CHAPTER 10 - DESIGN FLOOD DETERMINATION

10-01. INTRODUCTION

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

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

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

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

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

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

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

I. Review of general hydrologic features

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

B. Physical characteristics of the watershed.

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

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

A. Initial snowpack characteristics.

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

B. Determination of sequence of meteorological factors affecting melt.

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

D. Determination of rainfall.

1. Time distribution.
2. Total amount.

E. Determination of loss and runoff conditions.

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

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

A. Initial snowpack characteristics.

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

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

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

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

E. Determination of loss and runoff conditions.

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

10-02. OPTIMUM CONDITIONS FOR DESIGN FLOODS

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

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

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

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

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

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

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

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

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

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

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

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

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

10-03. COMPUTATION OF SNOWMELT FOR DESIGN FLOODS

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

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

Open or partly forested area:

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

Heavily forested area:

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

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

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

Heavily forested area:

$$M = 0.074\ (0.53T'_a + 0.47T'_d) \tag{10-3}$$

Forested area:

$$M = k(0.0084v)\ (0.22T'_a + 0.78T'_d) + 0.029T'_a \tag{10-4}$$

Partly forested area:

$$M = k'(1 - F)(0.0040\ I_i)\ (1 - a) + k(0.0084v)(0.22T'_a + 0.78T'_d) + F(0.029T'_a) \tag{10-5}$$

Open area:

$$M = k'(0.00508\ I_i)\ (1 - a) + (1-N)(0.0212T'_a - 0.84) + N(0.029T'_c) + k(0.0084v)\ (0.22T'_a + 0.78T'_d) \tag{10-6}$$

where:

M is the snowmelt rate in inches per day.

T'_a is the difference between the air temperature measured at 10 feet and the snow surface temperature, in ^oF.

T'_d is the difference between the dewpoint temperature measured at 10 feet and the snow surface temperature, in ^oF.

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

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

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

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

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

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

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

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

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

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

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

10-04. DESIGN FLOOD HYDROGRAPH SYNTHESIS

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

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

10-05. EXAMPLES OF DESIGN FLOODS INVOLVING SNOWMELT

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

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

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

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

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

10-06. SUMMARY

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

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

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

10-07. REFERENCES

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

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

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

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

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

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

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

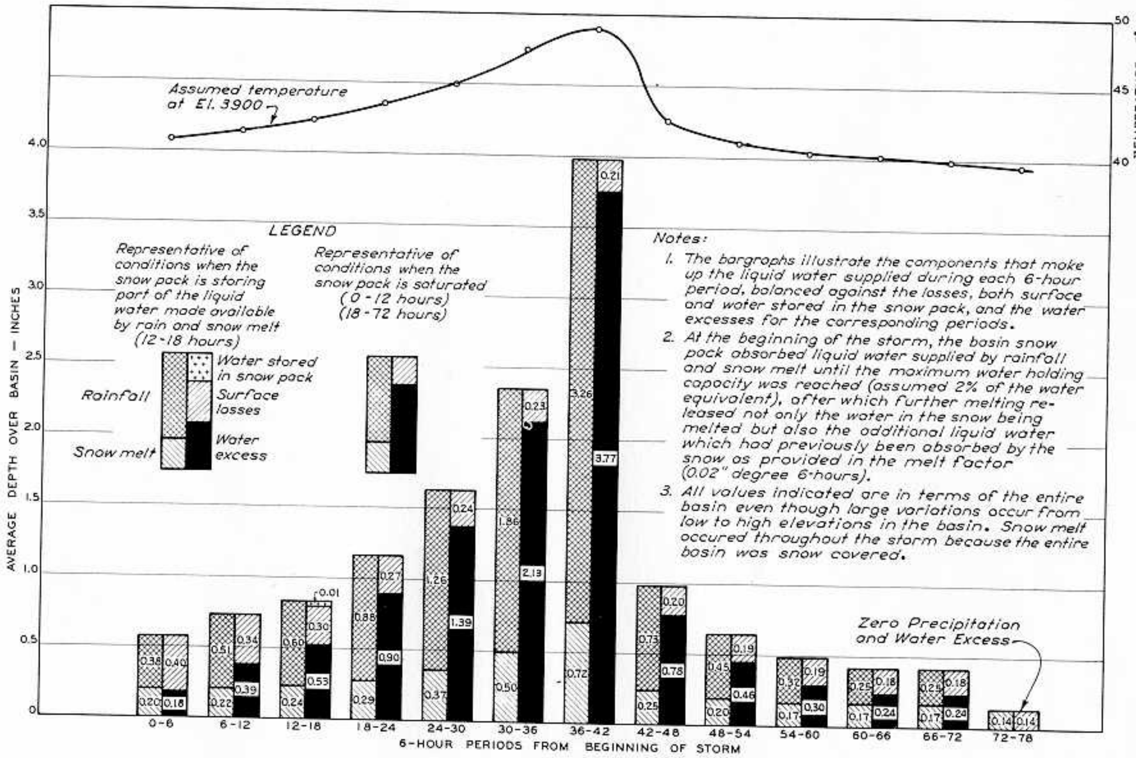


FIGURE 1

STANDARD PROJECT STORM HYDROLOGIC BALANCE

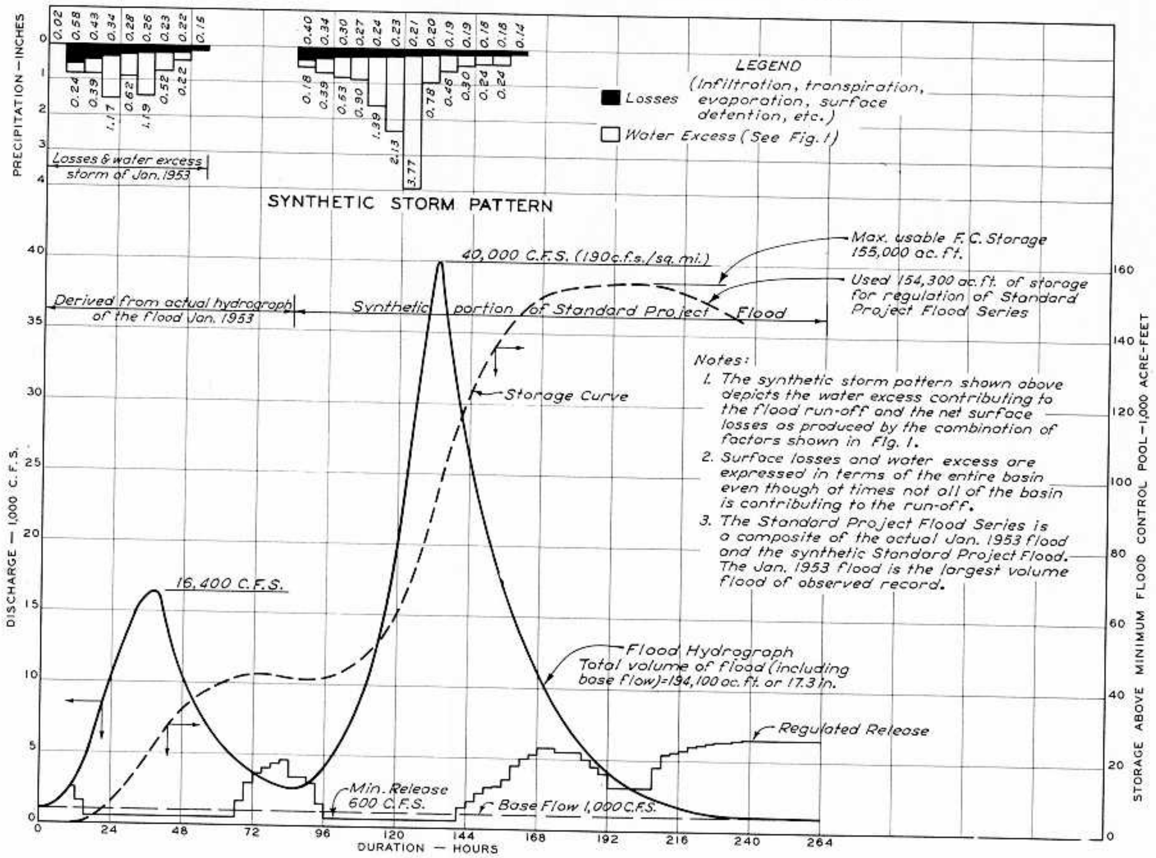


FIGURE 3

STANDARD PROJECT FLOOD SERIES

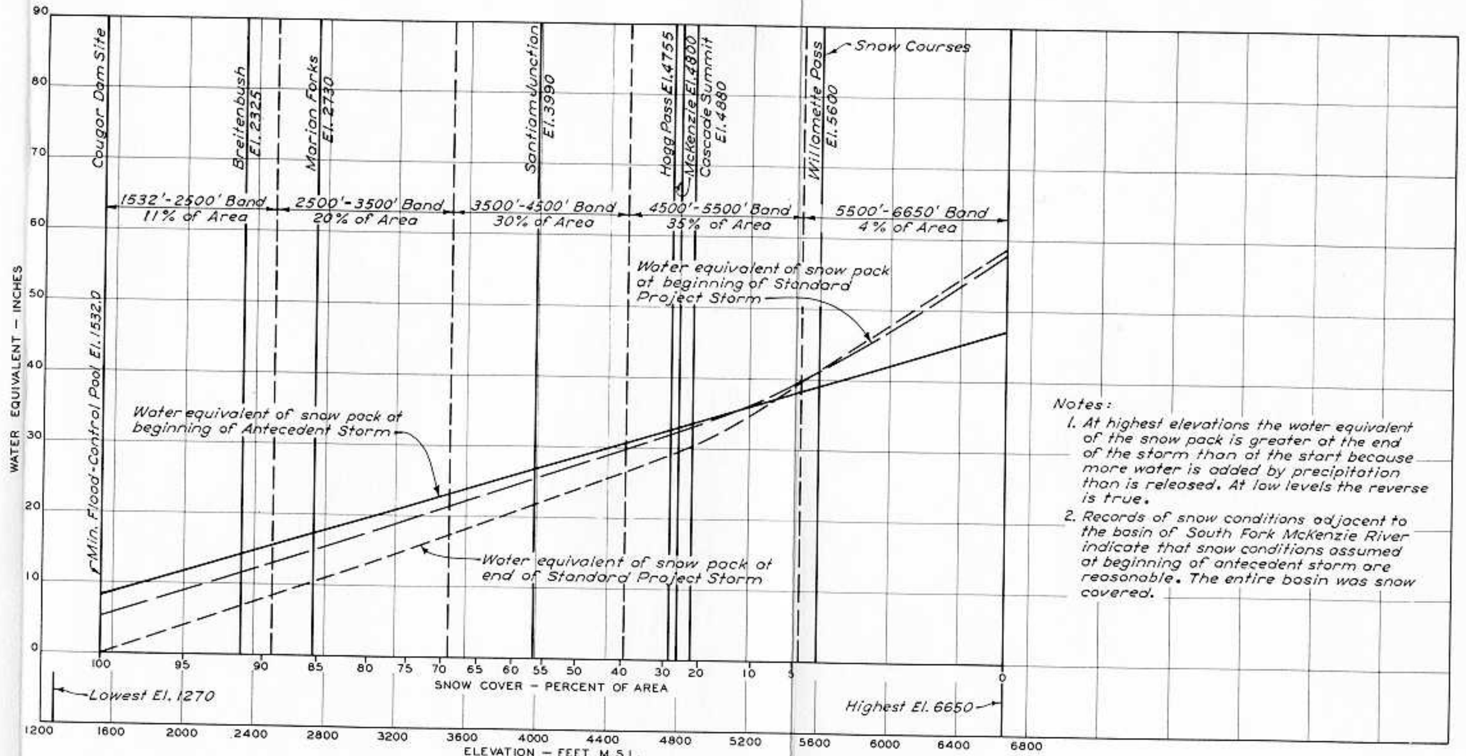


FIGURE 2

SNOW COVER DISTRIBUTION

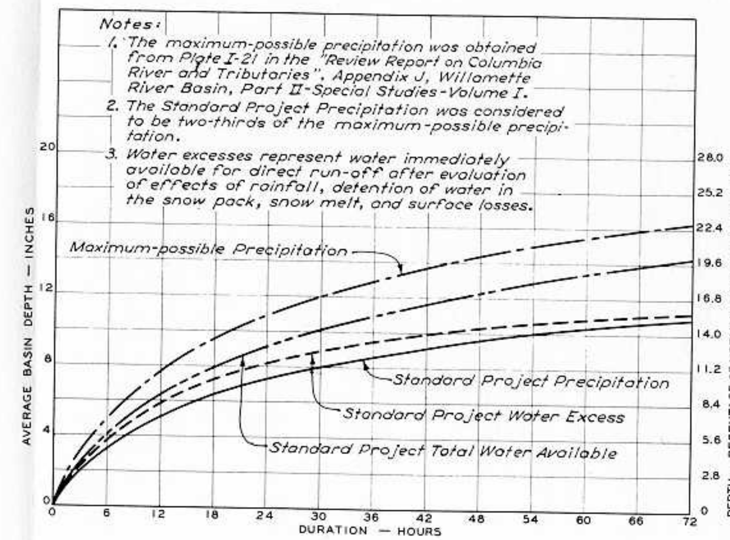
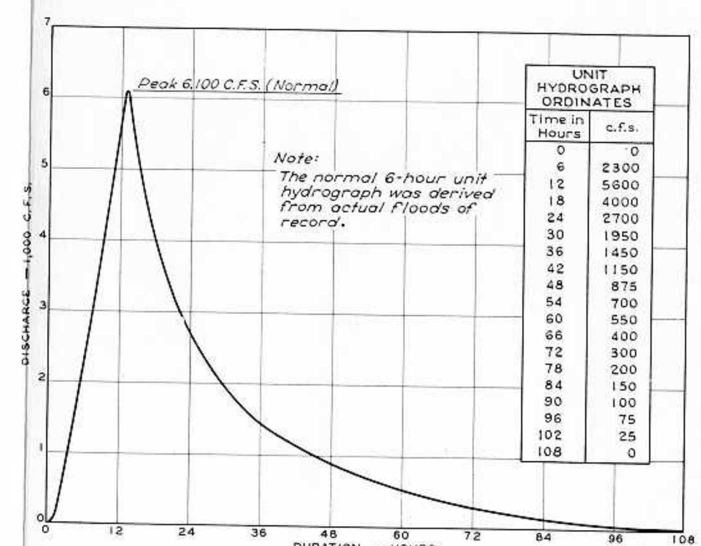


FIGURE 4

DEPTH-DURATION CURVES



UNIT HYDROGRAPH ORDINATES

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

FIGURE 5

6-HOUR UNIT HYDROGRAPH

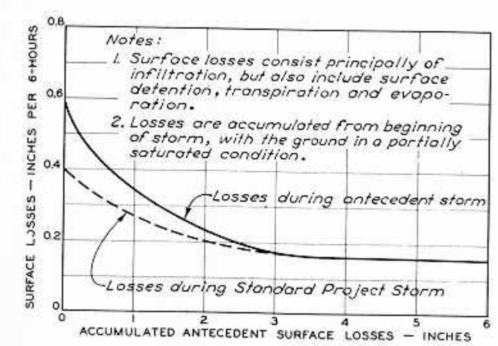


FIGURE 6

SURFACE LOSSES

WILLAMETTE RIVER BASIN, OREGON

SOUTH FORK McKENZIE RIVER

COUGAR DAM

STANDARD PROJECT FLOOD

SCALES AS SHOWN

PORTLAND DISTRICT, CORPS OF ENGINEERS NOV. 15, 1955

SUPERVISED: CHIEF, HYDROLOGY & METEOROLOGY SECTION
SUBMITTED: CHIEF, PLANNING BRANCH
RECOMMENDED: CHIEF, ENGINEERING DIVISION
APPROVED: COLONEL, CORPS OF ENGINEERS DISTRICT ENGINEER
DRAWN BY: R.T.D.
TRACED BY: R.U.
CHECKED BY: M.L.
TRANSMITTED WITH REPORT DATED DEC. 15, 1955

CU-20-2/12

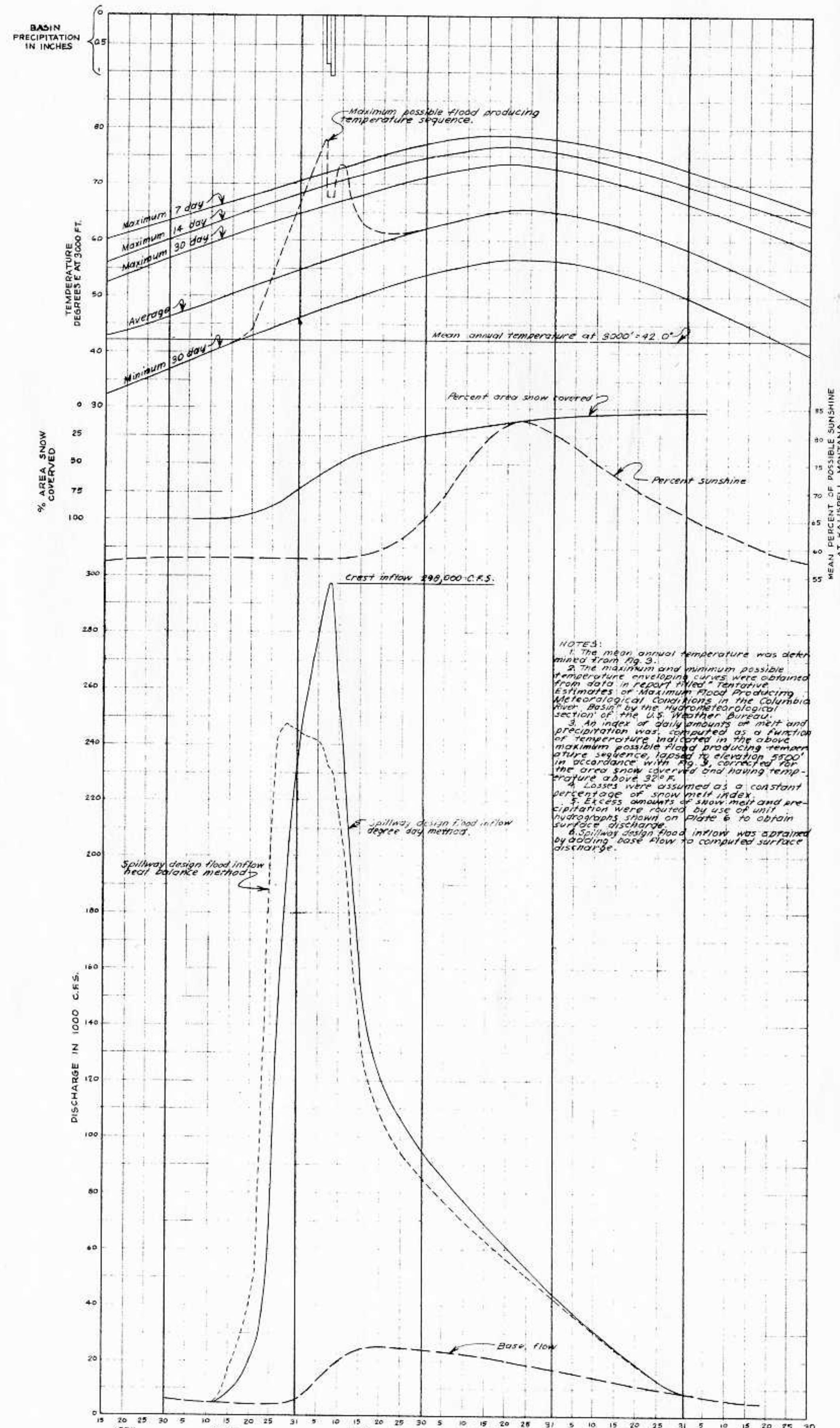


FIG. 1 SPILLWAY DESIGN FLOOD INFLOW TO LIBBY RESERVOIR

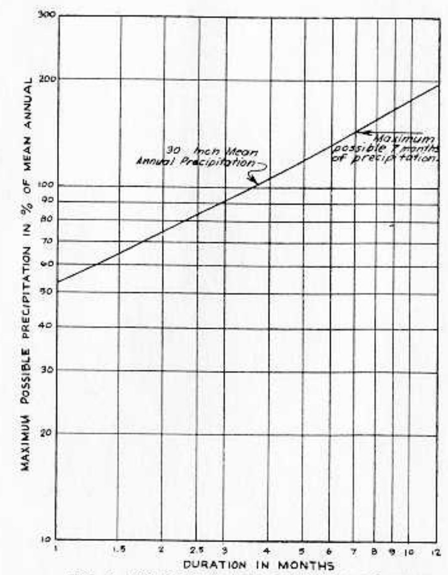


FIG. 2 PRECIPITATION DURATION CURVE

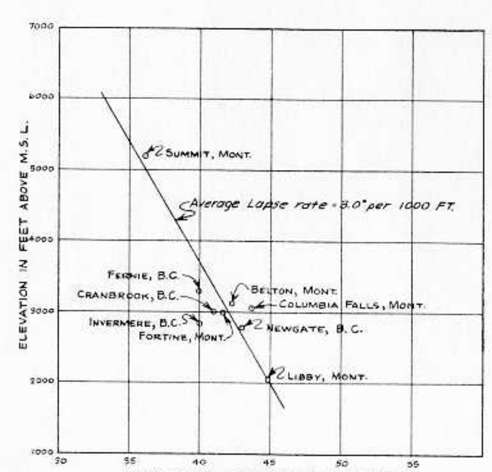


FIG. 3 TEMPERATURE-ELEVATION CURVE

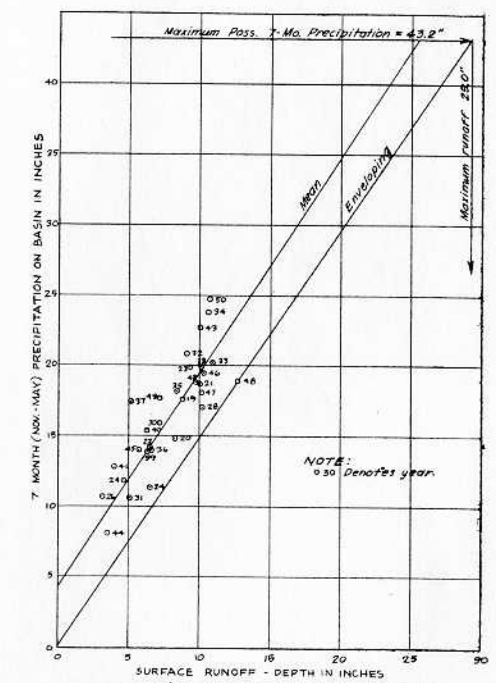


FIG. 4 PRECIPITATION RUN-OFF CURVE

KOOTENAI RIVER, MONTANA
LIBBY PROJECT

SPILLWAY DESIGN FLOOD INFLOW

In 1 Sheet — Sheet No. 1 — Scale: As Shown
Seattle District, Seattle, Washington — 29 July 1952

Prepared: — Submitted:

Recommended: — Approved:

Chief, Planning and Reports Branch — Chief, Engineering Division

Drawn by: M.E.T.
Traced by: W.E.L. — Transmitted with report dated 29-July-1952
Checked by: M.E.T.

File No. E-53-3-8