Chapter 10
Snowmelt Runoff Analysis for Engineering and Forecasting Applications

10-1. Problem Definition, Selection of Methodology

a. General. This chapter will discuss the practical aspects of analyzing snowmelt runoff for specific applications normally encountered within USACE. Discussed are the considerations needed in deciding on the methodology to use, the degree of detail with which snowmelt is to be analyzed, the selection of the modeling approach that should be used, and specifics of the analysis and simulation for specific applications. EM 1110-2-1417, Flood Runoff Analysis, contains a discussion of developing a hydrological engineering investigation in concert with the stage of planning and design.

b. Overview of applications and approaches. There are numerous alternatives for determining the best approach for computing snowmelt in hydrologic engineering analysis and forecasting. These range from simplified assumptions on discrete storm events to detailed simulation using energy budget principles and a distributed definition of the watershed. The choice depends on the degree of detail called for, the degree to which snow is a factor in affecting runoff, the resources available to do the analysis or maintain operational-forecasting capability, and data availability. For applications involving snowmelt, the choice for analysis is complicated by the need to consider a more detailed basin definition than for rain only, and by the range of options to consider in computing snowmelt. Table 10-1 summarizes some possible analysis alternatives and how they relate to given types of applications.

c. Selection of models. Chapter 11 contains summary guidance that will help with the selection of hydrologic models currently available for use in analysis and forecasting, and Appendix F presents detailed descriptions of the computer models. It is well to remember that successful application of a model depends upon the skill and knowledge of the user and a thorough understanding of the physical processes involved.

Table 10-1
Snowmelt Options[1]

		Basin Configuration		Melt Calculation			
Application	Example	Lumped	Distributed	Snow Conditioning	Simplified[2]	Temperature Index	Energy Budget
Single-event analysis- Rain-on-snow	Hypothetical floods in coastal mountains	Yes	Possibly	Assumed "ripe"	Possibly	Possibly	Possibly
Single-event analysis- Snow (plus rain)	Hypothetical floods in interior basins	Yes	Yes	Assumed "ripe"	No	Yes	Yes
Single-event forecasting- Rain-on-snow	Short-term flood forecasting	Yes	Yes	Optional	Possibly[3]	Yes	No
Single-event forecasting- Snow (plus rain)	Short-term flood forecasting	Yes	Yes	Optional	No	Yes	No
Continuous simulation, any environment	Long-term flood and drought forecasting; detailed design analysis	No	Required	Required	No	Yes	Possibly
Detailed simulation in small watersheds	R&D applications; analysis for detailed design; special applications	No	Required	Required	No	No	Yes

[1] Qualitative indicator shown for type of option that might typically be used for application. This is a guideline only. “Yes” or “No” indicates suggested option.
[2] Simplified approach might be to assume a constant- or variable-moisture input due to snowmelt.
[3] Would be appropriate only in situations where snowmelt is small compared with rain.

10-2. Hypothetical Floods

Developing a hypothetical flood entails using a hydrological model of some type to generate a streamflow hydrograph, given rain and snowmelt input of a specified magnitude. Two examples might be floods of estimated frequency for an ungauged area, using rainstorms of specified frequency for input, and an inflow design flood (IDF) for a proposed or existing dam, using probable maximum precipitation (PMP) as input. If snow is involved, then the decision must be made as to how snowmelt runoff is best computed, given the application being used and the range of alternative methodologies summarized on Table 10-1. In the following paragraphs, some alternative methods with varying complexity are described and two examples are given.

a. Simple approaches. In certain situations, a simple method for snowmelt runoff may be entirely satisfactory or, in fact, be required. A basin with rain on snow, in which rainfall is the dominant source of runoff during a flood, would not need snowmelt to be computed with a lot of detail, particularly in early stages of project planning. At its simplest, an assumed fixed rate of melt could be added to rainfall, or a variable rate could be estimated independently on the basis of a temperature-index approach. The snow could be considered fully primed prior to the onset of rain, and an adequate initial amount of SWE could be assumed available to contribute fully to the flood peak. These assumptions should be verified with an investigation of historical flood patterns and perhaps some sensitivity testing.

b. Example of a 100-year flood derivation, event-type model. The following is a hypothetical problem that uses a lumped-event model to derive a design flood. In this example, the temperature-index method is used to compute snowmelt, but the melt-rate factor was carefully estimated using the energy budget equation, and this factor was checked for sensitivity in affecting the outcome.

(1) Setting. This is assumed to be an ungauged watershed in which a synthetic unit hydrograph has been derived. A 100-year flood is to be derived for a reconnaissance study by using a 100-year storm taken from *NOAA Atlas II*. The only data on snow are based on nearby weather records that show that as much as 50.8 cm (20 in.) of snow has accumulated in midwinter. An average snow depth of 45.7 cm (18 in.) is assumed for the basin as an average. With an assumed snow density of 20 percent, this yields an initial SWE of 9.1 cm (3.6 in.). Table 10-2 is a summary of the initial assumptions for this problem.

Table 10-2
Summary of Input for Design Flood Derivation, Simple Approach

Item	Description
Drainage area	75 km (29 miles^2)
Forest cover	25 percent
Snyder's IUG[1] coefficients	$T_p = 2.1$; $C_p = 0.40$
Computation interval	1 hr
24-hr precipitation	9.4 cm (3.7 in.)
Maximum hourly precipitation	1 cm (0.4 in.)
Loss rate	Constant: 0.1 cm (0.04 in.)/hr
Initial snow depth	45.7 cm (18 in.) (basin mean)
Initial density	20 percent
Computed initial SWE	9.1 cm (3.6 in.)
Maximum air temperature	12 °C (54 °F) mid elev of basin
Snow condition	Assumed ripe

[1] IUG = Instantaneous Unit Graph.

(2) Melt determination. For this derivation, the temperature index approach will be used in computing hourly snowmelt. Since the basin is relatively open and subject to high-condensation melt, the melt-rate coefficient must be chosen carefully. This is done using Equation 5-19. With T_a = 12 °C (54 °F), v = 24 km/hr (15 mph), P_r = 8.9 cm (3.5 in.), and k = 0.7, the 24-hr snowmelt would be about 8.1 cm (3.2 in.). This suggests a value for C_m of 0.13 to 0.16 in Equation 6-1, using a base temperature of 0 °C (32 °F). A coefficient of 0.14 will be used initially and a sensitivity test done to see its relative influence. A temperature sequence for the storm will begin at near freezing and increase to the maximum in time to produce maximum melt that contributes to the flood peak.

(3) Model output. HEC-1 was used to simulate the conditions described above. Figure 10-1 is a listing of the output. A peak flow of 175.6 cu m/s (6200 cfs) results from the conditions assumed. Figure 10-2 is a plot of the hydrograph.

(4) Analysis of results. Several simulations were made with varying melt-rate factors. The results are shown on Figure 10-3. An incremental change in C_m by 0.02 results in about a 5- to 6-percent change in the peak of the design flood. The assumed melt-rate coefficient of 0.14 seemed reasonable for the physical conditions involved and for the design flood magnitude being derived. The initial SWE assumption of 9.1 cm (3.6 in.) was verified by inspection. There was approximately 4.8 cm (1.9 in.) of snowmelt before the maximum moisture input to the flood, indicating that the SWE could be reduced by 60 percent and still be fully contributing to the peak of the flood.

c. Detailed analyses. A more thorough analysis than discussed above would be required for detailed design studies and certain operational studies. Elements that would be required in a detailed study that are not reflected in the above example could include the following.

(1) Distributed modeling. This is generally used for rain-on-snow situations. For some spring-summer snowmelt areas, where summer rainfall is not highly significant, it may be possible to use a snow cover depletion curve as described in Chapter 8.

(2) Use of energy budget equations. If snowmelt is significant in influencing the magnitude of the flood peak, then energy budget equations should be used for computing it. This is necessitated by the need to better quantify the melt-rate magnitude as a function of the physical elements involved.

(3) Continuous simulation modeling. For settings requiring lengthy periods of simulation (e.g., spring-summer snowmelt), evapotranspiration and other factors should be taken into account.

(4) Model calibration. The problem with calibration using energy budget equations is finding the necessary solar radiation, wind, dew point, and temperature data that are required. A partial solution would be to employ the temperature-index methodology to calibrate the soil-moisture accounting and runoff-transformation portion of the model, using an extended period of record. The energy budget factors could then be calibrated on a shorter period of record or for a portion of the basin for the more difficult to obtain data. This would require a computer model that has the option of using both a temperature and energy budget approach in computing snowmelt.

(5) Thorough analysis of initial snowpack conditions. Where snowmelt volume is a dominant factor in determining the magnitude of the design flood, the initial size of the snowpack must be carefully derived. This implies using an independent statistical analysis of historical data, a special hydrometeorological analysis for extreme flood derivations, or continuous simulation during the winter-accumulation season for a period that spans enough years of record to provide a viable statistical sample. In addition to snowpack volume, the horizontal and vertical distributions need to be derived. Snow-condition effects also need to be developed, at least for rain-on-snow conditions. For spring snowmelt flood derivations, a ripe initial snowpack can be assumed since flood simulations typically begin in early spring.

(6) Melt-sequence derivation. The meteorological factors that are used as independent variables for computing melt must be carefully derived on the basis of historical sequences, using a degree of maximization appropriate for the design flood magnitude.

(7) Thorough analysis of rain-on-snow variations. Virtually every climatic region experiences a mixture of rain-on-snow alternatives, be it during the winter where rain dominates or during the springtime when rain may or may not be a significant factor in defining the design flood. The rainstorm magnitude and areal extent must be carefully developed, considering the relative magnitude of the design flood, ensuring that an appropriate combined probability of occurrence is reflected in the snow and rainfall combination.

d. Optimal conditions for probable maximum floods. Following standard USACE guidance, a PMF derivation requires maximization of the flood's components so that the resulting flood runoff is the

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                                   HYDROGRAPH AT STATION      1

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 DA   MON HR   ORD  PRECIP   TEMP  SNOMELT  SNOLOSS  SNOEXCS  RAIN  RAINLOS  RAINEXS SNO+RAIN  LOSS  EXCESS  COMP Q

 25  DEC 0000    1    0.00   40.0     0.00     0.00     0.00  0.00     0.00     0.00     0.00  0.00    0.00      20
 25  DEC 0100    2    0.00   41.0     0.04     0.04     0.01  0.00     0.00     0.00     0.04  0.04    0.01      27
 25  DEC 0200    3    0.00   42.0     0.05     0.04     0.01  0.00     0.00     0.00     0.05  0.04    0.01      55
 25  DEC 0300    4    0.00   43.0     0.06     0.04     0.02  0.00     0.00     0.00     0.06  0.04    0.02     102
 25  DEC 0400    5    0.00   44.0     0.06     0.04     0.03  0.00     0.00     0.00     0.06  0.04    0.03     163
 25  DEC 0500    6    0.00   45.0     0.07     0.04     0.03  0.00     0.00     0.00     0.07  0.04    0.03     235
 25  DEC 0600    7    0.00   46.0     0.07     0.04     0.04  0.00     0.00     0.00     0.07  0.04    0.04     315
 25  DEC 0700    8    0.08   46.7     0.08     0.02     0.06  0.08     0.02     0.06     0.16  0.04    0.12     482
 25  DEC 0800    9    0.09   47.3     0.08     0.02     0.06  0.09     0.02     0.07     0.17  0.04    0.13     807
 25  DEC 0900   10    0.09   48.0     0.08     0.02     0.07  0.09     0.02     0.07     0.17  0.04    0.14    1180
 25  DEC 1000   11    0.10   48.7     0.09     0.02     0.07  0.10     0.02     0.08     0.19  0.04    0.15    1507
 25  DEC 1100   12    0.10   49.3     0.09     0.02     0.08  0.10     0.02     0.08     0.19  0.04    0.16    1798
 25  DEC 1200   13    0.11   50.0     0.10     0.02     0.08  0.11     0.02     0.09     0.21  0.04    0.17    2061
 25  DEC 1300   14    0.11   50.7     0.10     0.02     0.08  0.11     0.02     0.09     0.21  0.04    0.17    2303
 25  DEC 1400   15    0.13   51.3     0.10     0.02     0.09  0.13     0.02     0.11     0.23  0.04    0.20    2538
 25  DEC 1500   16    0.14   52.0     0.11     0.02     0.09  0.14     0.02     0.12     0.25  0.04    0.21    2789
 25  DEC 1600   17    0.22   52.7     0.11     0.01     0.10  0.22     0.02     0.20     0.33  0.04    0.30    3125
 25  DEC 1700   18    0.25   53.3     0.12     0.01     0.10  0.25     0.02     0.23     0.37  0.04    0.33    3610
 25  DEC 1800   19    0.26   54.0     0.12     0.01     0.11  0.26     0.02     0.24     0.38  0.04    0.34    4160
 25  DEC 1900   20    0.31   54.0     0.12     0.01     0.11  0.31     0.03     0.28     0.43  0.04    0.39    4703
 25  DEC 2000   21    0.40   54.0     0.12     0.01     0.11  0.40     0.03     0.37     0.52  0.04    0.48    5338
 25  DEC 2100   22    0.30   54.0     0.12     0.01     0.11  0.30     0.03     0.27     0.42  0.04    0.38    5967
 25  DEC 2200   23    0.16   54.0     0.12     0.02     0.10  0.16     0.02     0.14     0.28  0.04    0.24    6196
 25  DEC 2300   24    0.12   54.0     0.12     0.02     0.10  0.12     0.02     0.10     0.24  0.04    0.20    5937
 26  DEC 0000   25    0.12   54.0     0.12     0.02     0.10  0.12     0.02     0.10     0.24  0.04    0.20    5507
 26  DEC 0100   26    0.11   52.7     0.11     0.02     0.09  0.11     0.02     0.09     0.22  0.04    0.19    5112
 26  DEC 0200   27    0.11   51.3     0.10     0.02     0.09  0.11     0.02     0.09     0.21  0.04    0.18    4760
 26  DEC 0300   28    0.11   50.0     0.10     0.02     0.08  0.11     0.02     0.09     0.21  0.04    0.17    4443
 26  DEC 0400   29    0.10   48.7     0.09     0.02     0.07  0.10     0.02     0.08     0.19  0.04    0.15    4154
 26  DEC 0500   30    0.09   47.3     0.08     0.02     0.06  0.09     0.02     0.07     0.17  0.04    0.13    3865
 26  DEC 0600   31    0.08   46.0     0.07     0.02     0.06  0.08     0.02     0.06     0.15  0.04    0.12    3565
 26  DEC 0700   32    0.00   45.0     0.07     0.04     0.03  0.00     0.00     0.00     0.07  0.04    0.03    3187
 26  DEC 0800   33    0.03   44.0     0.06     0.02     0.04  0.03     0.01     0.02     0.09  0.04    0.06    2721
 26  DEC 0900   34    0.01   43.0     0.06     0.03     0.02  0.01     0.01     0.00     0.07  0.04    0.03    2292


          EXPLANATION OF CODES

      DA MON HRMN: DAY, MONTH, HOUR, MINUTE
              ORD: ORDINATE NUMBER
           PRECIP: PERIOD PRECIPITATION, in
             TEMP: PERIOD TEMPERATURE, , degrees F
          SNOMELT: COMPUTED PERIOD SNOWMELT, in
          SNOLOSS: COMPUTED PERIOD SNOWMELT LOSS, in
          SNOEXCS: PERIOD SNOWMELT EXCESS, in
             RAIN: BASIN PERIOD RAINFALL, in
          RAINLOS: COMPUTED PERIOD RAIN LOSS, in
          RAINEXS: COMPUTED PERIOD RAINFALL EXCESS, in
         SNO+RAIN: TOTAL OF SNOWMELT PLUS RAINFALL FOR PERIOD, in
             LOSS: TOTAL OF SNOW LOSS AND RAIN LOSS FOR PERIOD, in
           EXCESS: TOTAL OF SNOW EXCESS AND RAIN EXCESS FOR PERIOD, in
           COMP Q: COMPUTED DISCHARGE FOR PERIOD, cfs
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Figure 10-1. HEC-1 output

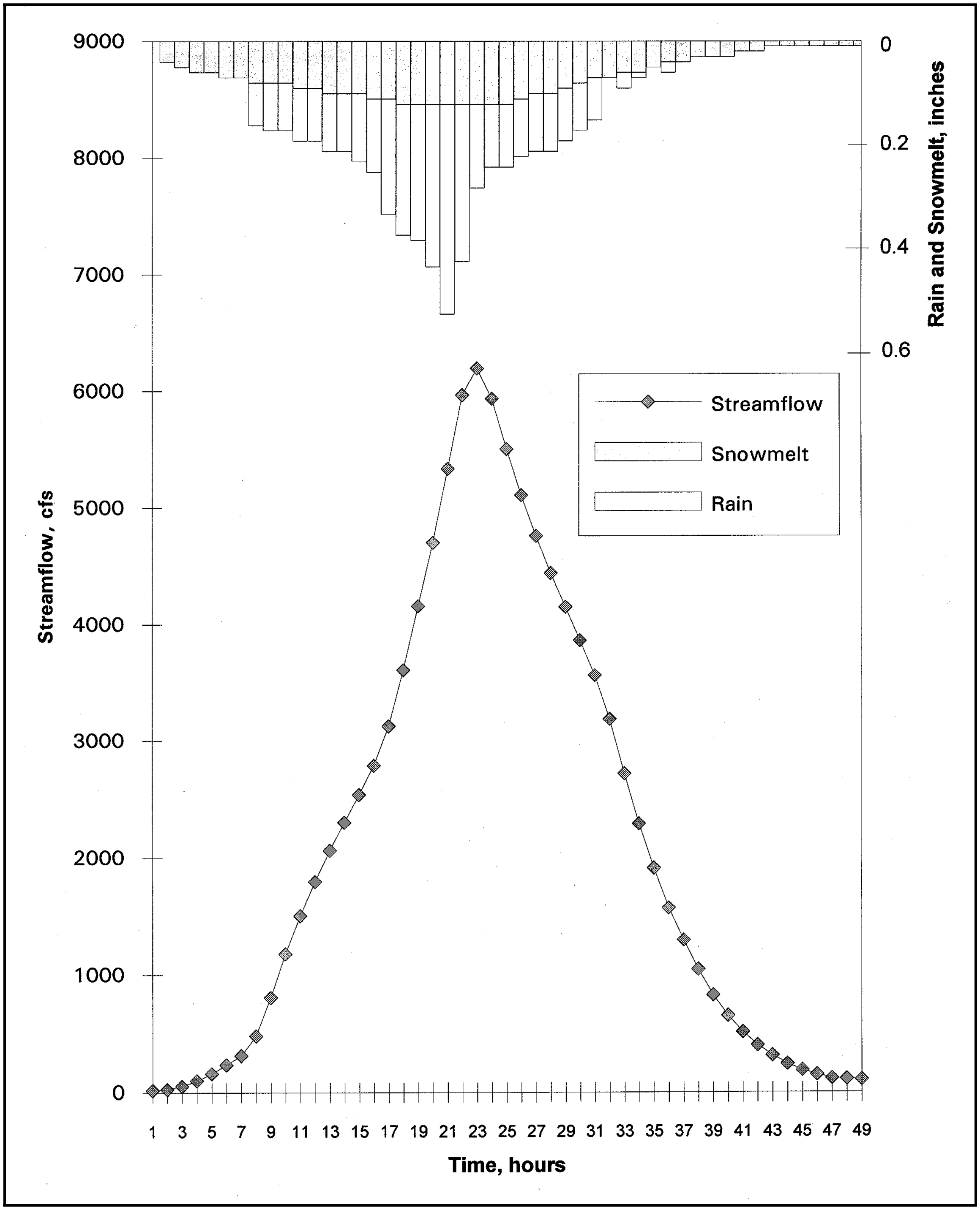


Figure 10-2. Plot of example design flood

maximum reasonably possible for a given basin. For snowmelt regimes, the components discussed below must be examined and maximized. The temperature index cannot be relied upon for a PMF derivation because of the lack of uniformity among basins of different environments, the significant changes in snowmelt rates that may take place within a given basin because of factors other than air temperature, and the danger of extrapolating to conditions beyond the limits to which the index applies.

Cm in/degF	Max Melt in	Peak kcfs
0.08	0.07	5.3
0.10	0.09	5.6
0.12	0.10	5.9
0.14	0.12	6.2
0.16	0.14	6.5
0.18	0.15	6.8
0.20	0.17	7.1

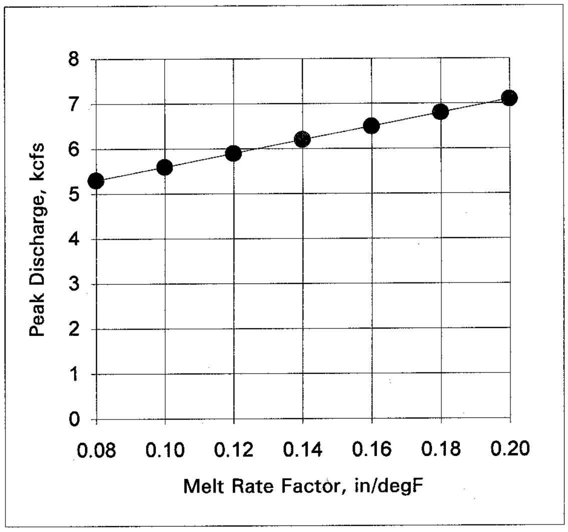


Figure 10-3. Sensitivity of melt-rate factor

(1) Optimal snowpack conditions. For spring-summer PMFs, the maximum possible SWE is usually derived from detailed studies of potential total-winter precipitation. The studies may use derived relationships in which the extreme can be readily inferred and generalized; i.e., maximum winter-season precipitation versus drainage and normal annual precipitation. For rain-on-snow conditions, it is usually assumed that sufficient water equivalent exists to provide snowmelt continuously through the rainstorm. A conservatively high assumption about snow condition is also appropriate; typically, an antecedent storm is assumed, so this would lead to ripe or nearly ripe snowpack conditions for the PMF itself.

(2) Optimal snowmelt conditions. For spring-summer snowmelt floods, the critical flood-producing meteorological conditions are those in which the winter snowpack accumulates with no significant melt, followed by a cold spring with minimum snowmelt and a continued increase in the snowpack. After the maximum snowpack has accumulated, there is a conditioning period during which the melt is moderate; the snowpack and underlying soil are conditioned to produce maximum runoff throughout the basin, and the snow-surface albedo may approach its minimum value. Finally, the meteorological factors affecting snowmelt are allowed to increase to their maximums, at a time when the heat input to the basin can be near its seasonal maximum. The prolonged period of continuous high-heat input is important in producing the maximum flood peak. Then, the runoff rates may approach the snowmelt rates for the snow-covered area, contributing to runoff at the time of the flood peak as an equilibrium inflow-outflow condition.

(a) The meteorological components used in the energy budget equations depend upon the degree of forest cover, as outlined in Chapter 5. The various components must be maximized individually using historical records as a guide. Examples of derived meteorological factors are given in the example below.

(b) For rain-on-snow settings, the temperature and wind-velocity time series during the rainstorm are again determined by considering historical conditions and extrapolating to reasonable maximum characteristic values.

(3) Optimal snow and rain combinations. The PMF derivation needs to have examined alternative possibilities for rain-snow combinations, most likely by simulating alternative scenarios. For spring-summer events, the critical combination is likely to be a large snowpack combined with a maximum melt sequence that is interrupted by a spring rainstorm. However, it may be unreasonable to maximize all these components, so a decision needs to be made

about which factor should be the dominant one in creating the PMF. Bearing on this is whether volume of runoff is a critical factor, as it might be for an IDF for a large reservoir or system of reservoirs.

(a) For instance, a maximized snowpack in conjunction with a severe but not maximized spring rainstorm may produce a flood with lower peak but higher volume than if a lower snowpack with a maximized spring rainfall were used. The former may be more critical for a large storage reservoir, while the latter would be appropriate for projects having less storage. A factor to consider in this analysis is whether the storage can be assumed to be fully available. The standard practice is to assume water supply forecasts will be accurate enough to dictate maximum drawdown prior to the flood—given that a large enough snowpack is involved. However, outlet and downstream channel conditions that might restrict drawdown rates under the generally wet winter conditions that would be associated with the PMF need to be considered.

(b) For rain-on-snow regimes, determining the rain-snow combination is less problematic. With rainfall dominating in governing the flood peak and volume, the SWE magnitude and temperature sequence would not be extrapolated to maximum values, but might still represent a relatively high probability of occurrence.

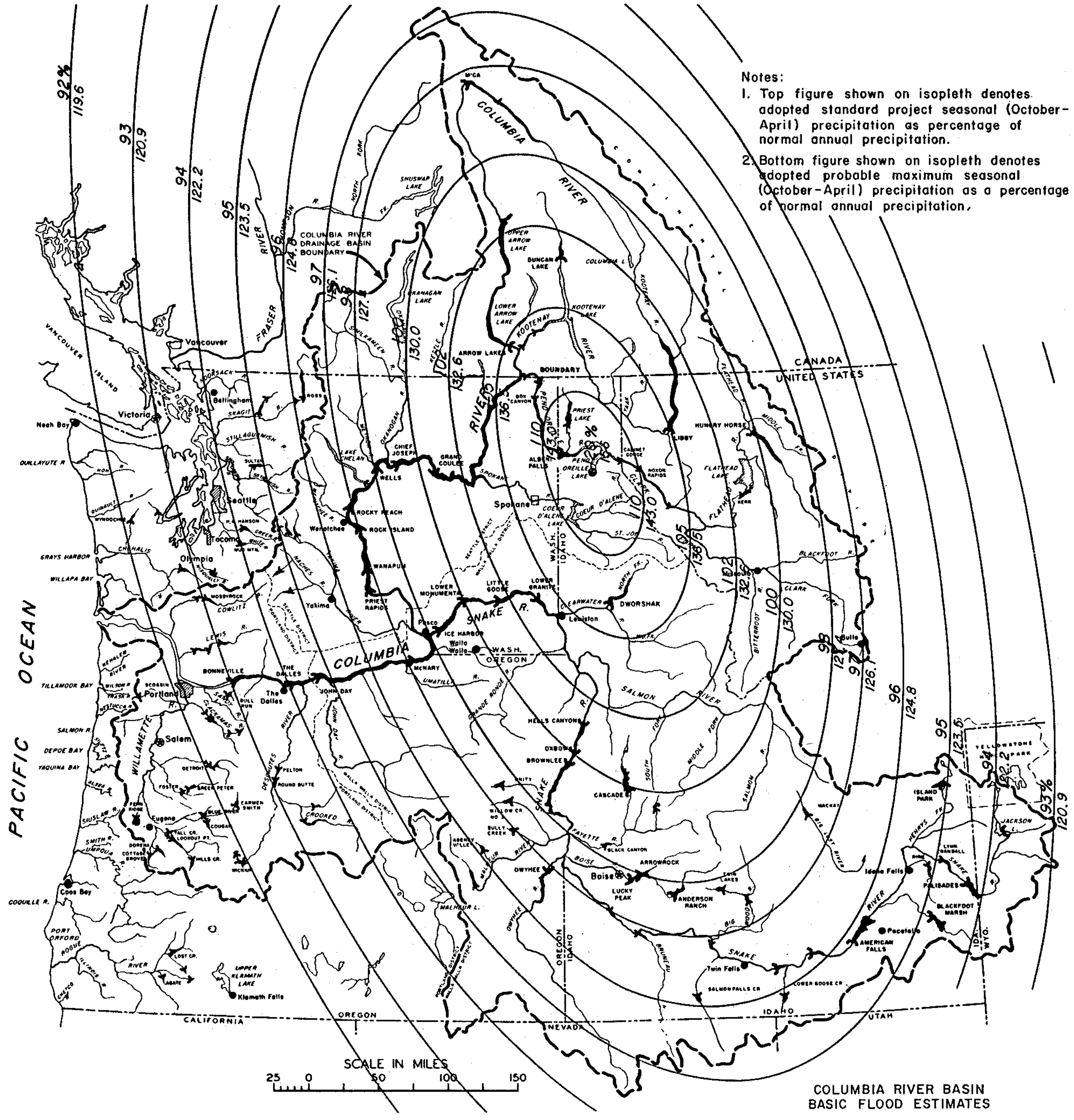
e. Example of detailed flood derivation. The following example is taken from a PMF study for the Columbia River Basin by the North Pacific Division, with assistance from the Hydrologic Engineering Center (USACE 1969). In this study the SSARR model was used to simulate the design flood for the entire basin at the site of Bonneville Dam (673 395 square kilometers (260 000 square miles)). The flood resulted from a maximized winter accumulation of snow combined with a critical sequence of spring temperatures interrupted by two spring rainstorms. Flood-control storage space was available in upstream storage reservoirs at the beginning of the flood, and the flood was regulated as much as possible by these projects according to a predetermined operating plan. A detailed explanation of the work is given in the 1969 report. Excerpts from that report are shown below as a general illustration of the concepts involved.

(1) Winter snow accumulation. A comprehensive study was undertaken to determine the initial SWE for the snowmelt runoff simulation. Precipitation frequency curves were developed for the October-April period for 54 stations in the basin, and from these, 100-year values were computed. Several approaches were then investigated for determining a relationship between the 100-year depth for subbasin areas as a function of the 100-year depth for the total drainage. An elliptical isopercental pattern for the 7-month precipitation was also derived, as shown on Figure 10-4. Then, using both statistical and hydrometeorological methods, a value representing the total basin PMP was adopted—this was established as 130 percent of the NAP. This value could then be distributed to subbasins using the isopercental pattern and the drainage area-precipitation depth relationship.

(2) Snowmelt calculation. The generalized energy budget equation for snowmelt in partly forested areas (Equation 5-25) was used for all subbasins. This required the derivation of time series for several meteorological variables during the 15 April through 31 July melt period. These variables were obtained by evaluating historical data and by referring to the snow investigations data and relationships.

(a) Examples of derived temperature and dew-point sequences are shown in Figure 10-5. The dew point was assumed to have a -9.4 °C (15 °F) depression from air temperature, except during the spring rainstorms, when this was reduced to -16.7 °C (2 °F). A lapse rate of -15.9 °C (3.3 °F) was used for both of these factors in applying them to different elevations in the basin.

(b) Solar radiation was computed as a sequence of daily averages with no attempt made to evaluate the slight variations with latitude within the basin. Except for the periods of rain and short transition periods, near-maximum values for the location, reflecting cloudless skies, were assumed to prevail. The adopted values of insolation were based on Figure D-8. An assumed albedo pattern decreasing from 80 percent in mid-April to 40 percent in July was derived. The shape of this function is based on snow investigations



Notes:

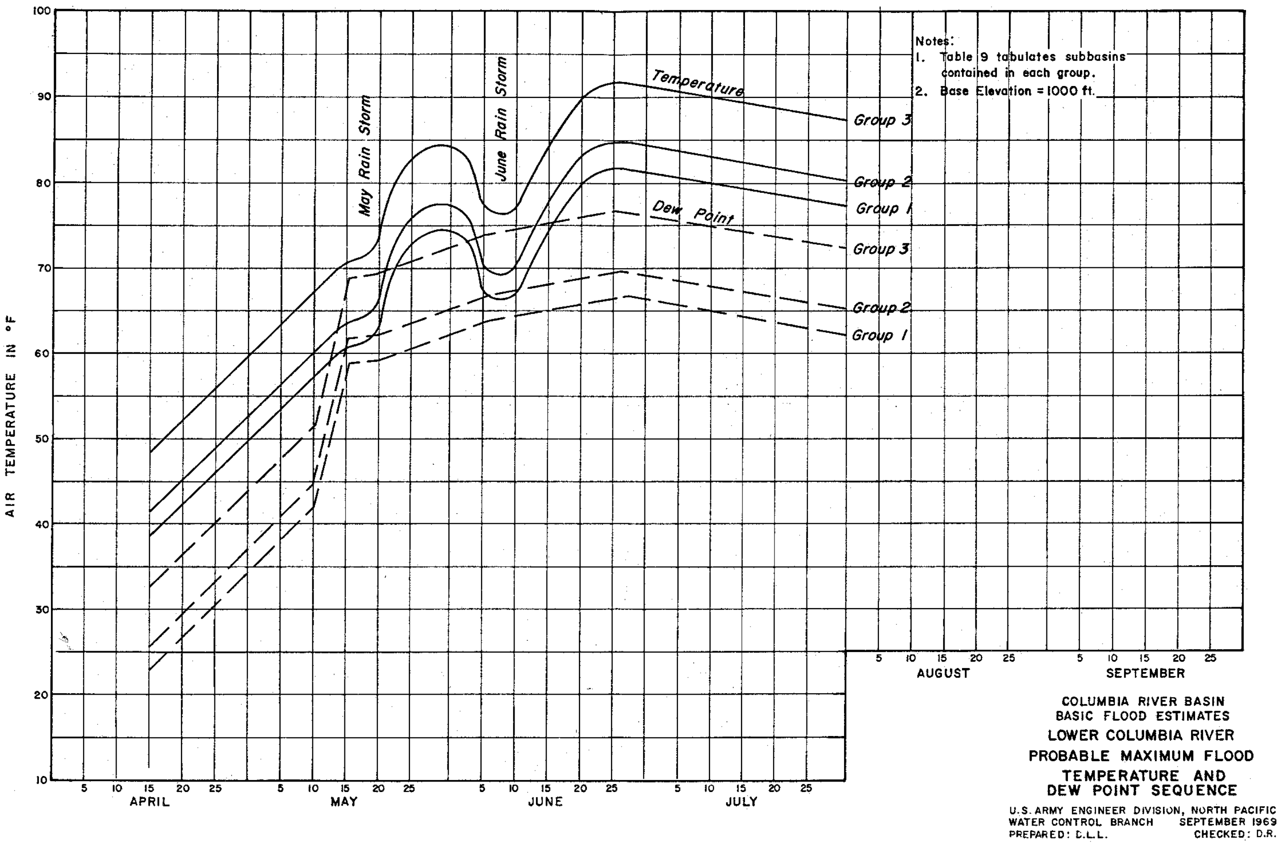
1. Top figure shown on isopleth denotes adopted standard project seasonal (October-April) precipitation as percentage of normal annual precipitation.
2. Bottom figure shown on isopleth denotes adopted probable maximum seasonal (October-April) precipitation as a percentage of normal annual precipitation.

COLUMBIA RIVER BASIN
BASIC FLOOD ESTIMATES

GEOGRAPHICAL DISTRIBUTION OF
STANDARD PROJECT AND PROBABLE
MAXIMUM SEASONAL PRECIPITATION

U.S. ARMY ENGINEER DIVISION, NORTH PACIFIC
WATER CONTROL BRANCH SEPTEMBER 1969
PREPARED: D.L.L. CHECKED: D.R.

Figure 10-4. Geographical distribution of Columbia River basin PMP



Notes:
1. Table 9 tabulates subbasins contained in each group.
2. Base Elevation = 1000 ft.

COLUMBIA RIVER BASIN
BASIC FLOOD ESTIMATES
LOWER COLUMBIA RIVER
PROBABLE MAXIMUM FLOOD
TEMPERATURE AND
DEW POINT SEQUENCE

U.S. ARMY ENGINEER DIVISION, NORTH PACIFIC
WATER CONTROL BRANCH SEPTEMBER 1969
PREPARED: D.L.L. CHECKED: D.R.

Figure 10-5. Temperature and dew-point sequence

data (Figure 5-5). The insolation and albedo patterns used in the study are shown on Figure 10-6.

(c) Wind velocity was assumed to be 24 km/hr (15 mph) at the 15.2-m (50-ft) level throughout the melt period, increasing to 48.3 km/hr (30 mph) during the two spring rainstorms.

(3) Spring rainstorms. Separate 3-day spring rainstorms were assumed for May and June. The depth for these storms was determined by subtracting October-April (and October-May) seasonal precipitation totals from October-May (and October-June) totals for each of the precipitation stations used in the analysis. These were normalized to percent of NAP for distribution throughout the basin. In effect, the monthly total was assumed to fall in the 3-day period. The two rainstorms are apparent in affecting the other meteorological variables in the above figures.

(4) Basin simulation. The model of the Columbia basin included 63 subbasin watersheds that fed runoff into an extensive river-reservoir simulation model. The river model included the effects of irrigation diversions, lakes, and reservoir operations. The resulting PMF at The Dalles Dam (613 830 square kilometers (DA = 237 000 square miles)) is shown on Figure 10-7.

10-3. Reservoir Regulation Studies

a. Overview. There are a variety of hydrological studies that may be required in support of a reservoir-regulation mission. Flood-control rule curves may need refining; new environmental regulations may require reconsidering of established rule curves; reallocating of storage may be proposed; forecasting procedures may need improving; etc. Such studies have the potential for requiring a relatively

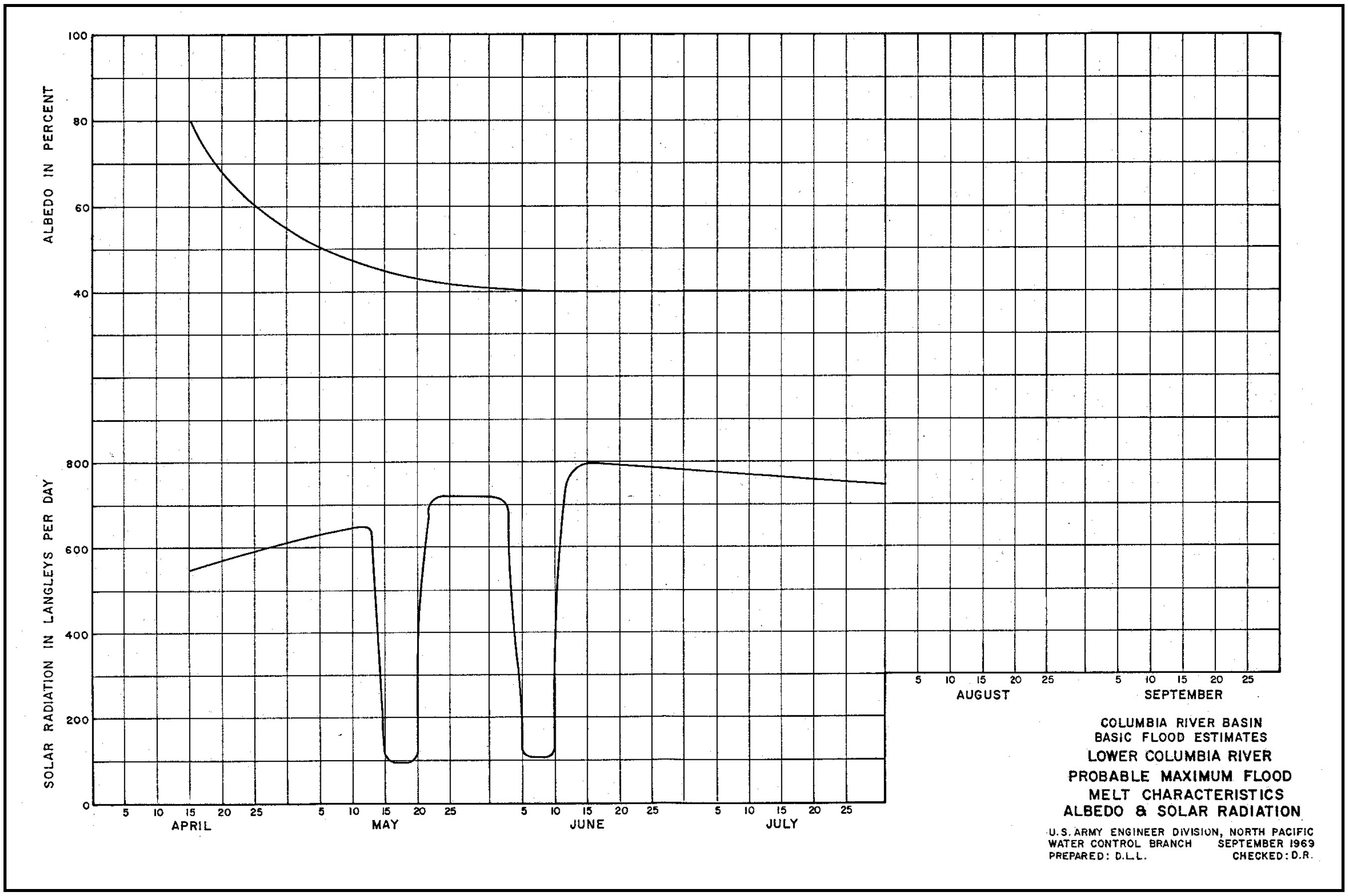


Figure 10-6. Solar radiation and albedo sequences

sophisticated study approach since regulation issues are often complex, involve significant project benefits, and have high public and political visibility. Because water-supply, as well flood-control, considerations may be involved, the use of continuous simulation modeling employing distributed models may be needed. In an environment with snowmelt, the following types of studies may be required.

(1) Water-supply forecasting. Water-supply forecasting procedures described in Chapter 9 may need developing or improving. It is common practice to update statistical procedures periodically to incorporate a larger statistical sample and make necessary corrections. If ESP procedures are to be used as described further in this chapter, continuous modeling is required.

(2) Streamflow forecasting. The development of streamflow forecasting models for guiding reservoir regulation can require extensive model calibration and testing and setting up of a real-time forecasting process if not already existing. The type of model structure would have to be decided upon depending upon the needs and type of snow environment (Chapter 4).

(3) Flood-control curves. Evaluation of flood-control rule curves may require specialized simulation studies that use more complex models for snowmelt runoff. An example of one such study is described below.

(4) Seasonal regulation studies. If operating guidelines are modified in any way, the effects of the changes need to be evaluated. This includes determining downstream flood-frequency curves and reservoir elevation-frequency curves, having the ability to meet desired operating objectives, etc. Typically, such studies use a reservoir system model,

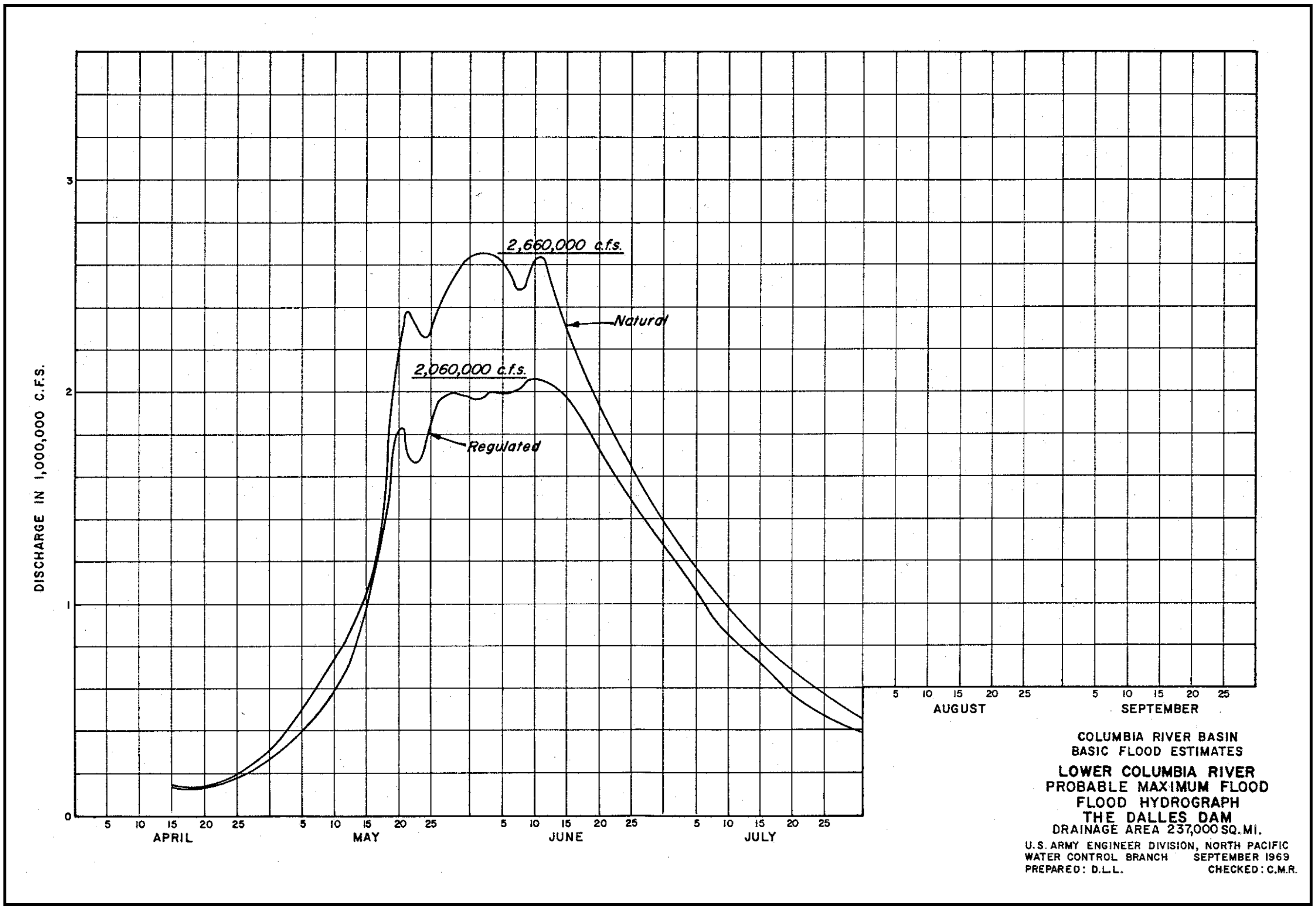


Figure 10-7. PMF, Columbia River at Dalles Dam

perhaps operating on a monthly time step, and using historical observed streamflow, rather than a runoff model. For flood-control evaluations, of course, a short-term computation interval is required. If the evaluation requires using synthetic hydrographs, then a snowmelt runoff model would be required. In reservoir studies for a snow environment, the ability to use water-supply forecasts in guiding reservoir drawdown would normally be assumed; however, a realistic portrayal of forecast error needs to be reflected in the studies. The assessment of this error itself requires a careful analysis.

b. Example of reservoir rule curve study. Snowmelt runoff modeling was employed in a 1987 analysis of rule curves for flood-control reservoirs in the Columbia River basin. In this area flood-control drawdown is based primarily upon water-supply forecasts using flood-control rule curves. These curves, however, include a factor of safety to account for unforecastable spring rainfall. The problem was to evaluate the magnitude of this factor of safety for all ranges of snow and rainfall magnitudes. There is limited historical experience of rain-on-snow events; several have happened, but in conjunction with larger snowpacks. Needed in this study was an evaluation of the effect of rain falling primarily on low snowpacks to ensure adequate flood control in low-snow conditions. This required the development of synthetic rain-on-snow combinations.

(1) For this analysis, a distributed (elevation-band) model, operated continuously through the year, was used. It was calibrated on the period of record, in most cases, using the temperature index for computing snowmelt. Several selected years, representing a range of snow-accumulation magnitudes, were used for the analysis, with emphasis placed on the

low-snow events. In a separate analysis, spring rainstorms were examined for depth, duration, and timing. Storms of specific frequency (100-year storms were used primarily) were derived using several different historical timing patterns. The synthetic floods were then created by simulating the known snowmelt situation with the several alternatives of possible 100-year spring rainfall imposed. Figure 10-8 is an example of four floods so derived, showing the historical reservoir inflow for a relatively low snowmelt year (1973) plotted against the synthetic floods.

(2) With knowledge of the potential reservoir inflow resulting from the spring rainfall, rule curves could be objectively established to make sure that storage space was available to contend with the spring rainfall and not change the overall downstream flood-control capability. This study resulted in a reduction in the flood-control requirement at several reservoirs for low snowpack conditions, which benefited operations for other project purposes. The existing and proposed flood-control rule curves are shown in Figure-10-9.

10-4. Operational Forecasting

a. Overview. Runoff and streamflow forecasting in a snowmelt regime is important for snowmelt runoff principles, primarily through the use of hydrological modeling. Since this takes place in real-time, instead of involving careful analysis of historical data and repeated computer simulations, some aspects of snow hydrology must be treated differently than they are in design applications. In this paragraph, those facets of operational forecasting that pertain to snow hydrology will be discussed.

b. Short-term forecasting. For this discussion, short-term forecasting is defined as making streamflow predictions for several days into the future using observed and forecasted precipitation and temperature. In addition to generating a streamflow time series for a given basin, the forecast may also include a river-reservoir system simulation that produces an outlook of lake and reservoir elevations, river elevations, etc., all based upon the watershed-simulation input. The following summarizes some key points to be aware of in a snow environment.

(1) Model formulation. The possibilities for alternative model configurations have been discussed in Chapter 4. Although a relatively thorough and complex model is always to be considered, practical problems with the forecasting environment may dictate the use of a simpler formula than the one that may have been used for design analysis. Since snowmelt applications deal with considerable topographical relief, some ability to define the vertical distribution is highly desired. Situations where a vertically lumped model might be used are as follows.

(a) Rain-on-snow basins with relatively low-snow contribution.

(b) Basins that are relatively flat.

(c) Spring snowmelt basins where rain is a minor factor.

(2) Time increment. The computational time step will typically be defined by the basin size and is often 3 to 6 hr for rain-on-snow settings and somewhat longer for large spring runoff basins. For large basins, the interval should not exceed 12 hr for near-term forecasts, if the diurnal melt variation is to be described adequately.

(3) Snowmelt method. A temperature index is used almost exclusively for forecasting, although wind and other data can help guide the use of this index, as has been discussed in Chapter 6.

(4) Temperature input. For spring snowmelt simulations, temperature becomes the key variable defining melt quantities. A period-average temperature is usually used for forecast model input. In rain-on-snow settings, temperature is extremely important in establishing the freezing level, which in turn defines at what elevation precipitation will be falling as rain or snow. Temperature observations and forecasts will also be used to compute snowmelt for the forecast. Temperatures established for a station need to be projected to other elevations within the basin using a lapse rate that also is subject to change over time.

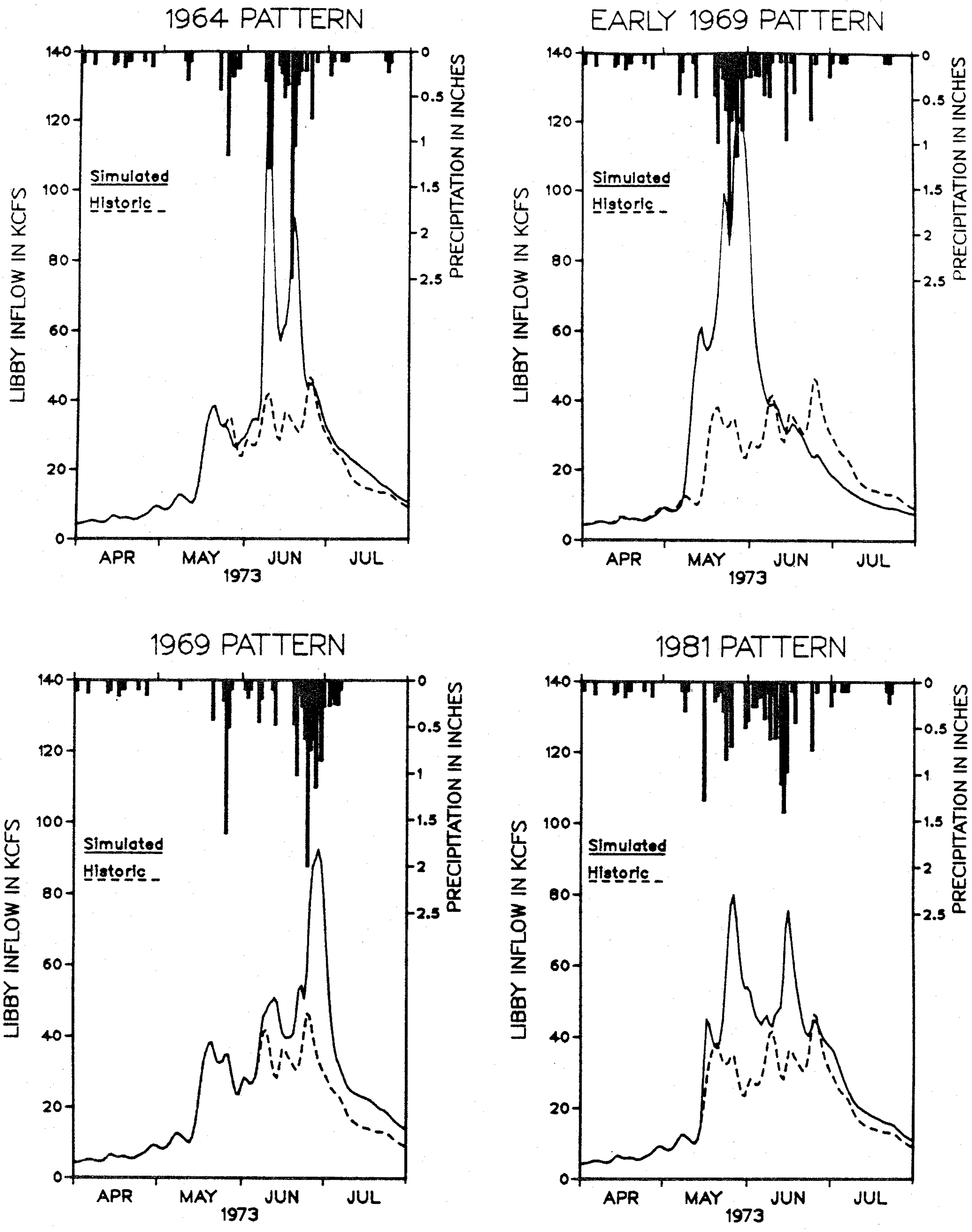


Figure 10-8. Hypothetical flood derivations, spring rain on snow

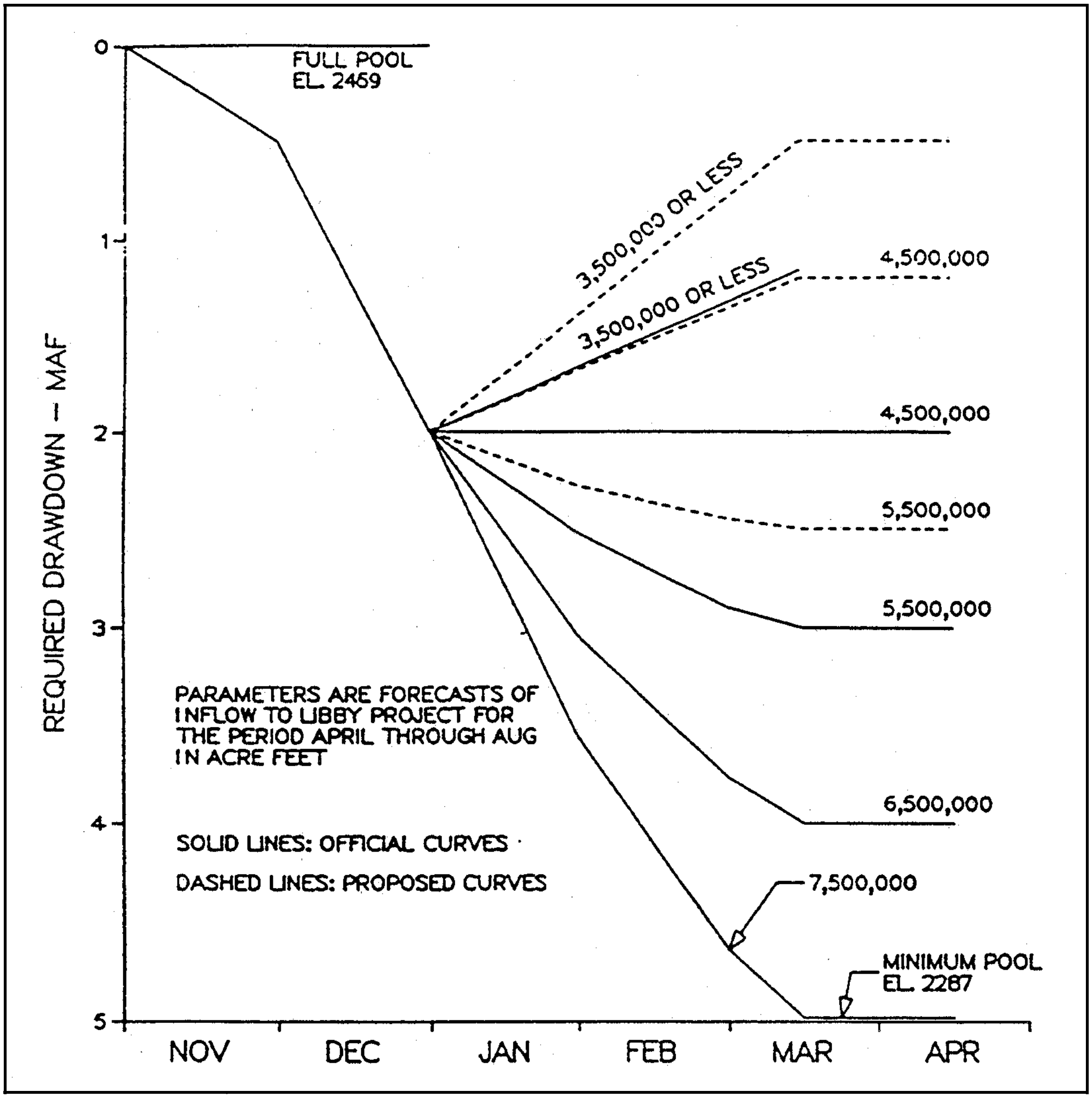


Figure 10-9. Comparison of original and revised rule curves, Libby project

(5) Rain input. For spring-summer flood basins, it may be possible to ignore light rainfall over snow-free areas, as discussed in Chapter 4.

(6) Snow-condition effects. This is often estimated intuitively by forecasters in a rain-on-snow setting rather than having it computed explicitly in the model. The effects on runoff are relatively small compared with other uncertainties, and they often occur early enough in the storm sequence so that they are of relatively minor importance for reservoir operations. In spring snowmelt, forecasting snow-condition effects are generally not a consideration.

c. Long-term forecasting. For this discussion, long-term forecasting is meant to include all forecasting extending beyond the above "short-term" definition. This would include seasonal-runoff-volume forecasts as well as streamflow forecasts extended over a long period of time. Since meteorological forecasting is not possible beyond several days into the future, long-term streamflow forecasts need to reflect hypothetical or probabilistic input. A special case of this type of forecast is ESP forecasting, discussed separately below.

(1) Figure 10-10 portrays a forecasting procedure employed in the Columbia basin, wherein a long-term extension is applied to a short-term forecast. The input for the long-term forecast is a hypothetical temperature sequence that has been determined by analysis of historical meteorological data. Alternative sequences with different characteristics can be used. The extended forecast is useful in guiding the operation of large storage reservoirs that fill over the April-July snowmelt period:

(2) The following are additional guidance for long-term forecasting

(a) Model formulation. Since simulation over a long-term period is involved, a model capable of handling evapotranspiration and other long-term effects is required.

(b) Time increment. Because of the hypothetical nature of the results, a longer computation time step is sometimes employed during the extended period.

(c) Snowmelt method. Since the long-range forecast extends into the late summer, the snowmelt methodology must have provision for automatically changing melt-rate coefficients as the season progresses.

(d) Temperature input. This is provided as a hypothetical time series as shown in the above example or as a series of historical traces as used in the ESP technique (described below). The hypothetical series could represent subjectively derived patterns, historical temperature (and precipitation) from notable historic events, or a series developed by a relatively sophisticated stochastic analysis.

(e) Rain input. In the Columbia example, long-term rainfall is ignored because it is usually unimportant. The results are used with the understanding that they contain some volumetric bias because of this assumption.

d. Extended streamflow-prediction technique. This technique, developed and called ESP by the National Weather Service Office of Hydrology, is widely used by forecasting and management agencies throughout the United States. It is particularly applicable in a snowmelt regime where the long-term storage effect of accumulated snow results in a definite association with runoff several months later. It entails simulating a sampling of historical meteorological time series every time the forecast is made—20 or 30 years of data would typically be used. Producing a seasonal snowmelt runoff forecast is illustrated in Figures 10-11 and 10-12. Early in the snow accumulation season, relatively little information about the year being forecasted has yet to be known, since only a small portion of the precipitation has accumulated for the year. The resulting display of model results has a large variance, not unlike the historical sampling of runoff data itself. As the season progresses, later forecasts take on the specifics of the year in question, and future variance created by the range of future meteorological possibilities diminishes. The ESP technique offers several advantages over other techniques in long-range forecasting.

- It is relatively rigorous, statistically.
- It permits a wide range of forecast products, including volume and peak flows.
- It provides error statistics and displays.

The drawback of the technique is that it uses considerable computer resources. On a large river with many subbasins, this drawback may preclude its use. ESP procedures require a continuous soil moisture accounting model that can operate through snow-accumulation periods as well as through extended periods of snowmelt.

10-5. Snow Modeling Considerations in Continuous Simulation

a. Overview. Continuous soil-moisture-accounting modeling is used regularly in snowmelt regimes, particularly in ESP forecasting and operational analysis. Because this modeling extends over long times, including the snow-accumulation period, additional facets of snow hydrology need to be considered beyond what is dealt with when modeling snowmelt only. The simulation process during snow

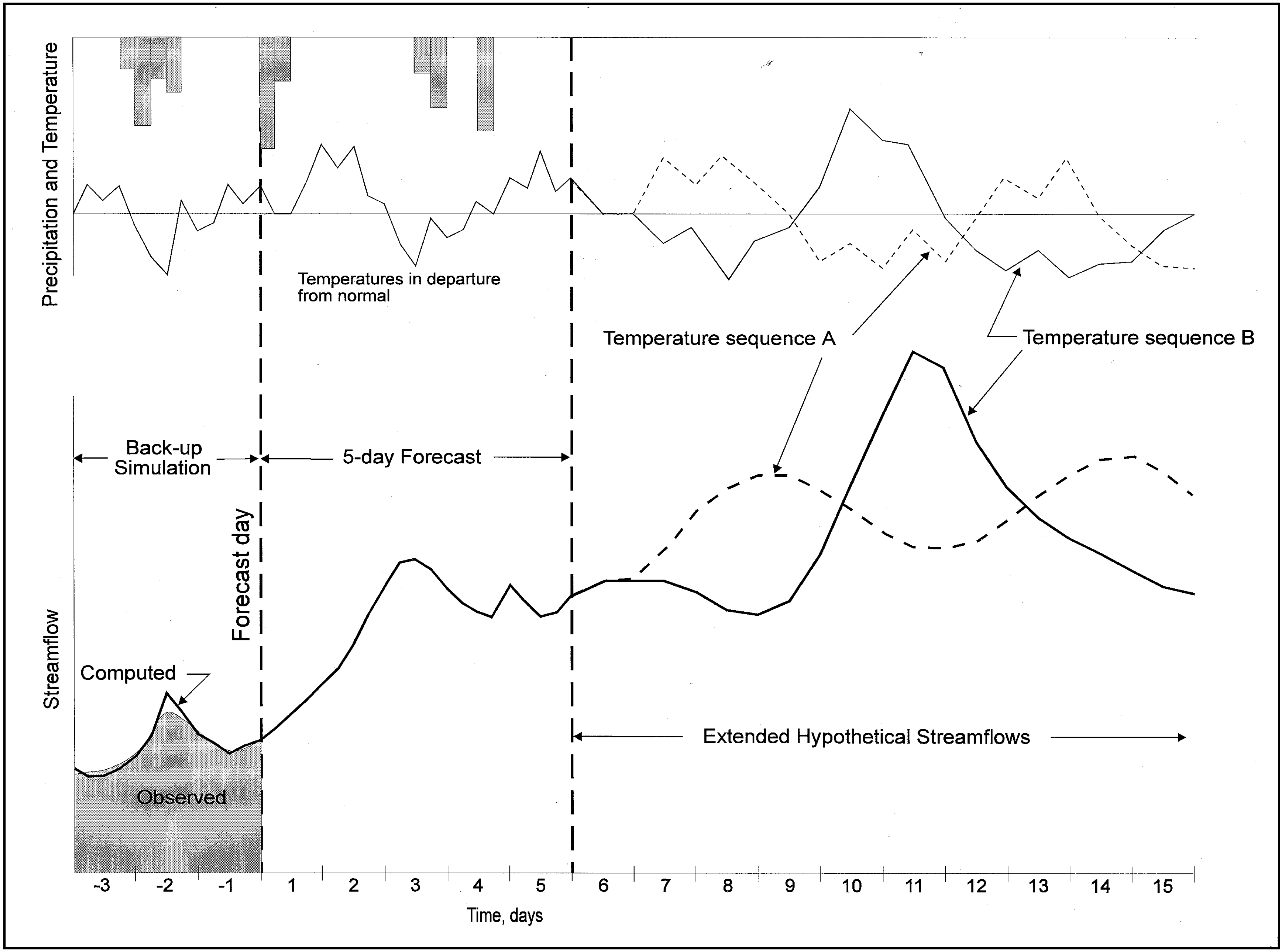
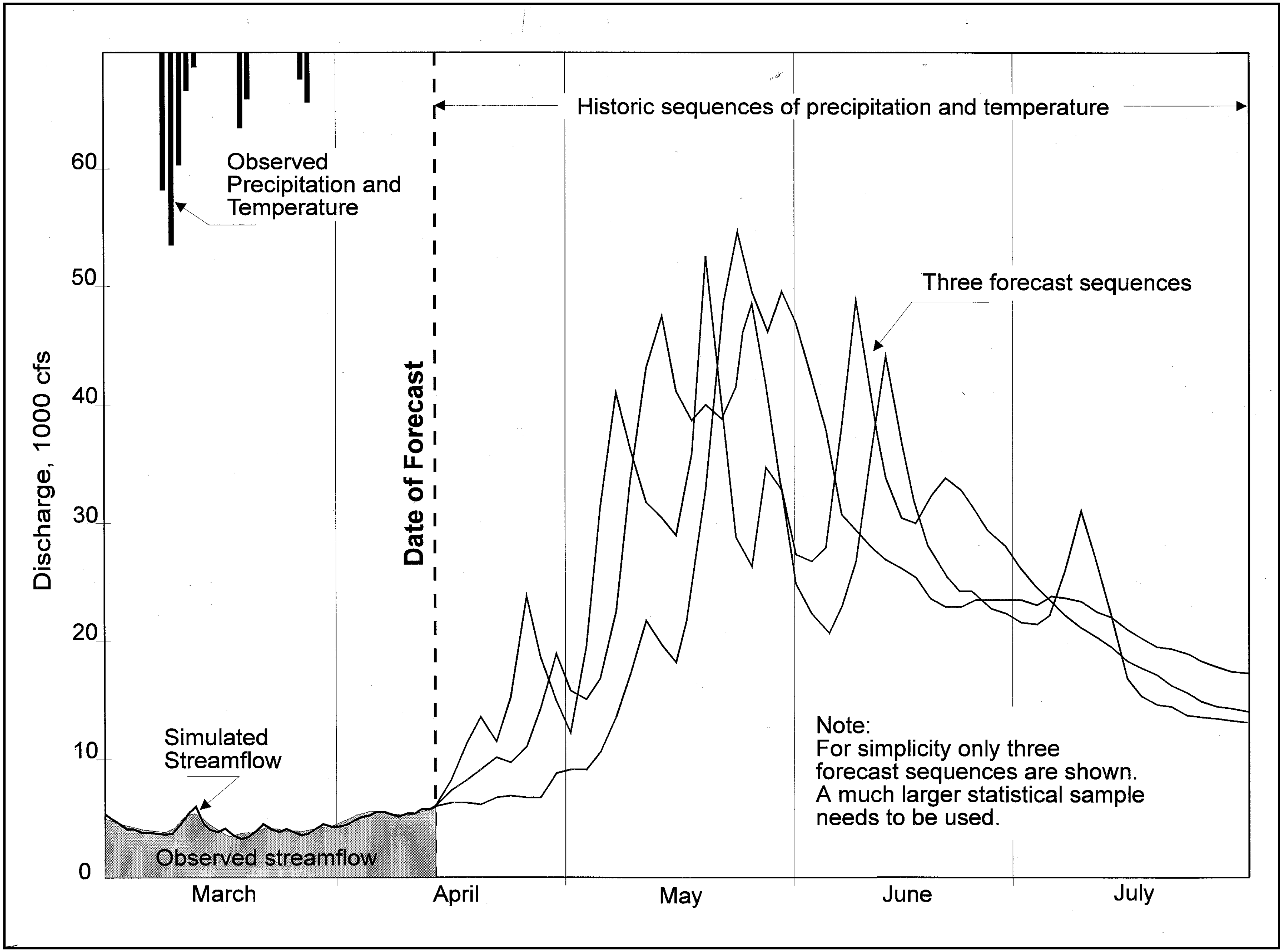


Figure 10-10. Example of short- and long-range streamflow forecasts



Note:
For simplicity only three
forecast sequences are shown.
A much larger statistical sample
needs to be used.

Figure 10-11. Hydrographs generated with the ESP technique (continued)

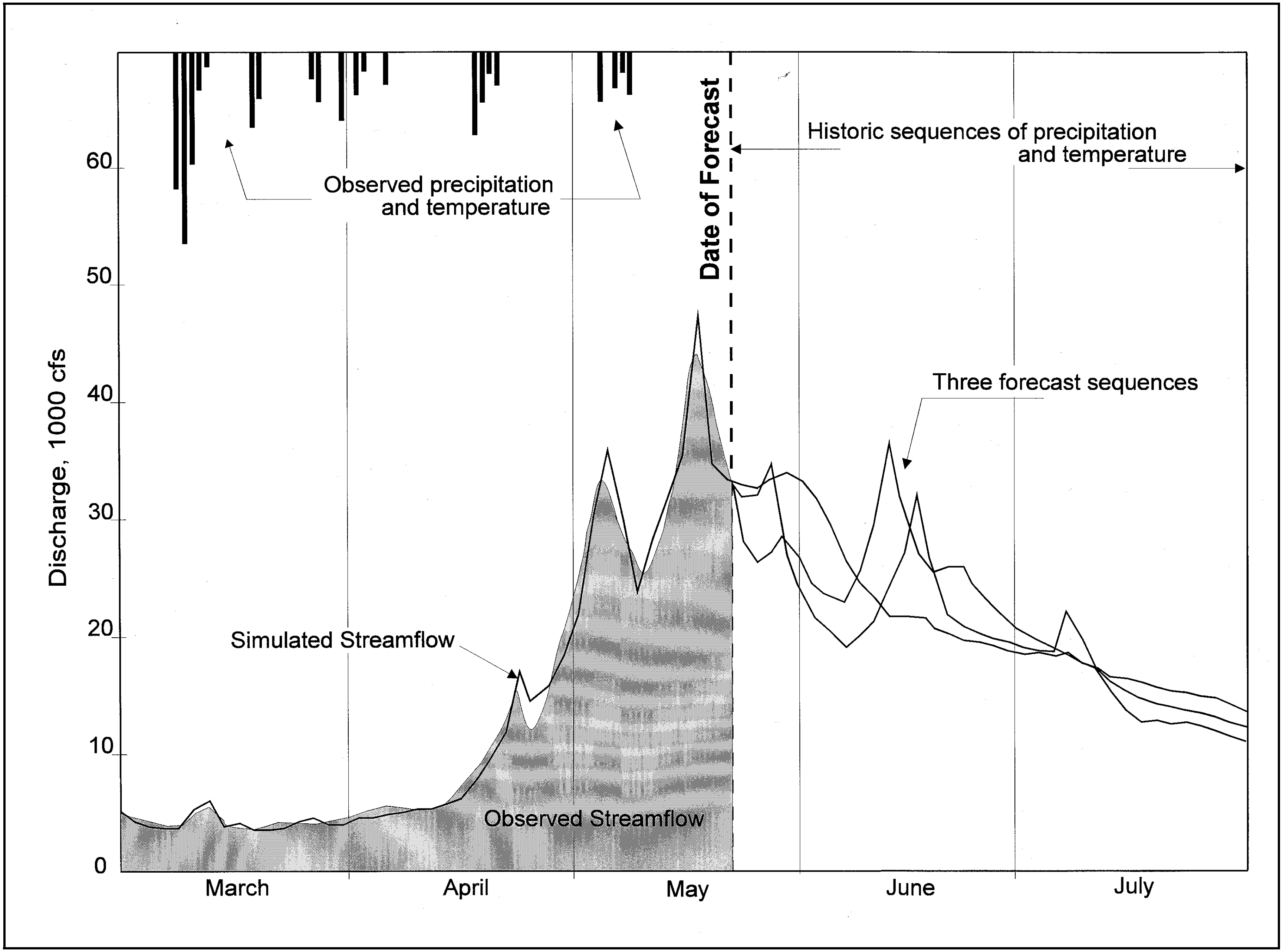


Figure 10-11. (concluded)

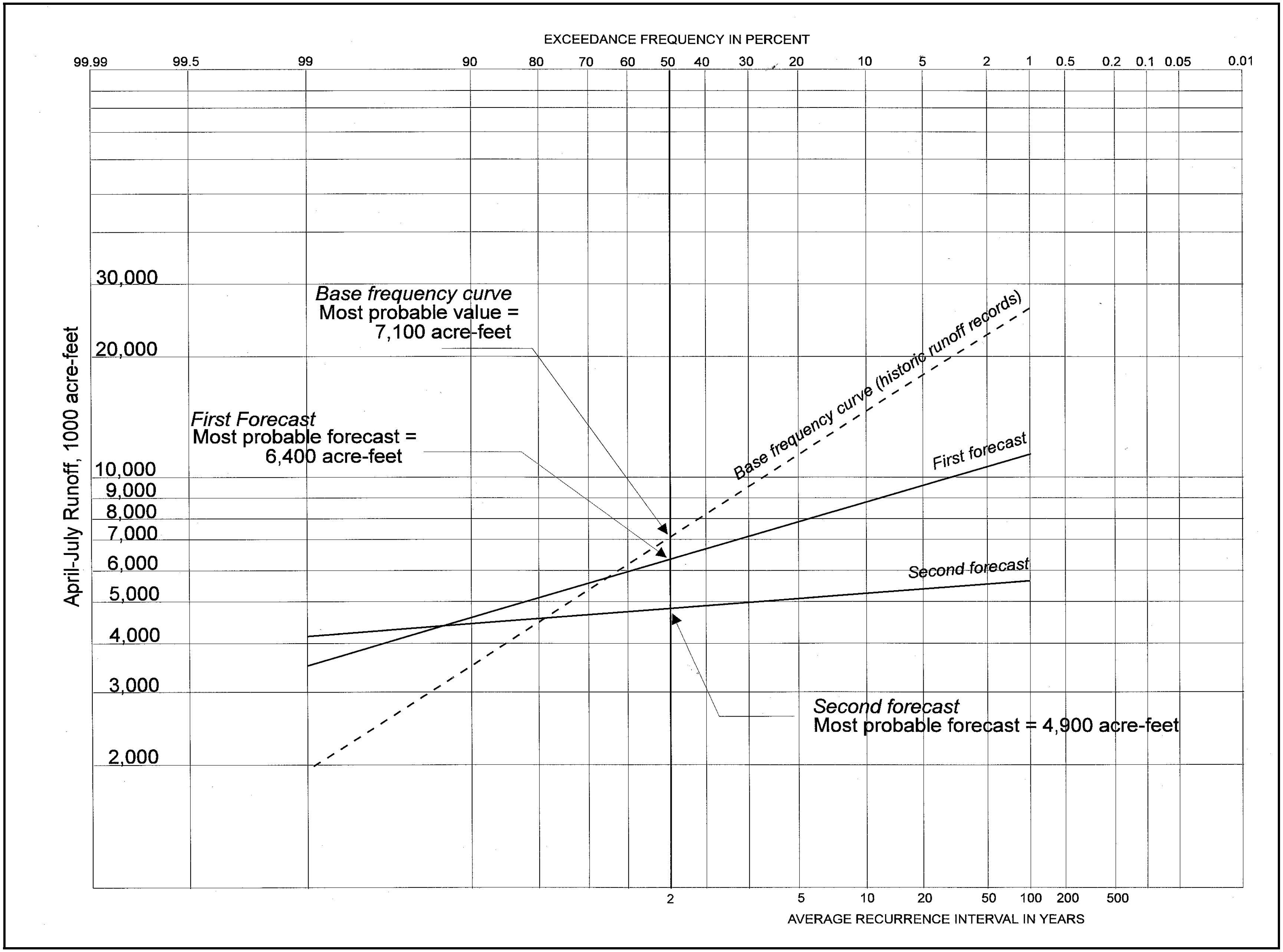


Figure 10-12. Statistical analysis associated with the ESP technique

accumulation and melt is illustrated by the algorithms shown in Figures 4-4 and 10-13, assuming an elevation-band model. Calibration of a continuous model typically uses a continuous period of data for many years, if not the entire period of record. The calibration must consider the long-term volumetric effects and seasonal water balance, along with the general ability to reproduce streamflow without bias. For snowmelt environments, the input variables are precipitation and air temperature (station maximum and minimums for a daily time step). The winter-snow accumulation is computed by the model. Observed snow measurements could be used as an additional means for judging the model calibration if desired.

b. Simulation guidance. The following summarizes some factors that need to be considered with this method of modeling.

(1) Time increment. Since the model operates through flood as well as low-flow periods, some models provide for an automatically changing computational period based upon rate of change of input.

(2) Snowmelt method. The temperature-index approach is essentially a requirement since such a large amount of historical data are employed. The model must be able to compute melt-rate coefficients as a seasonal variable. Melt from ground conduction could be added as melt source because of the extended computational periods involved.

(3) Temperature input. Temperature data are exclusively historical station data, generally input as daily maximums and minimums. These must be converted to area mean values through some form of weighting process, and it is desirable to have flexibility to vary the temperature weighting seasonally. A temperature station may, for instance, index an area's temperature differently during winter storms than it does during summer melt under clear skies. Air temperatures must also be lapsed to the appropriate elevation. A fixed lapse rate is typically used, although this could be made to vary seasonally also.

(4) Rain input. Historical station data are used as input, so a conversion to area means is required. As with air-temperature data, the conversion process should have some flexibility to consider seasonal variations. A factor to consider is that different gauge catch efficiencies result when precipitation is snow versus rain.

(5) Interception, evapotranspiration, and sublimation. These factors must be simulated, using whatever algorithm is available in the model. Temperature is usually the independent variable used to compute evapotranspiration. Sublimation of snow must also be accounted for, since this can be a significant loss over extended periods of time.

(6) Snow-condition effects. Continuous simulation modeling needs to account for these phenomena explicitly. A sample algorithm for this process has been presented in Chapter 7.

(7) Glacial melt. For areas having continental glaciers, melt from this source can be significant in late summer. If a specific glacier-melt routine is not provided in a model, this phenomenon could be represented by treating the glacial areas as separate subbasins and creating special characteristics using a standard model.

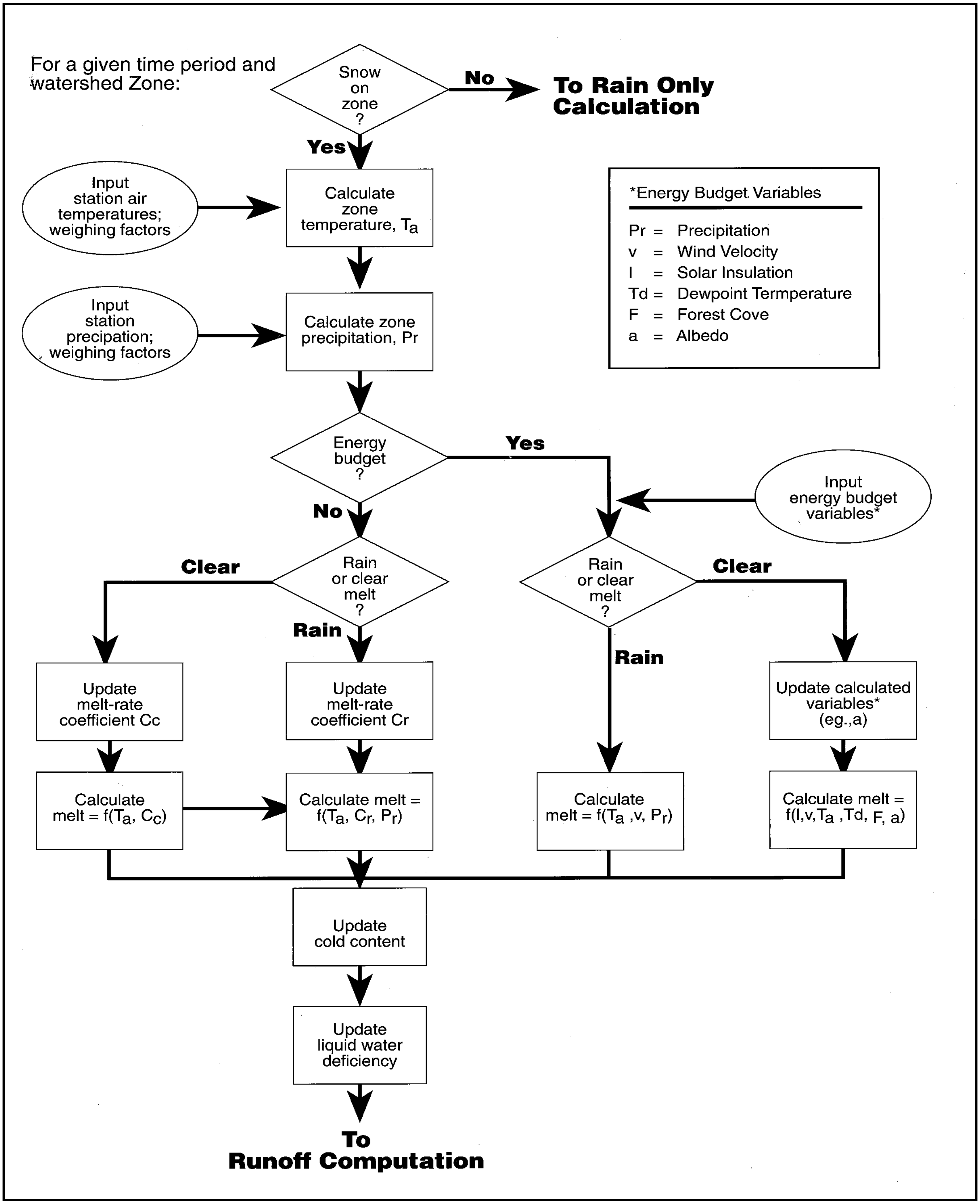


Figure 10-13. Algorithm of snowmelt simulation, continuous simulation model