Substituting these values in equation 11-1, and considering the September 1 water equivalent (W_1) to be zero, the January 1 water equivalent (W_2) is calculated to be 7.1 inches. For the corresponding 11-year period, the average unadjusted water equivalent on January 1, obtained from the snow charts, is 9.4 inches. The adjustment factor is therefore 0.75 (7.1 divided by 9.4). Accordingly, the basin snowpack water equivalents indicated by the charts must be multiplied by 0.75 to obtain the actual basin values. Computed basin water equivalents for February 1, March 1, and April 1 of the 1941-51 period are shown in table 11-1.

11-04.15 Generated runoff, Q_{gen}, for each of the three forecast periods is computed by the method previously discussed. Observed runoff is converted to generated runoff by subtracting the recession volume of the initial flow and adding the recession volume of the terminal flow to the observed runoff during the period. Recession volumes are obtained from the scale on the right-hand side of figure 3, plate 11-5. Calculated generated flows are shown in table 11-1.

11-04.16 Losses, L, were computed by Thornthwaite's method for each of the years of the 11-year study period. Temperatures used in the computations are temperatures at the mean elevation of the basin and were obtained by applying estimates of lapse rate to the temperature at Detroit. As previously defined, loss is that portion of water supply which is lost to runoff and includes water retained in soil as well as that lost by evapotranspiration. Distribution of losses, averaged over the 11-year period, is shown in the following tabulation:

Period	Evapotranspiration (inches)	Retention in soil (inches)	Loss to runoff (inches)
September through December	3.3	3.8	7.1
January	0	0	0
February	0	0	0
March	0.3	0	0.3
April	1.3	0	1.3
May	2.5	-0.2	2.3
June	3.1	-1.0	2.1
July	3.3	-2.0	1.3
August	1.7	-0.6	1.1
Annual Total	15.5	0	15.5

Losses for the February-August, March-August and April-August periods for each year are shown in table 11-1 and in the bar diagrams in figure 4, plate 11-6.

11-04.17 Evapotranspiration losses during the period February through June are largely a function of monthly heat index, since there is sufficient water available to meet the potential demand. An estimate of losses for forecasting purposes can be obtained by using the relationship of previously computed evapotranspiration losses and corresponding monthly heat indexes at a representative station. Plotted points in figure 2, plate 11-5 show the relationship of heat index and evapotranspiration loss during March, April, May, and June of the 11-year study period, and the curves show the most probable amount for given heat indexes for each of the months. In the preparation of forecasts, the heat index, expressed as degree-days,* is based on occurrence of either forecasted, assumed, or normal temperatures during the forecast period. Table 11-2 shows the most probable heat index at Detroit for each of the ranges of temperature used in the U. S. Weather Bureau's Average Monthly Weather Résumé and Outlook. The Detroit temperature for each forecast range was determined by plotting long-term records of Portland temperatures versus Detroit temperatures and establishing the ranges for Detroit in accordance with those established for Portland by the U. S. Weather Bureau.

11-04.18 The average annual precipitation for the selected 11-year record was determined by adding the annual computed loss, 15.5 inches, to the annual runoff, 67.7 inches, to obtain the average annual basin precipitation of 83.2 inches. In computing monthly values of the water balance, it was found that the basin precipitation for January, February, and March, as determined from the single station at Detroit, weighted in accordance with the basin normal annual precipitation, produced more reliable results than those obtained using several stations. The recording gages at Marion Forks, Santiam Pass, and Santiam Junction all had significant periods of missing data during the winter months. However, during the period of April through August, the records of all stations appear reliable and were, therefore, used in computing basin precipitation for this period.

11-04.19 Bar diagrams illustrating the water balance for the various forecast periods of each of the years, 1941 through 1951, are shown in figure 4, plate 11-6. The first bar in each group represents the snowpack water equivalent in inches over the basin at the beginning of the forecast season. Total precipitation occurring during the forecast season is represented by the second bar. Total length of the third bar represents the sum of the water equivalent and precipitation; the hatched portion represents loss, and the unhatched portion shows the amount available for runoff. Actual generated runoff is depicted by the fourth bar. Figure 2, plate 11-6, shows graphically the correlation between computed and actual generated runoff values.

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* Daily maximum temperatures above $32^{\circ}F$.

11-04.20 As mentioned previously, the water balance method of forecasting runoff permits use of the U. S. Weather Bureau's Average Monthly Weather Résumé and Outlook. The expected precipitation given in the Outlook may be used for the first 30 days of a forecast period, assumed or normal values being used for the remainder of the period. Table 11-3 shows the most probable basin precipitation for each of the ranges used in the Outlook for each of the months of February through June. The Detroit precipitation for each forecast range for each month was determined by plotting long-term records of Portland precipitation versus Detroit precipitation, and establishing the ranges for Detroit in accordance with those established for Portland by the U. S. Weather Bureau. Most probable basin amounts for given amounts at Detroit for the months of April through August were derived from records of all stations in the basin, adjustments for gage catch being made in accordance with meteorological characteristics of each month. Adjustments are such that the sum of the precipitation amounts for these months is in agreement with the April-through-August total computed by the water balance equation. Because of the relative insignificance of the July and August precipitation, no effort is made to classify the amounts by ranges. Instead, the average of 1.9 inches of basin precipitation for the two months is used for the expected amount.

11-04.21 Charts depicting the water balance for the entire year based on averages for the 11-year study period are shown in figures 1 and 3, plate 11-6. The graph at the bottom of figure 1 shows the change in the amount of water in ground storage; positive values indicate increases and negative values indicate decrease in ground and channel storage. Cumulative totals of the water-balance components for the year beginning on September 1 are shown in figure 3.

11-04.22 Analysis for forecasting by months. - As previously stated, the water-balance method of forecasting is developed with the objective of forecasting runoff for periods terminating before the end of the melt season as well as for periods ending at the completion of snow melt. For forecast periods ending prior to the end of the melt season, specifically with the months of January, February, and March, the water balance equation used is

$$Q_{gen} = P_r + M - L \qquad (11\text{-}2)$$

where Q_{gen} is generated runoff, P_r is basin rainfall, M is basin melt, and L is basin loss, all in inches. The basin melt is obtained by applying the monthly degree-days at Detroit and percentage of basin covered by snow to the charts shown in figures 3 and 4, plate 11-4. The percentage of snow cover is determined by a correlation of snow-course data and aerial reconnaissance data. Melts based on an arbitrary 0.01 inches per degree-day melt rate are obtained from the melt charts, using the degree-days* and percentage of cover for the given month. Corrected melt is obtained by multiplying the value from the chart by factors derived from runoff and degree-day relationships during rain-free periods in the basin. Approximate factors are as follows:

Month	Correction factor
January	1.0
February	1.4
March	1.8

11-04.23 To compute the probable percentage of the precipitation that will occur as rain during a given forecast period, the amount occurring as rain was determined for each of the months, January through March, of the 11-year study period. Snowfall, obtained by adding algebraically the melt and the change in snowpack water equivalent, was subtracted from basin precipitation to obtain rainfall, which, in turn, was expressed in terms of percent of basin precipitation. The percentages are plotted as a function of the number of degree-days* at Detroit as shown in figure 1, plate 11-5. The most probable percentages for use in forecasting are indicated by the curves drawn on the chart. Computations of the water balance for each of the months are shown in table 11-4.

11-04.24 Preparing the forecast. - Having used historical data to establish criteria for evaluating the components of the water balance, the criteria may be applied to forecasting runoff for a given period. Forecasts for the Detroit project are confined to seasons ending on August 31, at which time the snowpack is negligible. Steps in the preparation of the forecast are as follows: (1) evaluate snowpack water equivalent on the initial day of the forecast period; (2) determine precipitation expected during the forecast period; (3) determine loss expected during the forecast period; (4) take algebraic sum of (1), (2), and (3) above; (5) add antecedent recession volume and subtract estimated

* Daily maximum temperatures above 32°F.

terminal-recession volume to obtain runoff for forecast period. Recession volumes for given flows are shown in figure 3, plate 11-5.

11-04.25 Conclusion. - The foregoing computations of the components of the water balance for the North Santiam River above Detroit illustrate the adaptability of the water-balance principle to the development of forecast procedures. Since runoff forecasts made by any method are subject to inevitable errors arising from the inability to foresee unusual hydrometeorological events that will occur during the forecast period, any forecast method should be flexible enough to permit easy revision of the forecast to account for such unusual events as they occur. The water-balance method, by virtue of its inherent adaptability to revision, meets this important requirement.

11-05. SUMMARY

11-05.01 Index procedures rely upon the variance of the independent variables to establish their relationship with the dependent variable. The magnitude of the derived coefficients is a function of the units of measurement as well as the conditions of measurement at the point of observation in relation to basin averages. Therefore, the coefficients do not necessarily have any physical significance in the relationship. In addition, the coefficients which provide the best solution for the years of record used in developing the equation are not necessarily the best for application to other years. This results from improper weightings of the variables in arriving at a best fit of the historical data. Indexes should be selected on the basis of representing known physical processes. Since the coefficients have no physical significance, there is little possibility to check them rationally, except in extreme cases. The use of index relationships is valuable, however, in establishing weightings of variables known to represent physical processes, but it should be recognized that such weightings may vary with different periods of record used in their derivation. The weightings of the variables should be based on complete indexes of water-balance components for the entire water year. Forecasts should use these weightings both for conditions known at the time of the forecast, and for normal or assumed conditions subsequent to the forecast date. The principal limitation of index procedures results from inadequate lengths of record of basic data for statistical analysis. Although it is desirable to include indexes of all important variables affecting runoff, the number of variables that can be used with confidence is limited by the length of the historical record. By contrast, evaluation of the components in the water-balance method is not dependent upon length of record. Although historical data are used in the development of the method, the forecast of runoff is based on an appraisal of each component for the current year rather than upon the effect produced by a given set of conditions in past years.

11-05.02 It has been pointed out that the volume of seasonal runoff is dependent not only upon the magnitude of individual components, but also upon the interrelationship of these components. For example, losses from spring and summer precipitation are a function not only of total moisture supply, but are also dependent upon the areal extent of the snow cover during the spring and summer and, hence, indirectly upon the maximum snowpack accumulation. In water-balance computations, such interrelationships where they are important enough to warrant consideration, are taken into account in a rational way in the computation of the individual components. Similarly, in the index approach to seasonal runoff forecasting, the individual indexes which determine runoff should each be a rational expression of the particular parameter, including any interrelationships that exist. Neither the water-balance method nor the index method of weighting the several components will, in itself, evaluate such interrelationships.

11-05.03 The sparsity of data on many project basins imposes limitations upon the accuracy with which water-balance computations can be made. Although the true values of the components may never be exactly known, satisfactory results are usually obtainable by use of computed values. Errors in the computation of the components of the water balance are known to exist when the values fail to show a balance in the application of the water balance equation to past data. Although it is recognized that the existence of a balance does not necessarily indicate correct evaluation of each component, it is highly probable that the component values are reasonably accurate if they consistently provide a balance under varying conditions. Failure of the components to balance indicates that further refinement is necessary.

11-05.04 The reliability of both water-balance and index methods is largely dependent upon the hydrologic data available for development and application of the methods. No definite rules can be made regarding the reliability of each of the methods; final appraisal of the methods is made largely on the basis of results obtainable by each. It is probable that better results would be obtained by the index method on project basins having records of 25 or more years duration, particularly if the areal coverage instrumentation is not good. On the other hand, records of less than 10-years duration are generally inadequate for development of forecast procedures by index methods.

11-05.05 The usual criterion of accuracy for forecasting procedures is the relative degree of correlation obtained by each procedure on the basis of historical record. Although it is desirable to obtain a high degree of correlation with historical data for a derived relationship, that should not be the only basis of judgement. Of even greater importance is the rational selection of variables affecting runoff. Unless it can be shown that all of the variables which significantly affect runoff are accounted for in the forecast equation, and that the effect of each variable is in the correct order of magnitude from the standpoint of known physical relationships, little reliance can be placed on the statistically derived relationship regardless of the degree of correlation. A line of best fit for a relatively few years of historical data for a relationship derived from incomplete indexes of the water-balance components will sometimes show a higher degree of correlation for an early-season forecast than a procedure derived from complete water-balance indexes and applied to the early date of forecast. The greater accuracy of the former is meaningless and reflects only the forcing of the regression to obtain the best fit of data which do not adequately represent the entire runoff process.

11-05.06 Because of the wide variation in problems associated with seasonal runoff forecasting, definite recommendations regarding choice of forecast methods to be used cannot be made. The adoption of certain methods may be immediately ruled out by lack of adequate data. In some instances the data may be inadequate for development of acceptable forecast procedures regardless of the method employed, necessitating development or expansion of a hydrologic network to provide the required data.

11-05.07 Although forecast procedures of limited refinement may be adequate for given projects, consideration should be given to possible future development of water uses. Since length of hydrologic records is an important factor in the development of forecast procedures, future needs should be anticipated far enough in advance to permit establishment of a hydrologic network for providing an adequate record of hydrologic data. The requirements for the hydrologic network should be considered in the light of the hydrologic character of the area involved and anticipated requirements for forecasts. Site selection for obtaining point observations of the principal elements should be made on the basis of obtaining representative samples for the area involved, as set forth in chapters 3 and 4. A final incentive for improving forecast techniques is the knowledge that better seasonal runoff forecasts make possible better utilization of water supply, thus contributing toward development of additional uses of water resources.

11-06. REFERENCES

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TABLE 11-1

WATER BALANCE BY FORECAST SEASON
North Santiam River above Detroit Dam

ITEM	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	TOTAL	MEAN
						APRIL Thru AUGUST							
1. Precipitation 1/	17.42	13.22	16.10	10.00	14.27	8.60	14.63	16.18	8.78	11.05	5.98	136.23	12.38
2. April 1st W 2/	4.05	12.08	24.82	7.72	11.48	27.00	11.85	19.13	33.49	28.35	24.08	204.05	18.55
3. Supply (1)+(2)	21.47	25.30	40.92	17.72	25.75	35.60	26.48	35.31	42.27	39.40	30.06	340.28	30.93
4. Loss 3/	11.09	8.31	9.08	6.02	5.13	8.42	11.96	9.25	6.45	8.36	5.10	89.17	8.11
5. Computed R.O. (3)-(4)	10.38	16.99	31.84	11.70	20.62	27.18	14.52	26.06	35.82	31.04	24.96	251.11	22.82
6. Generated R.O. 4/	10.43	14.41	29.65	12.74	21.90	24.43	16.11	29.37	35.20	35.44	21.33	250.01	22.73
7. Percent Deviation	-0.5	17.9	7.4	-8.2	-1.3	11.2	-9.9	-11.3	1.8	-12.4	17.0	0.4	0.4
						MARCH Thru AUGUST							
1. Precipitation	20.25	17.89	27.04	15.52	27.19	18.44	23.40	24.12	14.91	25.77	15.79	230.32	20.94
2. March 1st W	6.30	11.64	24.90	7.20	5.89	23.81	11.18	15.19	34.69	26.74	18.45	185.99	16.91
3. Supply	26.55	29.53	51.94	22.72	33.08	42.25	34.58	39.31	49.60	52.51	34.24	416.31	37.85
4. Loss	12.39	8.91	9.08	6.32	5.33	8.52	12.76	9.25	6.65	8.36	5.10	92.67	8.43
5. Computed R.O.	14.16	20.62	42.86	16.40	27.75	33.73	21.82	30.06	42.95	44.15	29.14	323.64	29.42
6. Generated R.O.	13.28	19.26	38.31	17.75	27.40	31.19	23.36	34.90	43.19	46.97	27.02	322.63	29.33
7. Percent Deviation	6.6	7.1	11.9	-7.7	1.3	8.1	-6.6	-13.9	-0.6	-6.0	7.8	0.3	0.3
						FEBRUARY Thru AUGUST							
1. Precipitation	23.89	26.58	36.47	23.28	42.83	28.70	27.90	39.34	38.32	38.94	28.58	354.83	32.26
2. February 1st W	5.85	6.75	24.68	4.05	3.19	18.68	12.04	7.91	21.45	23.92	17.25	145.77	13.25
3. Supply	29.74	33.33	61.15	27.33	46.02	47.38	39.94	47.25	59.77	62.86	45.83	500.60	45.51
4. Loss	12.39	8.91	9.08	6.32	5.33	8.52	12.76	9.25	6.65	8.36	5.10	92.67	8.43
5. Computed R.O.	17.35	24.42	52.07	21.01	40.69	38.86	27.18	38.00	53.12	54.50	40.73	407.93	37.08
6. Generated R.O.	16.23	24.68	48.61	21.73	37.96	36.89	31.02	43.77	52.50	56.48	37.08	406.95	37.00
7. Percent Deviation	6.9	-1.1	7.1	-3.3	7.2	5.3	-12.4	-13.2	1.2	-3.5	9.8	0.2	0.2

1/- Precipitation values are inches over basin.
2/- W is snowpack water equivalent expressed in inches over basin.
3/- Loss is computed by Thornthwaite's method, and is expressed in inches over basin.
4/- Generated runoff is actual runoff minus initial recession-volume plus terminal recession-volume.

TABLE 11-2

MONTHLY TEMPERATURE AND HEAT INDEX RANGES

DETROIT, OREGON

Forecast 1/	Range: Temperature (°F)	Range: Heat Index (Degree-Days) 2/	Most Probable: Temperature (°F)	Most Probable: Heat Index (Degree-Days)
		February		
Much above	41.4 or more	558 or more	42.6	650
Above	39.1 - 41.3	472 - 557	40.2	500
Normal	37.2 - 39.0	382 - 471	37.6	400
Below	37.1 - 33.2	381 - 242	35.0	300
Much below	33.1 or less	241 or less	32.0	200
		March		
Much above	45.6 or more	801 or more	47.0	850
Above	42.1 - 45.5	701 - 800	43.8	750
Normal	39.6 - 42.0	550 - 700	41.3	600
Below	39.5 - 38.0	549 - 400	38.8	500
Much below	37.9 or less	399 or less	37.2	350
		April		
Much above	50.6 or more	1001 or more	51.2	1050
Above	48.3 - 50.5	901 - 1000	49.4	950
Normal	46.2 - 48.2	800 - 900	47.3	850
Below	46.1 - 44.0	799 - 700	45.2	750
Much below	43.9 or less	699 or less	43.6	650
		May		
Much above	57.7 or more	1301 or more	58.0	1350
Above	54.5 - 57.6	1201 - 1300	56.1	1250
Normal	52.5 - 54.4	1100 - 1200	53.8	1150
Below	52.4 - 51.0	1099 - 1000	51.7	1050
Much below	50.9 or less	999 or less	50.4	900
		June		
Much above	61.1 or more	1401 or more	61.6	1450
Above	59.1 - 61.0	1301 - 1400	60.0	1350
Normal	57.9 - 59.0	1200 - 1300	58.6	1250
Below	57.8 - 56.6	1199 - 1100	57.2	1150
Much below	56.5 or less	1099 or less	56.0	1050

1/ Forecast designations are those used in the U. S. Weather Bureau *Average Monthly Weather Résumé and Outlook*, and corresponding temperatures are mean monthly values.

2/ Heat indexes are based on computations for each of the months of the years 1941 through 1951 and are monthly totals of maximum temperatures above base 32°F.

TABLE 11-3

MONTHLY PRECIPITATION RANGES

NORTH SANTIAM RIVER ABOVE DETROIT DAM

Forecast 1/	Range		Most Probable	
	Detroit (inches)	Basin 2/ (inches)	Detroit (inches)	Basin (inches)
		February		
Heavy	11.2 or more	13.4 or more	13.7	16.4
Moderate	11.1 - 6.1	13.3 - 7.3	8.7	10.4
Light	6.0 or less	7.2 or less	3.8	4.5
		March		
Heavy	8.9 or more	9.9 or more	12.8	14.3
Moderate	8.8 - 4.8	9.8 - 5.3	7.4	8.3
Light	4.7 or less	5.2 or less	3.8	4.2
		April		
Heavy	7.0 or more	6.3 or more	8.5	7.6
Moderate	6.9 - 4.3	6.2 - 3.8	5.0	4.5
Light	4.2 or less	3.7 or less	2.6	2.3
		May		
Heavy	5.1 or more	4.5 or more	6.0	5.3
Moderate	5.0 - 3.6	4.4 - 3.2	3.9	3.4
Light	3.5 or less	3.1 or less	1.7	1.5
		June		
Heavy	3.2 or more	2.8 or more	4.3	3.8
Moderate	3.1 - 1.6	2.7 - 1.4	2.4	2.1
Light	1.5 or less	1.3 or less	0.9	0.8

1/ Forecast designations are those used in the U. S. Weather Bureau Average Monthly Weather Resume and Outlook.

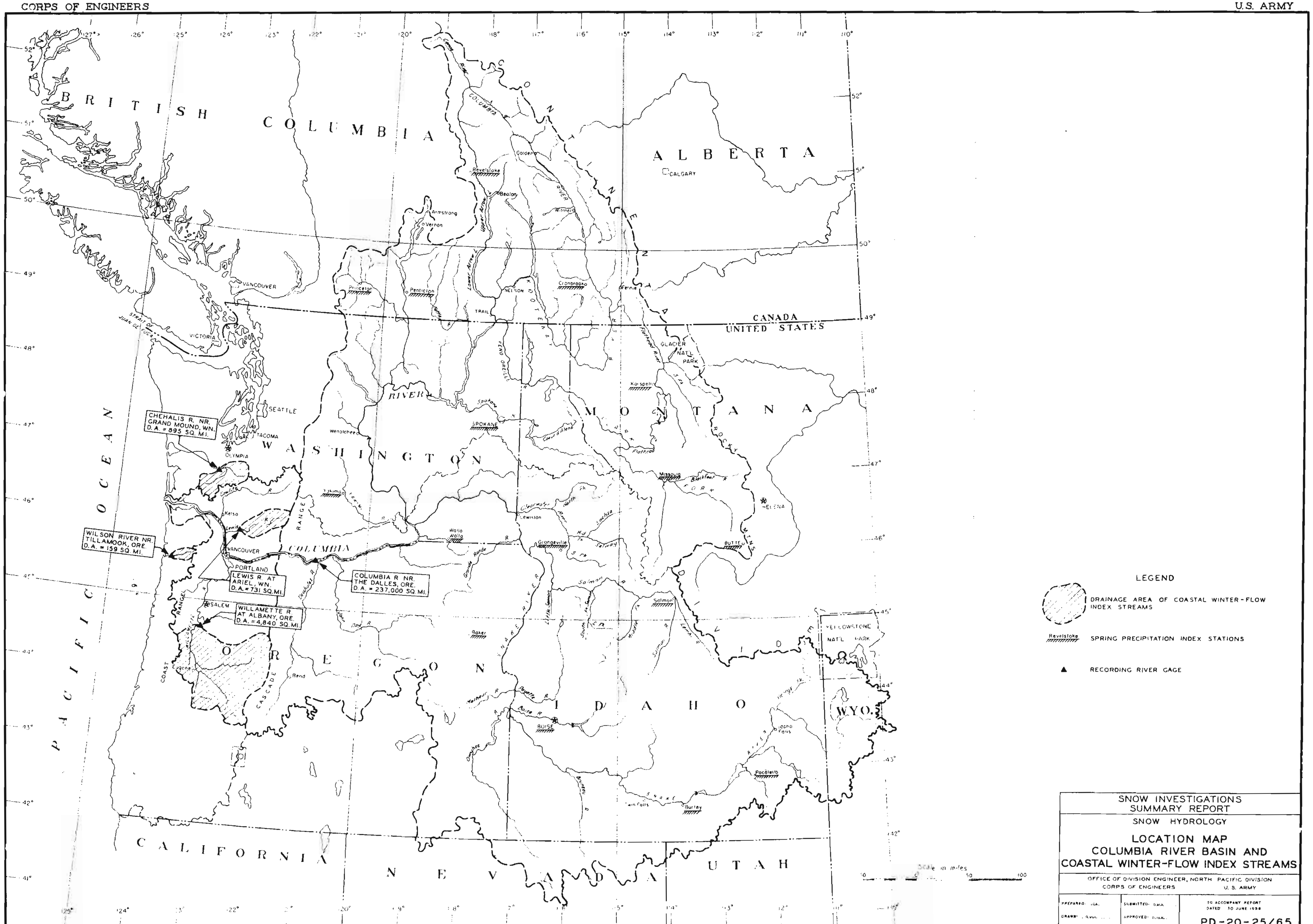
2/ Basin values are determined by water-balance studies for the period 1941 through 1951.

TABLE 11-4

WATER BALANCE BY MONTHS
North Santiam River above Detroit Dam

ITEM 1/	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	TOTAL	MEAN
						JANUARY							
(1) Degree Days 2/	420.00	353.00	239.00	303.00	385.00	266.00	183.00	368.00	154.00	78.00	218.00		
(2) Percent Snow Cover	54.00	73.00	87.00	64.00	58.00	90.00	60.00	65.00	92.00	98.00	82.00		
(3) Melt	1.07	1.23	0.83	0.80	1.05	1.02	0.25	1.20	0.45	0.15	0.68	8.73	0.79
(4) Change in Water-Equivalent	3.41	3.77	10.46	1.84	0.90	7.24	6.82	3.71	3.90	13.88	11.81	67.74	6.16
(5) Snowfall (3)+(4)	4.48	5.00	11.29	2.64	1.95	8.26	7.07	4.91	4.35	14.03	12.49	76.47	6.95
(6) Basin Precipitation	10.06	8.02	15.64	7.08	10.31	15.93	13.13	15.60	3.74	25.48	21.73	146.72	13.34
(7) Snowfall	4.48	5.00	11.29	2.64	1.95	8.26	7.07	4.91	4.35	14.03	12.49	76.47	6.95
(8) Rainfall (6)-(7)	5.58	3.02	4.35	4.44	8.36	7.67	6.06	10.69	-0.61	11.45	9.24	70.25	6.57
(9) Supply (3)+(8)	6.65	4.25	5.18	5.24	9.41	8.69	6.31	11.89	-0.16	11.60	9.92	78.98	7.18
(10) Loss 3/	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(11) Computed Runoff (9)-(10)	6.65	4.25	5.18	5.24	9.41	8.69	6.31	11.89	-0.16	11.60	9.92	78.98	7.18
(12) Generated Runoff 4/	6.57	5.24	7.08	4.38	8.39	9.85	7.12	11.64	1.50	6.80	9.91	78.48	7.13
(13) Percent Rainfall	55.00	38.00	28.00	63.00	81.00	48.00	46.00	69.00	-	45.00	43.00		
						FEBRUARY							
(1) Degree Days	536.00	423.00	538.00	403.00	371.00	309.00	514.00	306.00	278.00	281.00	369.00		
(2) Percent Snow Cover	49.00	90.00	88.00	54.00	66.00	87.00	62.00	75.00	93.00	100.00	87.00		
(3) Melt	2.24	2.52	3.50	1.09	1.26	1.47	1.99	1.15	1.40	1.75	1.89	20.26	1.84
(4) Change in Water-Equivalent	0.45	4.88	0.23	3.15	2.70	5.14	-0.86	7.28	13.24	2.82	1.20	40.23	3.66
(5) Snowfall (3)+(4)	2.69	7.40	3.73	4.24	3.96	6.61	1.13	8.43	14.64	4.57	3.09	60.49	5.50
(6) Basin Precipitation	3.64	8.69	9.43	7.76	15.64	10.26	4.50	15.22	23.41	13.17	12.79	124.51	11.32
(7) Snowfall	2.69	7.40	3.73	4.24	3.96	6.61	1.13	8.43	14.64	4.57	3.09	60.49	5.50
(8) Rainfall (6)-(7)	0.95	1.29	5.70	3.52	11.68	3.65	3.37	6.79	8.77	8.60	9.70	64.02	5.82
(9) Supply (3)+(8)	3.19	3.81	9.20	4.61	12.94	5.12	5.36	7.94	10.17	10.35	11.59	84.28	7.66
(10) Loss	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(11) Computed Runoff (9 -(10)	3.19	3.81	9.20	4.61	12.94	5.12	5.36	7.94	10.17	10.35	11.59	84.28	7.66
(12) Generated Runoff	2.95	5.42	10.30	3.98	10.56	5.70	7.66	8.87	9.31	9.51	10.06	84.32	7.67
(13) Percent Rainfall	26.00	15.00	60.00	45.00	75.00	36.00	75.00	45.00	37.00	65.00	76.00		
						MARCH							
(1) Degree Days	966.00	707.00	578.00	592.00	465.00	510.00	767.00	499.00	545.00	408.00	422.00		
(2) Percent Snow Cover	27.00	72.00	88.00	57.00	68.00	91.00	57.00	82.00	88.00	100.00	82.00		
(3) Melt	2.80	5.56	5.16	2.90	2.16	4.20	4.70	3.42	4.70	3.14	2.40	41.14	3.74
(4) Change in Water-Equivalent	-2.25	0.45	-0.08	0.52	5.59	3.19	0.68	3.94	-1.20	1.60	5.55	17.99	1.64
(5) Snowfall (3)+(4)	0.55	6.01	5.08	3.42	7.75	7.39	5.38	7.36	3.50	4.74	7.95	59.13	5.38
(6) Basin Precipitation	2.83	4.67	10.94	5.52	12.92	9.84	8.77	7.94	6.13	14.72	9.81	94.09	8.56
(7) Snowfall	0.55	6.01	5.08	3.42	7.75	7.39	5.38	7.36	3.50	4.74	7.95	59.13	5.38
(8) Rainfall (6)-(7)	2.28	-1.34	5.86	2.10	5.17	2.45	3.39	0.58	2.63	9.98	1.86	34.96	3.18
(9) Supply (3)+(8)	5.08	4.22	11.02	5.00	7.33	6.65	8.09	4.00	7.33	13.12	4.26	76.10	6.92
(10) Loss	1.30	0.60	0.00	0.30	0.20	0.10	0.80	0.00	0.20	0.00	0.00	3.50	0.32
(11) Computed Runoff (9)-(10)	3.78	3.62	11.02	4.70	7.13	6.55	7.29	4.00	7.13	13.12	4.26	72.60	6.60
(12) Generated Runoff	2.85	4.85	8.66	5.01	6.50	6.76	7.25	5.53	7.99	11.53	5.69	72.62	6.60
(13) Percent Rainfall	81.00	-	54.00	38.00	40.00	25.00	39.00	7.00	43.00	68.00	19.00		

1/- Items (3) through (12) are expressed in inches over basin.
2/- Degree days are monthly totals of degrees of maximum temperatures above base 32° F.
3/- Loss is computed by Thornthwaite's method.
4/- Generated runoff is actual runoff minus initial recession volume plus terminal recession volume.



SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

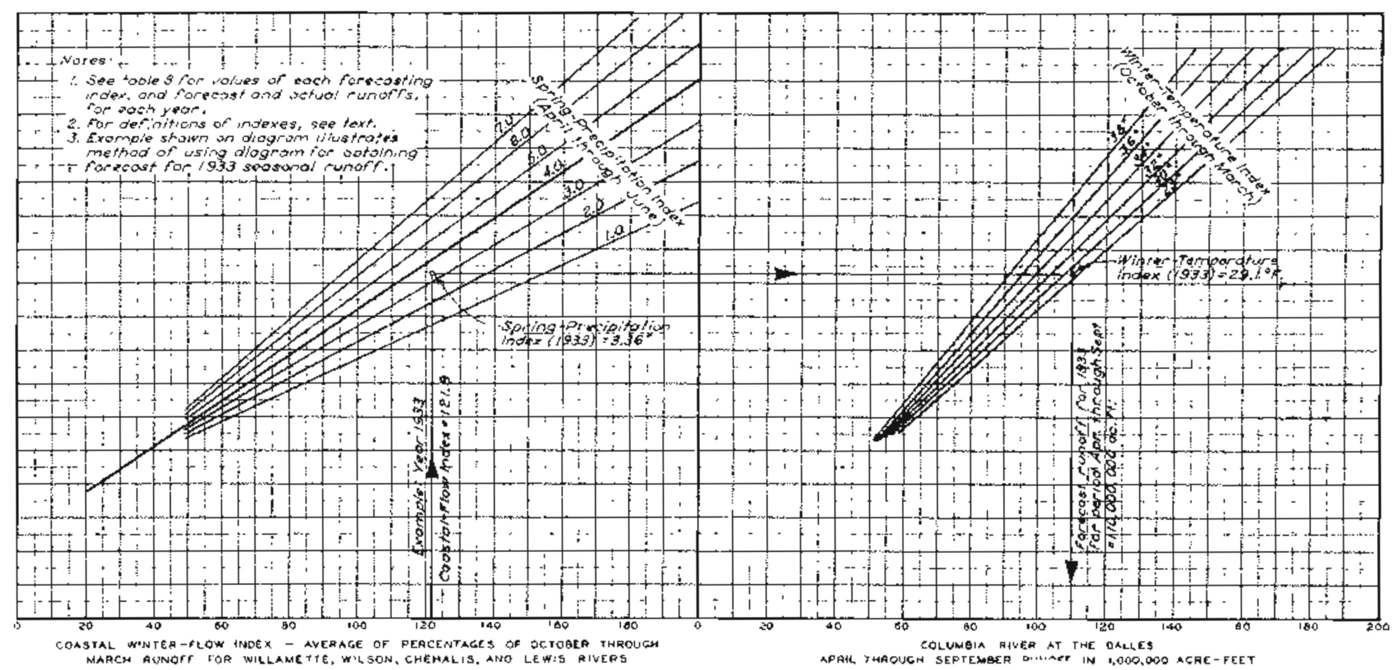
LOCATION MAP
COLUMBIA RIVER BASIN AND
COASTAL WINTER-FLOW INDEX STREAMS

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

TO ACCOMPANY REPORT DATED 30 JUNE 1956

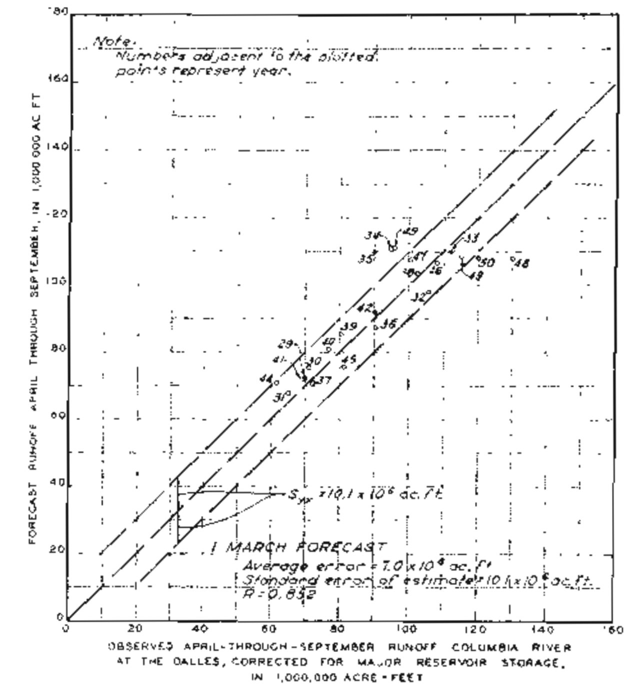
PD-20-25/65

PLATE 11-1



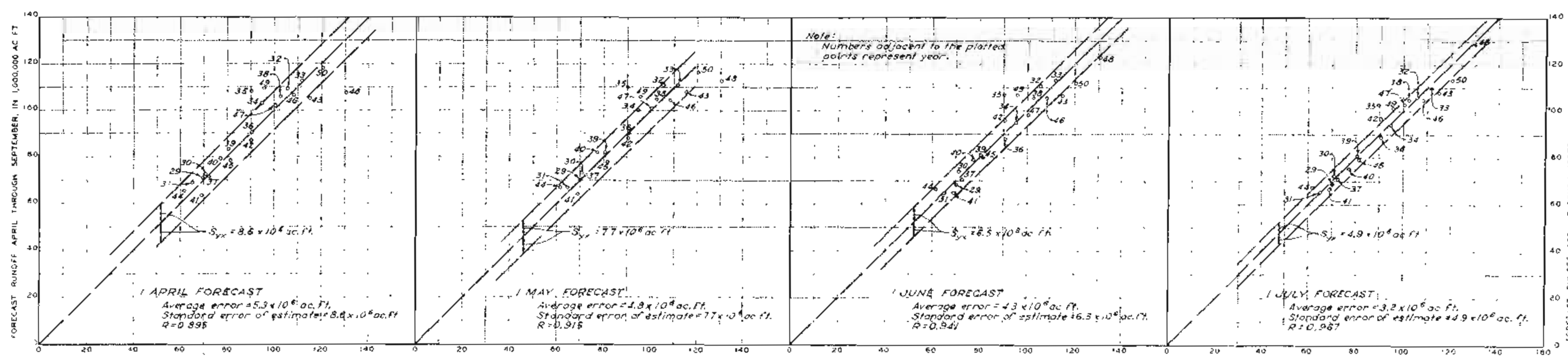
COAXIAL DIAGRAM FOR FORECASTING COLUMBIA RIVER APRIL-THROUGH-SEPTEMBER RUNOFF AT THE DALLES

FIGURE 1



FORECAST VS ACTUAL RUNOFF
(1 MARCH FORECAST)

FIGURE 2



FORECAST VS ACTUAL RUNOFF
1 APRIL, 1 MAY, 1 JUNE, AND 1 JULY FORECASTS

FIGURE 3

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

FORECASTING DIAGRAMS
COASTAL WINTER-FLOW INDEX METHOD

COLUMBIA RIVER NEAR THE DALLES

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

PREPARED [illegible] SUBMITTED [illegible] TO ACCOMPANY REPORT DATED 30 JUNE 1956
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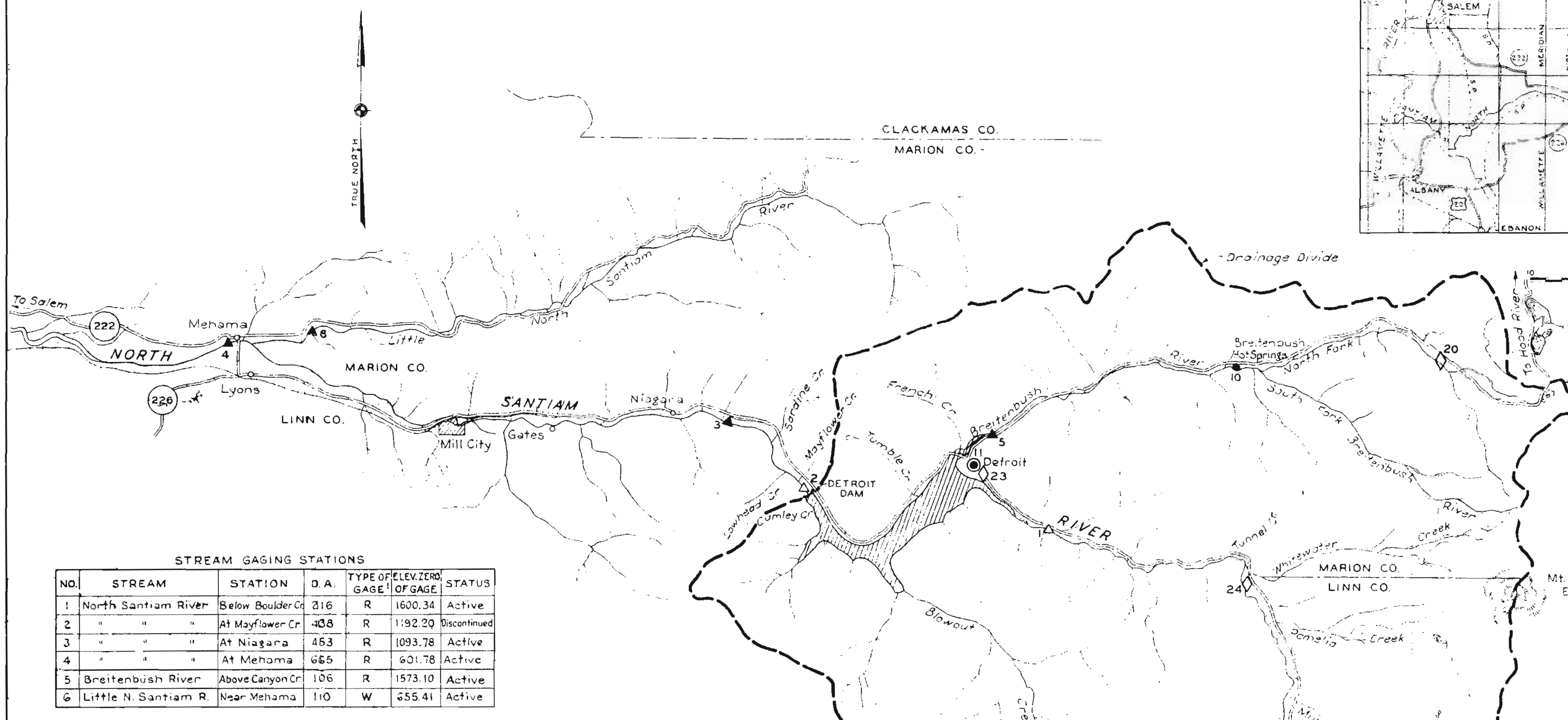
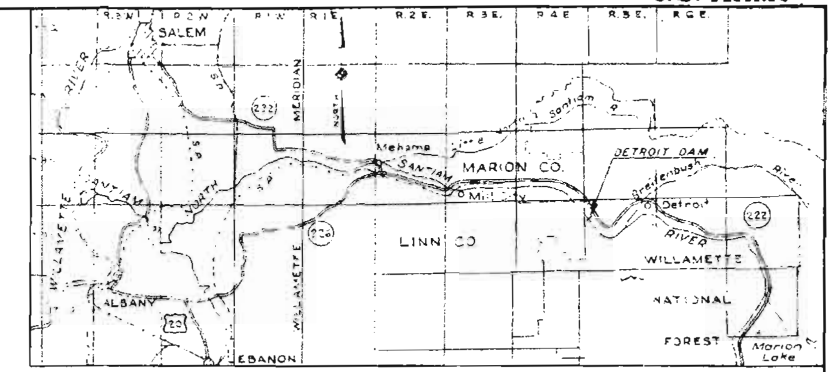
PD-20-25/66

PLATE 11-2





LOCATION MAP
SCALE IN MILES

STREAM GAGING STATIONS

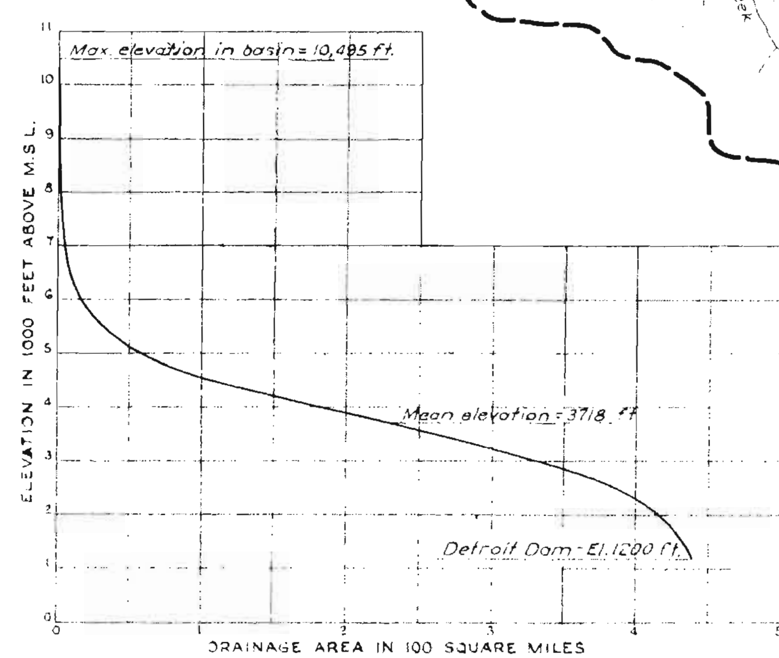
NO.	STREAM	STATION	D.A.	TYPE OF GAGE[1]	ELEV. ZERO OF GAGE	STATUS
1	North Santiam River	Below Boulder Cr.	216	R	1600.34	Active
2	" " "	At Mayflower Cr.	438	R	1192.20	Discontinued
3	" " "	At Niagara	453	R	1093.78	Active
4	" " "	At Mehama	655	R	601.78	Active
5	Breitenbush River	Above Canyon Cr.	106	R	1573.10	Active
6	Little N. Santiam R.	Near Mehama	110	W	655.41	Active

PRECIPITATION STATIONS

MAP NUMBER	STATION	ELEVATION	TYPE OF GAGE
10	Breitenbush	2225	R
11	Detroit	1452	N & R
12	Marion Forks	2445	R
13	Santiam Junction	3750	R
14	Santiam Pass	4800	R

SNOW SURVEY COURSES

MAP NUMBER	NAME	ELEVATION
20	Breitenbush	2325
2	Hogg Pass	4755
21	Marion Forks	2730
22	Santiam Junction	3990
23	Detroit	1500
24	Whitewater Bridge	2175



AREA ELEVATION CURVE — DETROIT DAM
DRAINAGE AREA 438 SQUARE MILES

SNOW INVESTIGATIONS
SUMMARY REPORT
SNOW HYDROLOGY

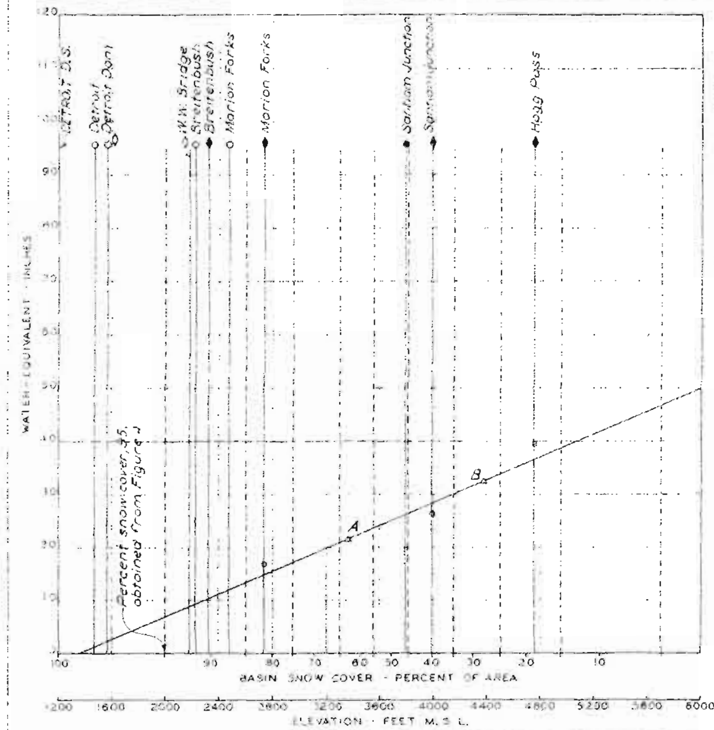
BASIN MAP

NORTH SANTIAM RIVER ABOVE DETROIT DAM
DRAINAGE AREA 438 SQ MI

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

TO ACCOMPANY REPORT DATED 30 JUNE 1956

PD-20-25/67



LEGEND

- ○ Precipitation, manual
- ● Precipitation, recorder
- ◊ Snow Course, supplementary
- ♦ Snow Course, regular

SNOW WATER-EQUIVALENT
North Fork, Santiam River
Above Detroit

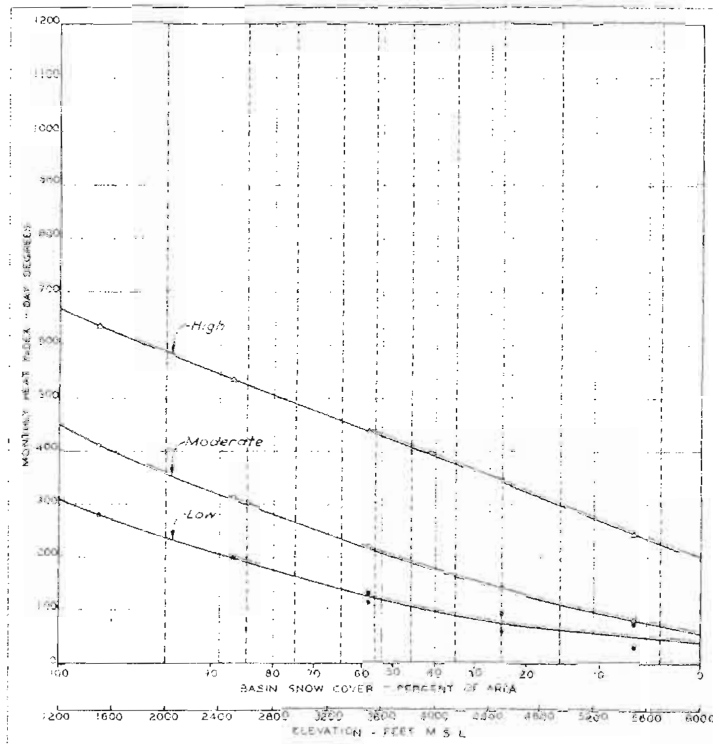
ZONE	INCHES
90 - 100	6.8
80 - 90	13.2
70 - 80	17.0
60 - 70	20.8
50 - 60	23.5
40 - 50	26.0
30 - 40	30.0
20 - 30	33.7
10 - 20	38.6
0 - 10	46.7
Wtd. Total	25.6
% Cover	95
Date	1 Feb. 1954

Corrected water-equivalent
$= 25.6(0.75) = 19.2"$

Notes:

1. Plotted points show depth of snow at named snow courses at given elevations.
2. Points A and B show mean snow water-equivalent depth and mean elevation at Marion Forks and Santiam Junction and Santiam Junction and Hogg Pass, respectively.
3. Line through A and B represents unadjusted depth of snow water-equivalent at all elevations.
4. Dashed lines indicate midpoint of each zone of 10 percent of basin area.
5. Intersections of dashed line and line through A and B show unadjusted mean depth of water-equivalent for each zone.
6. Summation of water-equivalent for each zone divided by 10 gives unadjusted basin snow water-equivalent.
7. Corrected basin snow water-equivalent is obtained by multiplying unadjusted basin snow water-equivalent by 0.75, a factor derived from water-balance studies.

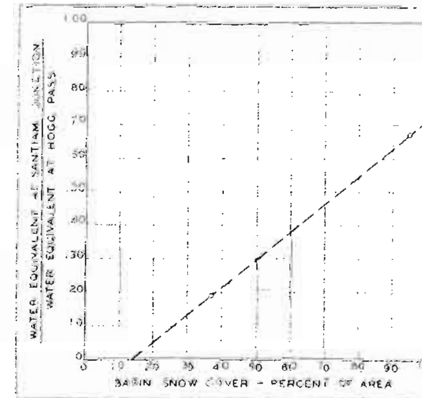
FIGURE 1 - SNOW WATER-EQUIVALENT



Notes:

1. Chart is sample determination of day degrees over basin for high, moderate, and low temperatures during February.
2. Plotted points represent monthly totals of day degrees at each elevation for given number of day degrees at Detroit, based on lapse rate determined from Medford radiosonde data, 3.5°F/1000 feet.
3. Dashed lines represent mean of each 10 percent zone of basin.
4. Intersections of dashed lines with curves represent day degrees for corresponding zones.
5. Melt in a given zone may be obtained by multiplying day degrees by rate of melt in inches per day degree.

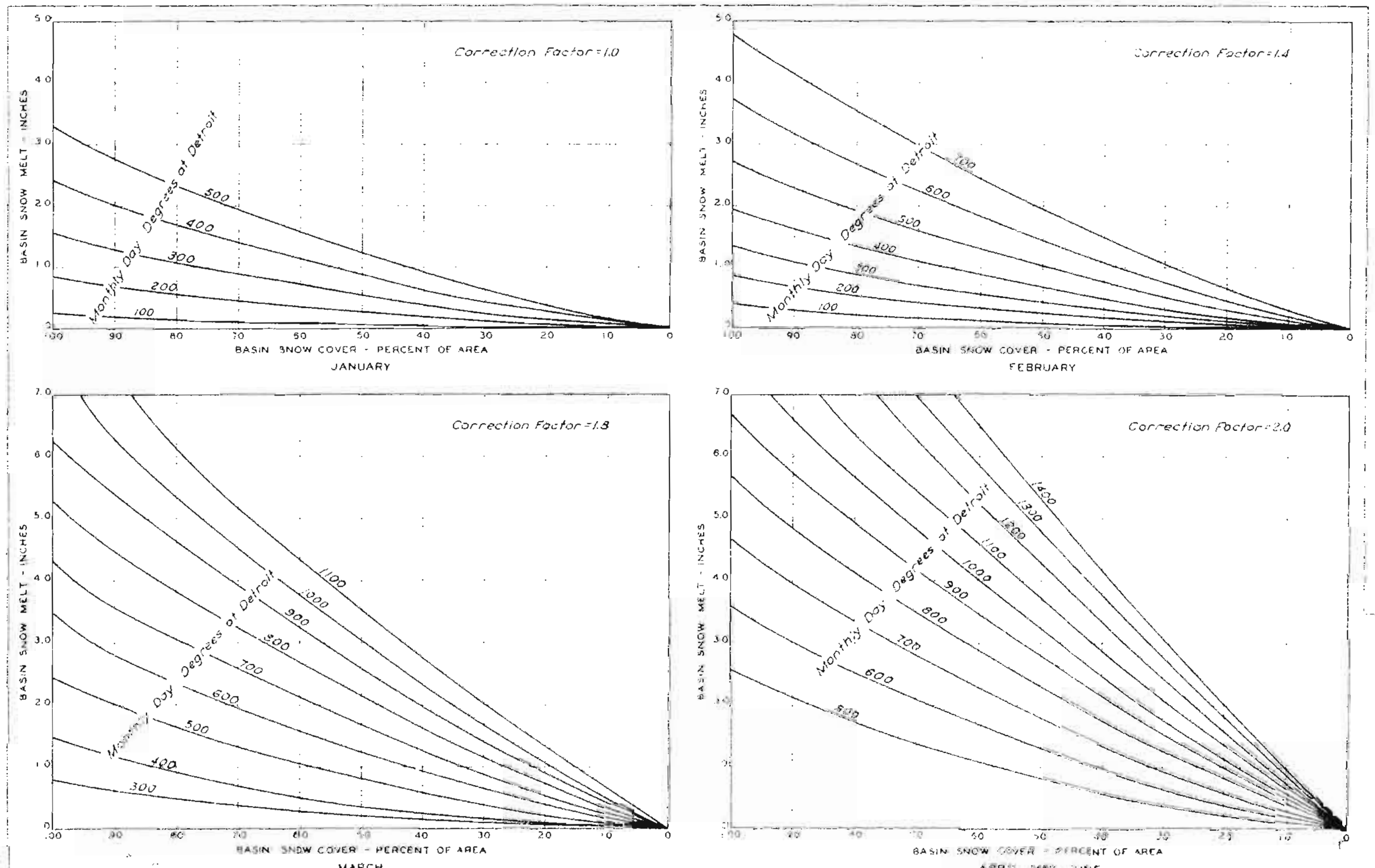
FIGURE 2 - FEBRUARY HEAT SUPPLY



Notes:

1. Plotted points show percent cover determined by aerial reconnaissance and ratio of water-equivalents of two key snow courses, Santiam Junction and Hogg Pass on same date.
2. Line connecting plotted points gives estimated percent snow cover for given ratio of depths of water-equivalent at the key snow courses.
3. Chart values not considered conclusive because of insufficient data and are shown principally for illustrating method of estimating percent snow cover.

FIGURE 4 - BASIN SNOW COVER



Notes:

1. Curves represent monthly totals of day degrees at Detroit.
2. Ordinate at intersection of given percent snow cover and line representing given day degrees at Detroit gives melt in inches over basin, assuming 0.01 inch per day degree melt rate.
3. Corrected basin melt is obtained by multiplying melt from chart by factor based on melt studies in basin and shown on each chart.

FIGURE 3 - BASIN SNOW MELT

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SNOWPACK WATER EQUIVALENT AND MELT

NORTH SANTIAM RIVER ABOVE DETROIT DAM
DRAINAGE AREA 438 SQ MI

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

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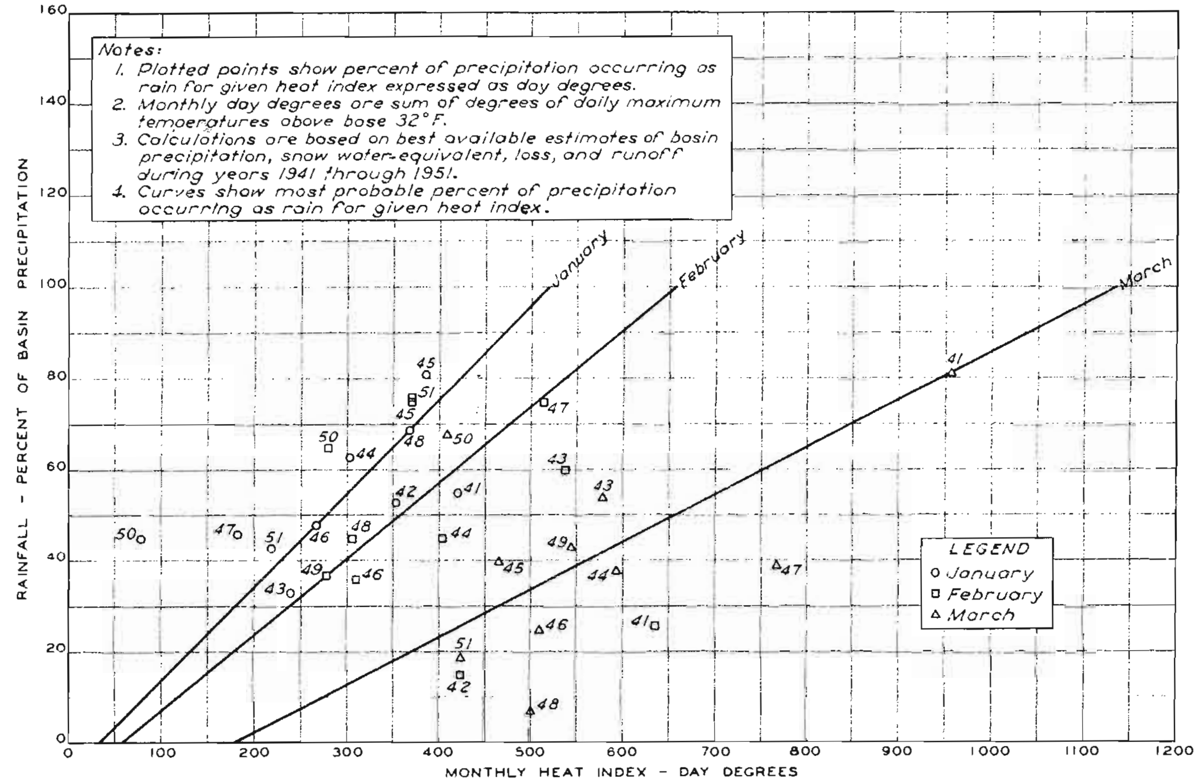

FIGURE 1 - PERCENT OF PRECIPITATION OCCURRING AS RAIN

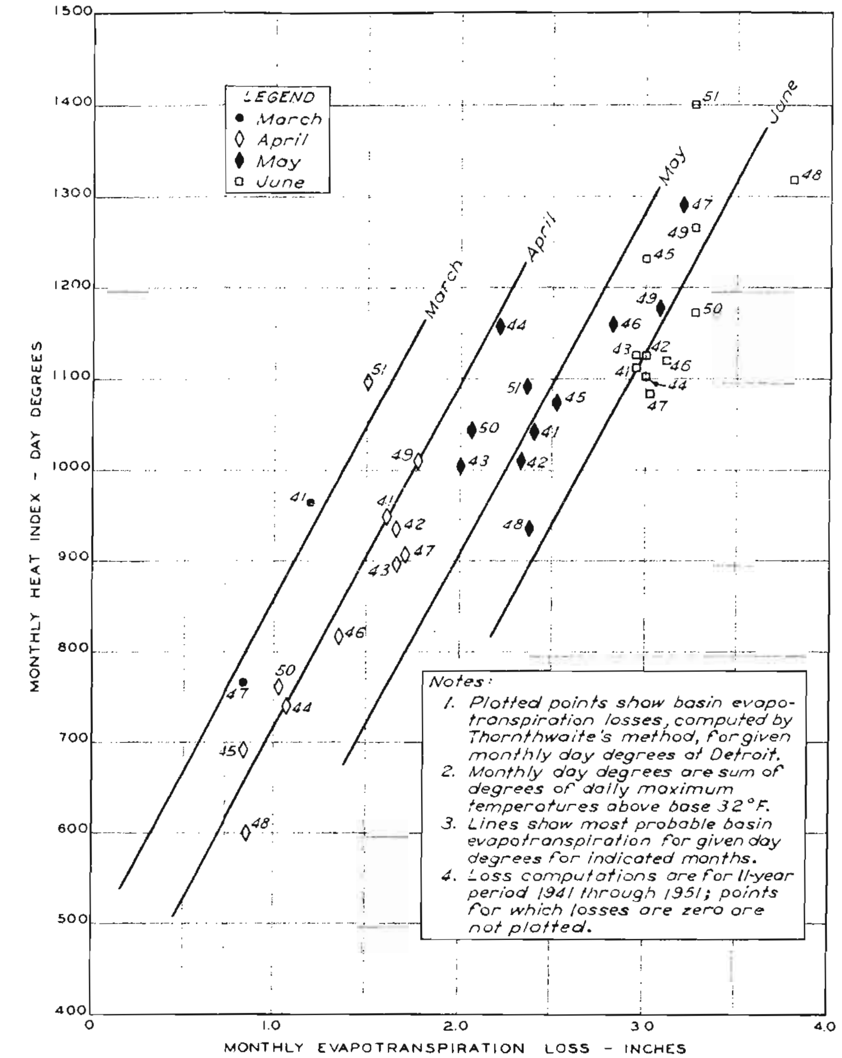

FIGURE 2 - LOSS BY EVAPOTRANSPIRATION

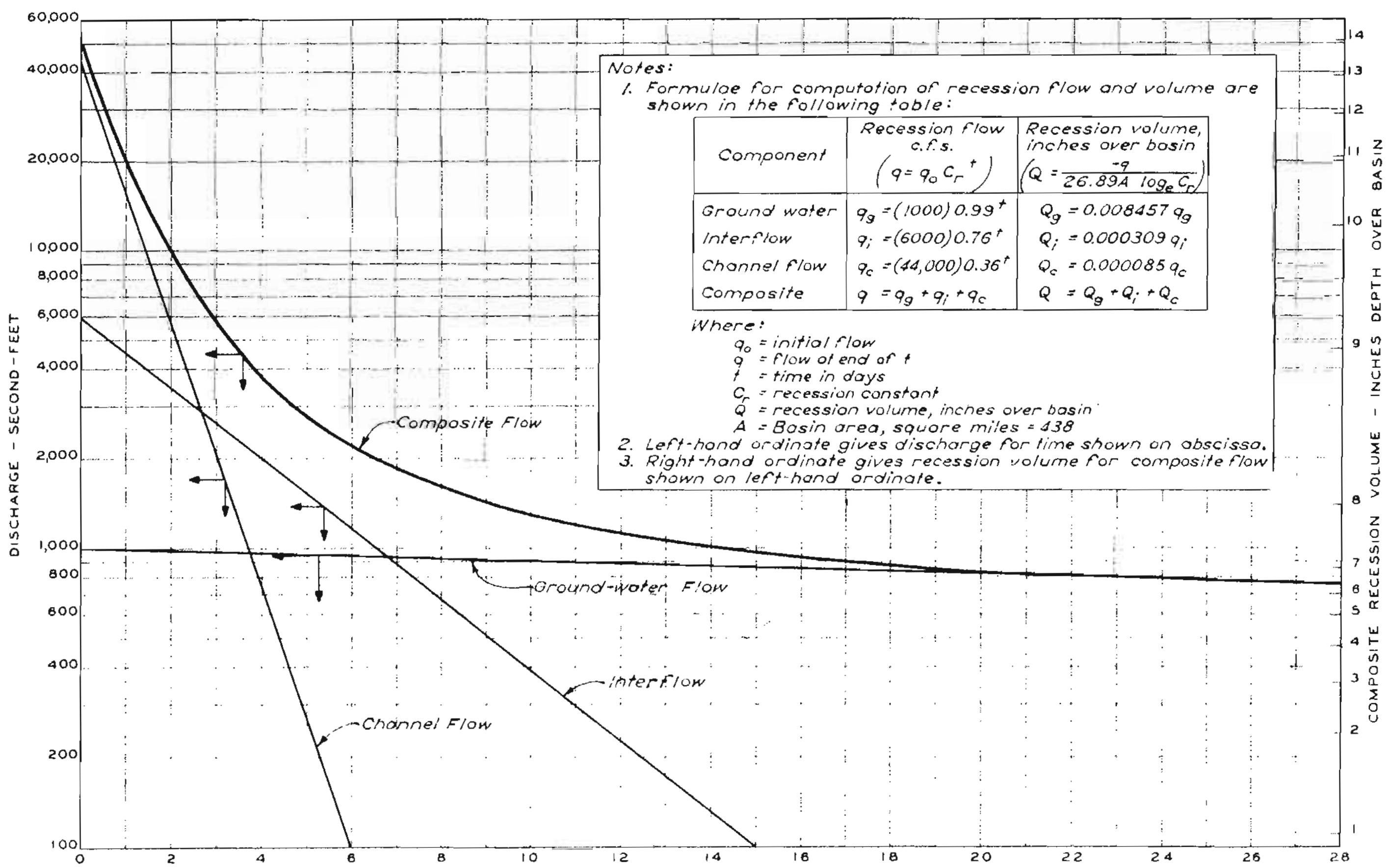

FIGURE 3 - STREAMFLOW RECESSION CHARACTERISTICS

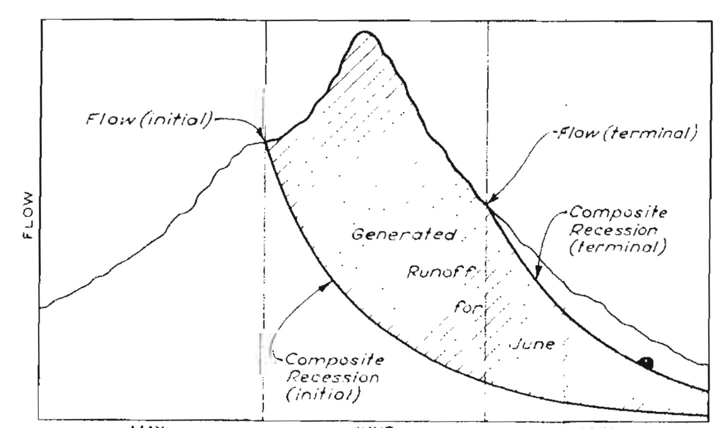

FIGURE 4 - DIAGRAM ILLUSTRATING GENERATED RUNOFF

SNOW INVESTIGATIONS SUMMARY REPORT

SNOW HYDROLOGY

PRECIPITATION, LOSS AND RUNOFF

NORTH SANTIAM RIVER ABOVE DETROIT DAM
DRAINAGE AREA 438 SQ MI

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

TO ACCOMPANY REPORT DATED 30 JUNE 1956

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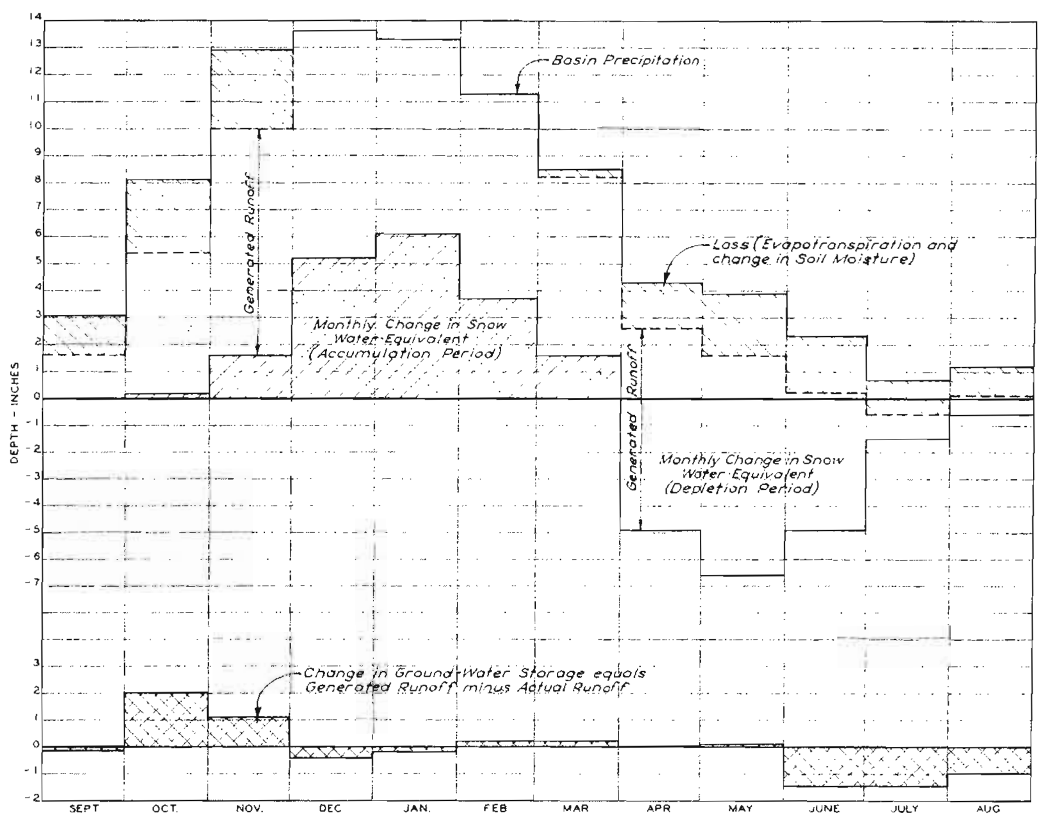


FIGURE 1 - MONTHLY COMPONENTS OF WATER BALANCE

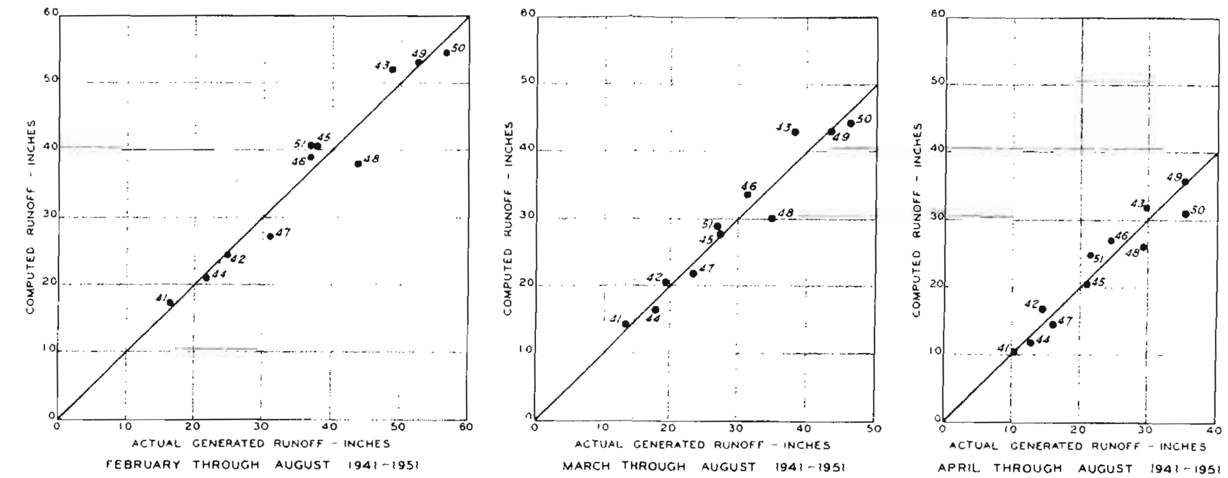
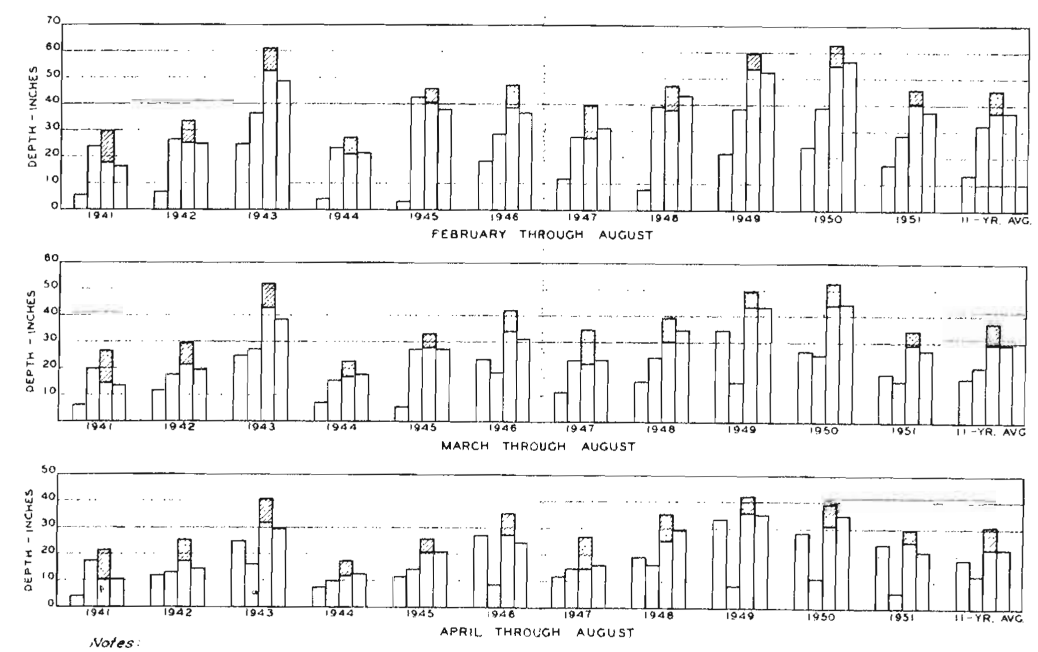


FIGURE 2 - COMPUTED VERSUS ACTUAL GENERATED RUNOFF



Notes:

1. *Bar diagrams show water balance for indicated seasons and years.*
2. *Bar at left shows initial depth of basin snow water-equivalent. Second bar shows basin precipitation. Total length of third bar gives sum of precipitation and water-equivalent; hatched portion represents amount deductible for loss, remainder representing expected runoff. Fourth bar shows actual generated runoff.*

FIGURE 4 - WATER BALANCE FOR FORECAST PERIODS

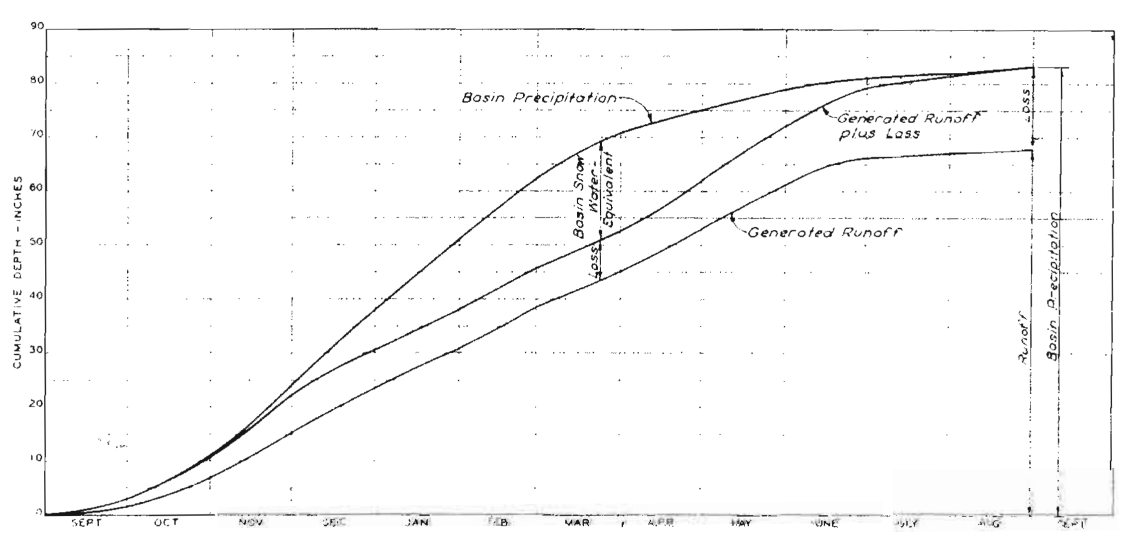


FIGURE 3 - CUMULATIVE COMPONENTS OF WATER BALANCE

Note:

Figures 1 and 3 represent monthly components of water balance for North Santiam River above Detroit Dam, based on mean values for period 1941 through 1951.

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

WATER BALANCE

NORTH SANTIAM RIVER ABOVE DETROIT DAM
DRAINAGE AREA 438 SQ MI

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

TO ACCOMPANY REPORT DATED 30 JUNE 1954

PD-20-25/70

CHAPTER 12 - RESERVOIR REGULATION

12-01. INTRODUCTION

12-01.01 General. - In the operation of reservoirs and other engineering works for the regulation of streamflow, two general types of problems are involved. One is concerned with short-term forecasts of inflow for the day-to-day planning of reservoir releases for power generation, flood control, etc. The other problem is concerned with seasonal runoff volume and is encountered in the determination of seasonal regulation schedules and flood control storage allocation and reservation diagrams. It is in the solution of this latter problem that the application of snow hydrology is especially useful and permits flexible and efficient use of multiple-purpose storage, by making flood control and conservation use of storage compatible on a seasonal basis. Ordinarily, in the case of rainfall, it is possible to estimate runoff volumes, with any degree of certainty, only a few days in advance of their occurrence. This follows from the fact that rainfall volumes can be accurately estimated only after the rainfall has actually fallen and been gaged. Then, only the natural lag time of the drainage basin remains before the resulting runoff is realized. This period may be extended somewhat by the use of 24- and 48-hour quantitative precipitation forecasts; however, the accuracy of such forecasts does not warrant their use without qualification. On the other hand, in the mountainous areas of the western United States (and elsewhere for areas having similar climatological conditions), it is possible to estimate accurately the volume of snowmelt runoff months in advance of its actual occurrence. Since the snowpack is, for the most part, deposited well in advance of its subsequent ablation by melting, it is, in effect, an immense natural reservoir. Its water content can be gaged quite accurately (either directly or indirectly) by any of the several methods outlined in the previous chapter. In this chapter, the manner in which runoff volume forecasts are utilized in the operation of reservoirs will be presented. Also, methods used in the day-to-day operation of reservoirs, based on short-term forecasts (see chap. 9), will be considered briefly.

12-01.02 Multiple-purpose reservoirs. - The climatic regime of the western mountain areas of the United States is such that the same reservoir storage space can be used for the usually incompatible requirements of flood control and conservation. The varied condition of rainfall and snowfall in this region are shown in plate 3-1, which gives the relationship between form of precipitation and elevation. Drainage basins whose runoff-producing areas are predominantly above 5000 to 6000 feet in elevation receive precipitation almost entirely in the form of snow. In these areas, winter rain runoff is usually negligible, with most of the annual runoff volume occurring during the spring and early summer as a result of melting of the accumulated snow. For basins lying within low and intermediate elevation ranges (below 5,000 feet), precipitation falls predominantly in the form of rain, and winter runoff from rainfall constitutes the primary source of streamflow. In the higher portions of these basins, however, a portion of the precipitation is accumulated in the form of snow, so that there is an appreciable contribution to runoff resulting from snowmelt during the spring. For both cases, reservoir storage regulation schedules may take advantage of the known storage of water in the snowpack for beneficial use on a seasonal basis. Reservoirs used in this manner are thus multiple-purpose in a true sense, unlike reservoirs where different portions of the total storage space are allocated for power generation, flood control, irrigation, etc., on a fixed and inflexible basis.

12-01.03 For reservoirs on streams whose drainage areas are low to intermediate in elevation (as in the case of tributaries along the coastal regions in western United States), the marked seasonal variation in precipitation allows the winter-rain-flood season to be rather definitely defined; generally speaking, by the time the spring snowmelt season begins, the threat of rain floods has passed for the year. The same reservoir space that was evacuated for control of winter rain floods may be filled from the volume of spring snowmelt, augmented by occasional runoff from spring rainfall, and thereby result in a full reservoir with non-damaging streamflow releases in downstream channels. The stored water may then be released to augment streamflow in the dry summer months and for power production during the fall in anticipation of the ensuing winter flood season. The spring filling of these reservoirs may be accomplished in accordance with a fixed seasonal regulation schedule as shown in plate 12-1, which was extracted from the reservoir regulation manual for Detroit and Big Cliff Reservoirs. 2/ Optimum use of the available storage for conservation as well as flood-control storage, however, requires that the possible variation in volume of snowmelt runoff also be considered in the filling schedule.

12-01.04 For reservoirs controlling flows from relatively high elevation areas, drawdown of the reservoir level is accomplished in accordance with the requirements for use of the stored water, either in the summer or through the fall and winter seasons. In the winter (usually beginning on the first of January), schedules may be prepared for providing flood control storage space on the basis of conditions known at that time, and revisions in the schedule may be made as the runoff potential develops through the winter and early spring. A storage allocation diagram giving the flood control storage required for different seasonal runoff volumes is shown as figure 1, plate 12-2. The use of such a diagram with its seasonal runoff parameter results, at all times, in the maximum possible flood control storage reservation compatible with the filling of the reservoir. Details of the construction of this diagram are given later in this chapter.

12-01.05 Peak flow forecasts. - Reservoir regulation for flood control requires predictions of peak flow as well as of volume. In the case of spring snowmelt floods, the peak rate of flow is, to a great extent, dependent upon variations in the rate of melt and hence upon the melt-producing meteorological conditions. Nevertheless, there exists a certain correlation between seasonal volume of runoff from snowmelt and the peak rate of flow. This is illustrated in figure 2, plate 12-2, which shows the relationship between peak flow and seasonal volume of runoff for the Columbia River near The Dalles, Oregon. The use of such a relationship in estimating peak flows requires, of course, a method of estimating volume of runoff.

12-01.06 Incidental relationships. - Figure 3 of plate 12-2 presents some frequency distributions of seasonal runoff volume, peak discharge, and date of peak discharge for the Columbia River near The Dalles, Oregon. These data are of incidental value in reservoir regulation. In figure 4 of plate 12-2, a flood control storage reservation curve for the Columbia River near The Dalles is shown which gives the amounts of storage required to control to specified discharges the various seasonal runoff volumes, or, conversely, the controlled discharges that would result from various seasonal runoff volumes and available amounts of storage.

12-02. DAY-TO-DAY REGULATION

12-02.01 The day-to-day regulation of reservoirs in accordance with short-term forecasts of reservoir inflow is, for the most part, connected with the regulation of flood flows and the generation of power. The regulation of reservoirs for such other conservation uses as irrigation, navigation, recreation, pollution abatement, and domestic water supplies, is usually planned on a longer-term or seasonal basis, and changes in outflows are required infrequently. While seasonal operation schedules are used for the long-term planning of power releases and flood control reservations, as was previously mentioned, the fact that the rates of reservoir inflow and regulated outflows cannot be foretold much in advance necessitates that the operation also be based on short-term forecasts of inflow. Short-term forecasts of reservoir inflow from either rain-on-snow events or from snowmelt alone can be made as described in chapter 9. For the generation of power, such inflow forecasts, combined with the power requirements for the project in conjunction with the system as a whole, determines the schedule of releases. For flood control operation, such other factors as inflow from uncontrolled downstream areas and available storage capacity in the reservoir also influence the releases. Because of the complex relationships involved, flood control regulation schedules are drawn up on a basis of historical data to best accomplish the desired flood control regulation.

12-03. SEASONAL REGULATION

12-03.01 Storage allocation for flood control. - In the multiple use of reservoir space for the contradictory requirements of flood control and conservation of spring snowmelt floods, storage allocation diagrams are customarily derived from historical data, as previously mentioned. Such a diagram for Hungry Horse reservoir on the South Fork of the Flathead River, Montana, 1/ is given as figure 1 of plate 12-2. Such diagrams are determined by computing the storage required, both before and during the melt season, to control to a given outflow, the maximum and other critical historical flood events. Parameters of the remaining runoff from any given date to the end of the snowmelt runoff season (usually 30 September) are drawn to envelop these historical flood data. It is customary to limit the slope of these parameter lines to the maximum permissible rate of drawdown of the reservoir (maximum permissible discharge) as governed either by outlet capacity or downstream channel capacities. Thus, in the diagram of figure 1, plate 12-2, the slope of the pre-melt-season drawdown curves is equivalent to 20,000 cfs (approximately 1.2 million acre feet per month) which is the approximate maximum outlet capacity of the reservoir (outlet valves plus allowable flow through power turbines). The enveloping curves during the flood season proper (1 May to 30 June in fig. 1, pl. 12-2) also indicate an increasing storage requirement with time for a given parameter value. This is in consequence of the increase in the potential flood flows from the same volume of runoff, that occurs as the melt season progresses. The Hungry Horse flood-storage allocation diagram is designed to provide flood control for the lower Columbia River and for the reach of the Flathead River immediately downstream from the dam and above Flathead Lake in Montana. It is based on the criteria of (1) restricting the reservoir releases to 3,000 cfs during the period beginning five days before the natural flow of the Columbia River at The Dalles, Oregon reaches 500,000 cfs and ending five days before it again decreases to 500,000 cfs (five days being the time of travel between Hungry Horse dam and The Dalles), (2) restricting the releases to control the Flathead River, as gaged at Columbia Falls, Montana, to certain non-damaging flows, the permissible flows depending partially upon the backwater effect in the river resulting from varying lake stages, and (3) maintaining a minimum release of 500 cfs at all times.

12-03.02 Safety factors. - Factors of safety, beyond what is actually required to envelop the plotted historical flood data, may be included in storage allocation diagrams. Thus, in figure 1 of plate 12-2, a factor of safety of 200,000 acre-feet was incorporated in the parameters prior to 1 May, decreasing, from that date, at a uniform rate such that it equals zero on 30 June. This factor of safety allows for errors in the forecast volume of runoff, thereby assuring adequate flood-control reservation. An additional factor of safety was incorporated in the Hungry Horse flood-storage allocation diagram for those parameters outside the range of the historical data. An analysis of the parameters of 2.0 million acre-feet and less, which are based on historical data, indicated an increase of 0.83 acre-foot in flood-control allocation for each acre-foot increase in volume of runoff. For the parameters in excess of 2.0 million acre-feet, no historical data were available; consequently, it was considered prudent to increase the incremental changes in the flood control allocation for these large floods to an amount equal to the increase in the volume of runoff. This change is apparent in the change in spacing of the parameter lines of the figure.

12-03.03 In the foregoing example, the factor-of-safety allowances were made to assure adequate flood-control allocations, at the expense of conservation storage, for situations more critical (from the flood control viewpoint) than those given by historical data or to allow for possible errors in the volume forecasts. Consequently, there is this added risk of not filling the reservoir, especially where errors in volume forecasts result in over-estimates of runoff volume. It is to be pointed out that factors of safety may also be provided from the viewpoint of conservation of water. There is also included in the storage allocation diagrams derived for Hungry Horse project, a factor of safety for refilling the reservoir at the expense of some flood control storage. By establishing a minimum release at the project of 3000 cfs for downstream flood control as measured at The Dalles, a flexibility of regulation is established. If late season forecasts indicate that original volume inflow forecasts were too high, release from the reservoir may be reduced to the minimum discharge of 500 cfs, and thereby refill storage at a faster than normal rate so as to assure the refilling of the reservoir by the season's end. A study of the Hungry Horse flood control storage allocation diagram 3/ indicates the factors of safety incorporated therein do not seriously affect the refilling of the reservoir even when possible errors in the forecast runoff volumes are considered. Moreover, forecasts which are some 200,000 acre-feet too low (approximately average error of Hungry Horse inflow forecasts) 4/, do not seriously affect the flood control operation of the reservoir. Concerning the testing of the flood control storage allocation diagram for Hungry Horse reservoir, the following excerpt from the previously cited study 3/ is quoted:

"The summary indicates that, with completely accurate forecasts, the reservoir would have refilled in every year of the 31 years studied. In 1931 and in 1942, both of which were very dry years, the reservoir would have refilled prior to the date of the last significant peak at The Dalles. The time required for the effect of spills at Hungry Horse to reach The Dalles is such that the latest significant peak at The Dalles would have been reduced by storage in Hungry Horse Reservoir in both years. If forecasts 200,000 acre-feet too low had been used, the reservoir would have refilled in every year of the 31 years, but would have refilled prior to the date of the latest significant peak in 10 of the 31 years. Of these ten years, only 1911, 1936, and 1948 were years in which the natural peak flow at The Dalles exceeded 500,000 cfs, and in each of these three years the time required for spilled flows at Hungry Horse to reach The Dalles would have been such that the latest significant peak at The Dalles would have been reduced by storage in Hungry Horse Reservoir. If forecasts 200,000 acre-feet too high had been used, the reservoir would have failed to refill in only four years of the 31 years studied and would not have refilled prior to the date of the latest significant peak at The Dalles in any year. The four years in which the reservoir would have failed to refill were 1931, 1937, 1941, and 1944, all of which were dry years, but the greatest deficiency would have been only 32,000 acre-feet in 1931 which is only slightly more than one percent of the live storage capacity of the reservoir. Therefore, such failure to refill under these assumed conditions has little significance."

12-03.04 Volume forecasts. - Forecasts of seasonal volume of runoff are, of course, necessary in the application of flood-control storage allocation diagrams (in the place of the observed historical values which were used in the derivation of the diagrams). Errors inherent in these forecasts may possibly result in the undesirable operation of a reservoir, as was discussed in the previous paragraph. Methods by which seasonal volume forecasts can be made were discussed in the preceding chapter. For situations where a definite method of seasonal-runoff forecasting is used in conjunction with the storage-allocation diagram in the operation of a reservoir, it is possible to assess, rather definitely, the effect of errors in the forecasting method upon the operation of the reservoir. The effect of errors in volume forecasts is also pertinent to the discussion in the section which follows, where volume forecasts are used to estimate peak flows.

12-04. PEAK-TO-VOLUME RELATIONSHIP

12-04.01 General. - As previously mentioned, there exists a general relationship between the peak snowmelt discharge and the seasonal snowmelt runoff volume for most basins which have appreciable winter snowpack accumulations. Since the volume of runoff from spring snowmelt can be estimated quite accurately some months in advance, it is likewise possible to make forecasts of peak flows resulting from springtime snowmelt well in advance of their actual occurrence. Intelligent application of long-range forecasts of unregulated peak discharges resulting from snowmelt requires full understanding of (1) the significance of peak-to-volume ratios, (2) the best method of applying them to specific cases, and (3) the probable accuracy of the estimates. Closely allied to the peak-to-volume determination is that of evaluating flood-control storage reservation requirements. Examination of the peak-to-volume relationship in this section is accompanied by an illustration of the relationship for the Columbia River near The Dalles, Oregon, one of the major snowmelt runoff rivers in the United States. Reference is made to the report, "Relationship between peak discharge and volume runoff of the Columbia River near The Dalles, Oregon" by the Water Management Subcommittee of the Columbia Basin Inter-Agency Committee (CBIAC), 6/ for a more complete discussion of peak-to-volume relationship for Columbia River near The Dalles.

12-04.02 Peak-to-volume diagram. - Figure 2 of plate 12-2 gives the basic relationship between peak flows and volume of snowmelt runoff for the Columbia River near The Dalles, Oregon. The peak flows given there are mean daily values and include adjustments for relatively minor flood control regulation by Grand Coulee and Hungry Horse dams during recent years. The seasonal runoff volumes used in the relationship were for the period April through September, and adjustments for storage in six major reservoirs were made. 5/ The entire 77 years of available record of flows for the Columbia River at The Dalles (1879 through 1955) were used in the determination of the relationship of figure 2. The regression line fitted to these data is as follows:

$$Y = 6.77X - 118 \qquad (12\text{-}1)$$

where Y is the peak daily flow in thousand cfs and X is the April through September runoff in million acre-feet. The standard error of estimate of the relationship amounts to 76.2 thousand cfs in contrast to the standard deviation of 172.6 thousand cfs for the peak flows. The resulting correlation coefficient is 0.90.

12-04.03 Time changes in relationship. - In recent years there has been a tendency for higher peak flows to be associated with a given volume of runoff for the Columbia River near The Dalles, Oregon. A study of the peak-to-volume relationship, analyzing the periods from 1879 through 1916 and from 1917 through 1955 separately, resulted in the following regression equations:

PERIOD	EQUATION	
1879 - 1955	$Y = 6.77X - 118$	(12-1)
1879 - 1916	$Y = 7.10X - 179$	(12-2)
1917 - 1955	$Y = 7.63X - 177$	(12-3)

where Y is the peak discharge in thousand cfs and X is the April-September volume of runoff in million acre-feet. Equation 12-1 is also repeated in the above tabulation for comparative purposes. Although this change in the relationship with time could be attributed to man-made changes in the basin, careful consideration of the nature and order-of-magnitude of such changes shows that such is not likely. The change in the relationship appears to be associated with the natural changes in climate that occurred within the period and therefore is characteristic of large-scale climatic variations.

12-04.04 Errors of estimate for prediction of peak discharge. - It is possible to combine the effect of errors in forecasts of runoff volume and of the historical peak-to-volume ratio by statistical relationships (see Wilm 7/ for a discussion of the statistical derivation of such relationships), whereby comparisons of reliability of estimates of peak discharge through use of differing periods of runoff may be determined. Tests of the relative accuracy of peak discharge forecasts, using total and residual volume forecasts, were made by the Technical Staff of the Water Management Subcommittee using data for the Columbia River near The Dalles. 6/ The results of these tests are tabulated below:

STANDARD ERROR OF ESTIMATE OF AN INDIVIDUAL MEAN PREDICTION
OF PEAK DISCHARGE
(In thousands of second feet)

For peak-volume relationships based on total and on residual runoff

Forecast Date	Period for which runoff volume forecast is made					
	April through June		April through July		April through Sept.	
	From Total Volume Forecast	From Residual Volume Forecast	From Total Volume Forecast	From Residual Volume Forecast	From Total Volume Forecast	From Residual Volume Forecast
1 April	106.3	106.3	101.8	101.8	102.8	102.8
1 May	102.8	104.1	90.6	86.6	95.4	94.4
16 May	98.9	107.0	86.5	83.6	85.7	83.3

In general it may be stated from this study that forecasts of peak discharge for Columbia River near The Dalles based on April through July runoff are most reliable, but that little difference exists in using the April through September period. The April through June period gives consistently poorer results. It is also seen that for both 1 May and 16 May forecast dates, there is a slight improvement by using residual rather than total volume forecasts; however, the differences are generally small and of little significance.

12-05. FLOOD CONTROL STORAGE RESERVATION

12-05.01 From what has been stated, it is apparent that a relationship exists between the seasonal runoff volume and the amount of storage which would be required to control the peak discharge near The Dalles, Oregon to some given regulated outflow. Diagrams giving this relationship may be determined from an analysis of historical data wherein the volume of runoff in excess of the desired regulated discharge rate is plotted as a function of the seasonal runoff volume and lines drawn to envelop these data. Several parameters of regulated outflow may thus be determined to give the flood control storage reservation associated with various regulated discharges. Such a diagram for the Columbia River near The Dalles, Oregon is included as figure 4 of plate 12-2. Also shown on this diagram is a line representing the volume of the record 1894 spring snowmelt flood.

12-05.02 The entire 77-year record for the Columbia River near The Dalles was used in the derivation of the diagram; however, only a few of the years were critical in determining the parameters. For example, those years whose peak discharges were less than the parameters obviously could not enter in their determination. The parameters were not drawn to envelop the 1948 flood data. With the exception of this year, all other pertinent data, including the 1894 flood, gave a consistent relationship which defined the parameters quite well. The data for 1948 were, however, so far out of line that to envelop them would result in grossly inefficient use of flood control storage space in all other years. It is necessary, therefore, that in utilizing this set of curves, provision must be made for the occurrence of exceptionally high peak-to-volume ratios, such as occurred in 1948. With the repetition of such an occurrence, it would be necessary to adjust upward the regulated discharge in the lower Columbia River during the progress of the flood. It is pointed out that the curves shown in figure 4 of plate 12-2 are provisional in nature and are presented as a guide for over-all flood control regulation of the Columbia River. The diagram assumes flood control storage which is 100 percent effective in controlling discharges in the lower Columbia River. Much of the present and planned flood control storage in the basin is so located that its effectiveness is considerably less than 100 percent, and appropriate factors must be applied to determine the amount at each project which is effective for downstream flood control.

12-06. SUMMARY

12-06.01 One of the most useful applications of snow hydrology is to be found in the reservoir regulation of snowmelt runoff. For areas where much of the winter precipitation is stored in deep snowpacks, there is an interval of several months between the time the precipitation falls and the time it melts and contributes to runoff. Since this portion of the total runoff can be gaged well in advance of its realization as streamflow, allowances can be made in the operation of reservoirs in anticipation of this runoff volume. For flood control operation, the reservoir can be drawn down in advance to allow for the estimated volume of inflow. At the same time, this forecast of future inflow volume assures that the reservoir storage space evacuated for flood control can be refilled for conservation uses from the spring snowmelt flood. Reservoirs operated in such a manner are multiple-purpose reservoirs in the true sense of the term.

12-06.02 For basins having deep winter snowpack accumulations, there exists a relationship between the peak discharge and the spring snowmelt flood volume. This peak-to-volume relationship is useful in advance flood-control planning. Like the volume forecast, estimates of peak flow can be made many months in advance of their realization.

12-06.03 Diagrams which serve as guides in the operation of reservoirs are prepared from historical streamflow data. Examples of such diagrams are: (1) seasonal regulation schedules, (2) flood-control storage allocation diagrams, and (3) flood-control storage reservation diagrams. The first of these is, basically, a curve showing the maximum allowable reservoir content as a function of the time of year (see plate 12-1). During the winter rain flood season, the reservoir is held in an evacuated condition, insofar as is possible, to provide storage space for the control of rain-on-snow floods. It is filled during the spring, as the danger of rain floods diminishes, by utilizing snowmelt runoff augmented by spring rains, thereby conserving water for use during the summer and fall months. It is drawn down in the fall to again provide flood-control storage space. Filling and drawdown rates are in accordance with channel capacities and available water. The second diagram, which makes use of forecasts of spring snowmelt runoff volume, indicates, as a function of time of year, the reservoir storage space that must be allocated to flood control for different parameters of seasonal runoff volume (fig. 1, plate 12-2). Rate of drawdown is controlled by existing downstream channel and outlet capacities. The required storage allocations are also governed by given permissible releases during flood-control operation. The third diagram, unlike the first two, does not include the time of year as a factor. It shows the amount of storage, as a function of flood volume, required to control snowmelt floods to various parameters of regulated outflow (see fig. 4, plate 12-2). Nothing is said of when or where the storage reservation must be available. With an existing flood control reservation, the diagram gives the regulated outflow which may be attained for various floods or the flood volume that can be controlled to a given outflow.

12-07. REFERENCES

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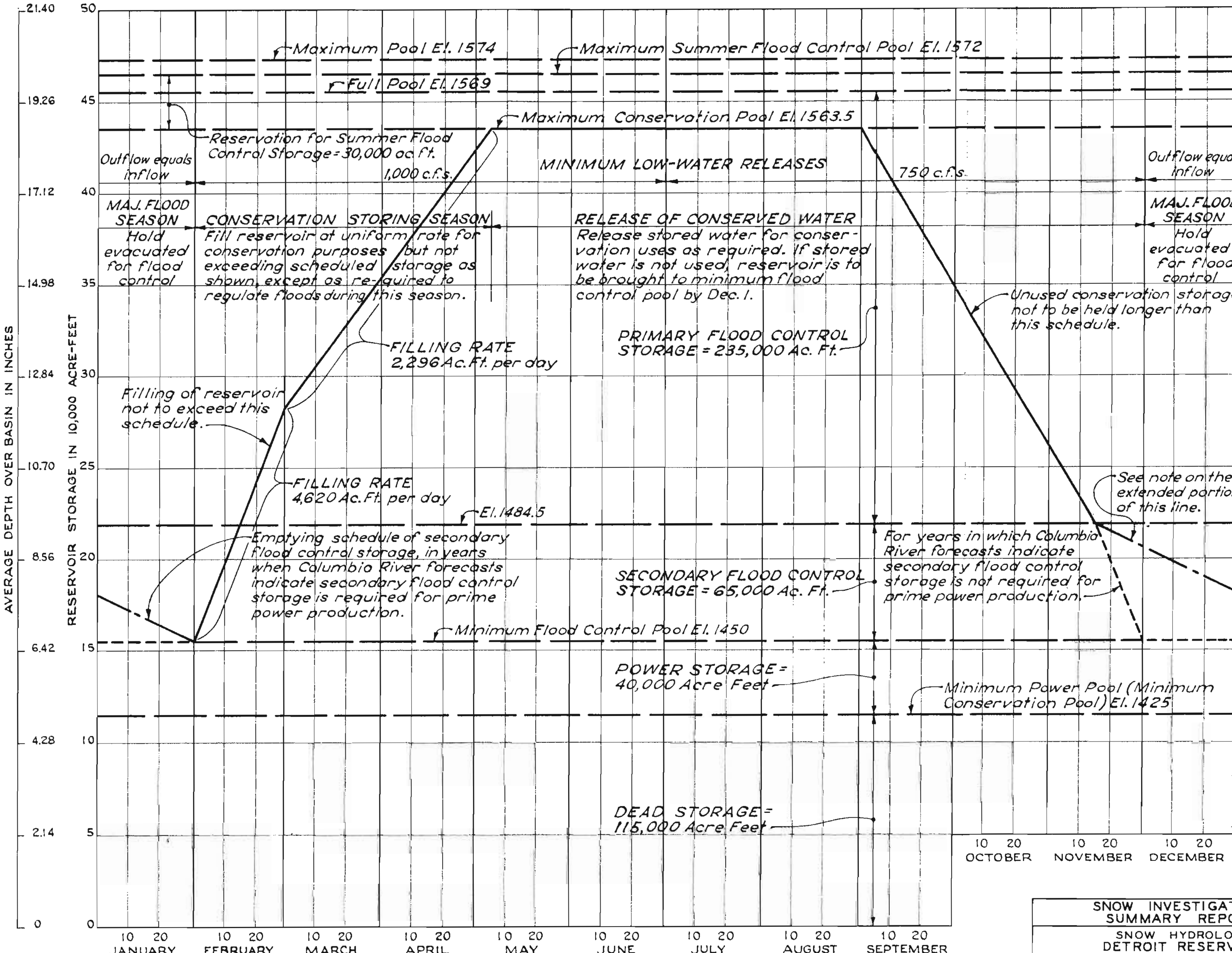


This diagram taken from Plate 20, Reservoir Regulation Manual for Detroit and Big Cliff Reservoirs, North Santiam River, prepared by Portland District, Corps of Engineers, 1 Sep 1953.

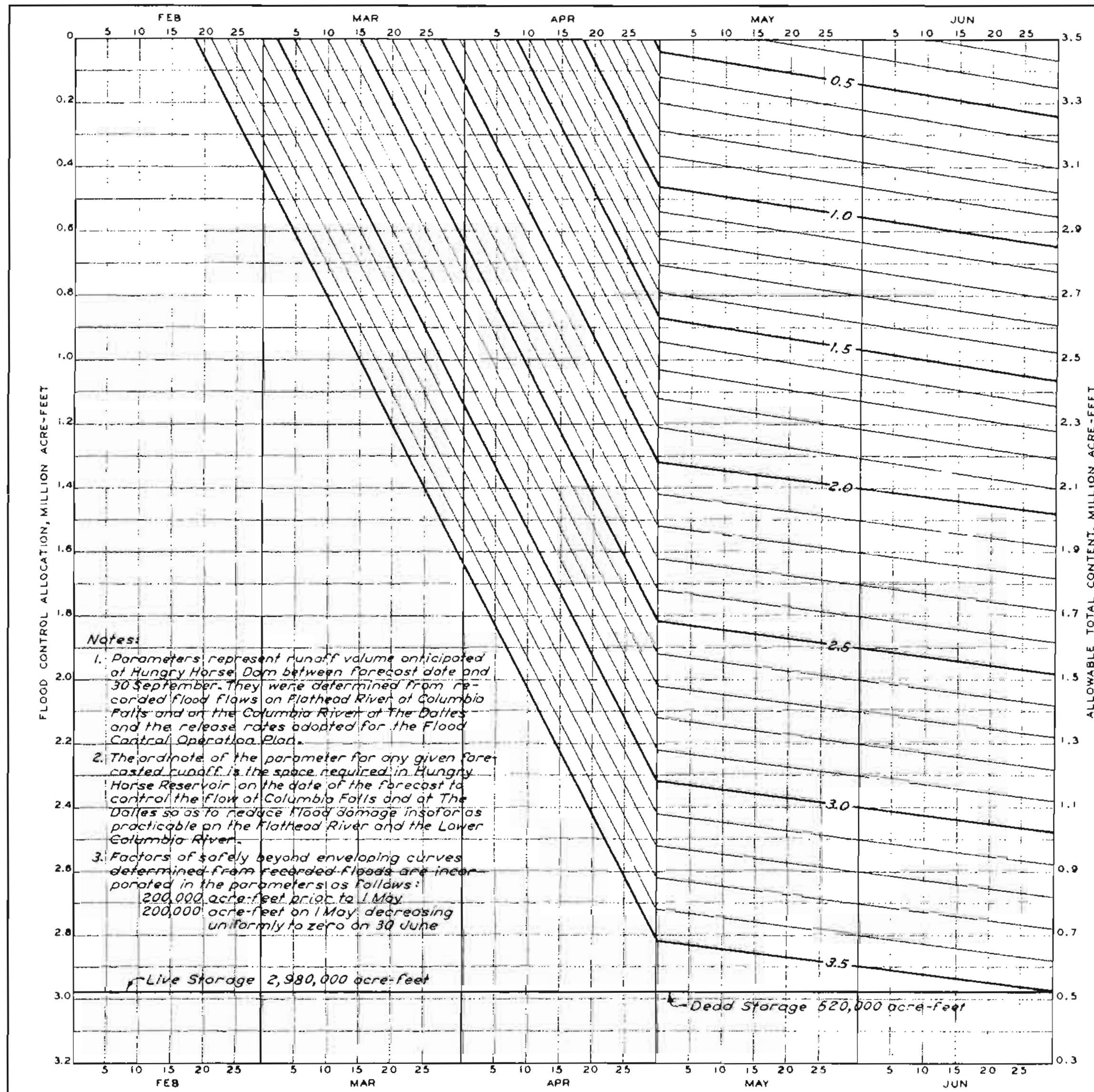
SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY
DETROIT RESERVOIR
NORTH SANTIAM RIVER, OREGON
SEASONAL REGULATION SCHEDULE

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

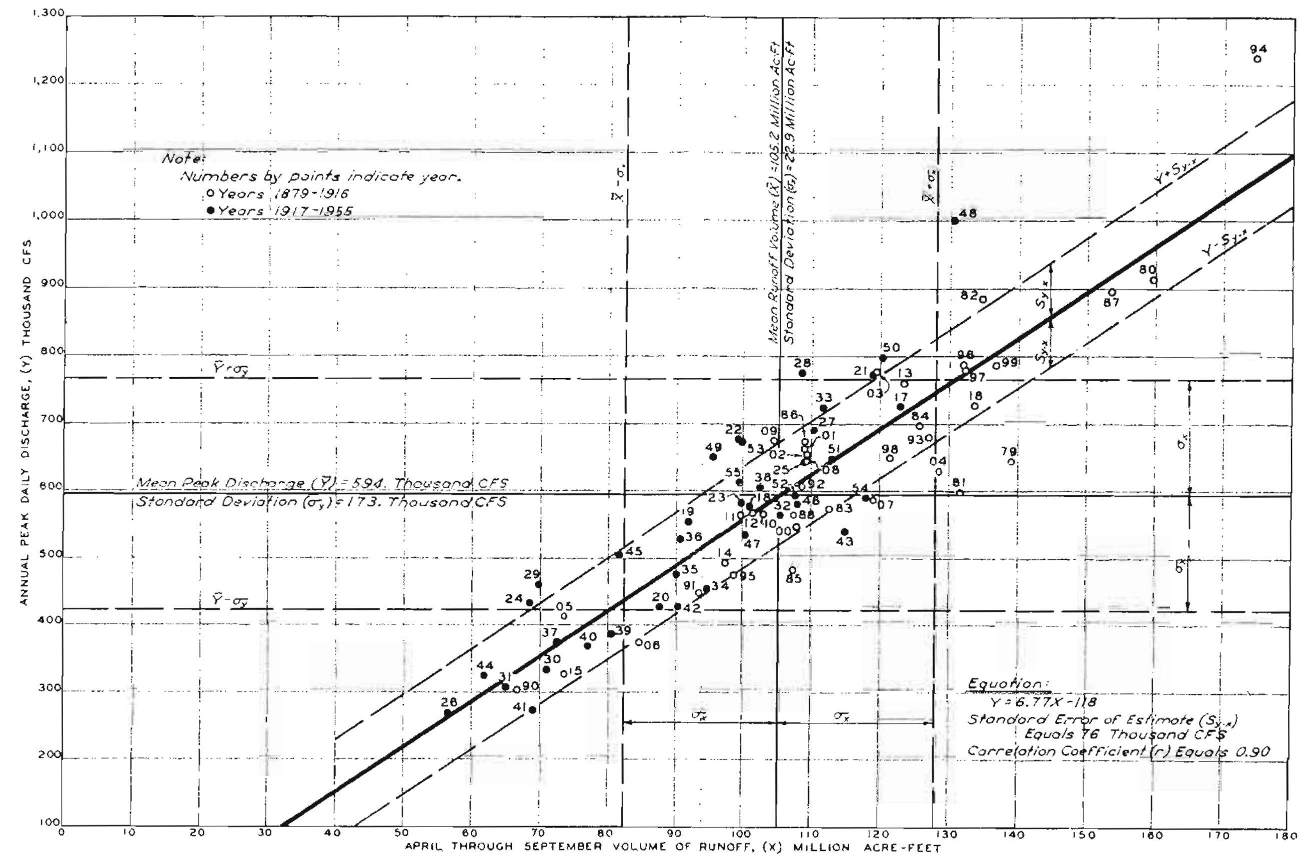
PREP: W.A.M./G.E.S. SUBM: C.E.M. TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: L.S.M. APPR: D.M.R.

PD-20-25/71



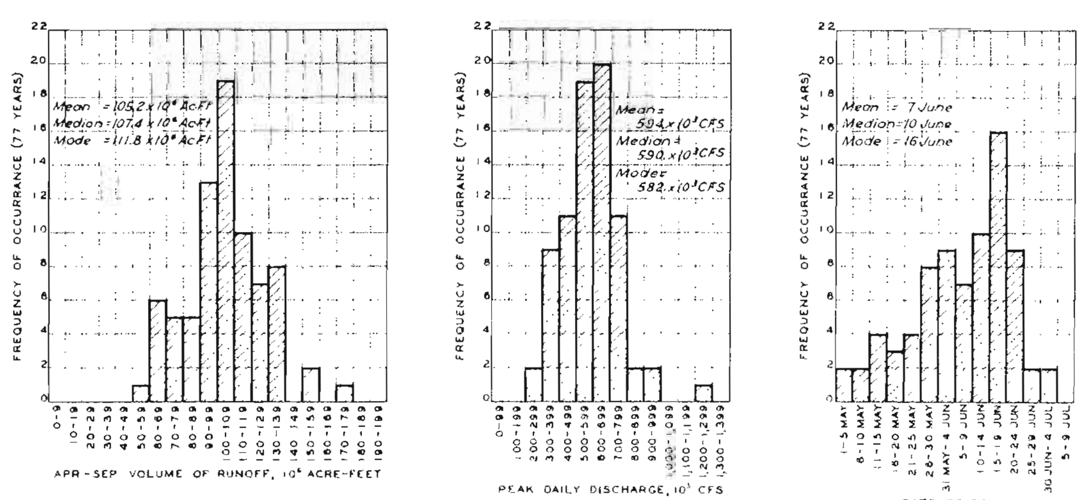
FLOOD CONTROL STORAGE ALLOCATION, HUNGRY HORSE RESERVOIR, MONTANA

FIGURE 1



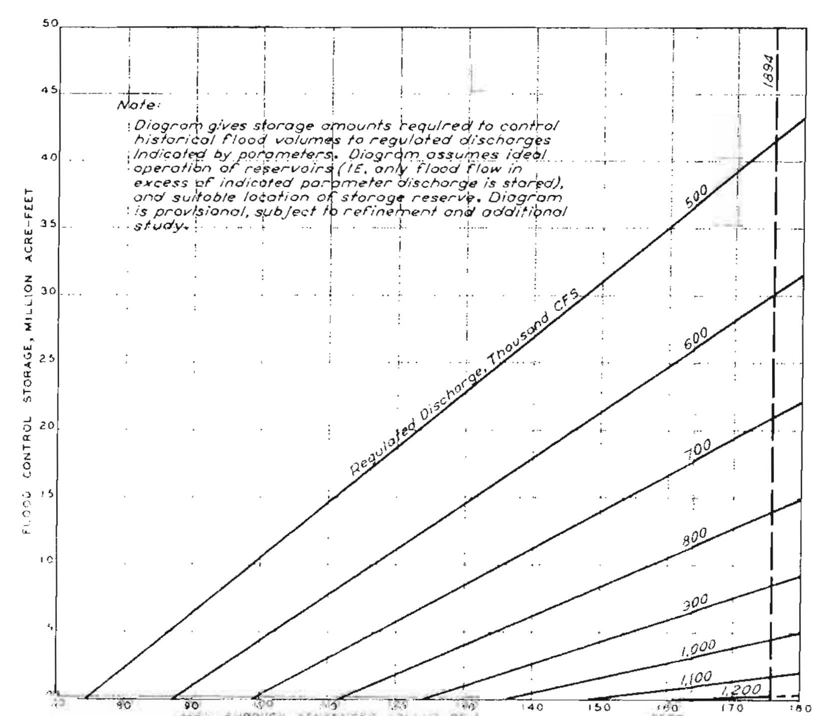
RELATIONSHIP BETWEEN PEAK DISCHARGE AND VOLUME OF RUNOFF FOR THE COLUMBIA RIVER NEAR THE DALLES, OREGON

FIGURE 2



FREQUENCY DISTRIBUTIONS FOR THE COLUMBIA RIVER NR THE DALLES, OREGON

FIGURE 3



FLOOD CONTROL STORAGE RESERVATION DIAGRAM, COLUMBIA RIVER NEAR THE DALLES, OREGON

FIGURE 4

Figure 1 was prepared by Hydrologic Studies Office, Bureau of Reclamation, Boise, Idaho. It is taken from the Reservoir Regulation Manual for Hungry Horse Dam, issued by Seattle District, Corps of Engineers, dated December 1952.

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

RESERVOIR REGULATION DIAGRAMS

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

PD-20-25/72

APPENDIX I

PUBLICATIONS OF THE COOPERATIVE SNOW INVESTIGATIONS

TECHNICAL REPORTS
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2. Bibliography of snow and ice (preliminary). June 1945.

3. Heat transmission constants of snow. (Draft) 9 December 1946.

4A. Terrain characteristics, Central Sierra Snow Laboratory Basin. June 1951.

5. Hydrometeorological Log of the Central Sierra Snow Laboratory 1945-1946. September 1947.

6-1. Classified outline of analytical program, Processing and Analysis Unit. 10 March 1947.

6-2. Progress Report of the Processing and Analysis Unit to 31 March 1948. August 1948.

6-3. Progress Report of the Processing and Analysis Unit to 31 March 1949. June 1949.

6-4. Progress Report, 1945-1950. March 1950 (Revised as of 1 June 1950).

6-5. Annual Progress Report, 1950-1951. November 1951.

6-6. Annual Progress Report, 1951-1952. July 1952.

7. Hydrometeorological Log of the Upper Columbia Snow Laboratory 1945-1946. July 1948.

8-1. Penetration of Solar Radiation into the Snowpack. March 1948.

13. Annotated brief bibliography of snow hydrology. 20 January 1950.

15-1. The storage and transmission of liquid water in the snowpack as indicated by dyes. March 1948.

16-2. Empirical methods of estimating snow melt runoff from temperature. March 1948.

17. Hydrometeorological Log of the Upper Columbia Snow Laboratory 1946-1947. May 1952

TECHNICAL REPORTS - Continued

18. Hydrometeorological Log of the Central Sierra Snow Laboratory 1946-1947. May 1952.

20-1. Hydrometeorological Log of the Upper Columbia Snow Laboratory 1947-1948. August 1949.

21. Hydrometeorological Log of the Willamette Basin Snow Laboratory 1947-1948, 1948-1949. August 1951.

22. Hydrometeorological Log of the Central Sierra Snow Laboratory 1947-1948. February 1952.

23. Hydrometeorological Log of the Central Sierra Snow Laboratory 1948-1949. November 1951.

24. Hydrometeorological Log of the Upper Columbia Snow Laboratory 1948-1949. January 1952.

25. Hydrometeorological Log of the Central Sierra Snow Laboratory 1949-1950. April 1952.

26. Hydrometeorological Log of the Upper Columbia Snow Laboratory 1949-1950. March 1952.

27. Hydrometeorological Log of the Willamette Basin Snow Laboratory 1949-1951. November 1952.

28. Hydrometeorological Log of the Central Sierra Snow Laboratory 1950-1951. August 1952.

29. Hydrometeorological Log of the Upper Columbia Snow Laboratory 1950-1951. June 1952.

30. Hydrometeorological Log of the Central Sierra Snow Laboratory 1951-52. April 1953.

APPENDIX I - Continued

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Corps of Engineers Analytical Unit, Cooperative Snow Investigations; and Corps of Engineers, Snow Investigations

1. MILLER, D. H., Albedo of the snow surface as related to weathering factors and stage of the season, December, 1950.
2. MIXSELL, J. W. and others, Influence of terrain characteristics on snowpack water equivalent, February 1951.
3. MONDRILLO, G., Estimating insolation from atmospheric conditions, March 1951.
4. HIMMEL, J. M., Lysimeter studies of rain-on-snow phenomena, June 1951.
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11. ARNOLD, B. and P. Boyer, Heat exchange and melt of late-season snow patches in heavy forest, May 1953.
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13. HUMPHREY, H. N. and T. H. Pagenhart, Additional studies of the influence of terrain characteristics on snowpack water equivalent, June 1953.
14. MONDRILLO, G., Preliminary unit-graph studies, Mann Creek, Willamette Basin Snow Laboratory, June 1953.

15. MILLER, D. H., Thermal balances and snowmelt runoff associated with upper-air flow over the western United States in May 1949 and May 1950, September 1953.

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18. BOYER, P. B., Analysis of January 1953 rain on snow, observations at Central Sierra Snow Laboratory, Soda Springs, California, May 1954.

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20. McCLAIN, M. H., Precipitation, evapotranspiration, and runoff, Willamette Basin Snow Laboratory, July 1954.

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22. MILLER, S., Forecasting seasonal runoff by the water-balance method, September 1954.

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APPENDIX I - Continued

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2. SNYDER, F. F. Heat balance and amount available for melting snow. June 1949.

3. PARSONS, W. J. Use of snow laboratory data by Sacramento District. November 1949.

4. HULLINGHORST, D. W. Progress report on project CW-171, Criteria for estimating runoff from snow melt. April 1950.

5. MILLER, D. H. The depletion method of estimating solar radiation absorbed by the snow. April 1950.

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APPENDIX II

COMPLETED TOURS OF DUTY, PROJECT CW-171

1) F. F. SNYDER (OCE) June 1949 - Initiation of Project Study of heat balance and amount available for melting snow, (Tech. Bull. 2).

2) C. PEDERSEN (Portland Dist.) June 1949 - UCSL studies; Relationship of radiation to various meteorological elements; seasonal variations of albedo, snow density, water equivalent; degree-day melt rate computations.

3) R. H. CONWAY (Walla Walla Dist.) June 1949 - Preliminary reconstitution 1948 flood, UCSL, to investigate criteria governing snowmelt; inquiries concerning degree-day vs. heat-balance methods.

4) N.J. MACDONALD (Seattle Dist.) June 1949 - Relationship studies; density of new snow vs. max. temp. at Summit, Mont., and Soda Springs, Calif.; normal annual precip. vs. topog., Columbia Basin (similar to USWB study of Colorado Basin); spillway design flood methods from unit hydrographs, UCSL.

5) E. W. McCLENDON (MRD) August,1949 - Study and review of snow hydrology problems; discussion of basic snow and frost problems; discussion of basic snow and frost problems in Missouri River Basin; mountain snowmelt vs. plains snowmelt.

6) M.E. THOMS (Seattle Dist.) Sept. 1949 - Snowmelt determinations published in "Report on Derivation of Standard Project Flood, Skagit River near Sedro Woolley, Washington."

7) W. S. HERING (Walla Walla Dist.) Sept. 1949 - Empirical evaluation of condensation and outward longwave radiation over snow (Tech. Bull. 7); study on upper air temp. as index of mean surface temp.

8) S. A. MILLER (Denver Dist.) Oct. 1949 - Study of temp. index, snow cover, and runoff relationships using concept of "active snowmelt line" (daily temp. trace through melt season of degrees required at index station to produce melt).

9) J. SUMMERSETT, JR., (Portland Dist.) Oct. 1949 - Study and review of snowmelt problems in Willamette Basin Snow Laboratory.

10) S. MILLER (Walla Walla Dist.) Nov. 1949 - Use of temperature data in determining incident radiation (formulas, correlations, results, presented). Discussion of snow hydrology problems, Lucky Peak Dam.

COMPLETED TOURS OF DUTY, PROJECT CW-171 - Continued

11) C.E. JENCKS (Portland Dist.) Feb. 1950 - Study and review; streamflow study of Blue River above Quentin Creek, WBSL.

12) F. C. MURPHY (Seattle Dist.) Feb. 1950 - Review of spillway design problems in Columbia Basin; specifically at Albeni Falls dam site.

13) H. LOBITZ, JR., (Walla Walla Dist.) June 1950 - Study of hydrograph reproduction by the degree-hour method using variable S-curves for distribution of the melt.

14) E. W. McCLENDON (MRD) Aug. 1950 (2nd visit) - Study and review of current methods of estimating streamflow from snowmelt (e.g. Tech. Bull. 8); hydrograph reconstitutions, 1948 and 1950, CSSL.

15) W.S. HERING (Walla Walla Dist.) Sept. 1950 (2nd visit) - Hydrograph reconstitution by thermal-budget method, applying S-curve principles, 1949, Boise River above Twin Springs, Idaho.

16) S. MILLER (Walla Walla Dist.) Nov. 1950 (2nd visit) - Hydrograph reconstitution by degree-day method using constant loss of 7,000 d.s.f., 1949, Boise River above Twin Springs, Idaho.

17) F.C. MURPHY (Seattle Dist.) Dec. 1950 (2nd visit) - Discussion and review; spillway design problems, Libby project.

18) R. ASCHENBRENNER (Walla Walla Dist.) Jan. 1950 - Various reconstitutions by degree-day and heat-balance methods, 1943 and 1949, Boise River above Twin Springs, Idaho.

19) N. J. MACDONALD (Seattle Dist.) Jan. 1951 (2nd visit) - Libby damsite spillway design study: 1947 hydrograph reconstitution by degree-day method, Kootenai River at Libby, Montana.

20) M. J. ORD (Walla Walla Dist.) Feb. 1951 - Discussion and review of Boise River studies and of general snow hydrology for application to District snowmelt runoff problems.

21) G. L. GAY (Portland Dist.) Feb. 1951 - Green Peter Dam Study.

22) R. H. CONWAY (Walla Walla Dist.) Mar. 1951 (2nd visit) - Reconstitution of '36, '43, '48, and '50 flood hydrographs by degree-day methods, Snake River at Heise, Idaho

23) M. E. THOMS (Seattle Dist.) Mar. 1951 (2nd visit) - Spillway design studies, Kootenai River at Libby, Montana: '42 and '48 flood reconstitutions by degree-day method, '47 and '48 reconstructions by heat-balance method.

24) S. MILLER (Walla Walla Dist.) Sept. 1951 (3d visit) - Runoff volume forecast study, Boise River above Lucky Peak, Idaho.

25) J. SUMMERSETT, JR. (Walla Walla Dist.) Oct. 1951 (2nd Visit) UCSL snow cover vs. heat-exchange study; discussion and study of reconstitution methods, degree-day vs. thermal budget.

26) D. E. PHILLIPS (Walla Walla Dist.) Feb. 1952 - Snow cover depletion vs. accumulated degree-days; flood reconstitutions using maximum temperatures as index.

27) D. M. ROCKWOOD (NPD) Jan. 1952 - Forecasting flood season runoff from early-season flows and temperatures for Columbia River at the Dalles.

28) M. J. ORD (Walla Walla Dist.) Feb. 1952 (2nd Visit) - Study and review of heat-balance factors; discussion of degree-day vs. heat-balance methods for basin application.

29) F.C. MURPHY (Seattle Dist.) Feb. 1952 (3rd visit) - Discussion and review of available procedures for runoff forecasting and reservoir regulation, Libby Dam.

30) M.E. THOMS (Seattle Dist.) Feb. 1952 (3d visit) - Flood reconstitutions, Kootenai River at Libby, Montana: degree-day and heat-balance methods.

31) R. H. CONWAY (Walla Walla Dist.) Mar. 1952 (3d visit) - Synthetic reconstitutions of Boise River floods, '43, '48, heat-balance method.

32) M. LARSON (Portland Dist.) Apr. 1952 - Study and review: Snowmelt studies CSSL, '49; work on project CW-170 (Radioisotope-radiotelemetering snow gage).

33) C. JENCKS (Portland Dist.) June 1952 (2nd visit) - Rain-on-snow studies, '52, WBSL: lapse rate study, WBSL.

34) M. E. THOMS (Seattle Dist.) Mar. 1953 (4th visit) - Studies preparatory to draft; "Forecasting inflows to Libby Reservoir."

COMPLETED TOURS OF DUTY, PROJECT CW-171 - Continued

35) N. J. MACDONALD (Seattle Dist.) Mar. 1953 (3d visit) - Seasonal forecast study, Albeni Falls Dam.

36) M. LARSON (Portland Dist.) Apr. 1953 (2d visit) - Forecasting and reservoir regulation procedures, Detroit Dam, (N. Santiam River, Ore.)

37) M.E. THOMS (Seattle Dist.) Oct. 1953 (5th visit) - Preparation of draft: "Determination of areal snow cover by aerial reconnaissance in Kootenai and Flathead Basins." (Tech. Bull. 15)

38) C.W. TIMBERMAN (MRD) Oct. 1953 - Study and analyses for draft: "Reconstitution of 1950 snow-melt flood on Cannonball River at New Leipzig, North Dakota;" also 1950 flood, Heart River Basin, North Dakota.

39) N. J. MACDONALD (Seattle Dist.) Dec. 1953 (4th visit) - Seasonal forecast procedure, Albeni Falls Dam.

40) H. D. WILDERMUTH (Los Angeles Dist.) Jan. 1954 - Design floods for Gila River basin above Painted Rock damsite; (sub-basins studied: San Francisco River at Clifton, Arizona, and Verde River at confluence with Salt River.)

41) H. N. HUMPHREY (SPD) Jan. 1954 - Same as 40 above.

42) C.A. BURGTORF (Garrison Dist.) Jan. 1954 - Reconstitutions of spring 1950 and 1952 snowmelt floods on Spring Creek above Zap, North Dakota.

43) G.E. GALLAGHER (Portland Dist.) Jan. 1954 - Criteria for forecasting seasonal runoff from snowmelt, Middle Fork Willamette River above Lookout Point Dam, Oregon.

44) K.A. JOHNSON (Omaha Dist.) Jan. 1954 - Reconstitution of spring snowmelt floods on Papillion Creek at Ft. Crook, Nebraska, 1948, and Spring Creek at Zap, North Dakota, 1952.

45) F.C. MURPHY (Seattle Dist.) Mar. 1954 (4th Visit) - Discussion and review, seasonal forecast procedures, Hungry Horse Dam.

46) J. W. HANSON (Portland Dist.) Apr. 1954 - Study and review, forecasting seasonal runoff, Columbia River at the Dalles.

47) S. NAIMARK (Portland Dist.) June 1954 - Daily operation schedule for Detroit Reservoir (N. Santiam River, Ore.)

48) K.W. WISE (Walla Walla Dist.) Sept. 1954 - Forecast procedure for Snake River above Moran, Wyoming.

49) N.J. MACDONALD (Seattle Dist.) Jan. 1955 (5th visit) - Forecast procedure for seasonal runoff into Hungry Horse Reservoir (So. Fork, Flathead River, Montana)

50) R. J. DEFANT (Portland Dist.) Jan. 1955 - Standard Project Flood for Cougar Dam (So. Fork, McKenzie River, Oregon).

51) N. J. MACDONALD (Seattle Dist.) Mar. 1955 (6th visit) - Seasonal runoff forecast, Hungry Horse Reservoir.

52) O.C. JOHNSON (Portland Dist.) Mar. 1956 - Seasonal runoff forecast, Lookout Point Reservoir (Mid-Fork, Willamette River, Ore.)

APPENDIX III

LIST OF SNOW HYDROLOGY SYMBOLS

Symbol	Concept
a	Albedo (reflectivity) of snow pack and/or ground ($a = I_r/I_i$)
A	Area (of snow cover, of drainage area, etc.)
b	Ablation (decrease in depth) of snow pack
B	Thermal quality of snow pack ($B = 1 - f_p/100$)
c_p	Specific heat (constant pressure)
C_r	Recession constant (ratio of current rate of flow to previous days rate of flow)($q_t = q_o C_r^{\,t}$)
d	Depletion (decrease in areal cover) of snow pack
D	Depth (of snow pack, etc.) Coefficient of determination
e	Vapor pressure a subscript denotes vapor pressure of air s subscript denotes saturated vapor pressure Base of Naperian logarithms Emissivity
f	Infiltration rate
f_p	Liquid-water content of the snowpack, in percent of W
f_p'	Liquid-water deficiency of the snowpack, in percent of W
f_p''	Liquid-water-holding capacity of the snowpack, in percent of W, ($f_p'' = f_p + f_p'$)
F	Forest cover

Symbol	Concept
G	Intensity of radiation (all wave) $\underline{d}$ subscript denotes radiation directed downward or toward the snow pack $\underline{u}$ subscript denotes radiation directed upward or from the snow pack
h	Rate of net heat transfer to snow pack from its environment ($h = h_c + h_e + h_g + h_p + h_{rl} + h_{rs}$) $\underline{c}$ subscript denotes convection (and conduction) from air $\underline{ce}$ subscript denotes convection-condensation from air ($h_{ce} = h_c + h_e$) $\underline{e}$ subscript denotes condensation (or evaporation) from air ($h_e = kq_e$) $\underline{g}$ subscript denotes conduction from ground $\underline{p}$ subscript denotes heat capacity of rain ($h_p = ki_rT$) $\underline{r}$ subscript denotes all-wave radiation ($h_r = h_{rl} + h_{rs} = G_d - G_u$) $\underline{rl}$ subscript denotes long-wave radiation ($h_{rl} = R_d - R_u$) $\underline{rs}$ subscript denotes short-wave radiation ($h_{rs} = I_i - I_r = (1 - a)\ I_i$)
H	Quantity of net heat transfer to snow pack from its environment ($H = H_c + H_e + H_g + H_p + H_{rl} + H_{rs}$)(subscripts as above for rate of net heat transfer)
i	Intensity of precipitation $\underline{r}$ subscript denotes rainfall $\underline{s}$ subscript denotes snowfall
I	Intensity of short-wave radiation $\underline{i}$ subscript denotes incident radiation $\underline{o}$ subscript denotes radiation at upper limit earth's atmosphere $\underline{r}$ subscript denotes reflected radiation ($I_r = aI_i$)
k	Coefficient, exponent, or conversion factor
k_c	Thermal conductivity

List of Snow Hydrology Symbols - Continued

Symbol	Concept
K_i	Solar radiation transmission coefficient for forest (ratio of radiation incident on snow surface beneath forest to radiation incident in open)
K_r	Ratio of downward long-wave radiation, R_d, to that of a hypothetical black body at air temperature ($K_r = R_d/\sigma T_a^4$)
l	Loss rate e subscript denotes loss by evaporation g subscript denotes loss by deep percolation t subscript denotes loss by transpiration et subscript denotes loss by evapotranspiration
L	Loss (quantity) (subscripts as above for loss rate)
m	Rate of snow melt (subscripts as above for rate of net heat transfer)
M	Quantity of snow melt (subscripts as above for rate of net heat transfer)
n	Number of items
N	Cloud cover
p	Atmospheric pressure
P	Quantity of precipitation r subscript denotes rainfall s subscript denotes snowfall (water equivalent)
q	Rate of stream flow, runoff, or discharge (water transport) e subscript denotes rate of condensation g subscript denotes rate of ground water discharge i subscript denotes rate of interflow l subscript denotes loss rate o subscript denotes initial rate

List of Snow Hydrology Symbols - Continued

Symbol	Concept
Q	Quantity of water (subscripts as above for rate of stream flow, etc.)
r	Correlation coefficient
R	Intensity of long-wave radiation (subscripts as above for intensity of radiation)
s_y	Standard deviation
s_{yx}	Standard error of estimate
S	Storage (= Inflow-Outflow)
t	Time c subscript denotes concentration time s subscript denotes storage time
T	Temperature a subscript denotes air temperature d subscript denotes dew-point temperature g subscript denotes ground temperature s subscript denotes snow temperature w subscript denotes wet-bulb temperature
U	Relative humdiity
v	Wind speed
V	Wind travel
w	Mixing ratio
W	Water equivalent of snow pack
W_f	Liquid water in snow pack $W_f = f_p\ W/100$
W_p	Precipitable water in atmosphere

List of Snow Hydrology Symbols - Continued

Symbol	Concept
z	Altitude, height
Z	Zenith angle of sun
λ	Wave Length (lambda)
ρ	Density, specific gravity ("density") of snow (rho)
σ	Stefan-Boltzmann constant (sigma)
ϕ	Latitude (phi)
β	(beta) Standard partial regression coefficient
μ	(mu) micron
π	(pi) 3.1416
Σ	(Sigma) sum of...
∞	infinity
$>$	greater than
$<$	less than
$\approx$	approximately equal to