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 $\underline{M}$ is the total daily snowmelt in inches for open or partly-forested basins, $\underline{T_a}$ is the mean daily air temperature at the 10-foot level in degrees F, $\underline{v}$ is the mean daily wind speed at the 50-foot level in mph, $\underline{P_r}$ is the total daily rainfall in inches, and $\underline{k}$ 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 <u>Short-term forecasts</u>. - 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 snytheses of runoff hydrographs are encountered in snow hydrology: (1) short-term forecasts and (2) the snythesis 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 snythesis, 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 snythesis.

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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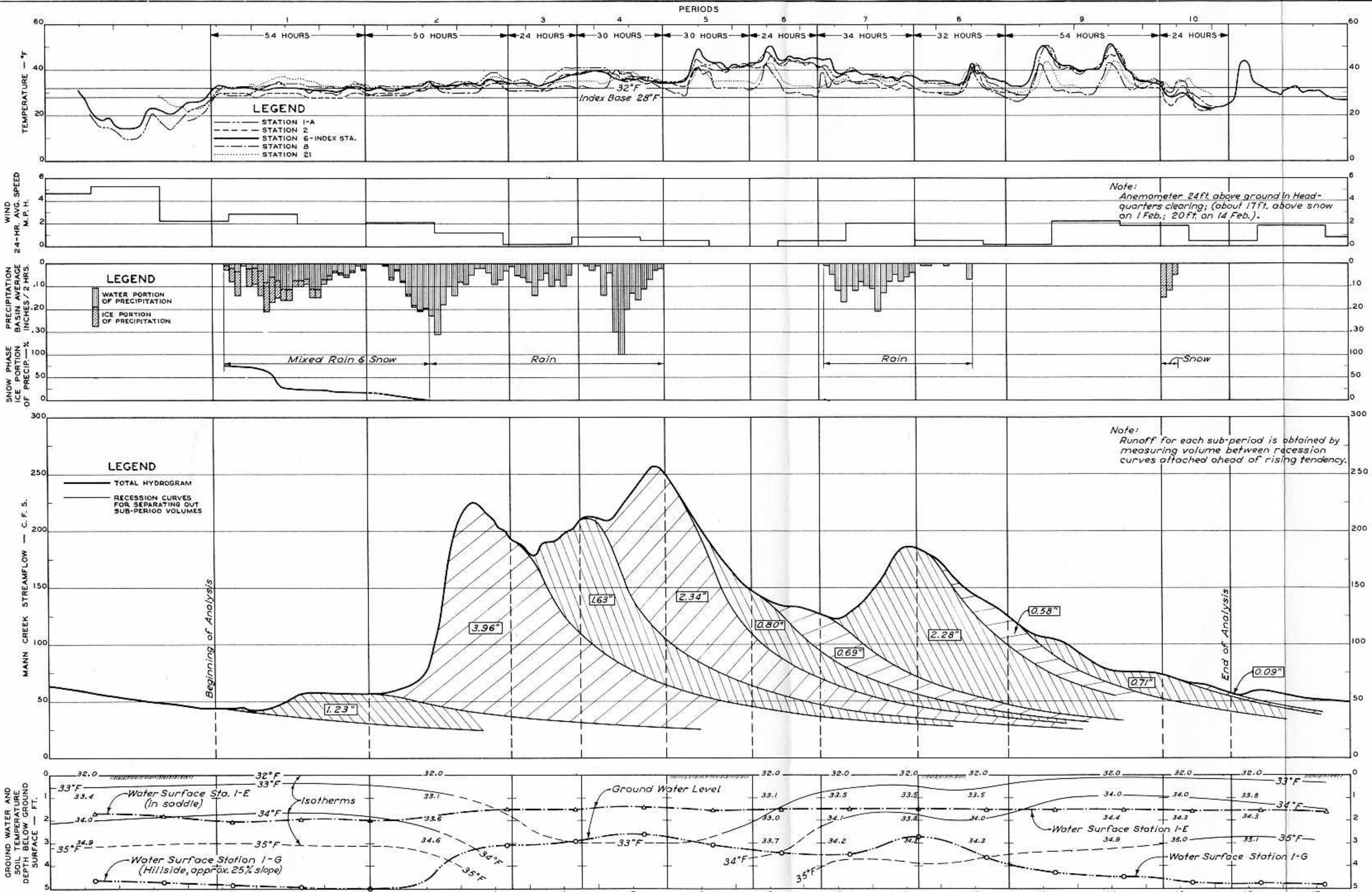


FIGURE 1 — HYDROLOGICAL AND METEOROLOGICAL LOG — JAN.-FEB. 1951

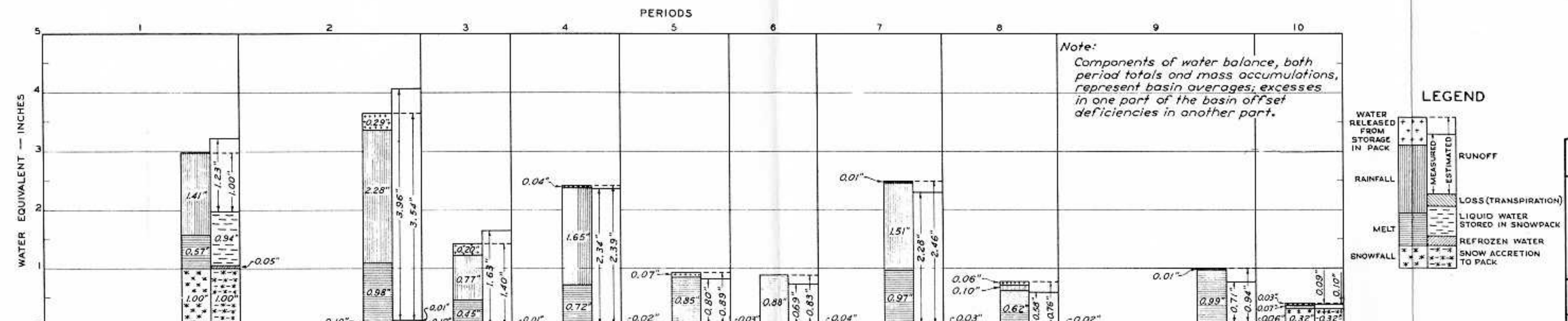
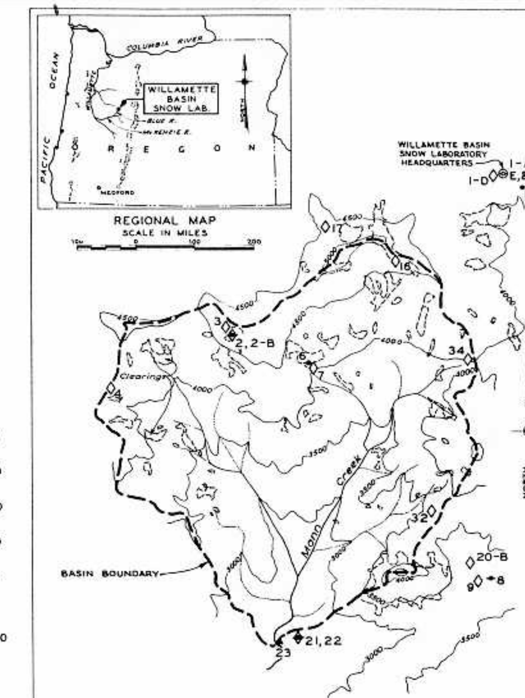


FIGURE 2 — COMPONENTS OF WATER BALANCE FOR EACH PERIOD



DENSELY FORESTED MANN CREEK TEST BASIN SHOWING LOCATION OF STATIONS

SCALE IN FEET

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-D, 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

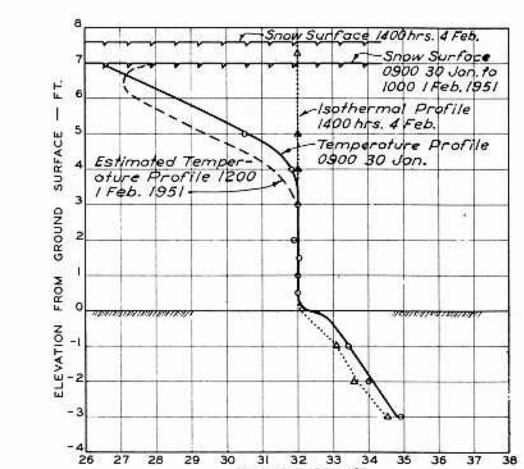


FIGURE 4 — GROUND AND SNOW-PACK TEMPERATURE PROFILES — HEADQUARTERS

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

PREPARED: [illegible] SUBMITTED: [illegible]
DRAWN: [illegible] APPROVED: [illegible]

TO ACCOMPANY REPORT DATED 30 JUNE 1956

PD-20-25/56

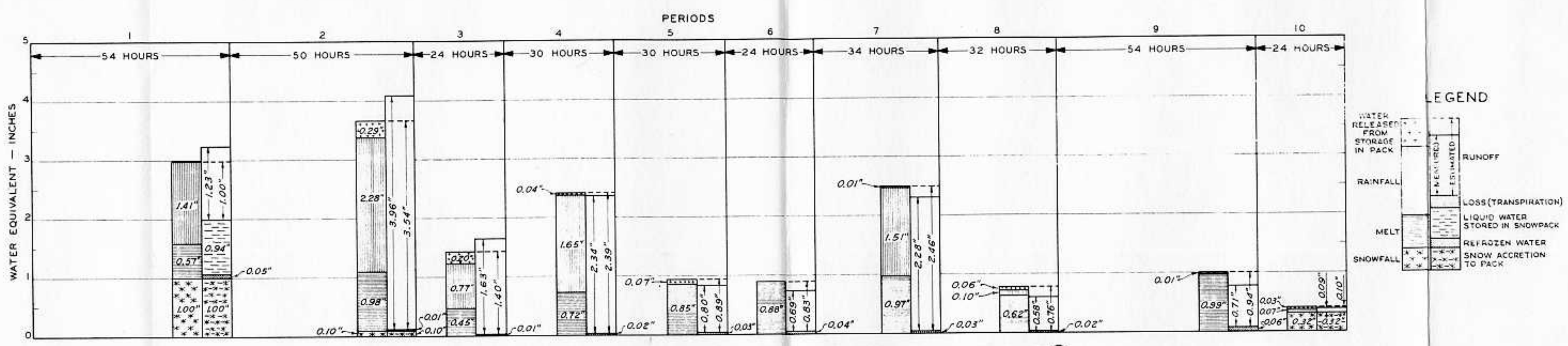


FIGURE 1 — COMPONENTS OF WATER BALANCE FOR EACH PERIOD①

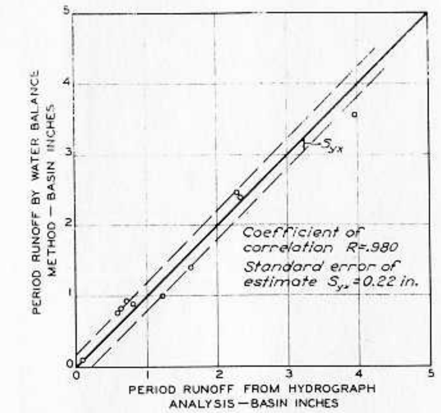


FIGURE 3 — RUNOFF COMPUTED BY WATER BALANCE METHOD COMPARED WITH THAT DERIVED FROM HYDROGRAPH ANALYSIS

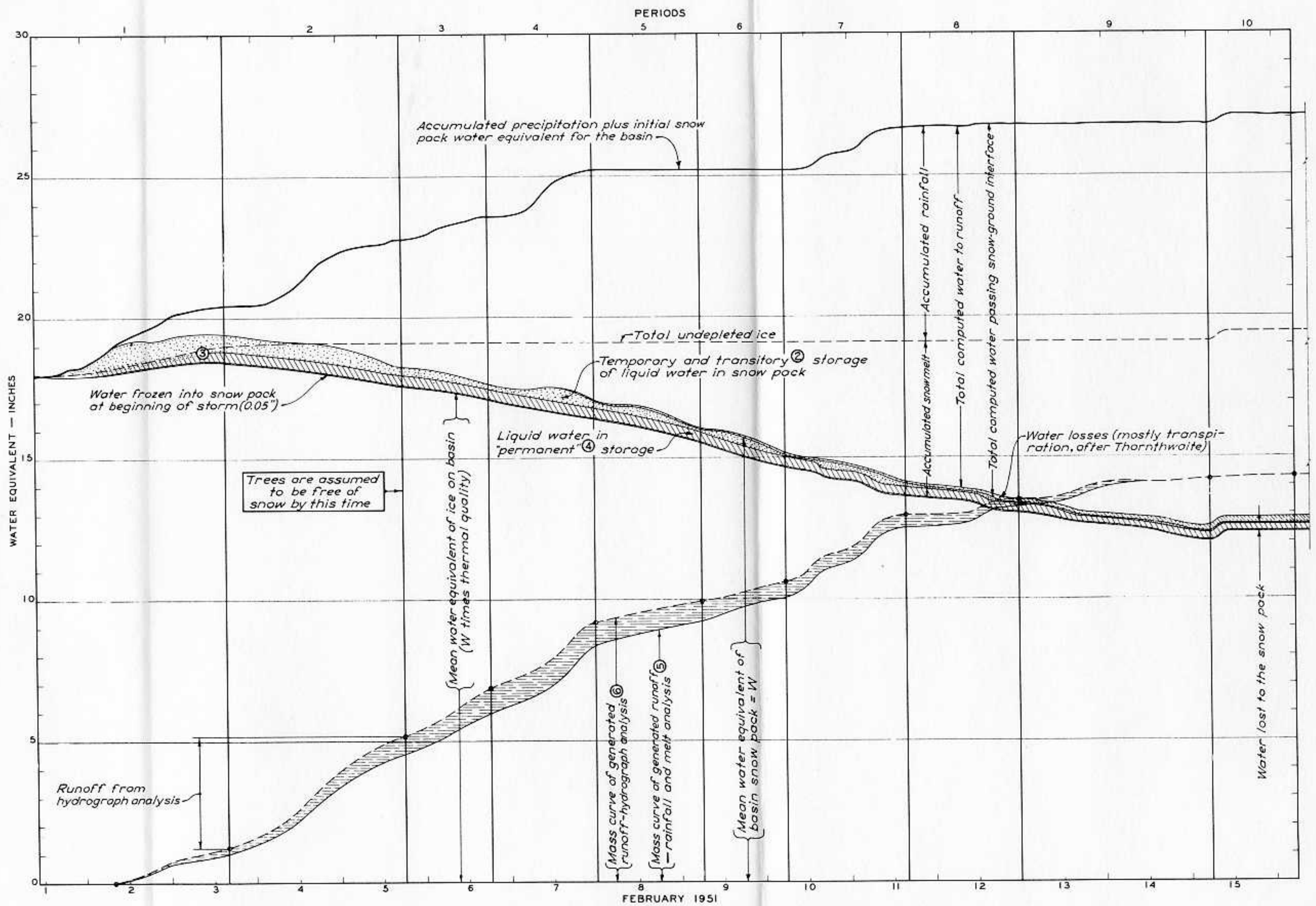


FIGURE 2 — ACCUMULATION AND DEPLETION OF HYDROLOGIC ELEMENTS (MASS CURVES)①

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

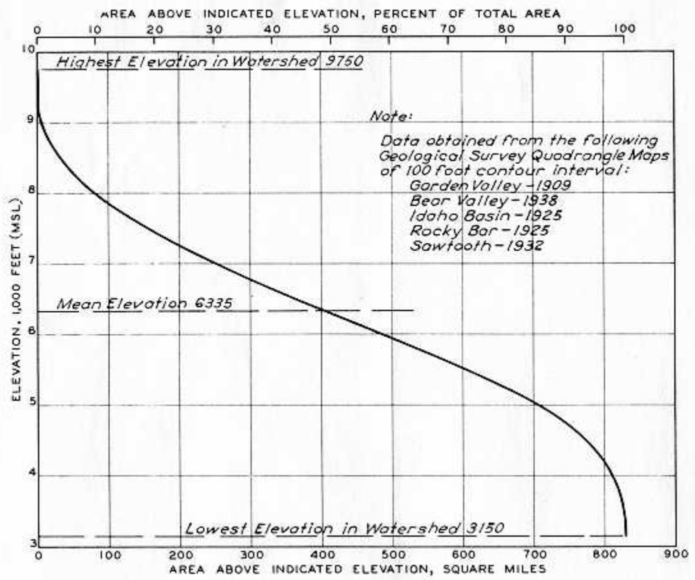
FEBRUARY 1951 WILLAMETTE BASIN SNOW LABORATORY
MANN CREEK DRAINAGE AREA 5.2 SQUARE MILES

SHEET 2 OF 2

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

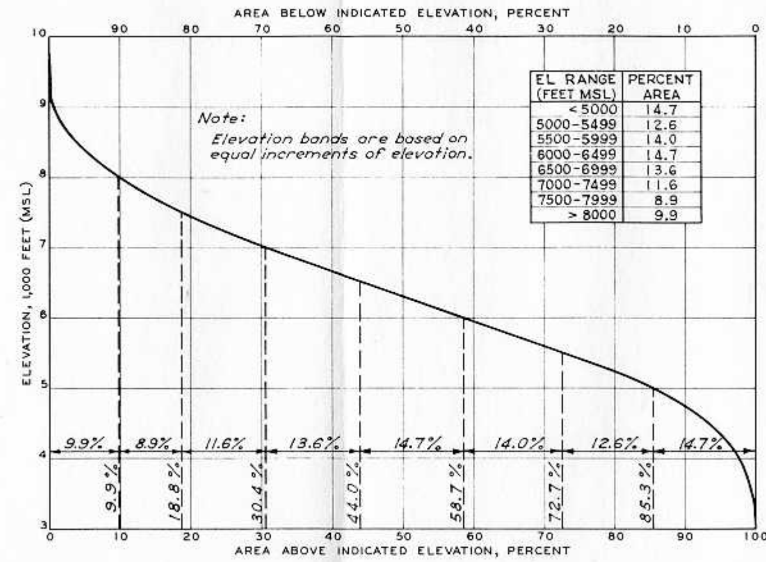
PREPARED: S.E.J.	SUBMITTED: P.B.B.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: B.V.	APPROVED: D.M.R.	PD-20-25/57

PLATE 9-2



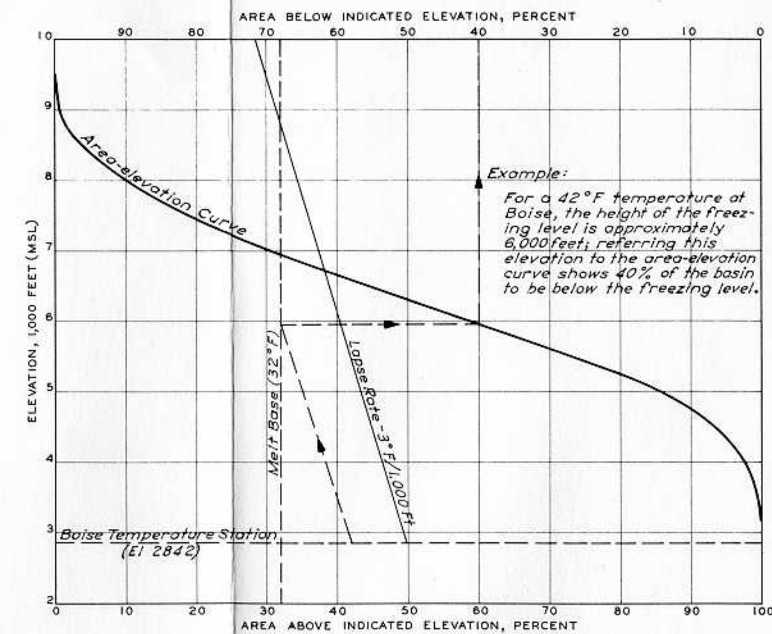
AREA-ELEVATION CURVE

FIGURE 1



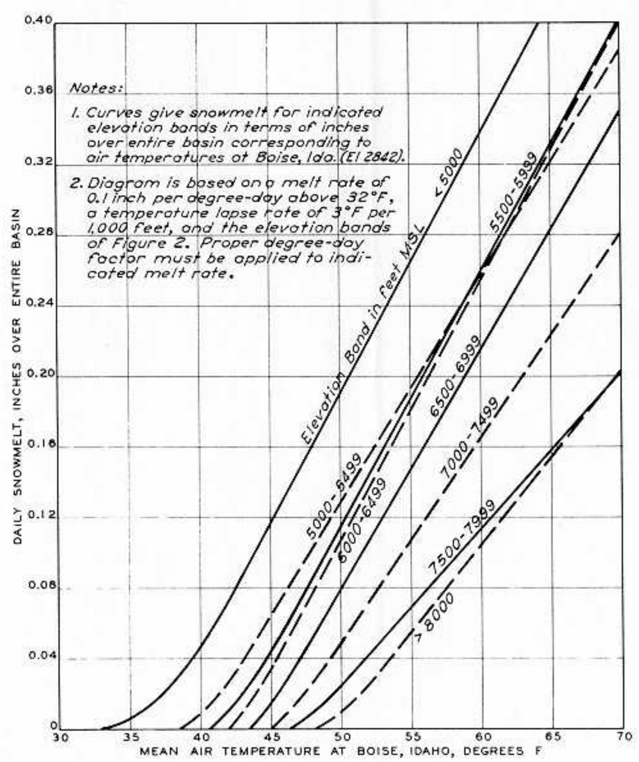
BASIN SUB-DIVISION INTO ELEVATION BANDS

FIGURE 2



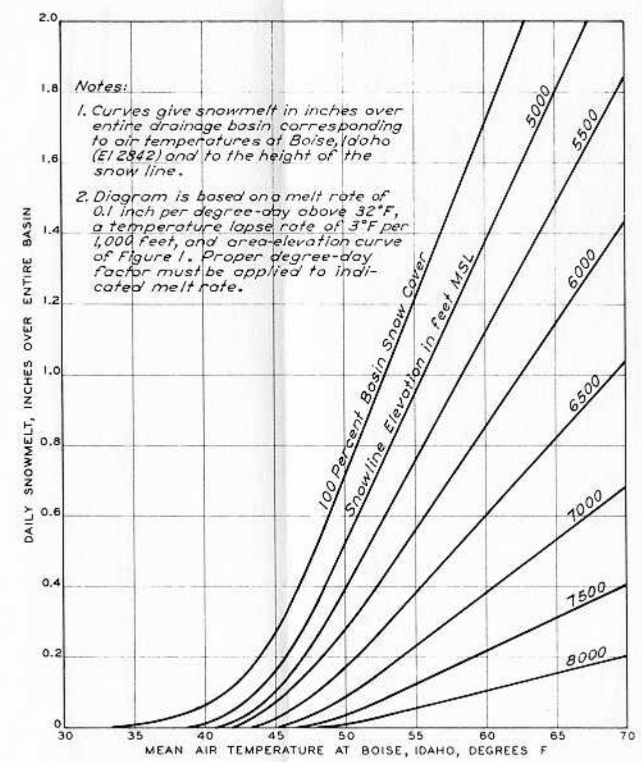
CONTRIBUTING AREA DIAGRAM

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

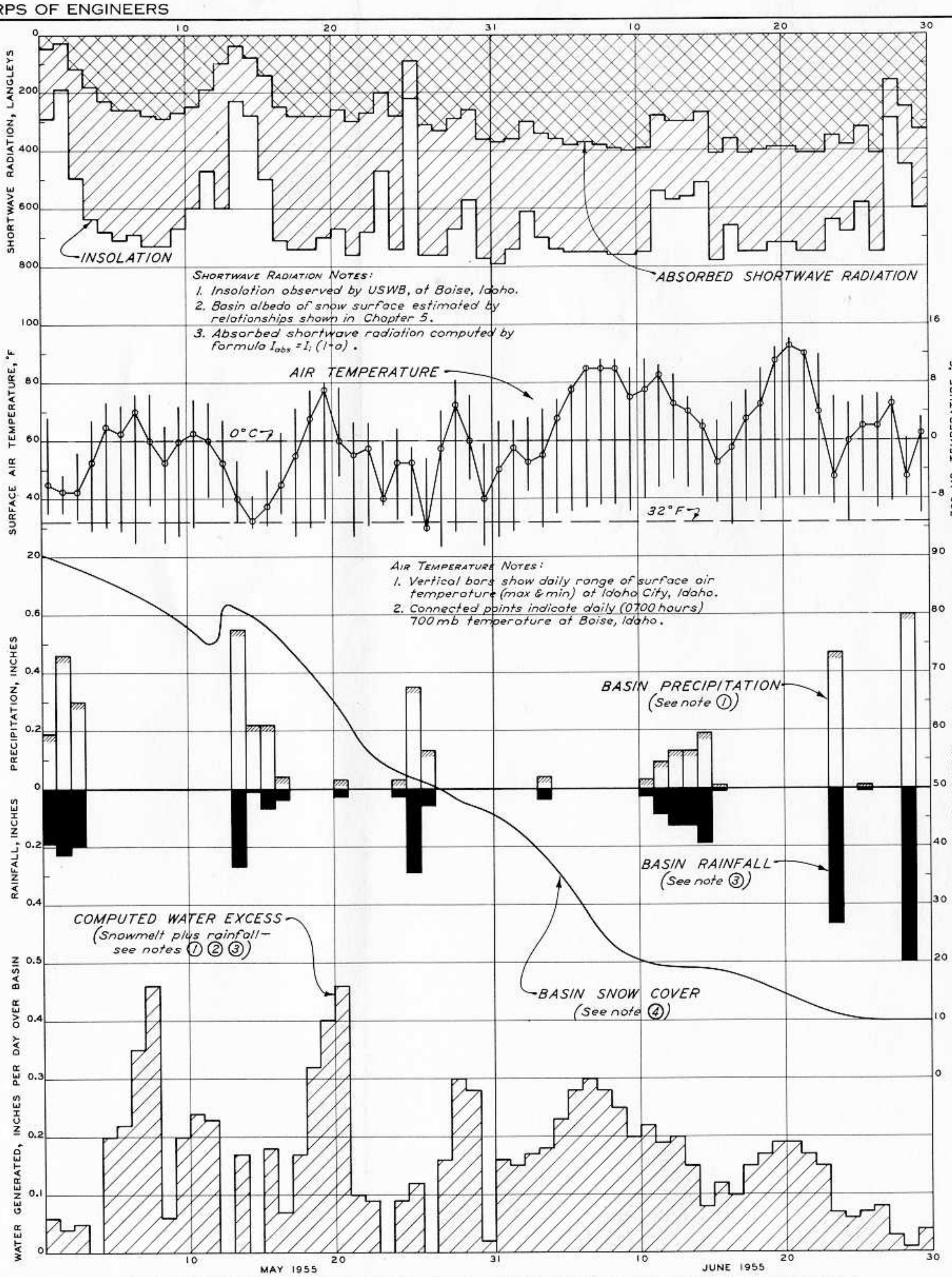
TEMPERATURE-INDEX COMPUTATION OF SNOWMELT

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

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

PREPARED: C.E.H. SUBMITTED: C.E.R. TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: B.V. APPROVED: D.M.R.

PD-20-25/58



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,*

$$\text{Basin Precip} = \frac{33.0}{113.0}\ \text{Precip Index}$$

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

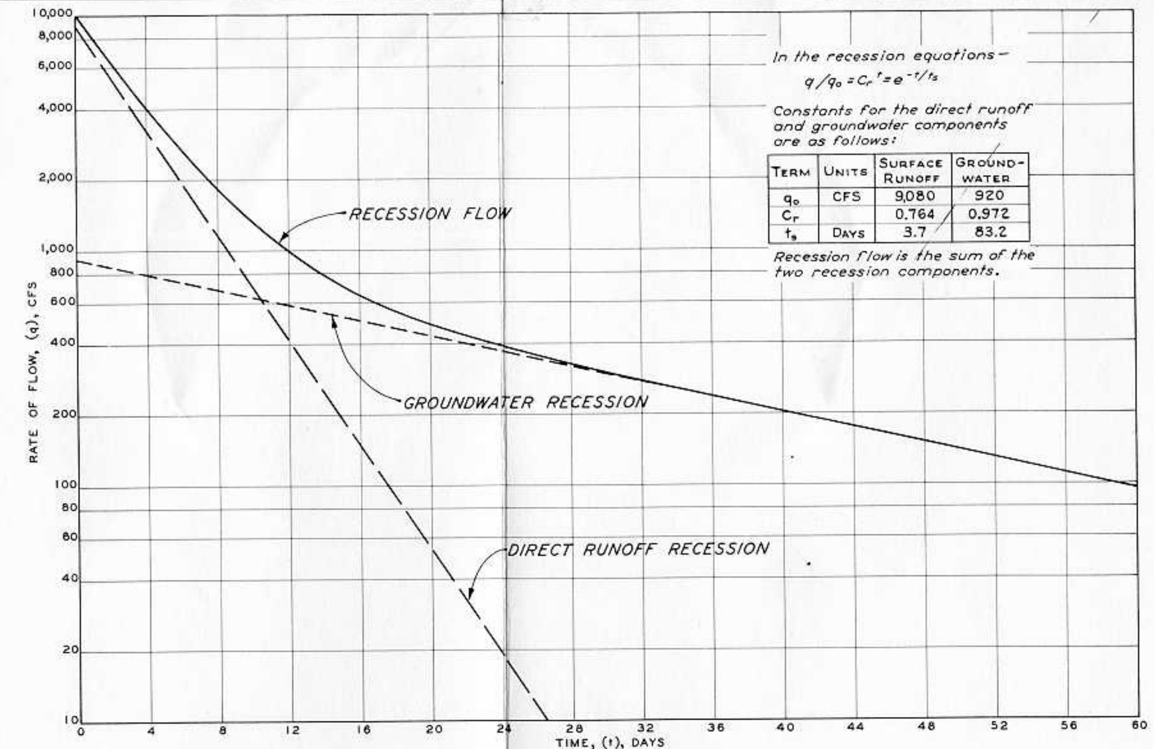
② *Snowmelt excess computed from equation,*

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

where $\underline{M}$ is the snowmelt in inches over the basin, $\underline{T_{max}}$ is is the daily maximum temperature at Idaho City, in degrees F, and $\underline{G}$ 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 minimun 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.*



In the recession equations—

$$q/q_o = C_r^{\,t} = e^{-t/t_s}$$

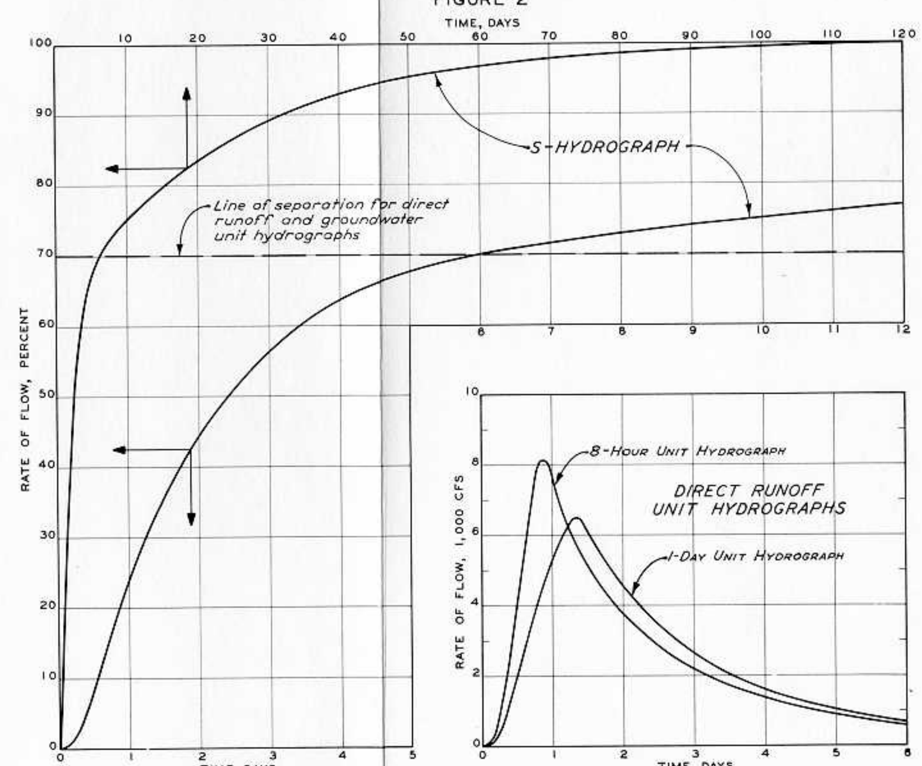
Constants for the direct runoff and groundwater components are as follows:

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

Recession flow is the sum of the two recession components.

RECESSION CURVES

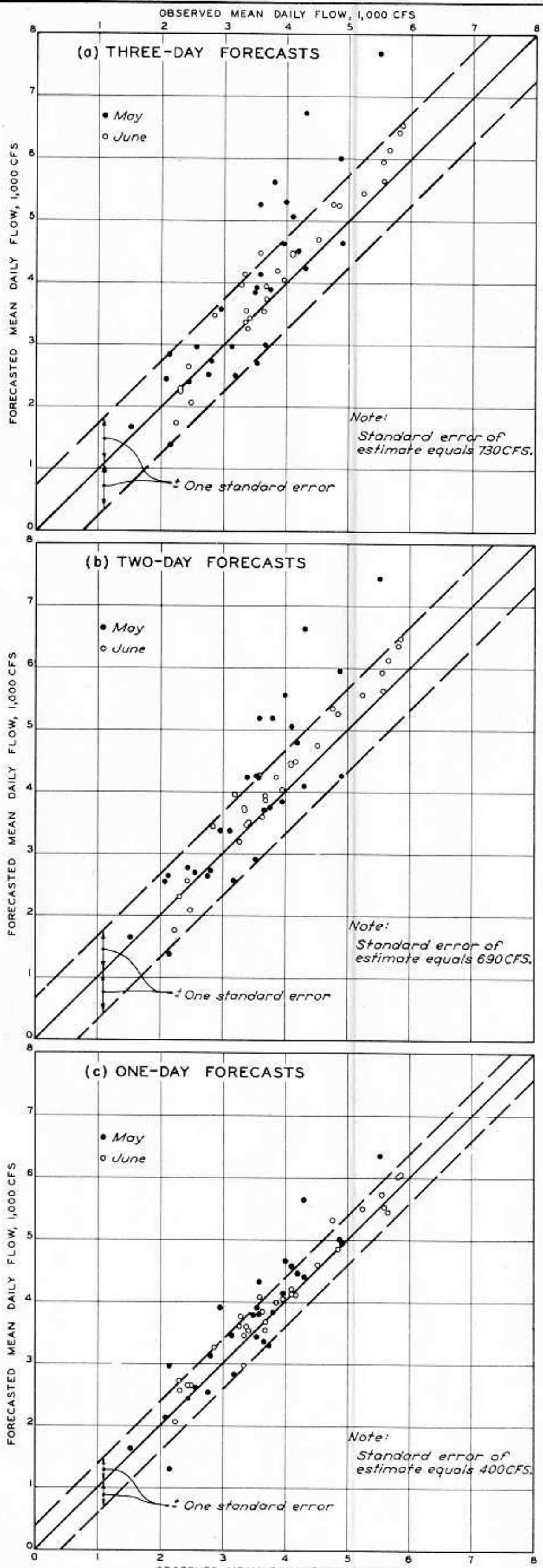
FIGURE 2



S-HYDROGRAPH AND UNIT HYDROGRAPHS

FIGURE 3

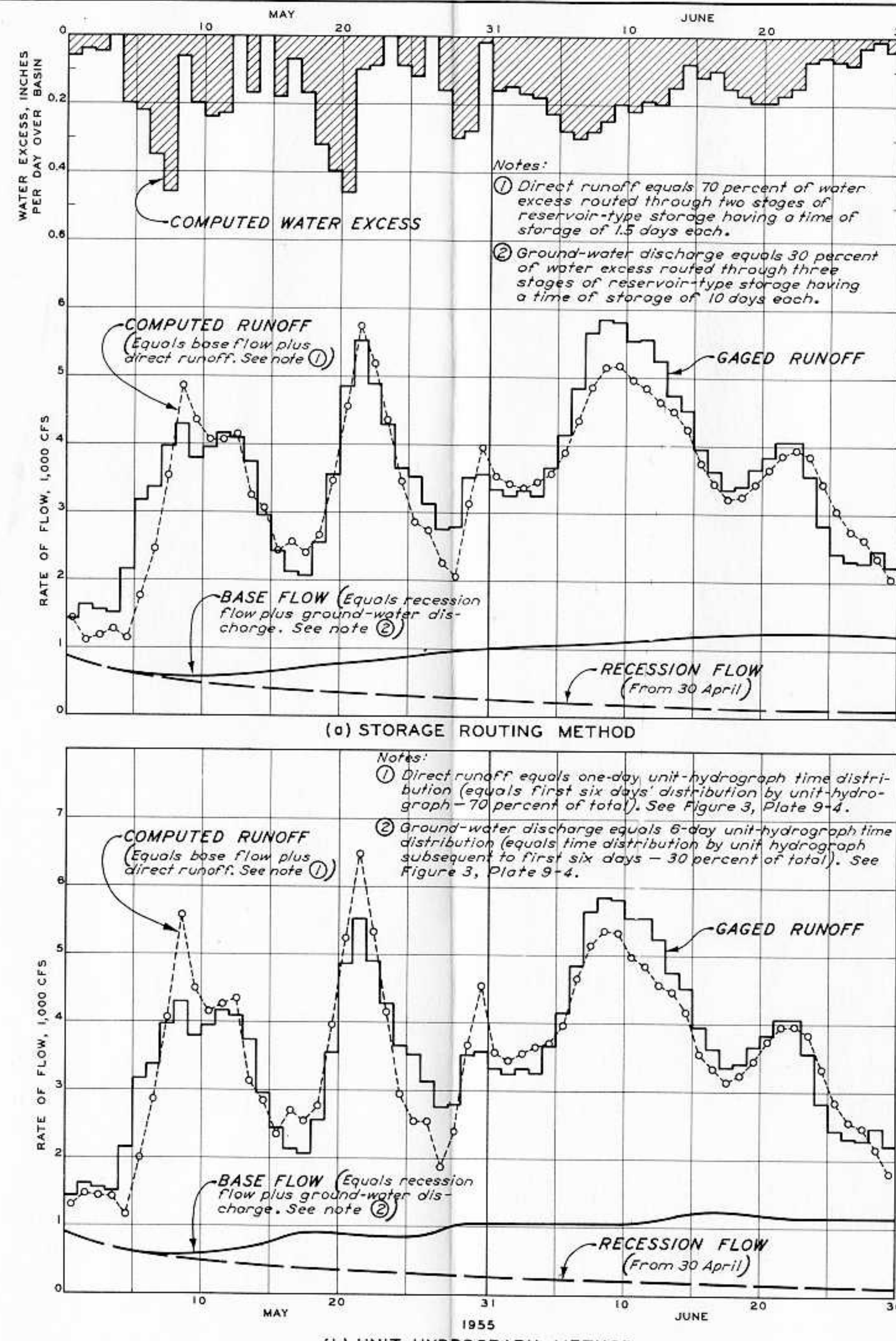
SNOW INVESTIGATIONS SUMMARY REPORT		
SNOW HYDROLOGY **FLOW FORECASTS AND RECONSTITUTION** BOISE RIVER NEAR TWIN SPRINGS, IDAHO 1955 SPRING SNOWMELT SEASON DRAINAGE AREA 830 SQUARE MILES SHEET 1 OF 2		
OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION CORPS OF ENGINEERS U.S. ARMY		
PREPARED: C.E.H. DRAWN: S.V.	SUBMITTED: C.E.H. APPROVED: D.M.R.	TO ACCOMPANY REPORT DATED 30 JUNE 1956 PD-20-25/59



MEAN DAILY FLOW FORECASTS

FIGURE 1

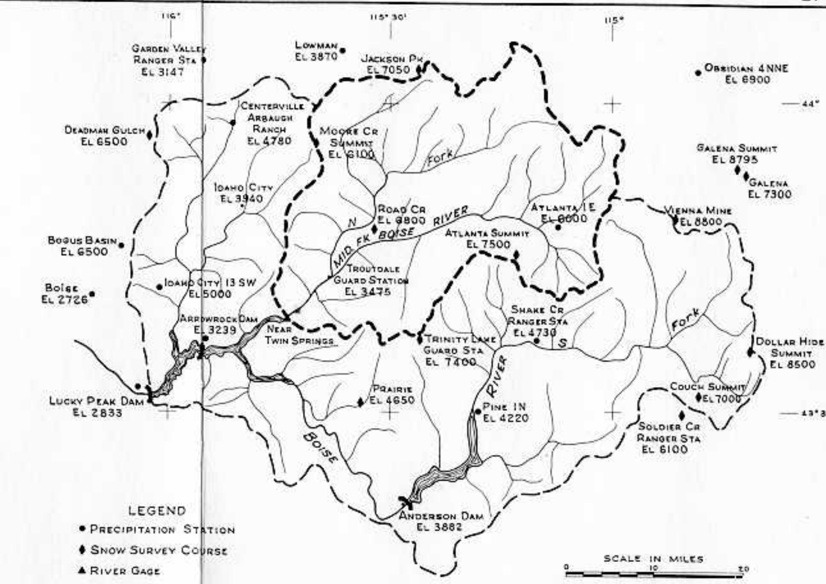
NOTE for FIGURE 1:
One-, two-, and three-day forecasts computed from values of snowmelt and rainfall described on Figure 1, Plate 9-4, utilizing distribution graph derived from S-hydrograph shown on Figure 3, Plate 9-4, and total recession flow from date of forecast based on recession curve shown on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



(b) UNIT-HYDROGRAPH METHOD

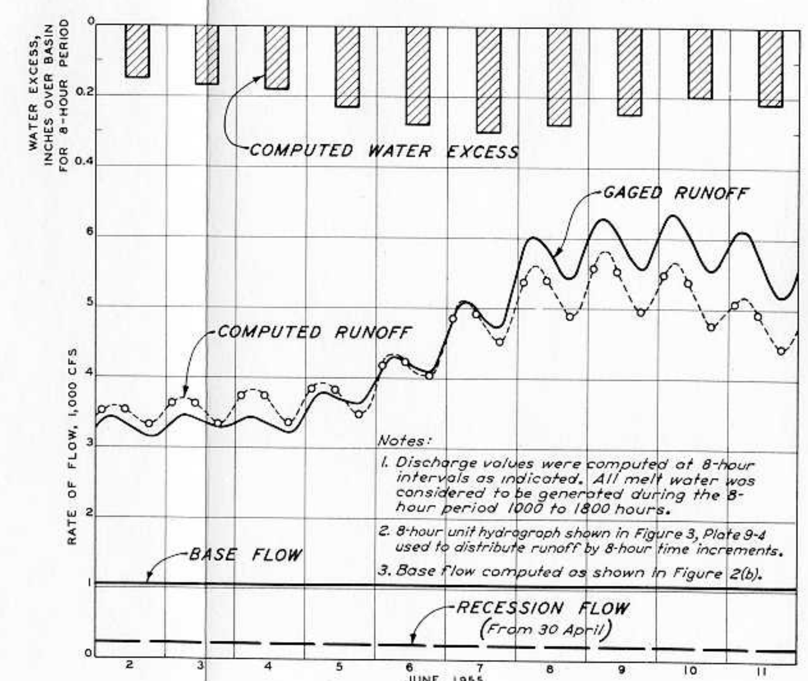
RECONSTITUTION OF SEASONAL HYDROGRAPH OF MEAN DAILY FLOWS

FIGURE 2



HYDROMETEOROLOGICAL STATIONS

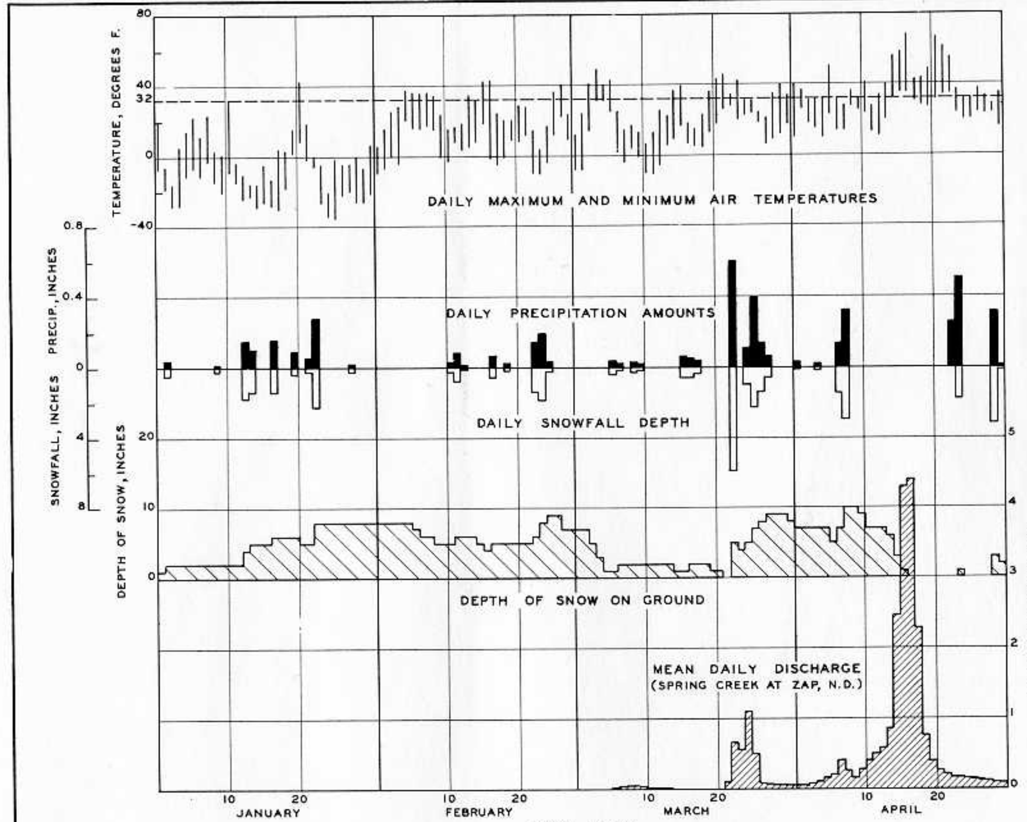
FIGURE 3



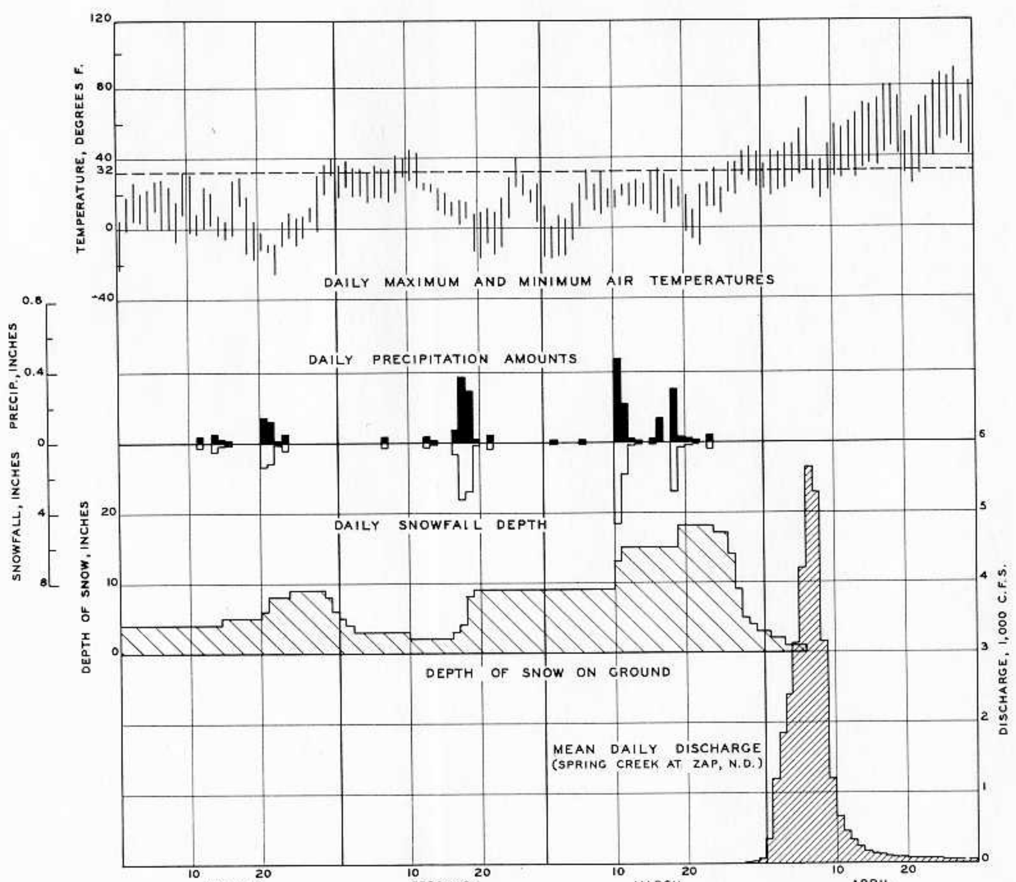
RECONSTITUTION OF HYDROGRAPH SHOWING DIURNAL FLOW VARIATION

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
OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION CORPS OF ENGINEERS U.S. ARMY
PREPARED: C.A.R. SUBMITTED: C.E.H. TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: R.R. APPROVED: D.M.R. PD-20-25/60



1950 DATA

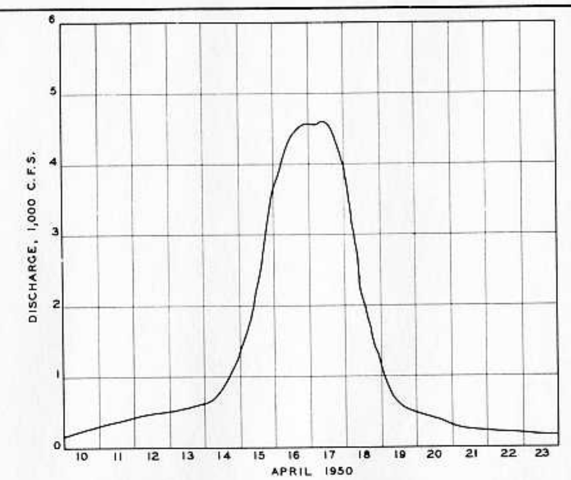


1952 DATA

HYDROMETEOROLOGICAL DATA

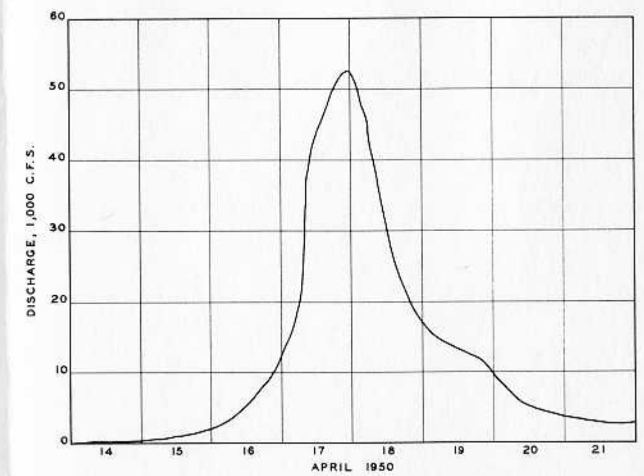
FIGURE 1

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



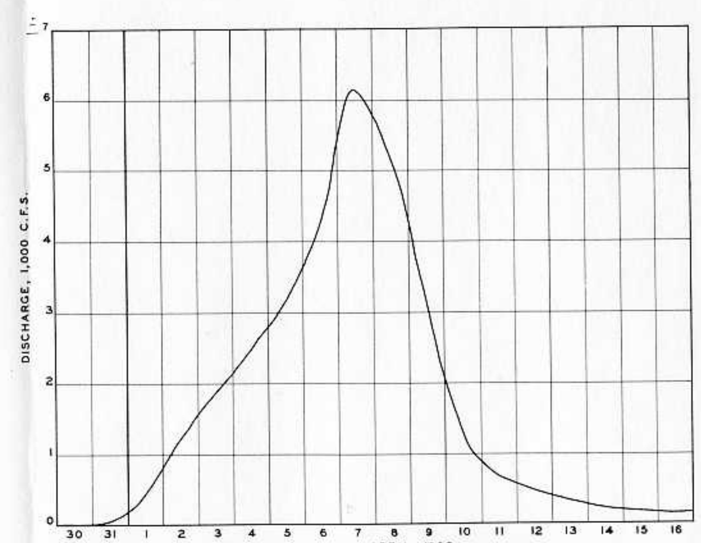
SPRING 1950 FLOOD HYDROGRAPH
FOR SPRING CREEK AT ZAP, N.D.
DRAINAGE AREA, 545 SQ. MI.

FIGURE 2



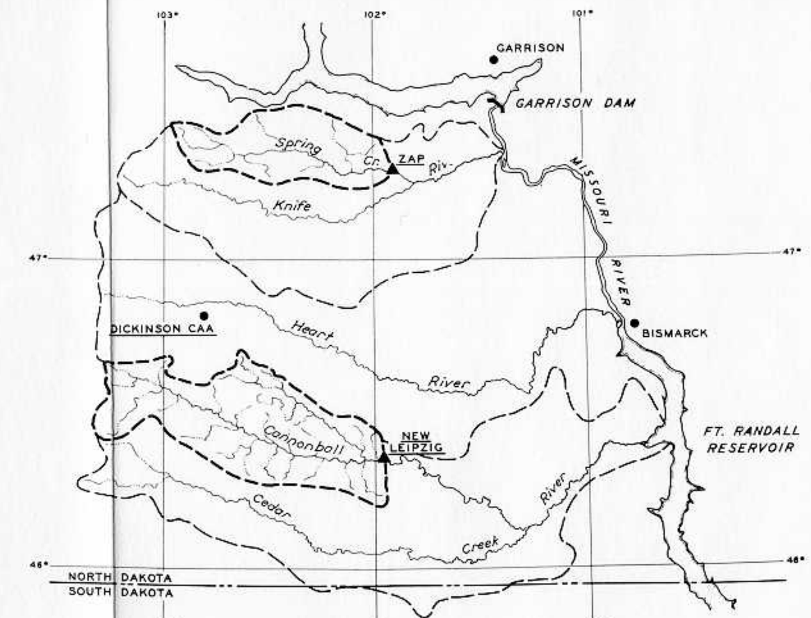
SPRING 1950 FLOOD HYDROGRAPH
FOR CANNONBALL RIVER NEAR NEW LEIPZIG, N.D.
DRAINAGE AREA, 1,180 SQ. MI., APPROXIMATELY

FIGURE 3



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

FIGURE 4



LOCATION MAP

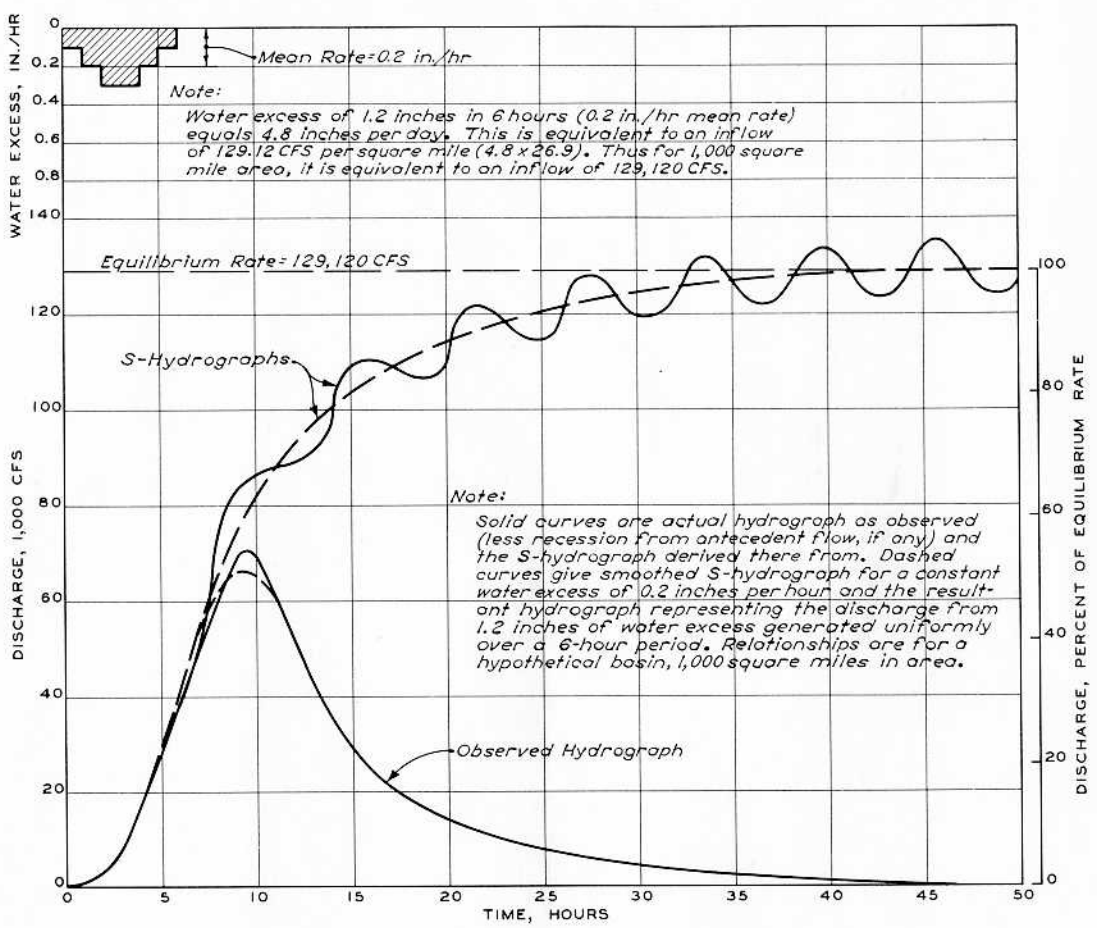
SNOW INVESTIGATIONS
SUMMARY REPORT
SNOW HYDROLOGY

SNOWMELT FLOODS IN GREAT PLAINS AREA

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

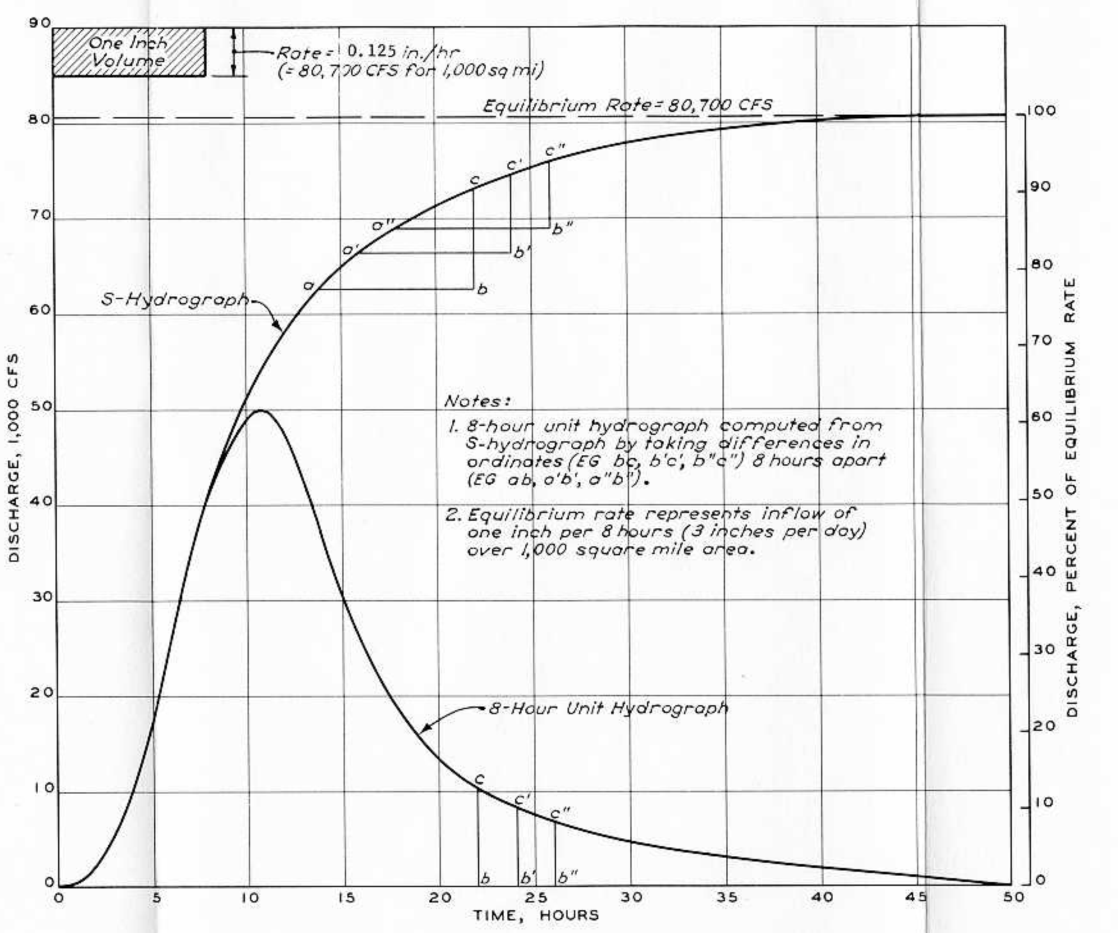
PREPARED: C.E.H. SUBMITTED: C.E.H. TO ACCOMPANY REPORT DATED: 30 JUNE 1956
DRAWN: H.E.B. APPROVED: D.M.R.

PD-20-25/61



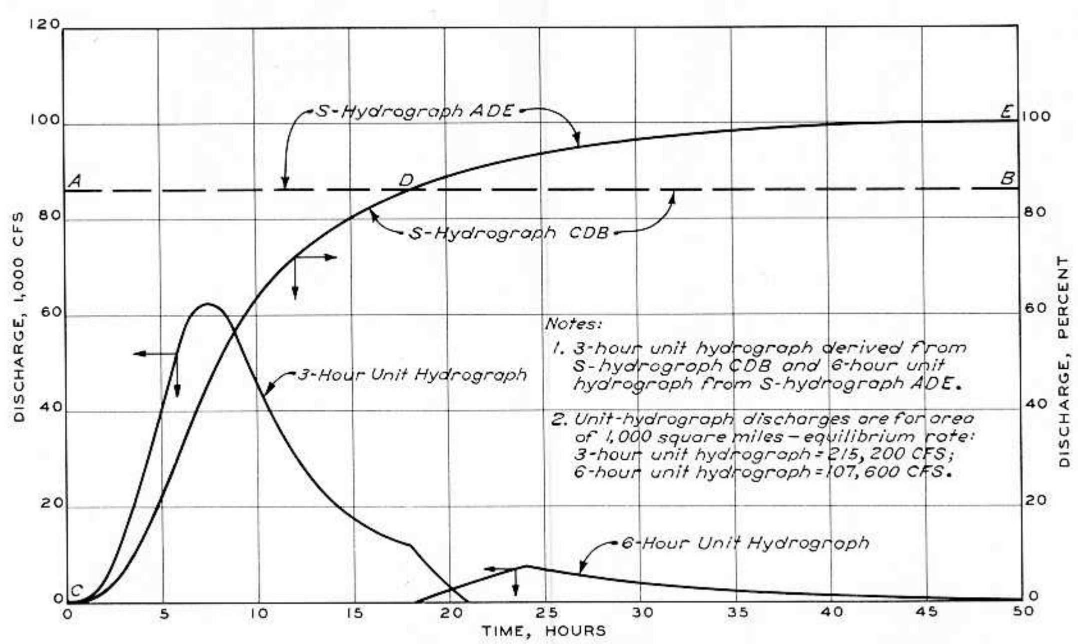
S-HYDROGRAPH — UNIT-HYDROGRAPH RELATIONSHIPS

FIGURE 1



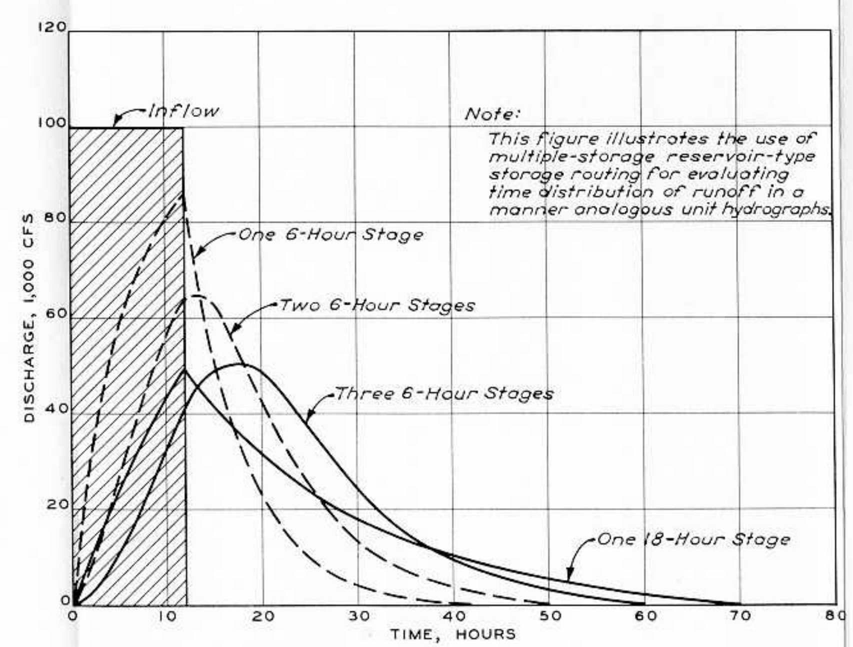
DERIVATION OF UNIT HYDROGRAPH FROM S-HYDROGRAPH

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: C.E.H.	SUBMITTED: C.E.H.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: B.V.	APPROVED: D.M.R.	PD-20-25/62

PLATE 9-7