CHAPTER 11 - SEASONAL RUNOFF FORECASTING

11-01. INTRODUCTION

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

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

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

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

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

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

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

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

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

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

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

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

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

11-02. INDEX PROCEDURES FOR FORECASTING SEASONAL RUNOFF

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

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

$$Y = a + bX,$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

11-03. EXAMPLES OF INDEX METHODS

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

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

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

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

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

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

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

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

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

$$y = a\ x + b$$

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

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

$$Y = aX_1 + bX_2 + c$$

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

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

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

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

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

11-04. EXAMPLES OF WATER-BALANCE METHODS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

---

* Daily maximum temperatures above 32°F.

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

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

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

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

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

Month	Correction factor
January	1.0
February	1.4
March	1.8

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

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

* Daily maximum temperatures above 32°F.

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

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

11-05. SUMMARY

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

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

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

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

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

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

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

11-06. REFERENCES

1/ ARKIN, Herbert and Raymond R. Colton, An Outline of Statistical Methods, (College Outline Series), Barnes & Noble, Inc., New York.

2/ BEAN, Paul L. and Philip W. Thomas, "A quantitative forecast-system for power- and flood-warning in the Androscoggin River basin, Maine," Trans. Amer. Geophys. Union, Pt. III, September 1940, pp. 835-846.

3/ BROOKS, C.E.P. and N. Carruthers, Handbook of Statistical Methods in Meteorology, (M.O. 538, Air Ministry, Meteorological Office), H. M. Stationery Office, London, 1953.

4/ EZEKIEL, Mordecai, Methods of Correlation Analysis, John Wiley & Sons, Inc., New York, 1941.

5/ KOELZER, Victor A., "Cumulative snowmelt runoff distribution graphs and their use in runoff forecasting," Proc. Western Snow Conference, April 1951, pp. 30-39.

6/ KOHLER, M. A. and R. K. Linsley, Jr., "Recent developments in water supply forecasting from precipitation," Trans. Amer. Geophys. Union, Vol. 30, No. 3, June 1949, pp. 427-436.

7/ LINSLEY, Ray K., Max A. Kohler, and Joseph L. H. Paulhus, Applied Hydrology, McGraw-Hill Book Company, Inc., New York, 1949.

8/ POTTS, H. L., "A photographic snow-survey method of forecasting runoff," Trans. Amer. Geophys. Union, Vol. 25, September 1944, pp. 149-153.

9/ SNEDECOR, George W., Statistical Methods, (4th Ed.), The Iowa State College Press, Ames, Iowa, 1946.

10/ STRAUSS, Fred A., "A revision of forecasting methods as practiced by the California Cooperative Snow Surveys," Proc. Western Snow Conference, April 1950, pp.49-59

11/ WILM, H. G., "Statistical control in hydrologic forecasting," Pacific Northwest Forest and Range Experiment Station, Research Note No. 61, January 1950.

12/ WATER MANAGEMENT SUBCOMMITTEE, CBIAC, "Review of procedures for forecasting seasonal runoff of Boise River above Diversion Dam, Idaho," January 1954.

13/ WATER MANAGEMENT SUBCOMMITTEE, CBIAC, "Review of procedures for forecasting seasonal runoff of Columbia River near The Dalles, Oregon," August 1954.

TABLE 11-1

WATER BALANCE BY FORECAST SEASON
North Santiam River above Detroit Dam

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

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

TABLE 11-2

MONTHLY TEMPERATURE AND HEAT INDEX RANGES

DETROIT, OREGON

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

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

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

TABLE 11-3

MONTHLY PRECIPITATION RANGES

NORTH SANTIAM RIVER ABOVE DETROIT DAM

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

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

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

TABLE 11-4

WATER BALANCE BY MONTHS
North Santiam River above Detroit Dam

ITEM 1/	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	TOTAL	MEAN
						JANUARY							
(1) Degree Days 2/	420.00	353.00	239.00	303.00	385.00	266.00	183.00	368.00	154.00	78.00	218.00		
(2) Percent Snow Cover	54.00	73.00	87.00	64.00	58.00	90.00	60.00	65.00	92.00	98.00	82.00		
(3) Melt	1.07	1.23	0.83	0.80	1.05	1.02	0.25	1.20	0.45	0.15	0.68	8.73	0.79
(4) Change in Water-Equivalent	3.41	3.77	10.46	1.84	0.90	7.24	6.82	3.71	3.90	13.88	11.81	67.74	6.16
(5) Snowfall (3)+(4)	4.48	5.00	11.29	2.64	1.95	8.26	7.07	4.91	4.35	14.03	12.49	76.47	6.95
(6) Basin Precipitation	10.06	8.02	15.64	7.08	10.31	15.93	13.13	15.60	3.74	25.48	21.73	146.72	13.34
(7) Snowfall	4.48	5.00	11.29	2.64	1.95	8.26	7.07	4.91	4.35	14.03	12.49	76.47	6.95
(8) Rainfall (6)-(7)	5.58	3.02	4.35	4.44	8.36	7.67	6.06	10.69	-0.61	11.45	9.24	70.25	6.57
(9) Supply (3)+(8)	6.65	4.25	5.18	5.24	9.41	8.69	6.31	11.89	-0.16	11.60	9.92	78.98	7.18
(10) Loss 3/	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(11) Computed Runoff (9)-(10)	6.65	4.25	5.18	5.24	9.41	8.69	6.31	11.89	-0.16	11.60	9.92	78.98	7.18
(12) Generated Runoff 4/	6.57	5.24	7.08	4.38	8.39	9.85	7.12	11.64	1.50	6.80	9.91	78.48	7.13
(13) Percent Rainfall	55.00	38.00	28.00	63.00	81.00	48.00	46.00	69.00	-	45.00	43.00		
						FEBRUARY							
(1) Degree Days	636.00	423.00	538.00	403.00	371.00	309.00	514.00	306.00	278.00	281.00	369.00		
(2) Percent Snow Cover	49.00	90.00	88.00	54.00	66.00	87.00	62.00	75.00	93.00	100.00	87.00		
(3) Melt	2.24	2.52	3.50	1.09	1.26	1.47	1.99	1.15	1.40	1.75	1.89	20.26	1.84
(4) Change in Water-Equivalent	0.45	4.88	0.23	3.15	2.70	5.14	-0.86	7.28	13.24	2.82	1.20	40.23	3.66
(5) Snowfall (3)+(4)	2.69	7.40	3.73	4.24	3.96	6.61	1.13	8.43	14.64	4.57	3.09	60.49	5.50
(6) Basin Precipitation	3.64	8.69	9.43	7.76	15.64	10.26	4.50	15.22	23.41	13.17	12.79	124.51	11.32
(7) Snowfall	2.69	7.40	3.73	4.24	3.96	6.61	1.13	8.43	14.64	4.57	3.09	60.49	5.50
(8) Rainfall (6)-(7)	0.95	1.29	5.70	3.52	11.68	3.65	3.37	6.79	8.77	8.60	9.70	64.02	5.82
(9) Supply (3)+(8)	3.19	3.81	9.20	4.61	12.94	5.12	5.36	7.94	10.17	10.35	11.59	84.28	7.66
(10) Loss	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(11) Computed Runoff (9 -(10)	3.19	3.81	9.20	4.61	12.94	5.12	5.36	7.94	10.17	10.35	11.59	84.28	7.66
(12) Generated Runoff	2.95	5.42	10.30	3.98	10.56	5.70	7.66	8.87	9.31	9.51	10.06	84.32	7.67
(13) Percent Rainfall	26.00	15.00	60.00	45.00	75.00	36.00	75.00	45.00	37.00	65.00	76.00		
						MARCH							
(1) Degree Days	966.00	707.00	578.00	592.00	465.00	510.00	767.00	499.00	545.00	408.00	422.00		
(2) Percent Snow Cover	27.00	72.00	88.00	57.00	68.00	91.00	57.00	82.00	88.00	100.00	82.00		
(3) Melt	2.80	5.56	5.16	2.90	2.16	4.20	4.70	3.42	4.70	3.14	2.40	41.14	3.74
(4) Change in Water-Equivalent	-2.25	0.45	-0.08	0.52	5.59	3.19	0.68	3.94	-1.20	1.60	5.55	17.99	1.64
(5) Snowfall (3)+(4)	0.55	6.01	5.08	3.42	7.75	7.39	5.38	7.36	3.50	4.74	7.95	59.13	5.38
(6) Basin Precipitation	2.83	4.67	10.94	5.52	12.92	9.84	8.77	7.94	6.13	14.72	9.81	94.09	8.56
(7) Snowfall	0.55	6.01	5.08	3.42	7.75	7.39	5.38	7.36	3.50	4.74	7.95	59.13	5.38
(8) Rainfall (6)-(7)	2.28	-1.34	5.86	2.10	5.17	2.45	3.39	0.58	2.63	9.98	1.86	34.96	3.18
(9) Supply (3)+(8)	5.08	4.22	11.02	5.00	7.33	6.65	8.09	4.00	7.33	13.12	4.26	76.10	6.92
(10) Loss	1.30	0.60	0.00	0.30	0.20	0.10	0.80	0.00	0.20	0.00	0.00	3.50	0.32
(11) Computed Runoff (9)-(10)	3.78	3.62	11.02	4.70	7.13	6.55	7.29	4.00	7.13	13.12	4.26	72.60	6.60
(12) Generated Runoff	2.85	4.85	8.66	5.01	6.50	6.76	7.25	5.53	7.99	11.53	5.69	72.62	6.60
(13) Percent Rainfall	81.00	-	54.00	38.00	40.00	25.00	39.00	7.00	43.00	68.00	19.00		

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

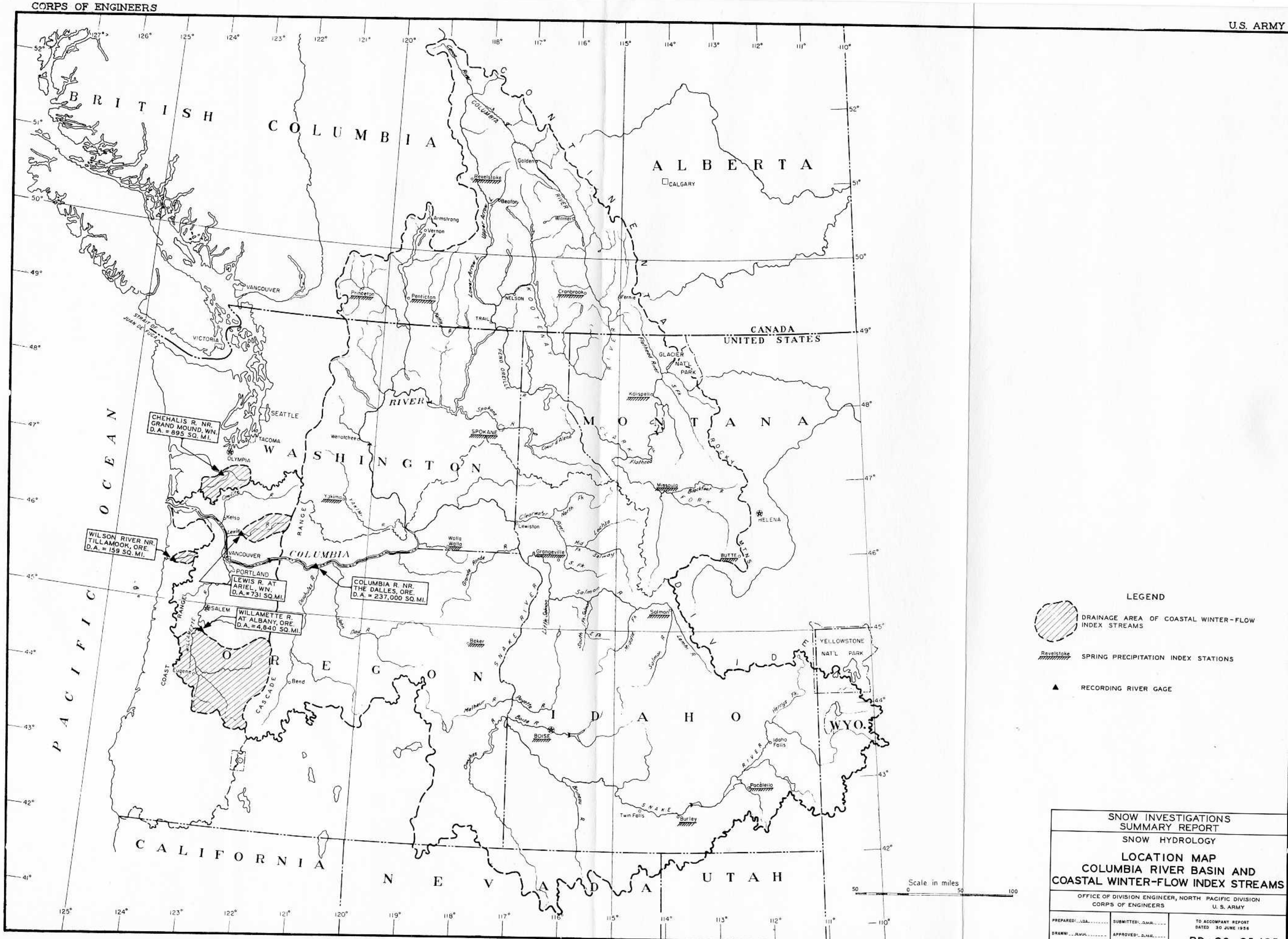
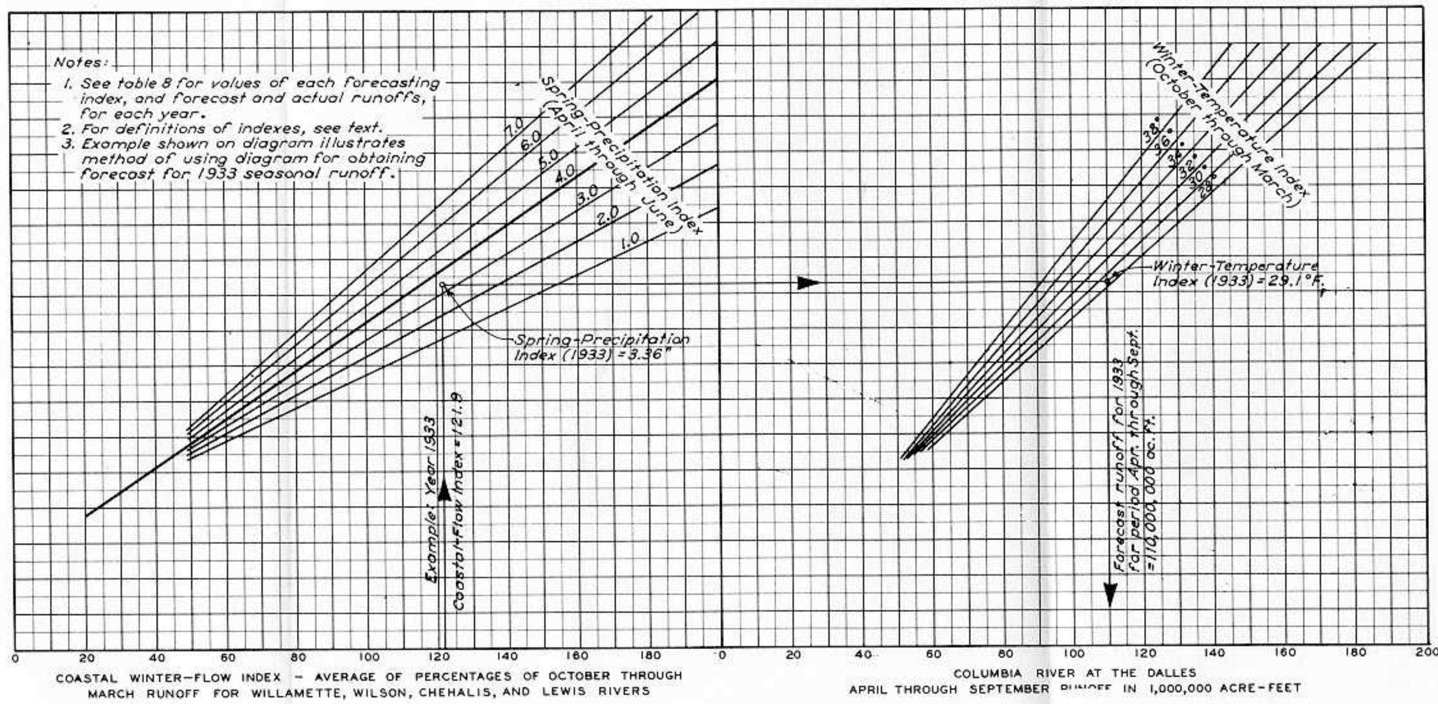
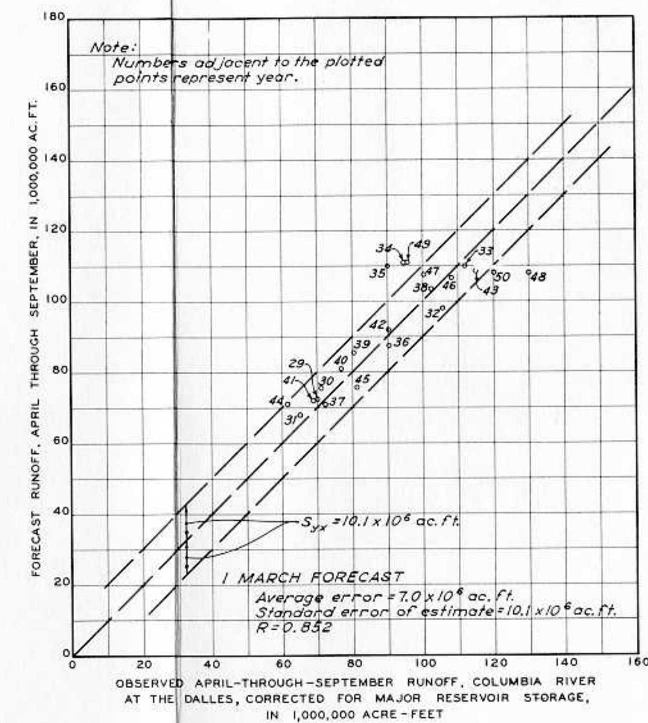

BRITISH COLUMBIA
ALBERTA
CALGARY
WASHINGTON
OREGON
IDAHO
MONTANA
WYO.
CALIFORNIA
NEVADA
UTAH
PACIFIC OCEAN
CONTINENTAL DIVIDE
CANADA
UNITED STATES
COLUMBIA
RIVER
SNAKE RIVER
STRAIT OF JUAN DE FUCA
VANCOUVER
VICTORIA
SEATTLE
TACOMA
OLYMPIA
PORTLAND
SALEM
Eugene
Bend
Kelso
Revelstoke
Golden
Beaton
Armstrong
Vernon
Wilmer
Princeton
Penticton
NELSON
TRAIL
Cranbrook
Fernie
GLACIER NAT'L PARK
Kalispell
SPOKANE
Wenatchee
Yakima
Walla Walla
Lewiston
Grangeville
Missoula
HELENA
BUTTE
Salmon
Baker
BOISE
Idaho Falls
Pocatello
Twin Falls
Burley
YELLOWSTONE NAT'L PARK
CASCADE RANGE
COAST RANGE
ROCKY MTNS
CHEHALIS R. NR. GRAND MOUND, WN. D.A. = 895 SQ. MI.
WILSON RIVER NR. TILLAMOOK, ORE. D.A. = 159 SQ. MI.
LEWIS R. AT ARIEL, WN. D.A. = 731 SQ. MI.
WILLAMETTE R. AT ALBANY, ORE. D.A. = 4,840 SQ. MI.
COLUMBIA R. NR. THE DALLES, ORE. D.A. = 237,000 SQ. MI.
LEGEND
DRAINAGE AREA OF COASTAL WINTER-FLOW INDEX STREAMS
SPRING PRECIPITATION INDEX STATIONS
RECORDING RIVER GAGE
Scale in miles
50 0 50 100
SNOW INVESTIGATIONS SUMMARY REPORT
SNOW HYDROLOGY
LOCATION MAP
COLUMBIA RIVER BASIN AND
COASTAL WINTER-FLOW INDEX STREAMS
OFFICE OF DIVISION ENGINEER, NORTH PACIFIC DIVISION
CORPS OF ENGINEERS
U. S. ARMY
TO ACCOMPANY REPORT DATED 30 JUNE 1956
PD-20-25/65

PLATE II-1



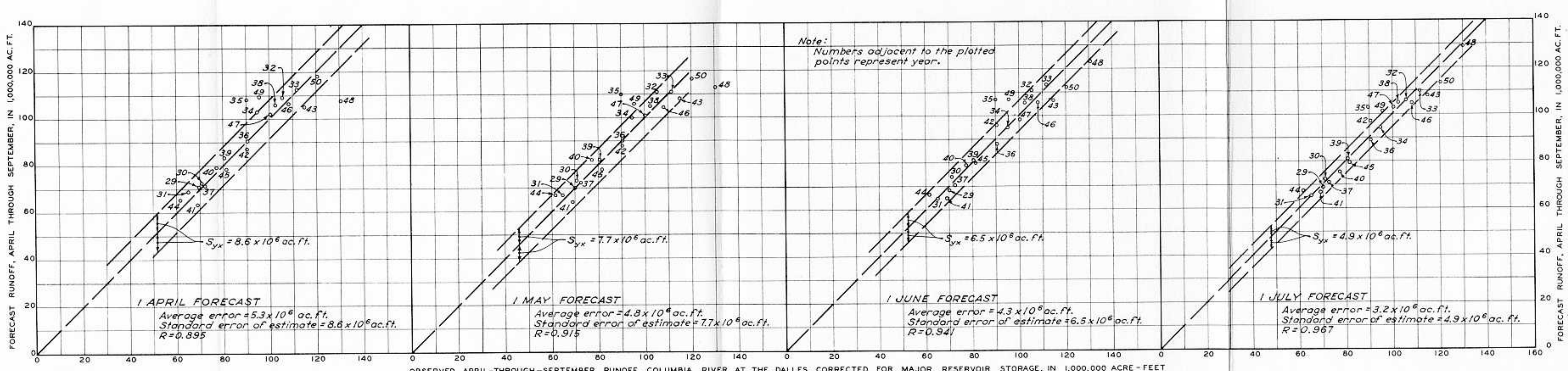
COAXIAL DIAGRAM FOR FORECASTING COLUMBIA RIVER APRIL-THROUGH-SEPTEMBER RUNOFF AT THE DALLES

FIGURE 1



FORECAST VS. ACTUAL RUNOFF
(1 MARCH FORECAST)

FIGURE 2



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

FIGURE 3

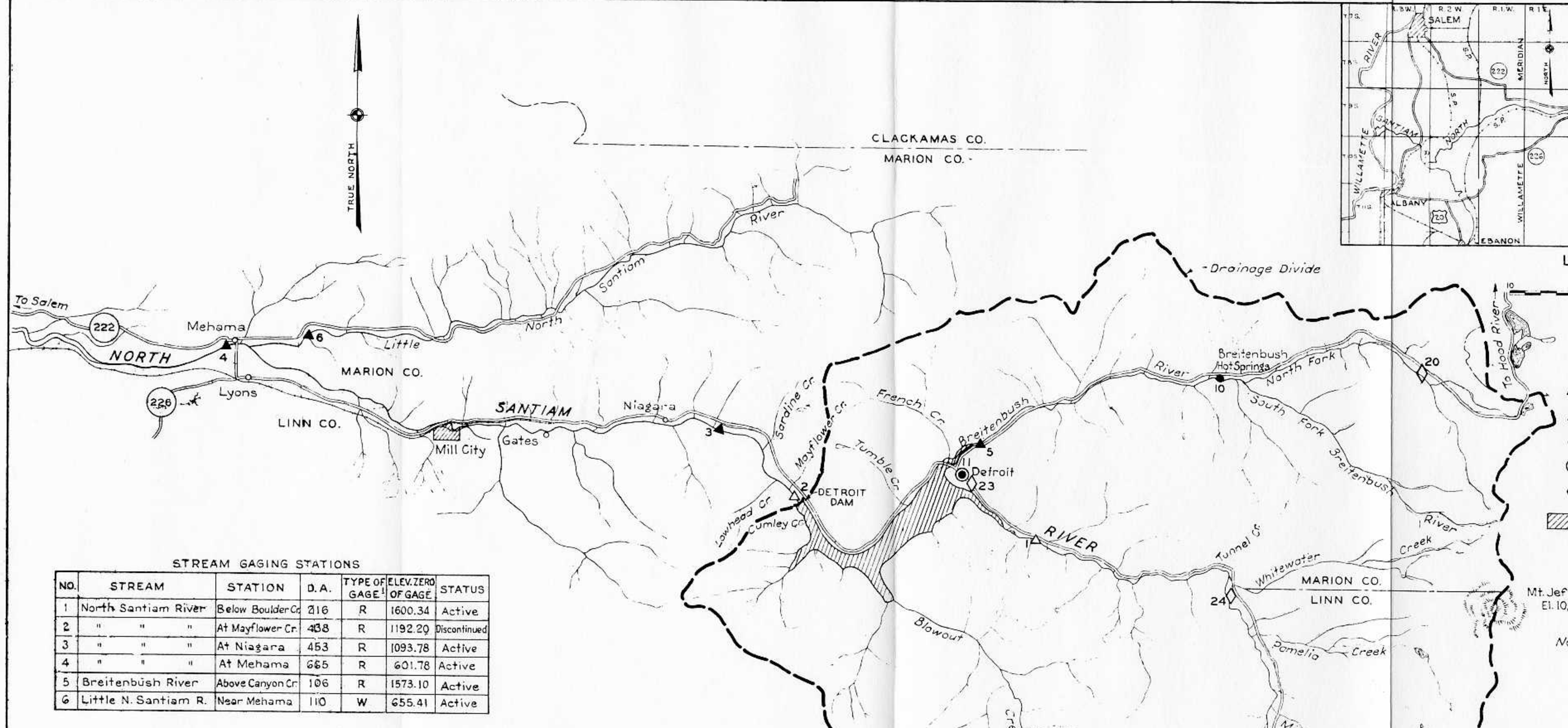
SNOW INVESTIGATIONS
SUMMARY REPORT
SNOW HYDROLOGY

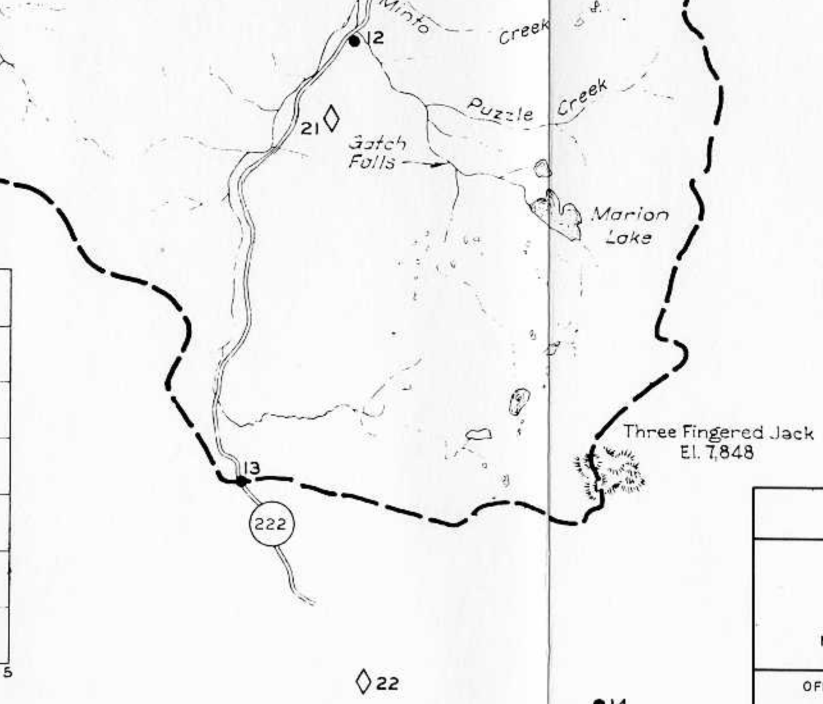
FORECASTING DIAGRAMS
COASTAL WINTER-FLOW INDEX METHOD

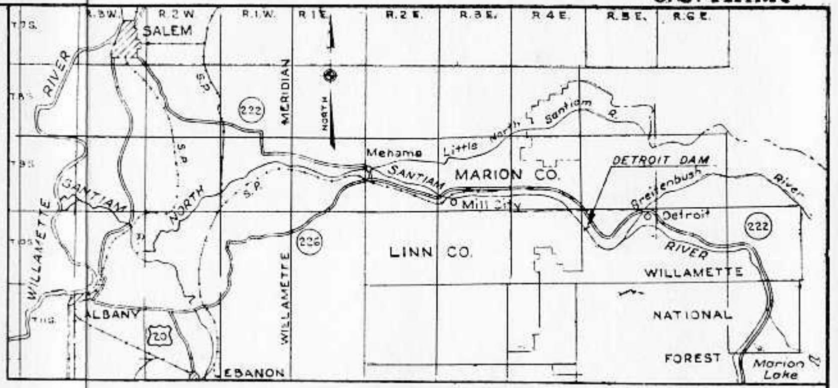
COLUMBIA RIVER NEAR THE DALLES

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

PREPARED: I.D.A.	SUBMITTED: D.M.R.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: E.H.	APPROVED: D.M.R.	PD-20-25/66







LOCATION MAP

SCALE IN MILES

10 0 10 20

LEGEND

- ▲ *Active Stream Gaging Station*
- △ *Discontinued Stream Gaging Station*
- ● *Recording Precipitation Gage*
- ○ *Non-recording Precipitation Gage*
- ◇ *Snow Survey Courses*
- ▨ *Detroit Reservoir*

Notes:

1. Types of Gages
Stream
R - Recorder
W - Wire weight
Precipitation
N - Non-recorder
R - Recorder

2. Hogg Pass not shown on map; located about 8 miles south of Three Fingered Jack.

STREAM GAGING STATIONS

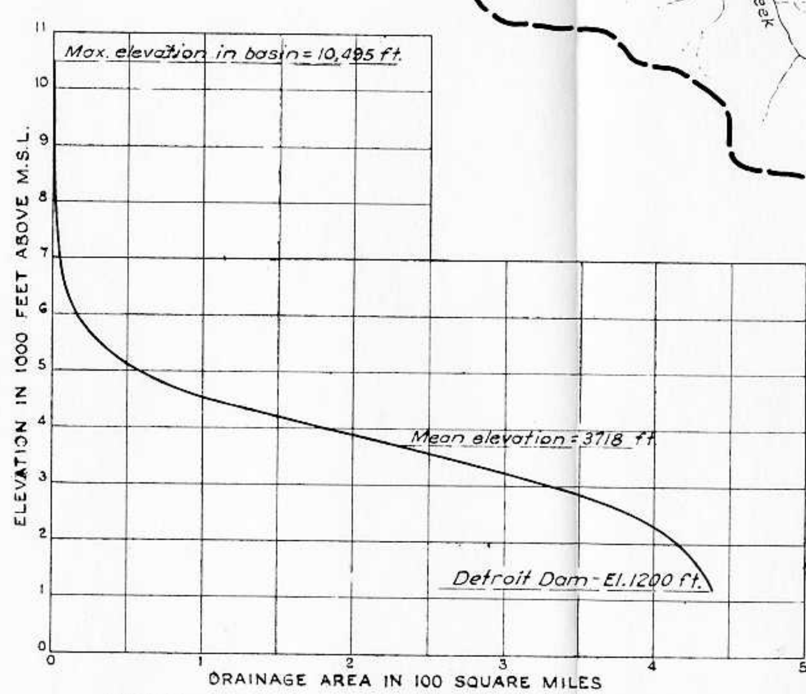
NO.	STREAM	STATION	D.A.	TYPE OF GAGE[1]	ELEV. ZERO OF GAGE	STATUS
1	North Santiam River	Below Boulder Cr.	216	R	1600.34	Active
2	" " "	At Mayflower Cr.	438	R	1192.20	Discontinued
3	" " "	At Niagara	453	R	1093.78	Active
4	" " "	At Mehama	655	R	601.78	Active
5	Breitenbush River	Above Canyon Cr.	106	R	1573.10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

PRECIPITATION STATIONS

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

SNOW SURVEY COURSES

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



AREA ELEVATION CURVE — DETROIT DAM

DRAINAGE AREA 438 SQUARE MILES

SNOW INVESTIGATIONS SUMMARY REPORT

SNOW HYDROLOGY

BASIN MAP

NORTH SANTIAM RIVER ABOVE DETROIT DAM

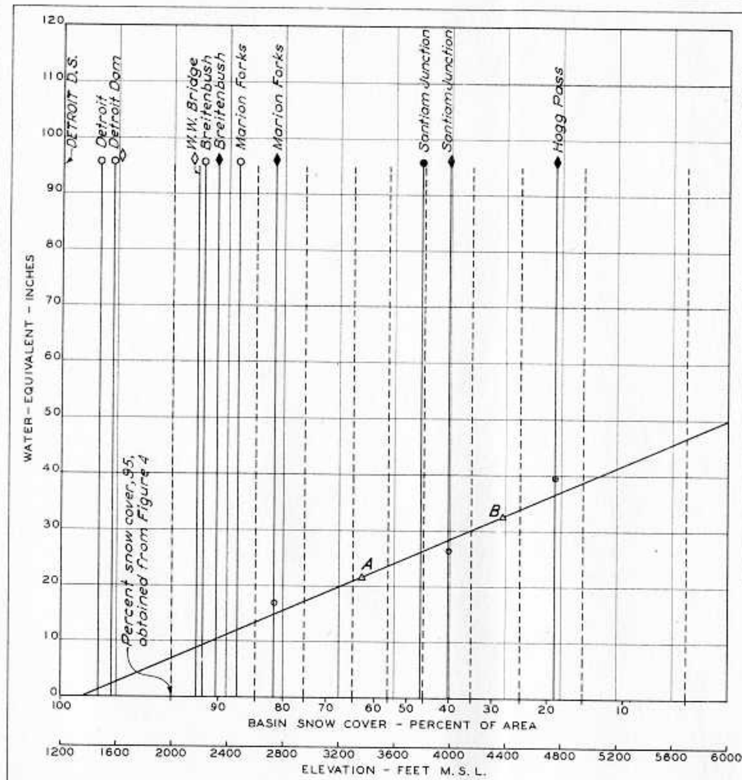
DRAINAGE AREA 438 SQ MI

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

PREPARED: ELE-MGH. SUBMITTED: S.M. TO ACCOMPANY REPORT DATED 30 JUNE 1956

DRAWN: JB:BJ. APPROVED: DML.

PD-20-25/67



LEGEND
- o Precipitation, manual
- • Precipitation, recorder
- ◊ Snow Course, supplementary
- ♦ Snow Course, regular

SNOW WATER-EQUIVALENT

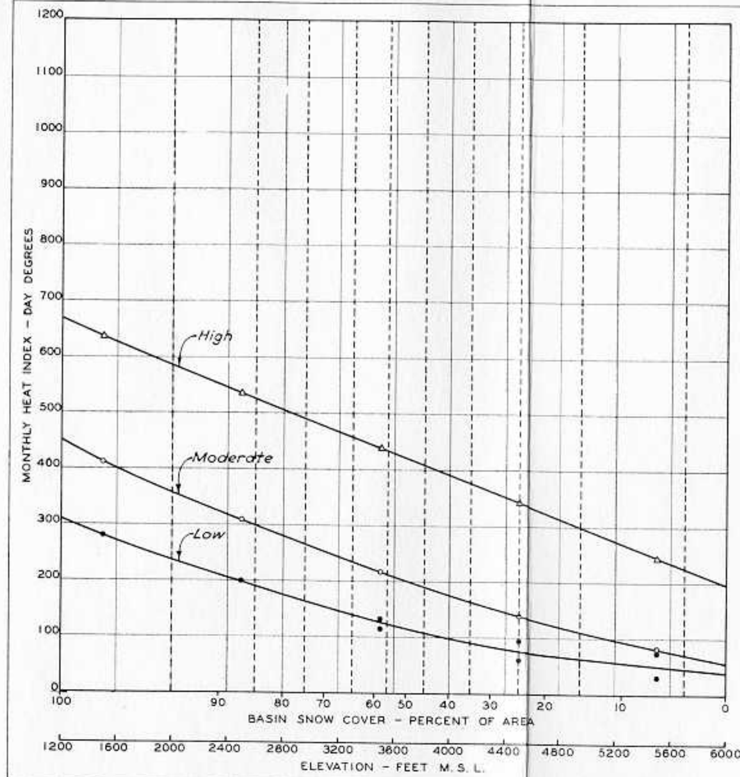
North Fork, Santiam River Above Detroit

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

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

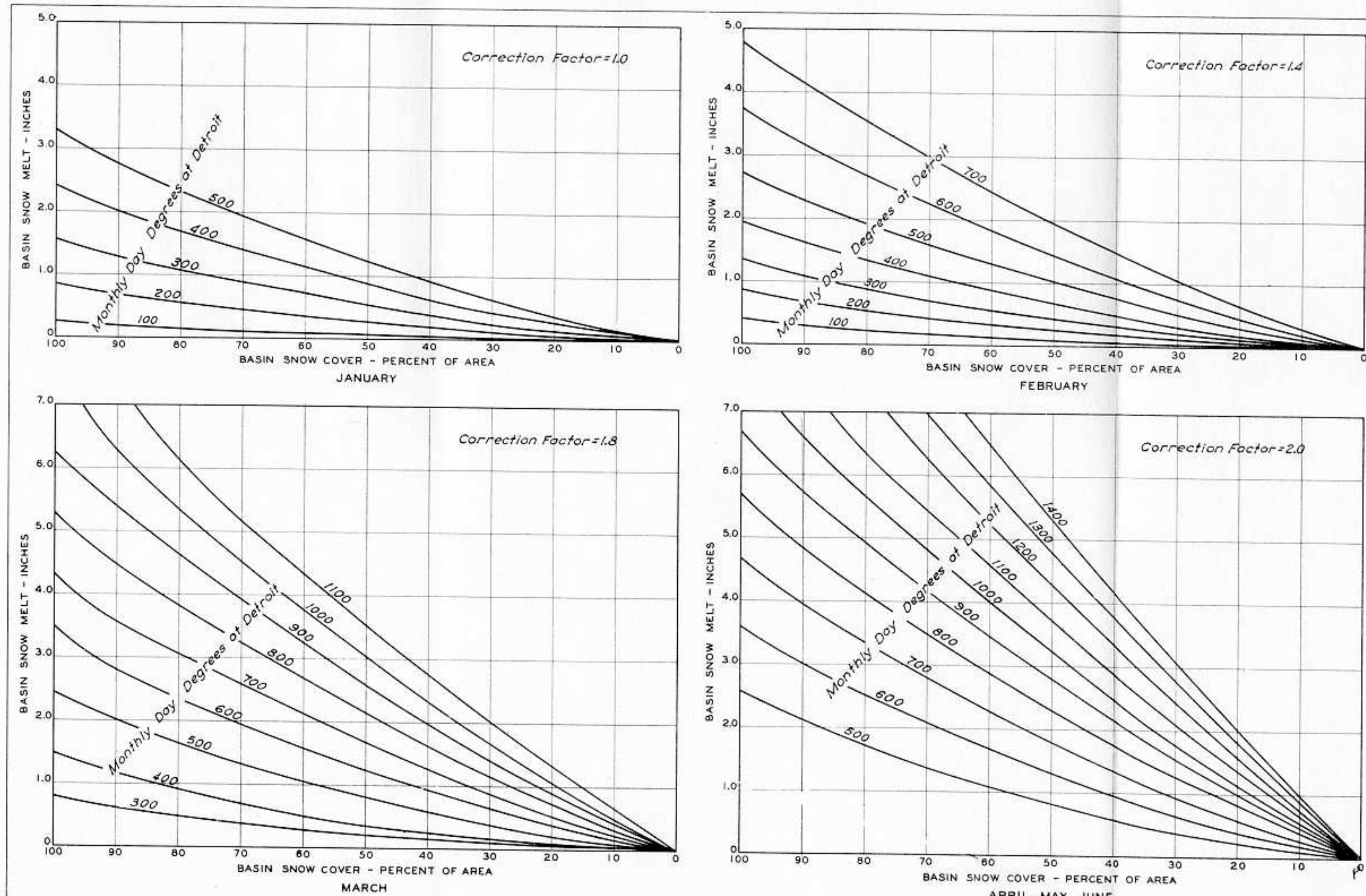
Notes:
1. Plotted points show depth of snow at named snow courses at given elevations.
2. Points A and B show mean snow water-equivalent depth and mean elevation at Marion Forks and Santiam Junction and Santiam Junction and Hogg Pass, respectively.
3. Line through A and B represents unadjusted depth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

FIGURE 1 - SNOW WATER-EQUIVALENT



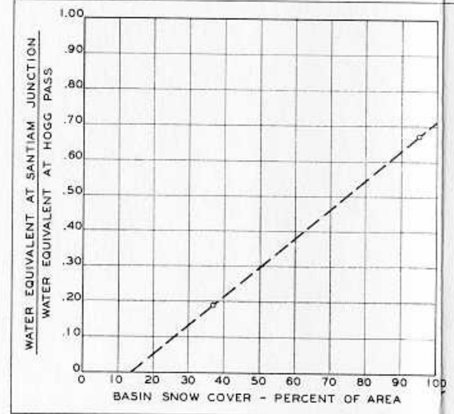
Notes:
1. Chart is sample determination of day degrees over basin for high, moderate, and low temperatures during February.
2. Plotted points represent monthly total of day degrees at each elevation for given number of day degrees at Detroit, based on lapse rate determined from Medford radiosonde data, 3.5°F./1,000 feet.
3. Dashed lines represent mean of each 10 percent zone of basin.
4. Intersections of dashed lines with curves represent day degrees for corresponding zones.
5. Melt in a given zone may be obtained by multiplying day degrees by rate of melt in inches per day degree.

FIGURE 2 - FEBRUARY HEAT SUPPLY



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

FIGURE 3 - BASIN SNOW MELT



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

FIGURE 4 - BASIN SNOW COVER

SNOW INVESTIGATIONS SUMMARY REPORT

SNOW HYDROLOGY

SNOWPACK WATER EQUIVALENT AND MELT

NORTH SANTIAM RIVER ABOVE DETROIT DAM
DRAINAGE AREA 438 SQ MI

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

PREPARED: M.W. SUBMITTED: S.M.
DRAWN: S.V. APPROVED: D.M.G.
TO ACCOMPANY REPORT DATED 30 JUNE 1956

PD-20-25/68

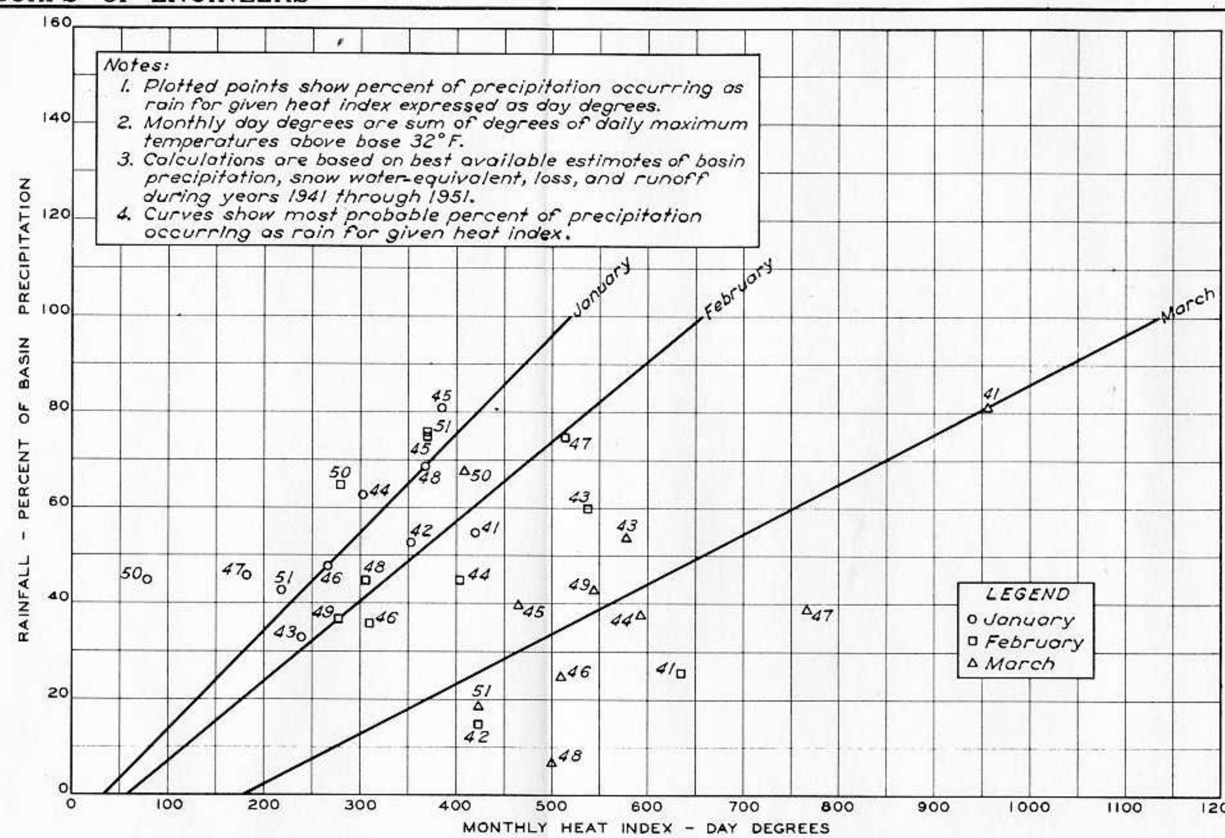


FIGURE 1 - PERCENT OF PRECIPITATION OCCURRING AS RAIN

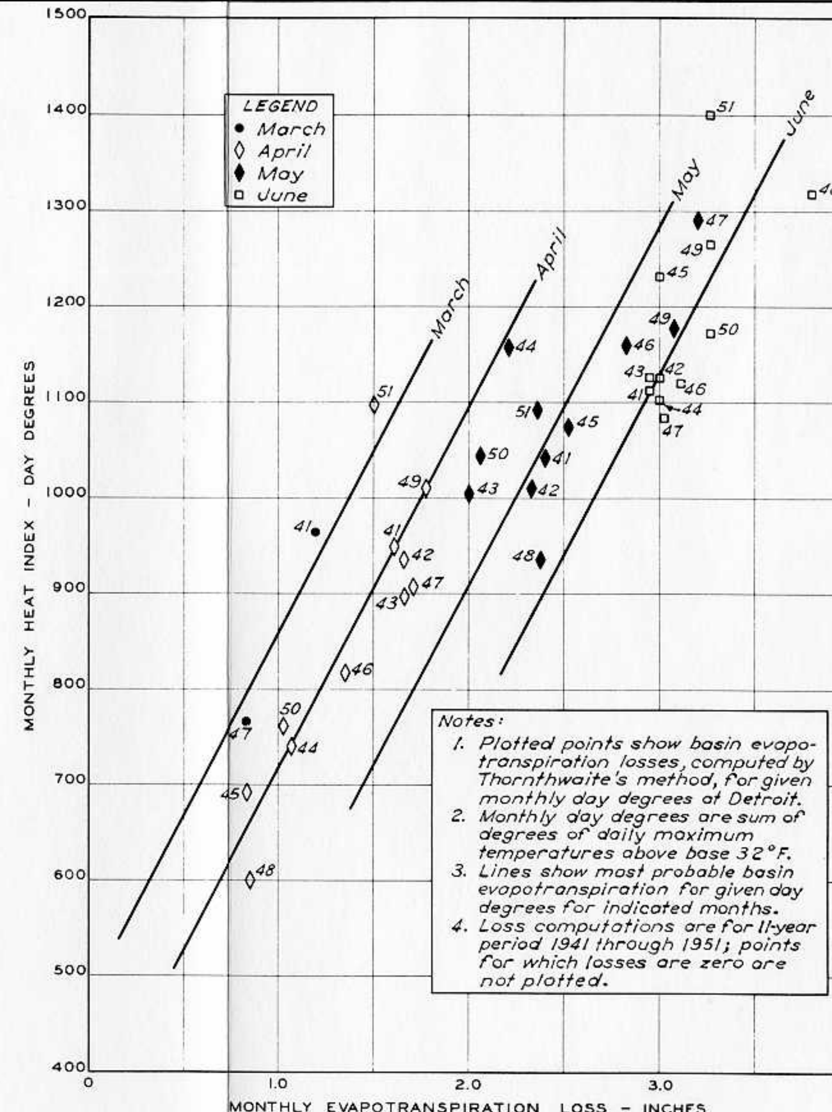
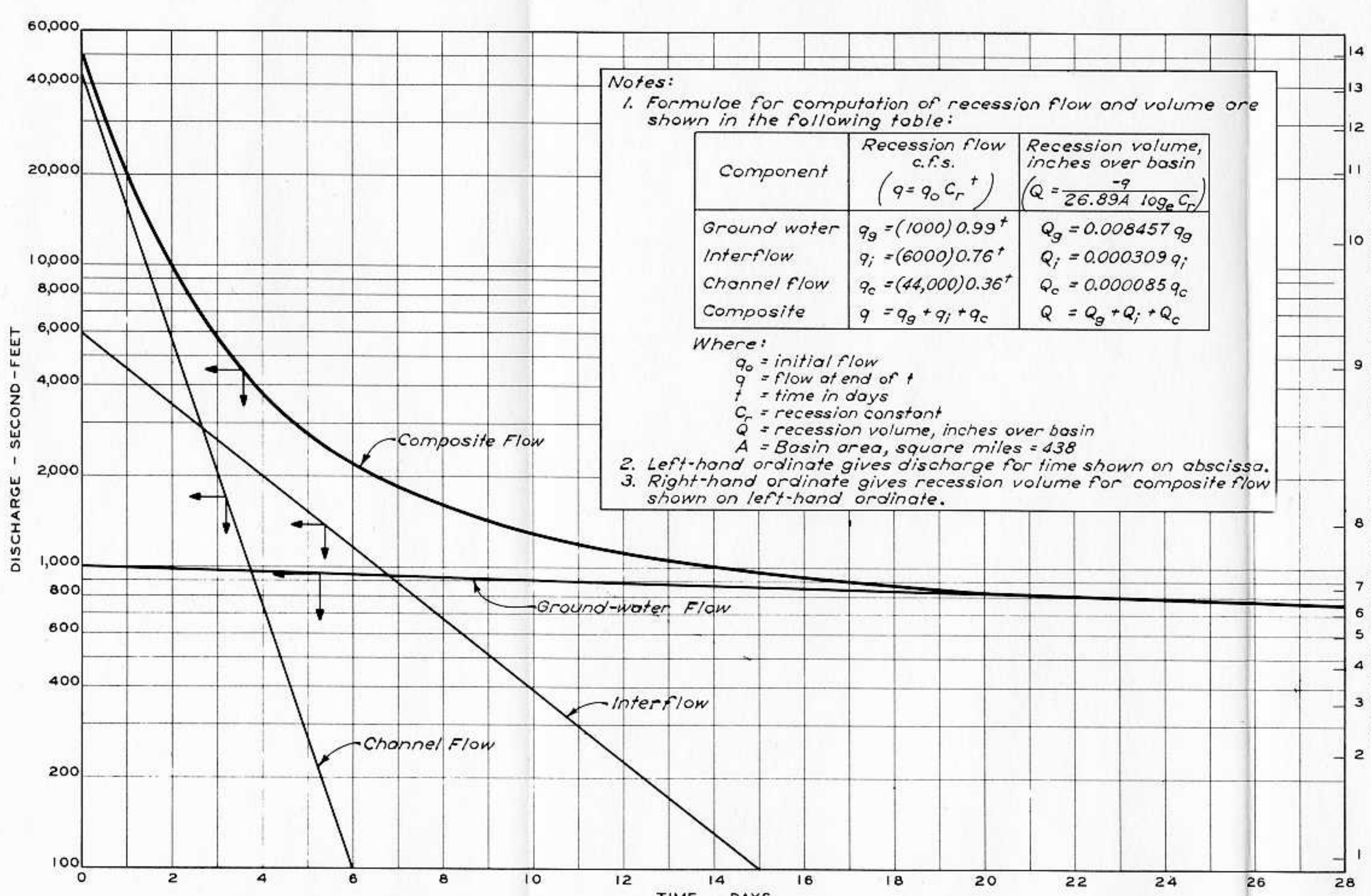


FIGURE 2 - LOSS BY EVAPOTRANSPIRATION



Component	Recession flow c.f.s. $(q = q_o C_r^{\,t})$	Recession volume, inches over basin $\left(Q = \frac{-q}{26.89A \log_e C_r}\right)$
Ground water	$q_g = (1000)\,0.99^t$	$Q_g = 0.008457\,q_g$
Interflow	$q_i = (6000)\,0.76^t$	$Q_i = 0.000309\,q_i$
Channel flow	$q_c = (44{,}000)\,0.36^t$	$Q_c = 0.000085\,q_c$
Composite	$q = q_g + q_i + q_c$	$Q = Q_g + Q_i + Q_c$

FIGURE 3 - STREAMFLOW RECESSION CHARACTERISTICS

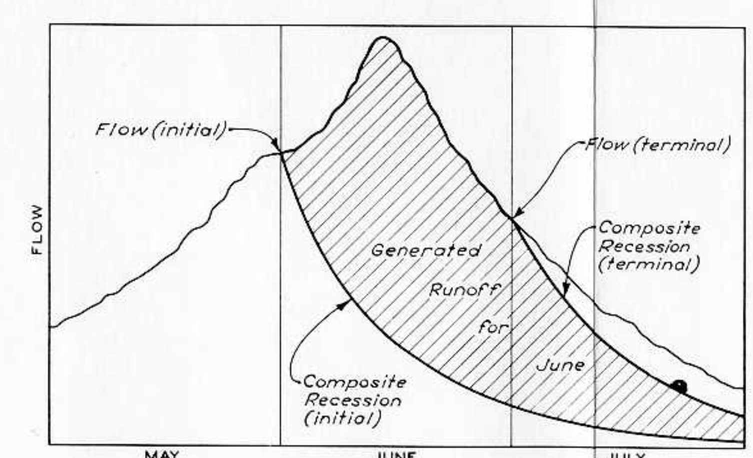


FIGURE 4 - DIAGRAM ILLUSTRATING GENERATED RUNOFF

SNOW INVESTIGATIONS
SUMMARY REPORT
SNOW HYDROLOGY

PRECIPITATION, LOSS AND RUNOFF

NORTH SANTIAM RIVER ABOVE DETROIT DAM
DRAINAGE AREA 438 SQ MI

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

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

PD-20-25/69

PLATE 11-5

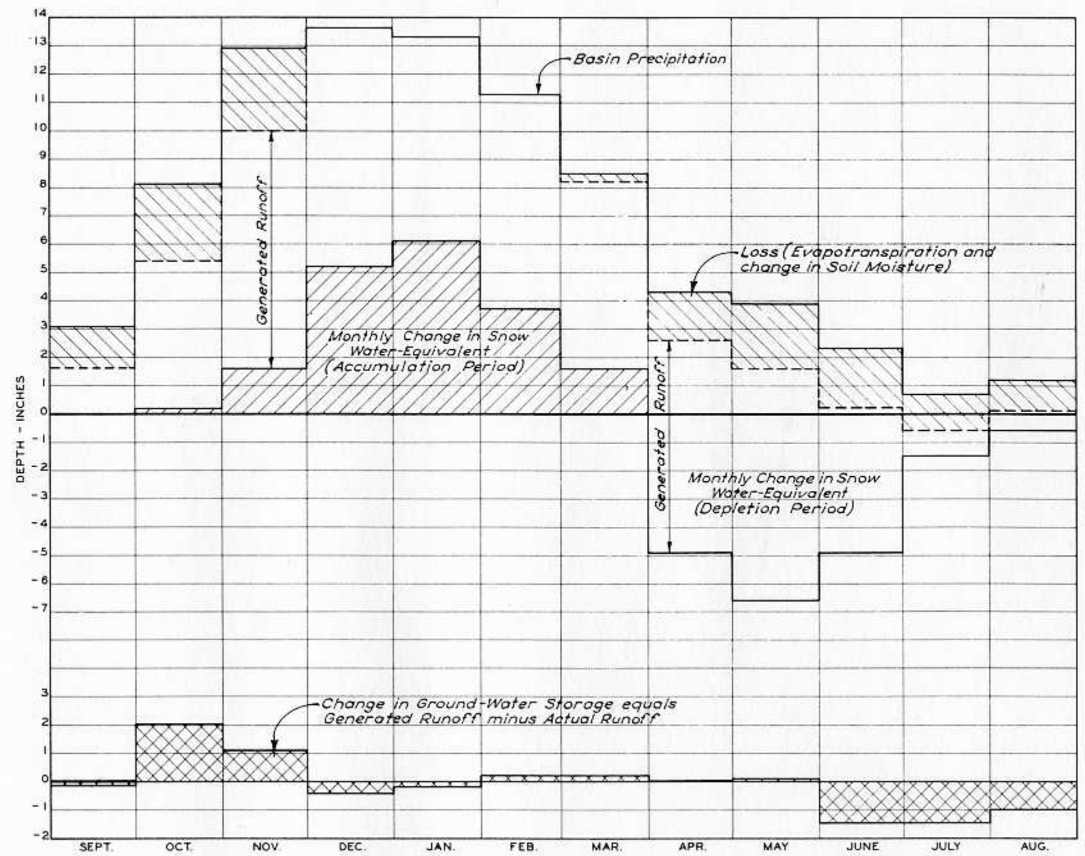


FIGURE 1 - MONTHLY COMPONENTS OF WATER BALANCE

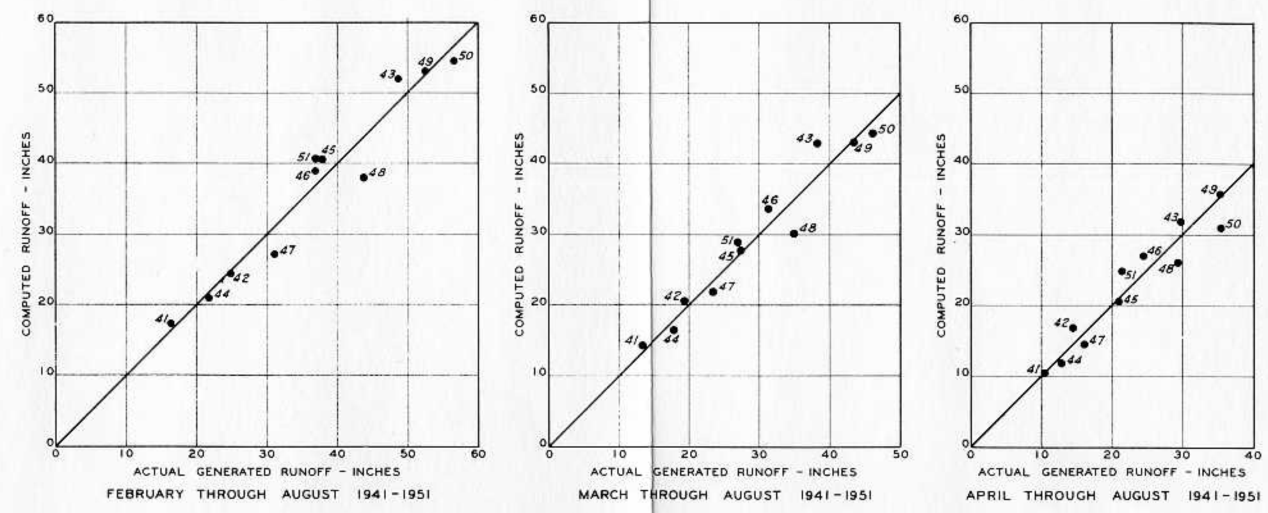
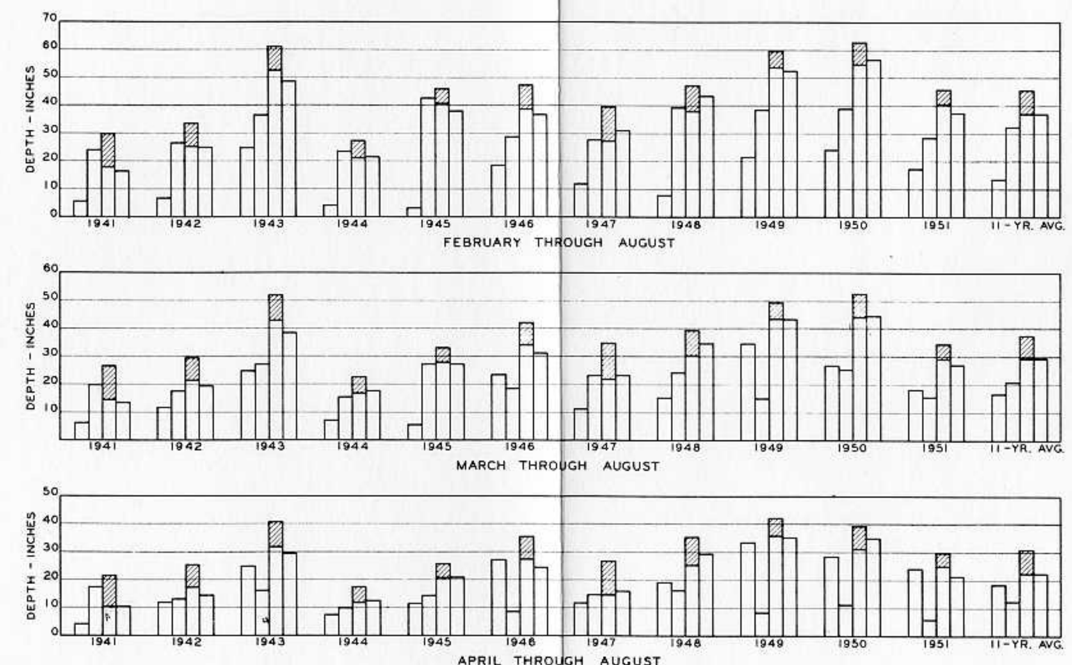


FIGURE 2 - COMPUTED VERSUS ACTUAL GENERATED RUNOFF



Notes:

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

FIGURE 4 - WATER BALANCE FOR FORECAST PERIODS

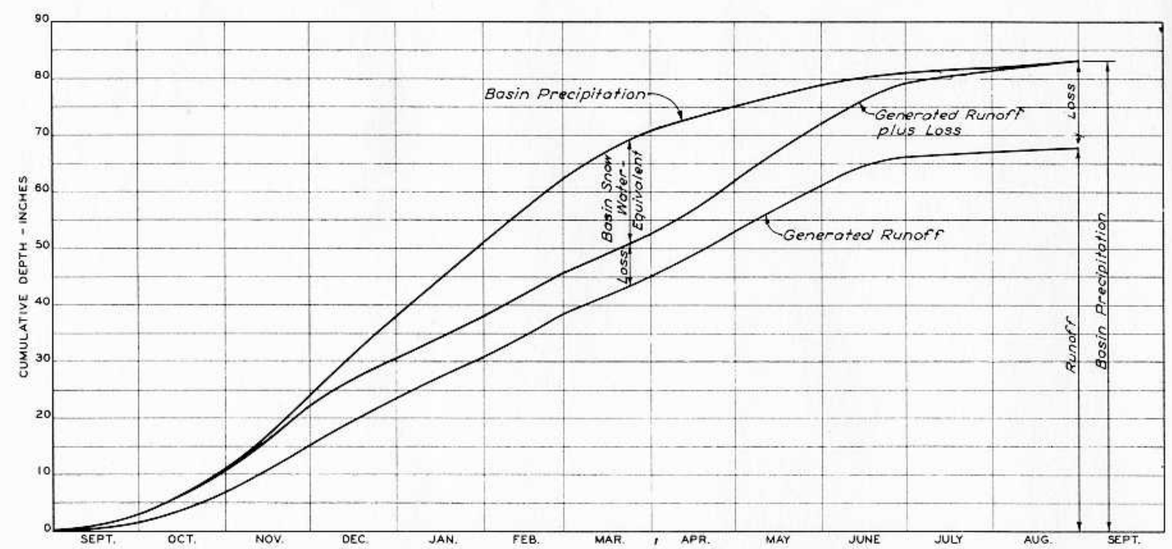


FIGURE 3 - CUMULATIVE COMPONENTS OF WATER BALANCE

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

SNOW INVESTIGATIONS
SUMMARY REPORT

SNOW HYDROLOGY

WATER BALANCE

NORTH SANTIAM RIVER ABOVE DETROIT DAM
DRAINAGE AREA 438 SQ MI

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

PREPARED: M.W.	SUBMITTED: S.M.	TO ACCOMPANY REPORT DATED 30 JUNE 1956
DRAWN: B.X.	APPROVED: D.M.R.	PD-20-25/70

PLATE 11-6