CHAPTER 3 - PRECIPITATION AND SNOW ACCUMULATION

3-01. INTRODUCTION

3-01.01 A fundamental problem confronting the snow hydrologist is the determination of the amount and distribution of precipitation and snowpack water equivalent in a given area at a given time. Inasmuch as the amount of snow in the accumulation phase of the hydrologic cycle is largely a function of amount of precipitation, it is desirable to consider snow accumulation and precipitation jointly in this chapter. Factors determining the amount and distribution of precipitation and of the snowpack are classified broadly as being meteorologic or topographic. Under the former are grouped such factors as temperature of the air, precipitable water therein, the circulation pattern, frontal activity, and stability of the airmass. Topographic factors include elevation, slope, aspect, exposure, forest, and vertical curvature. The effect of these factors upon amount and form of precipitation and snow accumulation is discussed herein. The problem of basic measurement is also considered, including characteristics of precipitation gages, problems of gage catch, both incremental and cumulative, and the use of snow courses and snow surveying techniques. Methods and reliability of measurements are discussed as well as techniques for translating individual values at a single point into an integrated basin total.

3-02. EFFECT OF METEOROLOGIC FACTORS ON PRECIPITATION

3-02.01 General. - Effects of meteorologic factors upon amounts and distribution of precipitation are given in various meteorological texts; therefore, comprehensive examination of these effects is not within the scope of this report. However, it is appropriate to consider briefly the more important factors and their effects upon precipitation. Basically, the requisites for production of precipitation are a supply of moisture from inflowing air and mechanisms for release of the moisture. Moisture is acquired by the air through evaporation, principally over ocean surfaces, and it is carried, largely in the form of water vapor, to the land by large-scale air movements. There is an upper limit to the amount of water vapor that can exist at a given temperature. Air that has reached this limit is said to be saturated. In saturated air, water vapor may undergo a change of state to water droplets or ice crystals. The mechanisms by which water droplets or ice crystals are precipitated from the atmosphere are complex and require that the multitude of minute droplets of condensed water which form clouds be combined into a smaller number of much larger drops. The two principal mechanisms theoretically proposed for producing moderate to heavy precipitation are (1) the colloidal instability of a mixed water-ice cloud at temperatures below $0^{o}C$ and (2) the coalescence of drops of un-uniform size in the gravitational field. It is believed that the two processes act together in the middle latitudes, the ice crystal process being dominant in the initiation of precipitation droplets and further growth being dependent upon the coalescing process. It is observed that, during winter storm conditions in the Pacific Northwest, all precipitation is initially in the form of snowflakes which later melt into raindrops at lower elevations. The level to which the snowflakes fall before melting is dependent upon the temperature distribution of the atmosphere. Since the moisture capacity of the atmosphere is a function of temperature, any action that will result in cooling of the air will tend to aid condensation, which in turn may produce precipitation. The principal means of cooling air in the atmosphere is through expansion, which is largely accomplished by lifting the airmass to levels of lower pressure. Frontal activity, orographic lifting, instability of the airmass, and convergence all tend to cause lifting and consequent precipitation.

3-02.02 Form of precipitation. - One aspect of precipitation is particularly important in the practical consideration of snow hydrology, that being the form in which the precipitation occurs. Of the many possible forms of precipitation, snow and rain are of prime importance, since they comprise the principal source of water deposited on the earth's surface from the atmosphere. Direct observation of form of precipitation is limited to first-order and airways meteorological stations, generally necessitating use of indirect methods for estimating areal distribution of rainfall and snowfall where required for hydrologic problems. Of particular significance, moreover, are mountainous areas where slight changes in airmass characteristics will cause relatively wide fluctuations of the boundaries between areas on which rain or snow is falling.

3-02.03 Estimation of form of precipitation. - No relationship has been found to define exactly, by use of meteorological parameters of airmass conditions, whether precipitation at a given level will occur in the form of rain or snow. Murray [15] attempted to relate the form of precipitation to such variables as the thickness of the 1000-700mb or 1000-500mb layers, the height of the freezing level in the atmosphere, and surface air temperatures. All of the variables tested showed a range of values for which either rain or snow could be expected. Each variable was analyzed on the basis of the statistical distribution of occurrences of rain or snow or both to determine the most probable frequencies of occurrence. The study showed that surface air temperature (approx. 4 feet) is as reliable as any other of the variables tested for differentiating between rain and snow. Accordingly, and since surface air temperatures are generally more available than upper air soundings, hourly observations of precipitation and surface air temperature at Donner Summit, California (elev. 7200 ft.) were used in a study of form of precipitation. Data for the period October through April for the 1946 through 1951 water years were used. Some 2400 occurrences of precipitation at air temperatures ranging from 29°F to 40°F were analyzed to obtain the distribution of occurrences of rain, snow, or mixed rain and snow. The results of this study are summarized in the following table which gives the percentage occurrences of both forms of precipitation for the various surface air temperatures:

FORM OF PRECIPITATION	SURFACE AIR TEMPERATURE, °F											
	29	30	31	32	33	34	35	36	37	38	39	40
SNOW (%)	99	99	97	93	74	44	32	29	8	8		3
RAIN (%)		1	2	3	12	31	51	57	81	90	100	97
MIXED RAIN AND SNOW (%)	1		1	4	14	25	17	14	11	2		
Number of occurrences, (all forms)	281	419	304	459	229	191	154	94	74	79	56	79

The above data are shown graphically in figure 1, plate 3-1. These data conform closely to those quoted by Murray for a markedly different condition of elevation and topography. Accordingly, they are believed to be applicable generally. On the basis of this analysis, the differentiation between rain and snow can be estimated from surface temperatures by assuming rain to occur whenever the air temperature is 35°F or greater, and assuming snow to occur whenever the air temperature is less than 35°F. Within the range of temperatures given in the above table, which includes all questionable precipitation forms, about 90 percent of the cases would be correctly designated by this 34-35°F division between rain and snow. When considering the various inaccuracies in measurements and application to specific problems, further refinements in estimating form of precipitation would be seldom if ever warranted.

3-02.04 Additional evidence supporting the selection of 34-35°F as the dividing line between rain and snow appears when the rate of fall of snowflakes and the relation between the freezing level and the average level of melting of snowflakes, are considered. Murray found that on the average there was an equal probability of rain or snow when the height of the freezing level was approximately 1000 feet above the ground. During times of significant precipitation, the atmospheric lapse rate is usually nearly wet adiabatic. With the freezing level at 1000 feet, the corresponding surface air temperature would be about 3°F warmer than freezing, or 35°F. The average rate of fall for snowflakes, determined by Nakaya 16/ for several of the predominant crystalline forms of snow, is about 50 cm/sec, which is equivalent to about 1.6 feet per second. Accordingly, it would take slightly in excess of 10 minutes for snowflakes to fall 1000 feet, which thus represents the average time of melting of snowflakes in the atmosphere.

3-02.05 An additional study shows the relative frequencies of forms of precipitation at varying temperatures for three elevations: 1000, 4000, and 7000 feet. Figure 2, plate 3-1, presents the results of this study. The frequency distribution of precipitation with surface air temperatures for the 7000-foot level was derived from the Donner

Summit data used in the form-of-precipitation study. For temperatures below 29°F, the frequency curve was extended on the basis of data presented by D'Ooge 5/ for the White Mountain Research Station (37°30'N, 118°10'W) located at an elevation of 10,600 feet. These data were corrected to elevation 7000 feet by assuming a wet adiabatic lapse rate, and frequencies were adjusted to give values comparable to the Donner Summit data. The combined curve shows schematically the average distribution of precipitation occurrences with varying temperatures. The equivalent distribution curves for 4000 and 1000 feet were determined simply by applying the wet adiabatic lapse rate to the surface air temperatures. This may be done with assurance since, during times of significant precipitation, the polar maritime airmasses usually dominant in this area are conditionally unstable, and the uplift along the mountain ranges causes the airmasses to release their instability, resulting in atmospheric mixing and the establishment of a wet adiabatic lapse rate of temperature. Also, during storm conditions, the horizontal variation of air temperature is relatively small because of the turbulent mixing which occurs, and the surface air temperatures at a given elevation are representative of the airmass temperature at that level. The relative frequencies of rain and snow forms of precipitation from the air temperature function may be applied to each elevation for which the average distribution of total precipitation with temperature is known, to determine the average snow and rain frequency distribution for that elevation. The frequency distribution of precipitation in the vicinity of CSSL is shown schematically in the diagrams of figure 2, plate 3-1. Inspection of these diagrams reveals that on the average approximately 95 percent of occurrences of winter precipitation at 7000 feet are in the form of snow, while at 4000 feet about 50 percent are snow. At 1000 feet, only 2 percent of the occurrences are snow. The diagrams in figure 2 represent average conditions on the west coast of the United States at latitude 39°N. They are, however, believed to be generally applicable along the windward side of major mountain ranges in western United States and Canada, with the exception that with increasing latitude there would be a slight lowering of the elevation levels. For example, it is estimated that at latitude 50°N, the elevations of the levels shown for the CSSL would be 6000 feet, 3000 feet, and sea level, an approximate decrease of 1000 feet per 10 degrees of latitude. It is emphasized that these conditions are based on averages over several years of record. Since for a given airmass the form of precipitation is particularly sensitive to changes in elevation, the distribution of rain and snow over a project basin for a particular occurrence or season must be evaluated individually on the basis of prevailing meteorological conditions.

3-03. EFFECT OF TERRAIN ON PRECIPITATION

3-03.01 General. - Over uniform level terrain, as, for example, open ocean or plains, the areal distribution of precipitation is a function entirely of meteorologic variables and their relation in time and space. In mountainous regions, on the other hand, precipitation distribution is largely a function of the character of terrain, upon which is superimposed the distribution due to meteorological conditions of airmasses, fronts, and general atmospheric circulation. The distribution patterns of precipitation over rugged terrain are, therefore, complex and in extreme conditions may well be considered to be as irregular as the terrain itself. To evaluate precipitation satisfactorily in mountainous regions, consideration must be given to the relationship of terrain to meteorologic conditions producing precipitation. An additional consideration of importance is the large scale atmospheric circulation, its seasonal variation, and its change with varying synoptic situations, during times of significant precipitation.

3-03.02 The effects of terrain on precipitation are broadly classifiable as being either large scale or local. Many of the factors are interrelated and there is no simple relationship which is applicable to all areas and conditions of terrain. In addition, errors in precipitation measurements used to represent conditions at a point impose further difficulty in establishing relationships between terrain and precipitation. Measurements must be corrected for known deficiencies (for example, those resulting from poor exposure of precipitation gages or poor conditions of snow sampling) before analyses are made. The relationships developed between uncorrected measurements and terrain features are meaningless.

3-03.03 Small-scale terrain effects. - Studies undertaken by the Snow Investigations to determine relationships between terrain and precipitation in the form of snow were concerned primarily with small scale or local influences. The laboratory basins provided data for such analyses; consequently generalized conclusions drawn therefrom were restricted to ranges of conditions experienced in the small laboratory areas. Since each laboratory has unique terrain features (e.g., at the CSSL the majority of steep slopes are south facing), the correlations are not valid for direct application to other areas. They do, however, show relative variation of measured amounts with respect to principal topographic features at the laboratories, and the method is illustrative of techniques which can be applied to other basins.

3-03.04 Snow laboratory analysis. - Snowpack water equivalent data from CSSL and UCSL were used for analysis of the influence of terrain characteristics upon precipitation accumulated in the form of snow. The water equivalent at each of the laboratory snow courses was related to parameters of aspect, slope, curvature, elevation, exposure, and vegetation, by use of multiple linear regression analysis. Research Notes 2 and 14 report the results of these investigations. The latter study incorporates data from 36 snow courses in the CSSL (including 16 special snow courses for which observations were made on 19 April, 9 May, and 22 May 1951). The observations for 19 April are most representative of snow accumulation since by the latter dates considerable melt had taken place. The early period also reflects to some degree the varying effect of melt over the basin, which began about 1 April. A multiple regression analysis for the 19 April data, using water equivalent of the snow courses as the dependent variable and parameters of aspect, slope, elevation, and exposure sector as independent variables, gave a correlation coefficient of 0.76 and showed the parameters of aspect, elevation, and exposure sector to be statistically significant. A graphical solution of the derived regression equation is given on plate 3-2. A summary of the studies showing the numerical effects of topographic characteristics on water equivalent at the CSSL for the period studied is as follows:

<u>Elevation</u> - Approximately 1- to 2.5-inch increase in water equivalent for each 100-foot increase in elevation.
<u>Slope</u> - Approximately 0.2- to 0.5-inch decrease in water equivalent for each 1 percent increase in slope.
<u>Aspect</u> - Approximately 0.25- to 1-inch increase in water equivalent for each 10° deviation of aspect from the south.
<u>Exposure sector</u> - About 0.5- to 0.75-inch decrease in water equivalent for each 10° increase in exposure sector (sum of the sectors of a circle of half-mile radius, centered at the snow course, within which there is no land higher than the points on the snow course).
<u>Curvature</u> - No definite indication found.
<u>Vegetation</u> - No definite indication found.

More detailed quantitative interpretation of the results is not believed to be warranted; however, qualitative interpretations may be made on the basis of these observations. The main deterrent to application of the results to other basins is the small range of conditions experienced at the laboratories.

3-03.05 <u>Forest effects.</u> - The effect of forest cover on the accumulation of snowpack water equivalent was not evident from the analysis of the CSSL data. This is due primarily to the fact that the snow courses did not adequately sample the range of conditions of forest effect, most snow courses being located in open areas. Later measurements made in connection with research work done by the Northern Rocky Mountain Forest and Range Experiment Station of the Forest Service clearly define the effect of forest in the accumulation of snow. Since the forest effect is considered primarily to be one of interception of precipitation, the results of the study are discussed in the paragraphs on interception loss in section 4-03.

3-03.06 <u>Large-scale terrain effects.</u> - Spreen's [18/] analysis of the effect of topography on winter precipitation for western Colorado is an attempt to correlate larger-scale terrain features with 11-year average winter-season precipitation, as measured by standard U. S. Weather Bureau precipitation gages. His parameters include elevation, slope, orientation, and exposure. Instead of using a multiple linear regression analysis, he chose to relate the variables by means of a graphical correlation technique. The derivation of some of the parameter curves appears to be somewhat arbitrary, particularly that of exposure, and the derived curves do not represent continuous functions of the variables. The method does, however, indicate the magnitude of terrain effects on precipitation in a general sense, and the results of his analysis show that the parameters used account for a high percentage of the variability of precipitation in that area. The reader is referred to the above cited report for the results of this analysis.

3-03.07 <u>Summary</u>. - Because of the lack of comprehensive data on the effect of terrain upon precipitation, it does not seem valid to apply the quantitative relationships for the snow laboratories to project basins. The values cited from analysis of laboratory data show only the effect of the integration of the existing meteorological conditions over the basin for a particular season, as they are related to the particular basin's terrain. For any other area, different relationships would be expected. In order to generalize on the effect of terrain, average seasonal amounts based on a period of several years would provide more usable information. Also, it would appear more reasonable to use the values of point precipitation or point water equivalent in terms of percentage of average basin amounts rather than using actual values, when considering the variation for individual years or occurrences.

3-03.08 In the final analysis, either basin precipitation or basin water equivalent must be estimated from measured values by sampling techniques. The gaged values, corrected for deficiencies in measurements, must be related to basin amounts on the basis of normals. Each measurement of precipitation, then, becomes an index of the basin amount in actual basin application. If the precipitation distribution pattern over a basin, for a season as a whole, is uniform from year to year, any well-located station will be a satisfactory index of basin amounts regardless of the terrain type being sampled. While there is variability in precipitation distribution from year to year, due primarily to atmospheric circulation and airmass characteristics at times of precipitation, experience in the western United States indicates that nearly all winter precipitation occurs at times of strong westerly circulation. The synoptic pattern during such times is generally characterized by the passage of mature occluded frontal systems entering from the Pacific Ocean, and the region is dominated by maritime polar airmasses. Therefore, in this region during conditions of significant winter precipitation, terrain variables such as aspect, slope, and curvature (but excluding elevation effects on snow accumulation) do not materially affect the reliability of any one well-located station as an index of basin precipitation.

3-03.09 When using snow course water equivalent measurements to represent either basin precipitation or the residual water stored on a basin as of a particular date, the same general considerations are involved as for total seasonal precipitation. There is, however, one important variable of terrain which is not proportionally represented on the basis of average meteorological conditions, that being elevation. The effects of elevation on the accumulated water equivalent vary considerably from season to season and year to year, due primarily to the variability of temperature, both during and between the storm periods. The airmass temperature determines the level of change between rain and snow forms of precipitation. Also, during the accumulation period there is differential melting which is primarily a temperature function and in turn varies with elevation. Both of these processes result in varying rates of accumulations of snow with elevation, depending on the temperature regime during the accumulation period, as will be discussed in the following paragraphs.

3-04. ELEVATION EFFECTS ON SNOW ACCUMULATION

3-04.01 General. - It has been pointed out in the previous section that, of all terrain parameters, elevation is the principal one which must be taken into account in determinations of basin water equivalent from point snow course measurements because of the variability, from season to season, of snowpack accumulation with elevation. In order to demonstrate the range of conditions that may be expected, an analysis of data for WBSL is given from which generalizations on the variation of the snowpack with elevation can be made.

3-04.02 The analysis for WBSL was chosen because of (1) the relatively large range of elevation sampled by the snow courses (2100 to 5000 feet msl), (2) the relative consistency of the effect of meteorologic and terrain influences, and (3) meteorological conditions which normally permit occurrence of either snow or rain forms of precipitation at any elevation. Data from CSSL are not amenable to such analysis owing to the limited range of elevation of snow courses. UCSL snow courses sample an area whose winter precipitation is nearly 100 percent snowfall, so that elevation change does not adequately reflect the result of varying percentages of rain and snow. The ordinary snow survey network established for seasonal runoff forecasting in non-laboratory basins is not adequate for this type of analysis because of insufficient density of sampling by snow courses. Data from Technical Bulletin 17, which evaluates snow conditions from 2000 to 7000 feet on the Yuba River basin, California during the heavy snow of December 1951 and January 1952, were used to provide an independent check on results obtained from the WBSL analysis.

3-04.03 WBSL study. - For each of the three water years, 1949 through 1951, snowpack water equivalent data from WBSL snow courses were adjusted to 1 January, 1 February, 1 March, 1 April, 1 May and 1 June, and plotted as a function of elevation. Straight lines were fitted to these points, giving due consideration to the relative exposures and reliability of measurements at each snow course; each line so derived shows the average depth of snow at various elevations of the basin. This line together with the zero base line forms a wedge hereinafter referred to as the snow wedge. Figure 1, plate 3-3, shows the plot of the snow wedge for each month in each of the three years at WBSL, as well as for the months of December, January, and February of the 1952 water year in Yuba River basin. Inspection of these diagrams reveals the relative changes in slope of the snow wedge within seasons as well as from year to year. The slope of the snow wedge plotted against time, to illustrate the seasonal change in slope, is shown in figure 2, plate 3-3. Adjacent to each of the plotted points is the water equivalent at the 5000-foot elevation, which indicates the relationship of the slope of the snow wedge to the magnitude of the water equivalent near the upper limit of the basin during the accumulation period. Finally, the relationship between the slope of the snow wedge and the water equivalent near the upper limit of the basin (5000 feet for WBSL and 7000 feet at Yuba River) during the accumulation period is shown in figure 3.

3-04.04 Accumulation period. - Inspection of figure 2, plate 3-3, shows that the slope of the snow wedge becomes progressively steeper through the accumulation period, but tends to remain more or less constant during the melt period. During the accumulation period, the variation in melt with elevation is a minor factor, the principal factor affecting the slope of the snow wedge being the change from rain to snow form of precipitation with elevation. Another factor affecting the slope of the snow wedge is the normal increase of precipitation with elevation. The plotted points for WBSL in figure 3, plate 3-3, show the relationship between depth of water equivalent at the 5000-foot elevation and the slope of the snow wedge during the accumulation period. A straight line fitted to these points shows an average increase in slope of the snow wedge of 0.3 inch per 100 feet for each increase of 10 inches of water equivalent at 5000 feet. The difference in the relationship which may occur between individual years is shown by the difference of accumulation characteristics for the 1949 and 1950 water years. The 1949 water year, which had near maximum of record snow accumulation at high elevations, was characterized by a relatively steep snow wedge; there was not an abnormal snowpack accumulation for the basin as a whole. By contrast, the 1950 water year with a similar amount of snow in the high portions of the basin, had relatively less change of water equivalent with elevation and as a result had a proportionally greater snow accumulation over the basin as a whole. This difference in snow wedges indicates the necessity for considering elevation effects in computing basin water equivalent. The three points for Yuba River basin for 1 December, 1 January, and 1 February, related to the water equivalent at 7000 feet, show an increase in slope of the snow wedge similar in magnitude to that for WBSL.

3-04.05 Melt period. - Data for the melt period, as represented by 1 May and 1 June observations, are not as reliable as data for the accumulation period, because of the varying effect of local exposures of snow courses on melt rates. Analysis of data from the heavily forested WBSL indicates that the slope of the snow wedge remains nearly constant during the melt period, with only a slight tendency to increase as the melt season progresses. The increase with respect to time is considerably less than that for the accumulation period. In order to evaluate rationally the changes in melt rates with elevation, it is necessary to consider all methods of heat exchange for specific conditions of environment. For the heavily forested WBSL, however, snowmelt runoff can be estimated fairly well by an air temperature function which indicates 0.041 inch of melt per degree-day of mean daily air temperature above 29° base (see chapter 6). During active melt periods in May or June, the mean daily temperature at the mid-point of the basin (elevation 3500 feet msl) is about 60°F, which represents an average daily ablation of the snowpack water equivalent of about 1.27 inches. Assuming an average temperature lapse rate of 3°F per 1000 feet over the snow-covered area, the melt at 5000 feet would be 1.11 inch per day, or 88 percent of the melt at the mid-point. Since the forest cover tends to decrease in density with elevation, average melt rates per degree-day tend to increase, so that actually the melt at the top of the basin is even closer to the mean melt rate for the basin than is indicated by the simplified illustration above.

3-04.06 Summary. - In general, the increase in the snowpack water equivalent with elevation varies widely from year to year and from season to season. During the accumulation period, the largest factor affecting the variation in snowpack accumulation with elevation is the form of precipitation which in turn is dependent upon meteorological conditions during times of precipitation. Secondary effects are the elevation differences in melt, both during and between storms, and the normal increase of precipitation with elevation. During the accumulation period there is a fair relationship between slope of the snow wedge and the total water equivalent in the upper portion of the basin. The relationship varies from year to year, however, so that in individual cases, the basin snowpack water equivalent must be adequately sampled throughout its range in elevation. After the time of maximum snow accumulation, the slope of the snow wedge becomes more or less constant. There is only a slight further increase in slope during the active melt period. During the active melt period, the slope of the snow wedge bears little relationship to the water equivalent of the snowpack at high elevations. Special care should be taken to adequately represent the actual basin condition from late-season snow surveys in evaluating basin snowpack water equivalent. It is pointed out that the above generalizations apply to the zones of elevation where straight lines adequately represent the variation of water equivalent with elevation. For areas lying above elevations where more than 90 percent of the precipitation during the accumulation season is in the form of snow, the slope of the snow wedge would tend to flatten, and curvature would be introduced into the lines.

3-05. POINT PRECIPITATION MEASUREMENTS IN AREAS OF SNOWFALL

3-05.01 General. - Proper appraisal of precipitation data necessitates a knowledge of the characteristics and limitations of the instruments used to gage precipitation catch and the observational procedures used in determining point precipitation values. Much has been written on the general problem of measuring precipitation, and reference is here made to a comprehensive summary of rain and snow gaging methods by Kurtyka. 11/

3-05.02 Gaging of snow. - The accuracy of snow measurement by standard rain gages is subject to sharp limitations due to the physical characteristics of the snow itself. These limitations have long been recognized through many experiments conducted both in this country and abroad. Experience gained at the snow laboratories in measuring winter precipitation has provided factual data on reliability of precipitation measurements in areas of snowfall and a measure of the gage-catch deficiencies involved. Wilson's report analyzing winter precipitation observations in the Cooperative Snow Investigations 23/ summarizes the problem of measurement of point precipitation, both by precipitation gages and snow courses. The study generalizes the effects of weather and exposure on measurement of precipitation, and emphasizes the importance of local environment in proper site selection for both precipitation gages and snow courses. The performance of precipitation gages at CSSL is reported in Research Note 21, wherein corrections for gage-catch deficiencies are evaluated quantitatively. Monthly and annual precipitation values for each of the laboratories, derived from observed values and adjusted to basin amounts, are an important link in the water balance computations presented in chapter 4. With adequate knowledge of gage characteristics and limitations, gage-catch deficiencies may be minimized and reasonable data adjustments may be obtained. Brief descriptions of commonly used gages and results of investigations on their performance with respect to snowfall are summarized in the following paragraphs.

3-05.03 Non-recording gages. - Precipitation gages may be classified broadly as non-recording and recording, the former being the most widely used. The standard gage adopted for use in the United States consists of an eight-inch cylindrical receptacle having a catchment area of 50.4 sq. in. To facilitate measuring, the receiver is funneled at the bottom to direct the flow of water into a measuring tube having a cross-sectional area one-tenth of the catchment area. Thus rainfall can be measured to the nearest one-hundredth of an inch by measuring the depth in the tube to the nearest one-tenth of an inch. In snowfall areas, the funneled receiver and measuring tube are removed, the snow falling directly into the open cylinder, to be later melted and poured into the measuring tube. Measurements are usually made by observers under the supervision of the U. S. Weather Bureau, the authorized agency for collecting, processing, and disseminating meteorological data. Observations using standard USWB 8-inch gages are made daily insofar as practical and must, in any case, be frequent enough that the capacity of the receiving can is not exceeded. Another type of non-recording gage, designed for use in areas where daily observations are impractical, is the storage gage. Such gages have sufficient storage capacity to hold precipitation occurring during periods as long as a year. In cold regions an anti-freeze solution (of an amount approximately equal to the expected seasonal catch) must be placed in the gage to prevent freezing and to facilitate melting of accumulated snowfall. 19/ Oil is added to the solution to retard evaporation. The standard type used in this country is the Sacramento storage gage, which has the form of a truncated cone to permit free fall of snow inside and thus discourage capping and also to increase the storage capacity. (See paragraph 2-06.13 for a discussion of the operation of this gage at the snow laboratories.)

3-05.04 Recording gages. - Recording gages are designed for use in locations where a continuous record is desired and for locations where the gage cannot regularly be attended by an observer. Of the many types in use, the most common in this country are the tipping bucket gage and the weighing gage. In the former, a record is made each time a counter-balanced receiving bucket tips to discharge its accumulating precipitation. With a clock mechanism, the time interval can be recorded. Its advantage of being self-discharging is offset by the fact that with one exception, which is currently being tested, this type of gage is not adapted to the measurement of snowfall. The gages most commonly used to measure both rain and snow are of the weighing type, in which a pen arm continuously records, on a clock-turned drum, the weight of the accumulated precipitation. Addition of oil and anti-freeze to the receiving bucket enables this type of gage to record volume and rate of precipitation for long periods of time, limited only by the necessity of periodic changing of the recording chart and emptying of the receptacle. The two most widely used of such weighing type gages are the Friez and the Stevens (discussed in paragraphs 2-06.11 and 2-06.12). Less widely used are float gages, in which the pen arm is actuated by a float in the receptacle containing the accumulated precipitation. For freezing conditions, the float is placed in a tube containing fluids such as oil or mercury which balance the hydrostatic pressure of the accumulated precipitation. The height of water in the gage may also be measured by use of a microsen transducer, which is a sensitive electric pressure-measuring device. Because of their limited use or inapplicability under snow conditions, neither these nor other recording gages such as the siphon-type or the water-wheel type are further discussed in this report.

3-05.05 A recent recording innovation, generally adaptable to the weighing-type gage, is a telemetering device which transmits recorded amounts of precipitation by radio or wire to receivers located at a distance from the gage. Such installations are particularly desirable where current rates of precipitation are desired from remote locations. Several district offices of the Corps of Engineers, among them the Portland District, have currently in operation a gage which makes use of such a device.

3-05.06 Source of errors. - Regardless of type of gage used, measured precipitation amounts may vary considerably from the actual amount falling at the gage site. Variations of measured amounts from true amounts are largely the result of improper catch by the gage and/or error in measurement of the amount received by the gage. Errors in measurement may be either personal errors, such as misreading the water line on the measuring stick, or errors resulting from improper functioning of the gage, the latter generally being confined to recording-type gages. Another source of error, particularly in connection with storage gages, is evaporation of liquid from the receptacle. Less common, but deserving of attention, is loss of liquid by leakage of the receptacle.

3-05.07 Performance of gages. - So many experiments on precipitation catch have been made that it must suffice here to summarize the results most pertinent to snowfall areas and especially those conclusions derived from Snow Investigations data.* Results of a number of

*A vast amount of general and specific information on snow catch and measurement, well annotated and indexed, is contained in the SIPRE "Bibliography on Snow, Ice, and Permafrost." 17/ A comprehensive summary of the experience gained from the five years of operation of the snow laboratories of the Cooperative Snow Investigations is presented by Wilson. 23/

studies indicate that the greatest single source of error in sampling precipitation is due to gage catch deficiency. The studies also indicate that the deficiency varies widely, being largely dependent upon wind speed, shielding of gage orifice, position of orifice with respect to ground, and percentage of precipitation occurring as snow. A secondary cause of gage-catch deficiency results from capping or bridging over of the gage orifice during snowfall. Controlled experiments in a low-velocity wind tunnel using sawdust to simulate snow have been performed by Warnick. [20] These experiments demonstrated the value of wind shields in reducing the catch deficiencies, and furthermore, as would be expected, showed catch deficiency to increase with wind speed. Warnick also reported on field tests made of various combinations of precipitation gage and wind shield types. Field experiments have also been made by many other investigators, among them Alter [1], Gerdel [6], and Helmers [8], to cite but three. Those tests indicate catch deficiencies even from shielded gages, both as a result of wind action and of capping.

3-05.08 Effect of turbulence. - Since gage-catch deficiency is largely the result of turbulence in the orifice, gage installations are made with the objective of reducing the wind speed over the orifice. Accordingly, gages are placed in locations sheltered from wind by trees or other objects. In addition, various types of shields have been designed to reduce turbulence at the gage orifice. The most widely known types are the Nipher and Alter shields. The Nipher type consists of a trumpet-shaped one-piece shield mounted with the flared end up and approximately at the level of the orifice. It is not suitable for precipitation in the form of snow, there being no provision for preventing snow from accumulating in the shield. The Alter shield is similar, but is comprised of loosely-hung metal strips which inhibit the accumulation of snow. Even with shielded gages, however, the deficiency of snow catch may be as great as 50 percent of the "true catch" for gages which are poorly located with respect to natural shelter.

3-05.09 Position of orifice. - Although the standard procedure has been to install all gages with the orifice in a horizontal position, investigations reveal that better catch is obtained if the orifice is placed parallel to the ground surface. [7] However, the general desirability of such non-horizontal installations is questionable since areal measurements are conventionally referred to a horizontal plane rather than a slope. Furthermore, considerable ambiguity may arise in defining the slope for a given gage in areas of very irregular topography.

3-05.10 Capping. - Capping is difficult to evaluate, and the magnitude and importance of its effects vary greatly according to circumstances. Experience at the snow laboratories indicates that although capping occurred rather frequently, its net effect on loss to total gage catch was usually either not significant or could be corrected by double-mass-curve analysis. A snow cap which builds up on the orifice often results in only a time delay to the gage catch, because the cap is effectively gaged when later settling of the snow into the gage is accomplished by the cutting action of the sharp-edged gage orifice. Frequency of servicing is important in evaluation of capping effects. For the snow laboratories, servicing of outlying gages varied from weekly to monthly intervals. Wind shields aggravate capping effects, but well-located gages in small forest clearings do not require wind shields. In general, windiness has much more effect on gage catch deficiency than does capping. Research Note 21 describes corrections required for capping deficiencies at CSSL. While records at UCSL were examined closely by double mass curves for loss of record by capping, no significant deficiencies were noted. Loss of record by capping at WBSL could be identified in the majority of cases, but frequency of servicing storage gages was sometimes inadequate for interpreting such deficiencies.

3-05.11 CSSL study. - A study of gage-catch deficiency of gages equipped with Alter wind shields, based on snow course measurements during periods of no melt or rainfall using 1947 through 1950 data at Central Sierra Snow Laboratory, was reported on in Research Note 21. Precipitation gage catch was compared with increase in snow course water equivalents at given locations for given periods of time, and adjustment factors for obtaining "true gage catch" were established. Wind speeds for individual storm periods were not available, but mean windiness was computed for each of 5 precipitation-gage stations having wind records. Mean wind speeds for January through March (which were the months during which the precipitation and snow measurements were made) were used to derive an average relation between gage-catch deficiency and wind, for precipitation in the form of snow. Correction factors and gage catch deficiencies for the various mean winter wind speeds are shown in the following tabulation:

Mean Wind Speed (m.p.h.)	Adjustment Factor	Gage deficiency in percent of "true catch"
0	1.00	0
1	1.03	3
2	1.12	11
4	1.30	23
6	1.50	33
8	1.67	40
10	1.89	47

Gage-catch deficiencies for given wind speeds shown in the above tabulation are not directly comparable to those obtained by other investigators. This is due to the fact that the mean wind speeds for the monthly periods are normally lower than mean winds during given storm periods such as are used in other investigations.

3-05.12 Catch deficiencies of rain vs. snow. - Comparisons of recorded precipitation and water equivalent of snow on the ground at Barrow, Alaska by Black [2] indicate that the deficiency in gage catch is 50 to 75 percent during the winter months.* Wilson, [22] in a discussion

* For this wind-swept area

following Black's report, presents a graphic summary of the work of a number of investigators, substantiating the conclusions given by Black. Gage catch deficiencies for various wind speeds, approximated from Wilson's graphic summary, are shown in the following tabulations:

Wind Speed, m.p.h.	Gage catch deficiency, percent of "true catch"	
	Predominantly Rain	Predominantly Snow
0	0	0
5	6	20
10	15	37
15	26	47
20	35	54
25	40	60
30	43	64
35	46	67
40	48	69
45	49	71
50	50	73

3-05.13 Summary of gage deficiencies. - The preceding paragraphs have described the deficiencies and limitations of point precipitation measurements with commonly used gages. The effect of turbulence by wind is the major cause of deficiency, and gages are considerably less efficient in catching snow than rain. Shielding aids in reducing the deficiency by up to 40 percent, but even shielded gages are not well suited to catching snow at sites which are exposed to strong winds. The best measurements of precipitation, either for use as a true point quantity or as an empirical index for a large area, are obtained by situating the gage in a well-sheltered location, so that windiness is reduced to a minimum. Deficiencies caused by capping, although random in nature, are usually not as serious as those caused by wind. Mechanical and observer errors are usually minor.

3-05.14 Site selection for precipitation gages. - Because of the wide use of point precipitation data for determining the precipitation on a given area, a study of the factors influencing the amount and variability of precipitation at a given point is of great importance. Wilson [23] divides the factors affecting precipitation into five categories, shown below with examples of each:

1. Storm experience; location with respect to storm path.
2. Physiography; position on, or distance to, large mountains.
3. Environment; distance from small ridge.
4. Site; height of nearby trees.
5. Gage; depth and diameter of funnel.

The precipitation pattern over the basin as a whole is largely determined by the first two factors listed, whereas the amount of precipitation received at a given point is influenced by all but the last factor. The problem confronting the hydrologist is determining how well a given precipitation gage observation represents the amount actually occurring in that vicinity. Wilson's study shows that there is considerable variability in amounts of precipitation caught by different gages even if they are as close together as 20 feet. In such instances the variations in catch are the result of factors such as height of gage above ground or snow surface, shielding of the gage, mechanical errors in recording gages, capping of orifice by snow, and errors in observation. The presence or absence of a wind shield and the type of shield are particularly important when a large percentage of precipitation is in the form of snow and accompanied by high winds.

3-05.15 Stations confined within distances of several hundred yards may show additional variation in amount of catch due to such causes as location with respect to trees, small ridges, or other obstructions. However, it is interesting to note that stations as far apart as 3000 feet may show less variation in gage catch than stations within a few feet of each other, indicating that site selection for obtaining reliable point precipitation is a complex problem. However, it is evident that stations showing the most consistent and greatest gage catch are those in locations where wind speed is low, and accordingly gages in well sheltered locations are considered most desirable. Because of the sparsity of stations in most project basins, all stations must be utilized to the fullest extent possible in evaluating the basin precipitations.

3-05.16 Mass curve analysis of precipitation records. - In addition to factors resulting in precipitation variations of a compensating nature, factors causing abrupt changes in precipitation regime must be considered. Such factors include change in gage location, environmental changes resulting from construction and removal of buildings and growth or removal of trees, and changes in observing techniques or type of installation. Inconsistencies resulting from such factors can be detected and corrected by use of the double-mass-curve technique. 10/ 14/ This method basically consists of comparing the accumulated precipitation of the station to be tested with the accumulated average amount at a group of base stations, all stations being within the same meteorological environment. Specifically, the process consists of plotting the accumulated values on a graph, the group average represented by the abcissa and the single station values by the ordinate. If the record of the station being tested is consistent, the plotted points will fall along a single straight line, the slope of which represents the ratio of the single station precipitation to the group average precipitation. If, however, there is a change in the precipitation regime of the station tested, a change in slope of the line will occur. The accumulated amount at the station at the point of change in slope is coincident with the accumulated amount on the date that the change took place. Records must be adjusted in accordance with the ratios of the slopes of the segments of the line. Selection of the period whose slope is considered most representative must be based on careful analysis of the basic data for the station. In some cases, a change in the slope of the line cannot be attributed to any known change in precipitation regime, necessitating determination of whether or not a broken double-mass curve is justified.[21]

3-06. RELATIONSHIP OF POINT PRECIPITATION TO AREAL DISTRIBUTION

3-06.01 General. - Special methods of integrating the individual point measurements of precipitation into an areal depth have been devised by hydrologists concerned with the western-mountain areas. For these areas of great snow accumulation the general use of averages or of Thiessen polygons is not applicable because of the marked orographic precipitation pattern and the inadequate distribution of precipitation stations. The orographic effect, however, tends to maintain the same general precipitation pattern from storm to storm and from year to year over small or moderate-sized drainage areas (that is, basins having drainage areas which are small compared to the area covered by general storms which pass over the region). This more or less fixed precipitation pattern makes possible the techniques described below to determine areal precipitation for individual storms and years, once the basic pattern is determined for any area.

3-06.02 Normal annual precipitation distribution. - The basic map used in the determination of basin precipitation amounts is one showing the normal annual precipitation (NAP) distribution by isohyets. (Normal seasonal precipitation excluding the summer months is often used in areas where appreciable amounts of precipitation fall as random local convective showers during the summer and thus distort the pattern from more general storms.) The NAP map is prepared from all available records in and adjacent to the area--for more stations than might report in any one storm--with isohyets carefully drawn for both the individual reporting stations and for topography; interpolation between stations is generally along contours to incorporate orographic effects.* The map may then be planimetered to determine the NAP. (For basins with few stations or with all stations at low elevations, it is sometimes necessary to estimate precipitation from runoff, loss rates being determined from adjacent basins having more precipitation data.) The necessity for computing annual precipitation from runoff and loss amounts may be appreciated when it is observed that in some basins, annual recorded runoff exceeds the average recorded annual precipitation amount. (See Research Note 20 which discusses such a situation in WBSL.)

3-06.03 The relatively unchanging pattern of precipitation over small mountainous areas makes it possible to estimate, with a fair

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*In general, orographic precipitation increases with elevation on the windward side of slopes and decreases to leeward. The view has been presented that for very high barriers, the maximum precipitation often occurs below the crest on the windward side.[12] There is considerable evidence, however, that the decrease in precipitation at the crest is sometimes more apparent than real, due to increased gage catch deficiencies and snow survey deficiencies at windy, exposed elevations.

degree of accuracy, basin precipitation from station precipitation amounts. That is to say, the ratio of station precipitation to basin precipitation is approximately constant for any given storm or group of storms, and hence the normal precipitation for any station bears a constant relation to the normal basin precipitation. Thus,

$$\frac{P_b}{P_a} = \frac{N_b}{N_a} \text{ or,} \qquad P_b = P_a \frac{N_b}{N_a}$$

where P_b is the desired basin precipitation, P_a is the gage catch at a particular station (or group of stations), N_b is the basin NAP, and N_a is the NAP for the station(s) used to determine P_a. Such an equation yields good results provided that the number and distribution of the stations used in the relationship adequately represent the basin. As a further refinement, if stations are not evenly distributed, they may be weighted in accordance with the fraction of the basin represented by each station. These weights are treated as coefficients by which the corresponding station precipitation and station normals are multiplied before substituting in the formula.

3-06.04 The assumption of a fixed relationship between the precipitation of any station and the basin precipitation can be considered at best an approximation. A more rational method is that of the isopercentual map. Here, storm (or annual) precipitation at the various stations is expressed in percent of NAP, and isopercentual lines are then drawn for these values. This isopercentual map may then be superimposed on the NAP map and isohyets shown for the particular storm by noting intersections. The NAP map reflects the normal topographic effects while the isopercentual map indicates deviations from normal. The fewer and more widely spaced the isopercentual lines, the more nearly does the individual storm conform to the normal pattern. The chief value of this approach over the more conventional direct drawing of an isohyetal map, lies in the ability to utilize quickly and with considerable confidence a detailed pattern of precipitation and still take into account much of the obvious variation of individual storms from the mean.

3-07. POINT MEASUREMENTS OF SNOW

3-07.01 General. - Measurements of snow include the water equivalent both of newly fallen snow and the net accumulation of snow. The latter is particularly useful for basin water supply forecasts, since it integrates in a single set of measurements the basin snowfall and melt. It thereby represents water remaining in storage in the snowpack. As in the case of total precipitation, snowfall or water equivalent must be measured by sampling at a point and extrapolating point values to represent basin amounts. The following paragraphs describe commonly used methods of measurement of snow, sources of error, limitations of measurements, and general requirements for locating snow courses.

3-07.02 Measurement of snowfall. - A simple method of measuring snowfall is by use of the snowboard. The board is placed on the ground or old snow surface to permit accumulation of new snow. An inverted rain gage cylinder is utilized to isolate a core of the new snow, which is then melted and measured in the same manner as rainfall. By measuring each fall of snow in this manner and replacing the clean board again to receive fresh snowfalls, accumulated total snowfall throughout the season may be known at any time. Such measurements are fairly reliable, provided that they are taken soon after each snowfall and that the snow on the board has not been subject to drifting, melting, or evaporation. Other devices based on the same principle as the snow board are Angot's snow basket, snow tables, and snow bins.[11/]

3-07.03 Another method of determining water equivalent of new snow is by multiplying the depth of new snow by an appropriate density factor. Studies based on data at CSSL indicate that a fair relationship exists between air temperature and density of new fallen snow.[4/] A graphical plot and discussion of this relationship is contained in chapter 8. Densities of new snow based on air temperatures are acceptable for determination of water equivalent if the period involved is sufficiently long to permit compensation of errors in density values.

3-07.04 Snow density. - The specific gravity of snow, (a dimensionless ratio) is commonly called the snow density (which properly would be mass per unit volume). Following usage, this terminology is used in this report. Snow density is generally expressed numerically as a percentage. The condition of snow density in the snowpack varies widely within the vertical structure of the snowpack as well as with time. Chapter 8 describes the changes of density that occur within the snowpack and the processes that affect the metamorphism of snow.

3-07.05 Snow stakes. - Snow stakes are often used to measure depths of snow accumulation. Water equivalent of the snowpack can be determined from depth measurements by evaluating the time-duration of processes affecting the settlement of the snow or by using known densities of snow under similar conditions of environment. The use of snow stakes does allow the evaluation of relatively short time increases or decreases in water equivalent without disturbing the snowpack sampling area. Also, snow stakes may be used where it is impractical to obtain water equivalent by direct sampling, particularly by reconnaissance from the air. This method has been used successfully by California Electric Power Company, as reported by Henderson.[9/]

3-07.06 Sampling of accumulated water equivalent. - Direct sampling of water equivalent is usually accomplished by use of snow sampling equipment, the most common of which are the Mount Rose and the Utah samplers. These two types are basically similar, being comprised of a tube fitted with a cutter on one end and a handle on the other end. The tube has an inside diameter of 1.485 inches (which makes one inch water equivalent weigh one ounce) and is made up of sections to facilitate transportation. Sampling consists of pushing the tube vertically into the snow to full snow depth, withdrawing the tube with the snow content, and weighing. Weighing scales are designed to give readings in inches of water equivalent; tare weight, of course, must be subtracted to obtain the weight of the snow. A record is made of the depth, length of core, weight, and any other useful information such as estimated moisture content of the underlying soil.

3-07.07 Sources of errors. - Water equivalent measurements are subject to a variety of errors. As in any type of work where measurements are made, snow surveying data are subject to such usual observer errors as misreading the sampler weighing scale. Probably the most common error is that resulting from an incomplete core of snow in the sampler tube. This may be caused by clogging of the cutter by corky snow, obstructions such as cones or sticks, or sticking of the snow to the tube. Such occurrences can generally be detected by comparing the length of core with depth of snow. Another source of error is sampling of ponded water in the lower portion of the core, resulting from poor snowpack drainage. In such cases the water equivalent may be computed by multiplying the depth of snow by densities obtained at reliable sample points. Where frequent observations are made, care must be exercised to avoid holes left by prior sampling. Any dirt or other foreign matter must be removed from the cutter end of the sample before weighing. The many details pertaining to snow surveying for the purpose of obtaining the water equivalent of the snowpack at a given point are beyond the scope of this report; for details the reader is referred to a comprehensive report on snow surveying by Marr. 13/

3-07.08 Snow courses. - The common practice in taking snow measurements is to sample the water equivalent at a number of points along an established line called a snow course. Snow courses are located with the objective of obtaining data representative of a given area, the number depending largely upon the terrain and meteorological characteristics of the area. Other factors such as accessibility, availability of funds, and purpose for which the data are to be used, must, of course, be considered in the establishment of the network of stations. Site selection should be based on the same general requirements as for precipitation gages, considering: (1) meteorological conditions with respect to storm experience; (2) position with respect to large-scale topographic features; (3) position with regard to local environmental features, such as exposure, aspect, orientation, and ground slope; and (4) conditions on the site itself, such as local drainage and the occurrence of brush and rocks. In addition, snow courses should be located to adequately sample ranges in elevation, and they also should be so located that they are representative of average basin melt conditions as well as basin snow accumulation. As is the case for precipitation gages, snow courses should be located in areas well protected from wind, since wind erosion and drifting snow cause unrepresentative snow accumulations. An ideal location consists of an opening in the forest surrounded by hills for protection from high winds, and sloped sufficiently to permit runoff of water beneath the snowpack. The number of sample points is variable, depending largely upon the consistency of the distribution of snow. Sample points are located with the objective of avoiding variations in snow depth due to causes such as drifting, interception by trees, and presence of boulders or other obstructions. If protection from wind is altogether lacking the sampling points must be spread over a wide area to average out variations due to drifting. In general, five snow-course sample points are probably adequate for well-located snow courses on which there is a minimum amount of irregularities caused by drifting or wind erosion, if the ground surface is smooth and clear of all obstructions, and if the snow course is not too close to the forest or other obstructions of a local nature to be influenced by local irregularities in deposition. When conditions are less than ideal, however, additional snow course points are required to adequately sample the water equivalent. Basic data from snow courses are obtained under cooperative arrangements between various Federal, state and private organizations and are coordinated and published for most of the western United States by the Soil Conservation Service. In California, the supervision of collecting and publishing snow course data is by the Division of Water Resources for the State of California.

3-07.09 As in the case of precipitation gages, snow courses also have certain limitations as measures of precipitation. Wilson discusses the reliability of snow course measurements in connection with measurement of winter precipitation at the snow laboratories. Reference is made to his article [23/] for comparative data showing reliability of individual point measurements of snow accumulation, as well as relative reliability of snow courses. Studies for CSSL have shown that a single, well-located snow course (such as station 5) will more adequately represent the basin water equivalent for this relatively small area than a group of poorly-located snow courses. Although care is exercised in selecting locations having stable physical features, changes affecting the deposition of snow at sampling points may occur. A common change in physical features is the removal of all or a portion of surrounding timber by causes such as fire, cutting, bug infestation, or severe wind storms. On the other hand an opposite effect can be produced by growth of brush or timber in the vicinity of the sampling points. In the latter case annual changes may not be detectable; nevertheless, the change over a period of years may be significant. Another important effect of physical changes is improper drainage of free water as a result of obstructions such as beaver dams or accumulation of debris in drainage channels in the snow course area. Occasionally physical features may change sufficiently to necessitate abandonment of the snow course. Often, however, the location is acceptable despite some changes in physical features. In such cases adjustment in records must be made, using the double-mass curve method as for precipitation.

3-07.10 Radioisotope snow gage. - A radioisotope-radio-telemetering snow gage has been developed by the Corps of Engineers (see para. 2-07.09) to make measurements of snowpack water equivalent at remote, unattended sites, and to transmit these data to a central receiving station. A general description of this gage and its operation is given in the following excerpt from the final report on its development and test performance: 3/

> "As presently developed, the equipment includes a gamma ray source, cobalt 60 (Co 60) enclosed in a lead collimating cylinder that is installed in a block of concrete set flush with the ground surface. The beam of gamma radiation leaving the lead collimating cylinder strikes a Geiger-Muller radiation-detector type (G-M tube) suspended 15 feet overhead. The G-M tube is designed to measure the residual radiation after attenuation by the snowpack. The pulses of electricity caused to flow in the G-M tube by the gamma rays are first amplified, then are divided by eight(for transmission), and then are fed into a frequency-modulated radio transmitter with a $\frac{1}{4}$-watt power output. The pulses are broadcast in the VHF range using a high-gain directionalized output antenna. The installation, which is operated on battery power (including high voltage for the G-M tube), is capable of sustained, unattended operation for eight months. The transmitter is operated for only short periods each day by means of an electrically wound, spring-driven clock with an automatic switching device."

Since the measurements made by the gage are non-destructive, the same point may be sampled over and over again, thus doing away with the need for numerous samples to average out errors which result from the unevenness of the underlying ground and other errors inherent in individual samples of the snowpack obtained with a snow tube. Moreover, the non-destructive aspect of the gage, in combination with its telemetering feature, makes it possible to take daily (or even more frequent) readings of the water equivalent in contrast to the monthly or bi-monthly data obtained by conventional snow-tube measurements. Thus it has the particular advantage of providing continuous information on increments of snowpack accumulation from storm to storm throughout the accumulation period, and also of providing a means of evaluating increments of melt during the ablation period, from an undisturbed snow sample point at a remote site. As presently developed, the gage can obtain an accurate measure of water equivalent up to about 40 inches, for an unattenuated counting rate of 20,000 counts per minute. The accuracy of measurement for a ten-minute counting period under this condition is illustrated by the relative magnitude of errors as follows:

Water equivalent (in.)	10	20	30	40	50
Std. error of est. (in.)	0.1	0.1	0.2	0.7	3.4

Using present equipment, this error of measurement may be reduced and an accurate measure of water equivalent in excess of 40 inches may be obtained by (1) increasing the strength of the radioactive source, (2) by decreasing the distance between the source and the sensing unit, or (3) by increasing the length of the counting period. In addition, to provide more accurate measurements at greater depths, such changes in the equipment as shielding the sensing unit from cosmic radiation or using multiple sources of radioactive material at varying heights above the ground have been considered. The figures given in the tabulation above are representative of the accuracy of the gages currently in use by the Sacramento District in the Kings River drainage above Pine Flat Dam.

3-08. RELATIONSHIP OF POINT VALUES TO BASIN WATER EQUIVALENT

3-08.01 General. - Having determined point values of all snow courses representative of an area, the problem is to utilize these values to determine the water equivalent on the area. The basin value may be expressed either as an index or as a quantitative measure such as inches depth over the basin. Volume of the snowpack is an important factor in forecasting seasonal volume of runoff, as a determinant of peak flow, and for short-term rate-of-flow forecasting based simply on depth of water equivalent. Index relationships are most commonly used for forecasting seasonal runoff volumes and to some extent for forecasting peak flows. Regardless of how a basin index is derived from point values, its usefulness is dependent upon how well it represents basin conditions, rather than upon its representativeness of the point values.

3-08.02 The relationship of basin water equivalent to point values is dependent upon the location of the snow courses chosen to represent the area. If the snow courses are distributed equally throughout all elevations of the basin, an arithmetic average of the point values will often provide a satisfactory index of the basin water equivalent. Refinements can often be made by weighting the snow course data in accordance with the percentage of the basin area represented by each. Averages of point values, whether weighted or unweighted, are generally acceptable only as indexes; i.e., unless properly adjusted, the average is not a reliable measure of the actual volume of water equivalent on a basin.

3-08.03 Elevation effects. - Of particular significance is the fact that on most basins, snow courses are not distributed evenly throughout all elevations, but are generally concentrated at the higher levels. As previously discussed, the distribution of snow over a given range of elevations can vary widely and, accordingly, measurements at high-level stations are not representative of the basin as a whole, particularly if the high elevations comprise only a small percentage of the basin area.

3-08.04 Snow charts. - A logical step toward the solution of the problem of unrepresentative snow-course data is the development of a method whereby each snow course is given weight corresponding to the percent of basin area that it represents. Because of the importance of variation of water equivalent with elevation, a chart on which water equivalent depth is plotted against elevation has been designed to facilitate computation of basin water equivalent. On the chart, as shown by the example on plate 4-2, it will be noted that water equivalent at a given snow course is plotted against its corresponding elevation.

A line connecting the points determines an area on the chart which is proportional to the water equivalent over the basin, provided that proper consideration is given to the area-elevation relationship of the basin. Using area-elevation data, an auxiliary scale representing percent of area is marked along the abscissa with each percentage located at its corresponding elevation. For convenience the chart is divided into zones, each of which represents 10 percent of the area, a dashed vertical line being drawn through the mean elevation of each zone. The intersection of the water-equivalent line at each of the dashed lines represents the average depth for the corresponding zone. The sum of the depths for each zone divided by 10, therefore, is an index of the mean water equivalent depth over the basin.

3-08.05 In addition to elevation, factors such as slope, exposure, and aspect have an effect upon distribution of snow on a basin, as pointed out in the discussion on terrain parameters. Accordingly, a snow course at a given elevation does not necessarily represent the water equivalent at that elevation throughout the basin. Therefore, plotted points representing water equivalent depths at snow courses do not necessarily fall along a well-defined line and generally show considerable dispersion. If all factors affecting distribution of snow were properly considered and an average basin depth for each elevation were established, then a line drawn through these average depths would indicate the true basin water equivalent. Since it is impractical to properly evaluate the effects of all factors on a basin, a line of best fit through plotted snow-course values may be drawn and the basin water equivalent derived from it may be used as an index. Such an index is more reliable than an average of snow course readings, inasmuch as each course is given weight in accordance with the percentage of basin area that it represents.

3-08.06 Index values vs. actual values. - It must be remembered that the discussion above concerns the establishment of an index which, though considered to represent with fair accuracy the changing conditions of the basin snowpack through the season, is not to be mistaken for an actual quantitative evaluation. However, if the basin water equivalent can be quantitatively evaluated by other means such as by subtracting runoff and loss from total precipitation, a ratio between the basin snow index and computed actual volume of snow can be determined. This empirical conversion factor can then be used for computing actual basin water equivalents from the snow chart values.

3-09. SUMMARY

3-09.01 This chapter has dealt with the measurement of precipitation and the accumulation of snow, and methods of estimating amounts over basin areas. The form of the precipitation, as rain or snow, was shown to be a function of meteorologic variables, and frequency diagrams illustrated the climatic averages of the relative proportion of winter rain and snow in the western United States, for varying elevation and temperature conditions. Both meteorologic and terrain conditions affect the amount and distribution of precipitation. In mountainous regions, the terrain effects may be classified as large or small scale, and it was shown that terrain differences cause wide variability of precipitation amounts, depending upon such factors as aspect, slope, curvature, and elevation, as well as location with respect to major mountain barriers and the opportunity for airmass modification. It was indicated that in the western United States, the major portion of winter precipitation occurs at times of strong westerly circulation and of uniform airmass characteristic, so that terrain effect, averaged over a winter season, causes a more or less constant relationship to exist between point precipitation and basin amounts for reasonably small basin areas. Elevation effects on snow accumulation, however, should be considered in the evaluation of the specific snowpack condition, because of the variability of form of precipitation and melt with elevation during the winter season.

3-09.02 Inasmuch as the primary hydrologic application of the evaluation of basin precipitation and snow is the forecasting of residual runoff, it is important to know (1) the accuracy and limitations of point measurements by existing techniques (precipitation gages, measurments of newly-fallen snow, and snow course measurements), (2) the factors affecting the reliability of individual measurements, and (3) the best methods of determining basin amounts from point measurements. The determination of basin precipitation or snow accumulation is usually the most important factor in the water balance, and the accuracy with which it is determined is dependent not only on the accuracy of the point measurement, but also on how well it may be used in estimating the total hydrologic balance of a basin. It should be recognized that new techniques, such as evaluation of precipitation by radar or atmospheric moisture balance may some day cause obsolescence of existing techniques of sampling precipitation. Chapter 4, which presents the hydrologic balances of each of the snow laboratories, presents further data from which the relative importance of the various terms of the water balance may be shown.

3-09.03 Deficiency of measurements by precipitation gages has been shown to result primarily from turbulence, and a knowledge of its effects is important not only in obtaining an estimate of the true precipitation at a point, but also in assessing the reliability of a point measurement as an index of precipitation over a large area. Precipitation gages are much more efficient in catching rainfall than snowfall, but gage deficiencies should be recognized as occurring with precipitation in either form. In general, the primary consideration in locating gages is to eliminate wind turbulence, by selecting locations where natural shelter will reduce mean wind speed to less than about 2 miles per hour at the gage orifice. The use of wind shields is necessary in areas where natural shelter is not available. Capping of the gage by snow may be serious in some instances, but experience at the snow laboratories shows this to be of relatively minor consequence, when gages are serviced weekly or oftener.

3-09.04 Evaluation of basin precipitation from point precipitation can be done for specific periods isopercentually by use of normal annual isohyetal maps. Point values of precipitation should be corrected for known deficiencies of gage catch. Where station coverage is adequate, a weighted average based on ratios of normal annual basin to station precipitation may be used. When storm types exhibit a seasonal trend, varying ratios by months may be applied to account for the affects of changing conditions on the basin-to-point precipitation ratio.

3-09.05 Snow courses exhibit variability in measured values because of the variety of conditions affecting deposition and measurement of snow. The primary factors influencing the accuracy of measurement and representativeness of snow courses are (1) drifting and turbulence, (2) early season melt or non-representative melt, (3) freezing of the snowpack during and after deposition, (4) ground surface conditions within the snow course area, (5) inadequate free-water drainage, and (6) a variety of errors which may be caused by faulty observer techniques. As in the case of precipitation gages, wind is a primary factor in the selection of snow-course sites. An adequate sampling of the range of elevation must be made in order that the varying slope of the snow wedge may be evaluated.

3-09.06 Basin evaluation of the snowpack water equivalent can be made through use of the snow charts described previously. The density of sampling required is dependent upon the relative homogeneity of the basin. Atmospheric circulation during significant winter precipitation in the mountains of western United States is such that the effect of terrain on the distribution of snow accumulation is believed to be fairly uniform from year-to-year within small to moderate-sized areas. Sampling of snow accumulation for conditions of terrain other than elevation may not be warranted. In locating snow courses, the main consideration is to obtain sites which are representative of basin conditions as a whole with regard to both snow accumulation and melt, and which adequately sample the range of elevation within the basin. The atmospheric circulation patterns during storm conditions should be taken into account, so that the combined effect of weather and large-scale terrain features on the site may be representative of the basin. Finally, the characteristics of the local environment should be carefully studied in order to obtain a site which possesses: (1) adequate sheltering from wind, (2) freedom from drifting to or from the site,(3) relative assurances of stability of characteristics over a period of time, (4) gentle, well-drained slopes, (5) a smooth ground surface, free of brush and rocks, and (6) representativeness of melt conditions for the basin as a whole.

3-09.07 Snow courses and precipitation gages both have their place in the evaluation of runoff potential for basin application. Limitations in the accuracy of point measurements are inherent in both. For a complete hydrologic balance, both the total precipitation and the water equivalent of the snowpack must be evaluated. When precipitation alone is used as a measure of runoff potential remaining at a given time, prior runoff may be subtracted from the total water-year runoff to obtain residual runoff. The snowpack represents a direct evaluation of residual runoff remaining in storage, but soil moisture and ground-water deficiencies must be evaluated. Precipitation amounts are particularly suited to early-season runoff evaluation. The water equivalent of the snowpack is suited to late-season evaluation of runoff, because residual errors are proportionally a smaller part of residual runoff for the snowpack than for total precipitation. In many basins, the sparsity of data requires the use of indexes of runoff potential (from either snow courses or precipitation gages), and the data must be handled statistically in order to define relationships. In such cases, the available period of record is an important consideration in the selection of indexes.

3-10. REFERENCES

1/ ALTER, J.C., "Shielded storage precipitation gages," Mon. Wea. Rev., Vol. 65, July 1937, pp. 262-265.

2/ BLACK, R.F., "Precipitation at Barrow Alaska, greater than recorded," Trans. Amer. Geophys. Union, Vol. 35, No. 2, April 1954, pp. 203-206.

3/ CORPS OF ENGINEERS, South Pacific Division, "Development and test performance of radioisotope-radiotelemetering snow-gage equipment," Civil Works Investigation Project CWI-170, May 1955, 74 pp. and appendix.

4/ DIAMOND, Marvin and W. P. Lowry, "Correlation of density of new snow with 700 mb temperature," Res. Paper 1, Snow, Ice and Permafrost Research Establishment, August 1953.

5/ D'OOGE, C.L., "Snowstorm initiation and air temperature," Bull. Amer. Met. Soc., Vol. 36, No. 3, March 1955, pp. 127, 137.

6/ GERDEL, R.W., "Snow studies at the Cooperative Snow Research Project, Soda Springs, California," Annual Report 1943-44 and 1944-45, U.S. Weather Bureau - University of Nevada.

7/ HAMILTON, E.L., "Rainfall sampling on rugged terrain," Tech. Bull. 1096, U.S. Department of Agriculture, Washington, D. C., December 1954, 41 pp.

8/ HELMERS, A.E., "Precipitation measurements on wind-swept slopes," Trans. Amer. Geophys. Union, Vol. 35, No. 3, June 1954, pp. 471-474.

9/ HENDERSON, T.J., "The use of aerial photographs of snow depth markers in water supply forecasting," Proc. West. Snow Conf., 21st Ann. Meet., Boise, Idaho, April 1953.

10/ KOHLER, M.A., "On the use of double-mass analysis for testing the consistency of meteorological records and for making required adjustment," Bull. Amer. Met. Soc., Vol. 30, 1949, pp. 188-189.

11/ KURTYKA, J.C., "Precipitation measurements study," Report of Investigation No. 20, Illinois State Water Survey Division, 1953, 178 pp.

12/ LEE, C.H., "Precipitation and altitude in the Sierra," Mon. Wea. Rev., Vol. 39, 1911, pp. 1092-1099.

13/ MARR, J.C., "Snow surveying," Misc. Pub. No. 380, U.S. Dept. Agric., Washington, D.C., June 1940, 45 pp.

14/ MERRIAM, C.F., "Progress report on the analysis of rainfall data," Trans. Amer. Geophys. Union, Vol. 19, Part I, 1938, pp. 529-532.

15/ MURRAY, R., "Rain and snow in relation to the 1000-700mb and 1000-500mb thicknesses and the freezing level," The Meteorological Magazine, No. 955, January 1952, pp. 5-8.

16/ NAKAYA, Ukichiro, Snow Crystals, Harvard Univ. Press, 1954, pp. 108-116.

17/ SNOW, ICE AND PERMAFROST RESEARCH ESTABLISHMENT, "Bibliography on snow, ice and permaforst," SIPRE Report No. 12, (continuing project; Vols. 1-8 publ. as of July 1955), Corps of Engineers, U.S. Army, Wilmette, Illinois.

18/ SPREEN, W.C., "A determination of the effect of topography upon precipitation," Trans. Amer. Geophys. Union, Vol. 28, No. 2, April 1947, pp. 285-290.

19/ U.S. WEATHER BUREAU, "Operation and Maintenance of storage precipitation gages," U.S. Weather Bureau (Washington, D.C.), 1951.

20/ WARNICK, C.C., "Experiments with windshields for precipitation gages," Trans. Amer. Geophys. Union, Vol. 34, No. 3, June 1953, pp. 379-388.

21/ WEISS, L.L. and W.T. Wilson, "Evaluation of significance of slope changes in double-mass curves," Trans. Amer. Geophys. Union, Vol. 34, No. 6, December 1953, pp. 893-896.

22/ WILSON, W.T., "Discussion of 'Precipitation at Barrow, Alaska, greater than recorded,' by R.F. Black," Trans. Amer. Geophys. Union, Vol. 35, No. 2, April 1954, pp. 206-207.

23/ WILSON, W.T., "Analysis of Winter precipitation observations in the Cooperative Snow Investigations," Mon. Wea. Rev., Vol. 82, No. 7, July 1954, pp. 183-195.