CHAPTER 6 - SNOWMELT INDEXES

6-01. INTRODUCTION

6-01.01 General. - Temperature indexes of snowmelt have been widely used to estimate runoff from snowmelt for areas where its contribution to total runoff warranted consideration. Temperature was used because it was generally thought to be the best index of the heat transfer processes associated with snowmelt and because it was (and in many cases will continue to be) the only reliable and regularly available meteorological variable. At the present time, however, a general understanding of the thermal budget of a drainage area and its snowpack enables the hydrologist to select or to establish necessary instrumentation for obtaining other appropriate meteorological variables suited as indexes of snowmelt in a specific area. This can be done in the light of the broader understanding of the physical and thermodynamic aspects of snowmelt learned from work of the Snow Investigations and from other studies as discussed in the previous chapter.

6-01.02 In hydrologic practice an index is either a meteorologic or hydrologic variable whose variations are associated with those of the element it serves to estimate and which is more readily measured than the element itself. An index may be used to represent basin values from point measurements, both in space and in time, where average fixed relationships are known to exist between the measured and basin values. The purposes of indexes are (1) to allow a readily observed measurement to represent hydrologic element or physical process not ordinarily measured, and (2) to allow a single value or group of measured values to represent basin averages in time and space, in order to simplify observational and computational requirements in actual practice. The reliability of indexes depends upon (1) how well the element or physical process is described by the measured variable, (2) the random variability of the measurement, (3) the variability between point values and basin averages, and (4) the representativeness of the measured value. The index relationship may be described either by a coefficient (such as a degree-day factor) or by a formula in the case of more complex linear or curvilinear functions and may be either constant or variable depending upon the variability of associated factors.

6-01.03 Data. - The specific kinds of data required for detailed thermal-budget analysis are rarely available to the hydrologist concerned with project basins. By necessity, he must use the ordinarily available data for determining snowmelt runoff in hydrologic studies. The most generally available data are daily maximum and minimum temperatures, humidity measurements and surface wind speeds; less frequently are found stations having continuous temperature, humidity, and wind records; and few and far between are stations having solar radiation or even duration of sunshine recorders. Occasionally, hourly cloudiness data may be obtained from nearby airway stations.

6-01.04 Scope. - This chapter includes a discussion of index theory, the relative importance of the various indexes with respect to varying degrees of forest cover, and index-loss relationships during clear-weather spring melt. Preliminary analyses with laboratory data demonstrate the technique of index evaluation and degree of accuracy of the regression function that can be achieved with complete information on shortwave and longwave radiation, albedo, snow cover, and hourly data on air and snow-surface temperatures, relative humidity, and wind. Secondary analyses demonstrate the effectiveness of daily temperature, humidity, and wind data when used as convection and condensation indexes. As an illustrative example, snowmelt runoff coefficients are derived for the Boise River at Twin Springs, Idaho. A separate section deals with the general effectiveness of temperature indexes only. Finally, general basin snowmelt equations applicable to rain-on-snow and rain-free situations are presented.

6-02. INDEXES FOR THERMAL-BUDGET COMPONENTS

6-02.01 General. - Known physical laws and established empirical relationships governing the water and heat economy of the snowmelt-runoff process form the basis for the derivation of snowmelt-runoff indexes. The water balance and thermal budget have been discussed in detail in chapters 4 and 5, but will be reviewed briefly as needed for development of the theory, assumptions, derivation, and application of snowmelt indexes. The heat transfer processes which are of primary importance in producing snowmelt are radiation (shortwave and longwave) and convection of sensible heat and moisture in the atmosphere (commonly termed convection and condensation). Heat transfer from rain and underlying ground are secondary and are considered only briefly. Appropriate indexes for each of the primary heat transfer processes will be discussed in the following paragraphs.

6-02.02 There is no universal index for describing accurately the snowmelt-runoff regime for all areas. Index coefficients vary with local conditions of weather, time, snow condition, vegetation and terrain, being limited in applicability to the specific area, time of year, and weather conditions for which they are derived. Index studies carried out in the Snow Investigations have been concerned primarily with conditions of so-called "clear-weather melt." (The term clear-weather as used in this connection refers to periods of no precipitation but places no restriction on the extent or density of cloud cover.) Before proceeding to the discussion of indexes, a brief review of the water balance for clear-weather melt periods will be made.

6-02.03 The general equation for runoff is written as the sum of the terms of the water balance (see chapter 4). The water balance for rain-free periods during active spring melt is:

$$Q = M - L \qquad (6\text{-}1)$$

where Q is generated runoff, M is snowmelt, and L is loss. The main assumptions which permit index-analysis of equation (6-1) are: that loss is equal to evapotranspiration, and that evapotranspiration is estimated by the same indexes that describe melt. The assumption for the active melt period that all loss is in the form of transpiration requires that all initial losses for conditioning the snowpack for runoff (see chapter 8) and satisfying soil-moisture deficits have been met over the entire basin area. All transitory storage in the soil and underlying rocks is assumed to be accounted for through use of generated runoff values derived by use of average empirical flow recession curves (see Res. Note 19). Daily values of runoff so determined become the dependent variable for the index equations. The condition of no loss to deep percolation on the three laboratory basins is predicated on the water-balance studies presented in chapter 4. The CSSL Lower Meadow lysimeter has an impervious subdeck upon which melt water is collected, thereby eliminating the possibility of loss by percolation into underlying soil or rock.

6-02.04 During periods of local climate, when advection of heat and moisture into the basin is at a minimum, there appears to be a fixed proportion of available energy used for transpiration and melt in forested areas. Reference is made to the discussion on the thermodynamics of evapotranspiration for WBSL contained in the Supplement to Research Note 19 and paragraph 4-05.17, where it was shown that evapotranspiration water loss under this condition represents about 10 percent of the melt.

6-02.05 Shortwave radiation. - The importance of shortwave radiation in the melt budget for direct evaluation of snowmelt depends, for the most part, on areal extent and density of forest cover. In densely forested areas direct observations of solar radiation are not essential as a snowmelt parameter since 80 to 90 percent of the incident radiation energy is absorbed by the forest. In densely forested areas very little of the shortwave energy passes through the forest canopy to the snow surface, and the energy stored in the forest is released to the snow by longwave radiation, convection, and condensation. In open and partly forested areas, however, shortwave radiation is highly important, having increasing importance with decreasing forest cover. If no observations of shortwave radiation are available, estimates should be made by extrapolation from nearby stations, by means of the atmospheric depletion technique, such as described in Technical Bulletin 5 and Research Note 3, or where duration of sunshine data are available, from the chart adapted from Hammon, Weiss, and Wilson 5/ shown in figure 3, plate 6-1. The last-mentioned is the most recent and apparently most accurate technique. The authors report a coefficient of correlation of 0.97 and a standard error of 36 ly/day for observed versus estimated insolation. Independent application of the chart to Boise, Idaho, data for the months of May and June 1955 yielded the same degree of association (R = 0.97), which is equivalent in the present sample to a coefficient of determination, D, of 0.94, with a standard error of estimate, $s_{y.x}$, of 40 ly/day. The method requires knowledge only of the duration of sunshine and, with date, latitude, and a seasonal correction factor (tabulated on the chart), yields in 8 steps the estimated value of insolation for the day.

6-02.06 Diurnal temperature range is a fair index of solar radiation in heavily forested areas, accounting for 65 percent of its variance in UCSL during the spring of 1947 (see fig. 1, plate 6-1). The degree of association is less for the partly forested CSSL, as shown in fig. 2, plate 6-1, where there was only 50 percent determination for data recorded in the spring of 1954. Unfortunately, the poorer correlation with temperature exists where radiation is important and most needed, namely in partly forested or open areas. Studies of variables affecting maximum temperature at CSSL indicate that within that environment over snow, the daily maximum air temperature increases about 1.3°F per 100 ly increase in incident radiation; decreases about 1.2°F per mph wind speed increase at the one-foot level; and increases about 0.75°F per degree F increase in 10,000-foot level temperature. Maximum temperature* by itself, then is a poor index of solar radiation, its magnitude reflecting variations associated with other processes.

* As measured over snow.

The minimum temperature is also sensitive to surface wind conditions, and increasing wind tends to prevent the minimum temperature from falling as low as on calm nights. Accordingly, wind tends to decrease the spread between maximum and minimum temperature. Also, any change in airmass between times of minimum and maximum temperature would affect the spread between them. In general, diurnal temperature range is not as adequate for estimating shortwave radiation as duration of sunshine data.

6-02.07 Longwave radiation. - Unlike shortwave radiation, longwave radiation is important for all degrees of forest cover. The net effect of longwave exchange on melt does vary with the degree of forest cover and this variation must be taken into account in the design of an index for the longwave component of the thermal budget. As discussed previously, the net effect of longwave exchange in the open is usually negative, constituting the principal mode of heat loss from the snow surface. In densely forested areas, on the other hand, there is practically no longwave loss to the night sky, and the snow exchanges longwave radiation mostly with the forest canopy. Both snow and forest radiate as pure black bodies, and since the temperature of the forest canopy is generally above freezing during periods of active melt, the forest canopy radiates more longwave energy to the snow than the snow is emitting by virtue of its own temperature (which cannot exceed 32°F). Thus, under dense forest the net exchange is nearly always positive in the direction of the snow, and the snow-surface temperature is rarely below freezing during the melt period. With a fixed snow-surface temperature, the radiation exchange between the snow and forest canopy may be described by the temperature of the forest canopy only. For index purposes an approximate linear relation has been adopted. (See fig. 1, plate 6-2). With the assumption that air and forest canopy have the same average temperature, the index for longwave radiation exchange is simply the temperature of the air. The use of air temperature as a longwave index is ideally suited to densely forested areas but is inadequate as a simple index for open areas.

6-02.08 Convection. - The relative importance of convection as a heat transfer process at open sites has been a controversial subject and is difficult to evaluate from direct observation. The eddy conductivity studies appear not to have adequately separated sensible heat transfer from effects of radiation and condensation, and greater importance is consequently assigned to convective transfer than may actually be the case. In regression analyses of the 1954 CSSL lysimeter data, only five percent of the variance of the lysimeter runoff was explained by the convection parameter. In the same study, omission of the convective parameter resulted in a negligible decrease of accountable variance, demonstrating the relative weakness of convective heat transfer from air to snow at an open site. An explanation for this weakness is that the melt contribution due to sensible heat transfer is so small as to be nonsignificant with respect to contribution of the other heat-transfer processes (namely radiation). For forested areas, on the other hand, the convection parameter has greater importance, since it indexes the combined heat-transfer processes of convection and longwave exchange in the forest. Since both longwave exchange and convective transfer are temperature functions, they may be combined as shown in figure 1, plate 6-2. The index used for convective transfer (X_3) is a parameter consisting of the product of temperature difference and wind:

$$X_3 = (T_a - T_b)v \qquad (6\text{-}2a)$$

where $\underline{T_a}$ is air temperature, $\underline{T_b}$ is snow surface temperature or temperature base, and $\underline{v}$ is wind travel. Where hourly data are available, best results are obtained with a parameter for the day, computed from the sum of the hourly parameters for the twenty-four hour period from sunset to sunset. When hourly temperatures and winds are not available, as is generally the case in practice, daily maximum or daily mean temperature, and a daily index of wind may be substituted with some loss of accuracy. In this case, the base temperature, T_b is evaluated statistically by methods discussed in paragraphs 6-03.19 to 6-03.21, and the function is used in equation 6-2a as a product of wind and air temperature. Investigations have shown that the general effectiveness of maximum and mean temperatures varies from area to area and even from season to season within a single area. Therefore, either maximum temperature or mean temperature, 1/2 (max + min), may be used for the daily index. Investigations of a daily wind index have included total 24-hour wind travel (sunset to sunset) and 12-hour daytime wind travel (sunrise to sunset). For CSSL, daytime wind travel was found superior to the 24-hour wind, and thus was also used in the UCSL studies. There are other indexes of wind which may be useful, but which have not been evaluated as yet, such as 24-hour winds for some period other than sunset to sunset, (say midnight to midnight), instantaneous wind speed at a specific time of day, etc. The temperature base for the daily convection parameter may be computed from the regression analysis as will be shown later in paragraph 6-03.20.

6-02.09 Condensation. - As with convection, the condensation parameter for the open site is relatively unimportant compared with radiation. It was found in a study of the 1954 CSSL lysimeter data, that less than 3 percent of the lysimeter runoff variance was lost to the accountable variance when the condensation parameter was omitted. (The net decrease in accountable variance with omission of both the convection and condensation parameters was still less than 3 percent.) The importance of the condensation parameter, however, increases with the presence of forest cover. In CSSL, where effective forest cover is approximately 30 percent of the basin area, nearly 40 percent of the runoff variance was lost to the accountable variance when the condensation parameter was omitted. The form of the condensation parameter (X_4) is:

$$(X_4) = (e_a - e_s)\, v \qquad (6\text{-}2b)$$

where $\underline{e_a}$ is vapor pressure of the air, $\underline{e_s}$ is vapor pressure of the snow surface or a derived vapor pressure base, and $\underline{v}$ is wind travel for the time interval represented by mean $\underline{e_a}$ and $\underline{e_s}$. Hourly values of the variables constituting the condensation parameter yield better results than a daily index. However, the only daily condensation indexes tested on laboratory data have been (1) with WBSL data: maximum vapor pressure for the day, (2) with CSSL data: vapor pressure at 1800, the most consistent hour of daily CSSL maximums, and (3) with UCSL data: vapor pressure at 1400, the most consistent hour of daily UCSL maximums. As in the case of the convection parameter, bases are derived statistically when daily values are used. There are also other possible condensation indexes that might prove worthy of investigation, such as maximum or mean dewpoint temperature, etc.

6-02.10 Summary. - The following table summarizes the relative importance and proper selection of thermal-budget indexes of clear-weather melt, as determined from statistical studies of daily clear-weather snowmelt runoff at the snow laboratories, for varying degrees of effective forest cover:

Thermal Budget Component	Forest environment			
	Heavily Forested Area, WBSL	Forested Area, UCSL	Partly Forested Area, CSSL	Open Area, Lysimeter
Effective forest cover	90%	85%	30%	0%
Absorbed shortwave radiation	N - 10/	N - 10/	S - 2/	S - 2/
Longwave radiation exchange in open	N - 10/	N - 10/	S - 3/	S - 3/
Longwave radiation exchange in forest	S - 1/	S - 1/	N - 1/	N - 10/
Convective heat exchange from atmosphere	S - 4/	S - 5/	S - 5/	N - 6/
Heat of condensation or evaporation by moisture exchange between atmosphere and snow surface	S - 7/	S - 8/	S - 8/	N - 9/

S = Significant clear-weather melt index
N = Non-significant clear-weather melt index

1/ Adequately indexed by convection parameter
2/ Observe directly or estimate by index relationship of solar radiation and snow albedo
3/ Observe directly or estimate by minimum temperature and airmass-temperature index
4/ Daily or hourly convection parameter, excluding wind
5/ Daily or hourly convection parameter, including wind
6/ Daily or hourly convection parameter, including wind; may be omitted in active shortwave radiation melt periods
7/ Daily or hourly condensation parameter, excluding wind
8/ Daily or hourly condensation parameter, including wind
9/ Daily or hourly condensation parameter, including wind; may be omitted during periods of active shortwave radiation melt
10/ Non-existent or negligible heat-transfer process

The most striking deficiency in the above table is the lack of an index for longwave radiation exchange in the open. Although air temperature has been found to be a fair index of downward longwave radiation, the variability of the snow-surface temperature at an open site does not permit air temperature alone to act as an acceptable index of longwave exchange between snow and sky. It was found, however, in preliminary studies on the partly forested CSSL, that measured longwave radiation in the open was a significant variable in the estimation of Castle Creek runoff. It was further found that substitution of incident shortwave radiation for net longwave exchange in the open gave an equal level of determination from estimation of Castle Creek runoff. For runoff from an unforested site, however, incident shortwave radiation was found nonsignificant as a substitute for longwave exchange in the open. For open and partly forested areas, longwave exchange in the open is an essential part of the thermal budget. If longwave exchange in the open is not measured, as will most often be the case, it should be estimated. An empirical method for estimating longwave exchange in the open in the Boise River basin is presented in figure 1, plate 6-2.

6-02.11 Figure 3, plate 6-2 illustrates graphically the relative importance of radiation, convection, and condensation parameters in explaining the variance in daily runoff values, at Mann Creek, WBSL; Skyland Creek, UCSL; Castle Creek, CSSL; and the Lower Meadow lysimeter at CSSL, which have a relative effective forest cover of 90,85, 30, and 0 percent respectively. Effective forest cover is defined as the percent of the basin effectively shielded from direct radiation to the sky (both longwave and shortwave), based on an average in time and space for the active melt period. In the case of UCSL, the radiation term is absorbed shortwave and explains practically none of the variance in runoff, while longwave radiation exchange is adequately indexed by the convection and condensation parameters. The radiation term at CSSL for both Castle Creek and the lysimeter is allwave net exchange, as measured by the non-selective radiometer. The increasing importance of an adequate radiation index for decreasing extent of forest cover is shown by this diagram.

6-03. EVALUATION OF INDEXES FOR CLEAR-WEATHER MELT

6-03.01 General. - The preceding section defined the components of basin heat exchange in terms of thermal budget indexes for clear-weather periods. In this section there are described the analytical techniques used to evaluate the index coefficients and their relative strengths for different areas, as determined from laboratory data.

6-03.02 <u>Analytical procedure</u>. - The general form of the snowmelt runoff equation in terms of heat indexes is

$$Y = b_1X_1 + b_2X_2 + b_3X_3 + ... + b_iX_i + . . . + c \quad (6-3)$$

where Y is generated snowmelt runoff, the X_i's are the independent variables (indexes), and b_i's are the associated coefficients found by regression, and c is the regression constant. The symbols and units associated with the indexes used in equation 6-3 are given in the following table:

Variable	Description	Symbol	Unit	Index for
Y	Daily generated volume of snowmelt runoff, depth over snow-covered area	Q	in.	
X_1	Daily total shortwave radiation absorbed by snow in the open	I_{net}	ly	Shortwave
X_2	Longwave radiation loss in the open or daily total incident shortwave radiation in the open	R_{net} or I_i	ly	Longwave exchange in open
X_3	Convection parameter = daily maximum temperature multiplied by 12-hour wind travel, 0600-1800 daily	$T_{max}v_{12}$	°Fmi	Convection and longwave exchange in forest
X_4	Condensation parameter = vapor pressure at a specified time, t, multiplied by 12-hr wind travel (0600-1800 daily)(t = 1800 for CSSL; t = 1400 for UCSL)	$T_{DA}V_{12}$	°Fmi	Condensation
X_5	12-hr wind travel, 0600-1800 daily	v_{12}	mi	Temp. & v.p. bases
X_6	Daily maximum temperature	T_{max}	°F	Convection and LW exchange in forest
X_7	Vapor pressure at time, t, or max. v.p. (t=1800 for CSSL; t=1000 for UCSL; daily max. vapor pressure WBSL)	e_t or e_{max}	mb	Condensation

(Continued)

Variable	Description
X_i	General term for any of the above variables with appropriate subscript $(i = 1 - 7)$
b_i	Coefficient of any of the above variables to give runoff; determined by regression analysis
c	A constant whose value is the magnitude of runoff given by any regression equation when all $X_i = 0$. (Also: a constant whose value is the magnitude required for the regression equation to give the mean value of the dependent variable when means are substituted for all X_i's.)

By following a planned sequence of dropping, adding or substituting different hydrometeorologic variables and repeating the regression analysis with different combinations, a set of regression equations is obtained with different regression coefficients for any one variable. The change in magnitude of regression coefficients for the same hydrometeorologic variable from one regression equation to another shows how these coefficients compensate for the presence or absence of one or more of the other variables. Differences between coefficients of determination for the various regression equations measure the relative effectiveness of the variables which have been dropped, added, or substituted. Thus, the analytical schedule set up in the following table was designed to provide a systematic procedure for answering specific questions as to relative effectiveness of the hydrometeorologic variables used:

Runoff Function	X_1	X_2	X_3	X_4	X_5	X_6	X_7
(1)	*	*	*	*	*		
(2)		*	*	*	*		
(3)	*		*	*	*		
(4)			*	*	*		
(5)	*	*				*	*
(6)		*				*	*
(7)		*				*	
(8)						*	*
(9)	*	*					
(10)	*						
(11)		*					
(12)			*		*		
(13)				*	*		
(14)						*	
(15)							*

(See table on page 202 for definition of variables X_1 through X_7.)

Questions relative to each function are listed below, with question numbers corresponding to function numbers listed above:

(1) What is the accuracy of runoff estimated from the important variables: radiation, convection, and condensation?

(2)(3)(4) What is the effect on the accuracy if radiation is omitted, and runoff is estimated only from convection and condensation parameters? (for use where radiation data are unavailable.) Does incident shortwave radiation add anything to the accuracy?

(5) What is the effect on the accuracy of (1) if wind is omitted from the convection and condensation parameters? (For use where wind data are unavailable.) How important is wind speed in the relationship?

(6)(7)(8) What is the effect on (5) if radiation is omitted and runoff is estimated from temperature and vapor pressure only?

(9) How well can runoff be estimated from shortwave radiation only, omitting the convection and condensation parameters?

(10)-(15) How well does each of the variables by itself estimate runoff?

Not all functions listed in the above table were evaluated for each basin or for all years for any basin. It became readily apparent, after analysis of the 1949 data for UCSL that, as expected for a densely forested area, solar radiation was unimportant as a runoff index in this basin. Consequently, all of the functions involving absorbed shortwave radiation were omitted from the analysis of the 1950 data, since albedo information for this year was incomplete as well. Incident radiation was carried in a few of the 1950 regression functions with the same lack of effectiveness demonstrated by the 1949 data. Regression coefficients and measures of accuracy are summarized in tables 6-1 to 6-4 and discussed in subsequent paragraphs.

6-03.03 Daily indexes of snowmelt. - Analyses of the 1954 lysimeter and Castle Creek runoff data have demonstrated that best results are obtained when firsthand observations of the important melt index variables are available and when hourly data are used in the computation of the convection and condensation parameters. The main consideration in the selection of snowmelt-runoff indexes is to reduce as much as possible variations for representation of basin amounts, from measured values, both in space and time. When considering location of index stations, proximity to the melt zone and representativeness of the station must be balanced against quality of data. At the snow laboratories this was no problem because measurements of meteorologic variables were made within the drainage area of the laboratory, and index stations were selected on the basis of known quality of record. However, to evaluate the effect of time variation, convection and condensation were computed first by hourly parameters and second by daily parameters. In the case of clear-weather melt in the open, as measured by the lysimeters, errors in estimating convection and condensation by daily parameters are difficult to detect since radiation is the prime variable for an open site. For Castle Creek, on the other hand, the over-all determination is sensitive to the kind of parameter used for convection and condensation (hourly or daily) because these heat-transfer processes represent a significant portion of the total melt. The following table lists coefficients of determination obtained from analysis of 1954 data.

Convection and condensation parameter	Total determination, D	
	Lower Meadow Lysimeter, CSSL	Castle Creek, CSSL
Hourly values	.97	.94
Daily values	.95	.84

For the densely forested WBSL, where both temperature and vapor-pressure parameters (without wind) are used to represent the melt process, maximum daily, mean daily, and mean daytime values are about equally good in estimating snowmelt runoff. This reflects the relatively small variance of winds in a heavily forested area. In general, it may be stated that daily parameters may be used for estimating snowmelt runoff, but with some loss of reliability for partly forested areas, or for open areas when melt by shortwave radiation is small.

6-03.04 Regression analysis of laboratory data. - General relative effectiveness of various parameters was discussed in paragraph 6-02.10. It is not desirable herein to make comparisons of all combinations of variables and areas. Instead only those comparisons will be made which emphasize the role of a particular index in the area for which it is derived. First is presented a general discussion of the effectiveness of melt parameters for the lysimeter and for each of the laboratories, to illustrate variation of the relative importance of melt indexes with varying amounts of forest. This is followed by a more detailed discussion of the magnitude of the regression coefficients for the radiation and condensation-convection parameters. Also, the statistical derivation of temperature and vapor-pressure bases is discussed.

6-03.05 Unforested site (Lower Meadow lysimeter, CSSL, 1954). - Statements concerning the effectiveness of the various parameters for an unforested site are based on regression analyses of the 1954 lysimeter data (Research Note 25). Regression coefficients, constants, and measures of accuracy for this site are presented in table 6-1. The following information for various functions, extracted from table 6-1, provides comparative data on coefficients of determination from which it is possible to assess the relative importance of the melt parameters:

Eq. No. Table (6-1)	Independent Variables 1954 Lower Meadow Lysimeter, CSSL	Coeff. of Determination
(1)	Allwave radiation, convection, condensation	.97
(5)	Convection, condensation (omits allwave radiation)	.46
(3)	Allwave radiation (omits convection and condensation)	.94
(4)	Shortwave radiation only	.65
(9)	Maximum air temperature only	.23
(10)	Mean daily air temperature only	.08

Comparing equation (1) with equations (3) and (5), it can be readily seen that omission of allwave radiation (5) results in loss of more than half of the explained variance of equation (1), whereas omission of convection and condensation (3) results in a negligible loss. This comparison clearly demonstrates that allwave radiation is the controlling variable for the melt regime at an open site. It can be further seen by comparing (3) and (4) that approximately 30 percent of the accountable variance explained by allwave radiation is lost when the longwave component of allwave radiation is omitted. For the best estimates of snowmelt runoff from an open area, then, it is imperative to have good estimates for both shortwave and longwave radiation. When allwave radiation measurements are not available, estimates of the shortwave and longwave components must be made. Shortwave radiation may be indexed by duration-of-sunshine data as explained earlier in paragraph 6-02.05, and appropriate albedo estimates may be applied to give estimates of absorbed shortwave radiation exchange. Minimum air temperatures in conjunction with an upper-air temperature index (as will be described later in connection with the Boise River melt indexes) may be used to provide estimates of longwave radiation exchange. Convection and condensation parameters without radiation are inadequate for estimating clear-weather melt in the open, while air temperature* alone is totally inadequate, as shown by the poor determination where maximum or mean daily air temperatures are used.

6-03.06 <u>Partly forested area (Castle Creek, CSSL)</u>. - Conclusions concerning the relative importance of thermal-budget indexes in the estimation of snowmelt runoff from a partly forested area are based on regression analyses of clear-weather data from three years of record at CSSL. Results of these analyses are presented in table 6-2. Equation 1 on that table, derived from data for 1954 utilizing hourly convection and condensation parameters and measured longwave and shortwave radiation exchange in the open, is presented as a basis of comparison for other equations. Generalizations as to the effectiveness of individual melt parameters for this type area (30% effective forest cover) can be made by comparisons of coefficients of determination for each equation. For areas of this type, adequate representation of melt processes for both the open and forested areas should be included in the melt indexes, and the problem is therefore more complex than for either open or completely forested areas. For Castle Creek, the radiation melt indexes represent mainly the melt in the open, while the convection-condensation parameters represent melt both in the forest and in the open. There are interactions between the two which would not necessarily be accounted for in a

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* As measured over snow

strictly rational approach but are contained in the regression coefficients in the statistical approach. Deductions made from regression analyses are therefore mainly limited to showing the effectiveness of various parameters in estimating melt for the periods under analysis. The magnitudes of regression coefficients for the individual parameters can be rationalized only for those equations containing indexes for all thermal-budget components with hourly parameters for convection and condensation. Also, it is shown that the relative effectiveness of individual parameters varies with the melt conditions for each year. Even with these limitations, however, some interpretations concerning relative importance of the variables may be made.

6-03.07 When all indexes of thermal-budget components for Castle Creek are used, the coefficient of determination is 93 percent for two of the three years, and 84 percent for the third, (see equations 1, 3, and 5 in table 6-2). This indicates that the complete thermal-budget index accounts for all but about 10 percent of the variance of snowmelt runoff from this partly-forested area. The importance of radiation in the snowmelt runoff equation is shown by a loss of determination ranging from about 10 to 45 percent where allwave radiation in the open is omitted. Omission of the open-area longwave index represents a loss of determination of melt ranging from 3 to 10 percent. Convection and condensation parameters by themselves show a total determination of between 47 and 83 percent, while shortwave radiation by itself accounts for 22 to 71 percent of the variance of daily melt in individual years. Daily temperature and vapor-pressure parameters without wind account for between 14 and 67 percent of the variance. Maximum temperature alone is an erratic melt index for Castle Creek; it has practically no correlation with daily runoff during 1954, but it explains about 50 percent of the runoff variance in the 1952 and 1951 clear-weather periods of the present study. General effectiveness of temperature alone is discussed in section 6-06.

6-03.08 Forested area (Skyland Creek, UCSL). - The relative importance of thermal-budget indexes of melt for a forested area were tested on Skyland Creek, UCSL, for clear-weather periods in 1949 and 1950. Lodgepole pine forest with trees ranging to 50 feet in height covers about 90 percent of the area, and the average canopy density of the forested area is estimated to be 80 percent, with a resultant effective forest cover of 85 percent. Table 6-3 lists the results of the regression analyses of snowmelt runoff for Skyland Creek. The following tabulation summarizes the relative effectiveness of individual parameters for 1949, the year for which a complete analysis was performed:

Equation No. (Table 6-3)	Independent variables (Skyland Creek, UCSL, 1949)	Coefficient of Determination
2	Abs. shortwave radiation, convection, condensation	0.89
4	Convection, condensation	0.90
7	Incident and absorbed shortwave radiation	0.29
10	Convection	0.73
12	Condensation	0.48
6	Maximum temperature, 1400 vapor pressure	0.60
14	Maximum temperature	0.54

Note that convection-condensation parameters excluding shortwave radiation in equation 4 adequately indexed the melt, since they include the effect of longwave radiation exchange in the forest. Apparently, in equation 2, neither absorbed nor incident shortwave radiation contributed significantly to the determination of melt. Maximum temperature and 1400 vapor pressure without wind, in equation 6, shows the damaging effect of omitting wind from the convection and condensation parameters, which in 1949, caused the determination to drop from 90 to 60 percent. In 1950, however, the decrease in determination was less pronounced when wind was omitted from the melt equation (see table 6-3). Maximum temperature alone provided a fair index of melt in both years, the determination ranging from 54 to 62 percent. In general, it is seen that for this type of area, accurate determination of melt quantities requires parameters which include the effect of wind, to express convection and condensation, but that maximum temperature alone may be used to provide a fair estimate of daily melt if it is impractical to obtain the necessary data on wind and humidity for a more complete evaluation.

6-03.09 <u>Heavily forested area (Mann Creek, WBSL)</u>. - Analyses on four separate periods of clear-weather snowmelt runoff data for Mann Creek, WBSL, provided the basis for determining the relative effectiveness of melt parameters for a heavily forested area. Here, the forest consists of large trees (predominantly Douglas fir whose heights generally range from 150 to 200 feet) and has an estimated effective cover of 90 percent (see plate 2-9). No measurements of solar radiation were obtained at WBSL because of its expected minor importance in the direct melt process at this location, but observations of solar radiation obtained at Medford, Oregon (approximately 100 miles south of the laboratory) were tested in the melt equation and were found to be non-significant in the estimation of runoff. Longwave radiation between the snow and forest, convection, and condensation are the three primary processes of direct heat transfer to the snowpack. Parameters involving air temperature and vapor pressure thus adequately index snowmelt at WBSL. Wind was not a regularly measured variable at WBSL, but an index of wind by use of upper-air data did not provide a significant improvement in the determination of melt. The following tabulation summarizes the effectiveness of the melt parameters shown in table 6-4; the mean determination for the four periods was obtained by weighting the values for the separate periods by the number of observations in each sample.

Equation Nos. (Table 6-4)	Mann Creek WBSL Independent variables	Mean coefficients of determination
1-4	Maximum daily temperature and vapor pressure	0.79
5-8	Mean daily temperature and vapor pressure	0.81
9-12	Maximum daily temperature	0.71
13-16	Mean daily temperature	0.61

The above summary shows that either maximum or mean daily combined temperature and vapor pressure parameters are about equally effective in estimating snowmelt runoff at WBSL, but that there is a loss of 10 to 20 percent determination by omission of the vapor pressure term. It also shows that for estimating snowmelt at WBSL without vapor pressure, maximum temperature provides a better estimate than mean temperature.

6-03.10 <u>Summary of laboratory melt indexes</u>. - The following tabulation presents a comparative summary of the coefficients of determination showing the effectiveness of the primary melt parameters used in the study, for each of the four environments studied:

Summary of Effectiveness of Melt Indexes

Laboratory and environment	Snowmelt parameters used in multiple linear regressions								Coefficients of Determination			
	Abs. Shortwave Radiation in open	Net Longwave Radiation in open	Convection and condensation				Air Temp. only					
			Wind incl.		Wind excl.							
			Conv.	Cond.	Conv.	Cond.	Maximum	Mean				
									(1954)			
Open Site:	x	x	x	x					.97			
Lower	x	x							.95			
Meadow	x								.65			
lysimeter,			x	x					.46			
CSSL							x		.23			
								x	.08			
									(1954)	(1952)	(1951)	
Partly	x	x	x	x					.93			
forested	x		x	x					.90	.65	.90	
area:			x	x					.47	.59	.83	
Castle					x	x			.14	.58	.67	
Creek, CSSL	x								.51	.22	.71	
							x		.01	.54	.58	
									(1949)	(1950)		
Forested	x		x	x					.89			
area:			x	x					.90	.81		
Skyland					x	x			.60	.77		
Creek, UCSL	x								.23			
							x		.54	.62		
									(1951)	(1950)	(1949)	(1949)
Heavily					x	x			.80	.77	.93	.80
forested							x		.70	.72	.73	.70
area: Mann								x	.65	.61	.64	.49
Creek, WBSL									April	May	May	April

6-03.11 Radiation coefficients for unforested sites. - Greater confidence in statistical techniques is inspired when regression coefficients can be shown to agree favorably with "expected values" estimated from rational considerations only. Of the variables employed in these analyses, radiation lends itself most readily to the derivation of rational coefficients. For example, the rational radiation melt coefficient would be obtained from an expression involving the latent heat of fusion of ice, (80 cal/gm), and the free-water content of the snow (f_p). Thus a snowpack having a free-water content of 3% (as in Research Note 25) would require 80 x 0.97 x 2.54 = 197 langleys per inch of melt. The expected melt coefficient for inches of melt per langley is the reciprocal of 197, or 0.00508. Regression analysis of the 1954 lysimeter data yielded a radiation melt coefficient of 0.00541, which is only 7 percent larger than the expected rational value. It should be noted here also that the regression value is subject to systematic errors in the data traceable to calibration of the radiation instruments, calibration of the lysimeter orifice, and the assumed lysimeter area. The rational value depends on the assigned free-water content, which itself is subject to experimental error. To illustrate how relatively small errors may affect the results, it can be demonstrated that systematic errors of approximately two percent in all variables could have made rational and regression coefficients identical. Also, the rational value was derived on the basic assumption that the lysimeter snow surface is horizontal; approximately 4 percent increase in the rational factor would be expected due to the slope of the lysimeter. Errors of this order of magnitude are reasonable in the light of adjustments made in the original data and clearly demonstrate the remarkably close agreement between the rational and regression coefficients. Since the calibration of the instruments may vary from year to year, it should also be borne in mind that corresponding variations may be expected in derived regression coefficients.

6-03.12 The 1954 lysimeter data are again cited to demonstrate how incident shortwave radiation acts as a substitute for the longwave loss and why its coefficient is negative. The following are values of coefficients derived for two functions, one containing allwave radiation, and convection-and-condensation parameters and the other containing absorbed shortwave radiation, incident shortwave radiation, and convection-and-condensation parameters. The only difference is that in the second function incident shortwave radiation has been substituted for the longwave loss component of allwave radiation in the first.

(1) Regression coefficient, allwave radiation 0.00541

(2) Regression coefficient, absorbed shortwave radiation (I_{net}) 0.00669
Regression coefficient, incident shortwave radiation (I_i) -0.00128

At first glance, the coefficients of the second function do not appear to be compatible with the first. However, the two terms comprising allwave radiation melt (M_G) in the second function:

$$M_G = 0.00669\ I_{net} - 0.00128\ I_i \qquad (6\text{-}4a)$$

can be reduced algebraically to

$$M_G = 0.00541\ (I_{net} - 0.24\ a\ I_i) \qquad (6\text{-}4b)$$

where the quantity in parentheses is the estimate of allwave radiation from absorbed and incident shortwave, for a snow surface albedo, a. The over-all coefficient of determination for the second function (2) is less than that for the first, due to the imperfect relation between incident shortwave radiation and longwave radiation loss. However, the resulting regression coefficients obtained from either function are identical. The above computation thus explains the apparently high coefficient obtained for absorbed shortwave radiation and accounts for the minus sign associated with the coefficient for incident radiation, and further demonstrates the validity of using absorbed and incident shortwave radiation as indexes of allwave melt. However, as will be shown later, the use of incident shortwave radiation as a separate index produces undesirable effects which may offset the gain in determination.

6-03.13 Radiation coefficients for partly forested areas. - The previous discussion has been concerned with radiation melt regression coefficients for an unforested site. The next problem to be considered will be examination of the behavior of the radiation melt coefficient when the regression is performed for runoff from a partly forested area, namely Castle Creek basin, with 30% effective forest cover. Regression equation 1, table 6-2, shows that the absorbed shortwave radiation melt coefficient was 0.00312 for the entire basin. This value appears reasonable when considering the amount of bare area in the open during the melt period.

6-03.14 Selection of radiation parameter. - Referring again to the summary of regression coefficients listed in tables 6-1 and 6-2, and rewriting the radiation coefficients for the combined radiation parameter as described in 6-03.12, comparisons may be made of functions containing absorbed and incident shortwave radiation and of functions containing only absorbed shortwave radiation. Convection and condensation parameters (adjusted for temperature, humidity and wind at one foot) are included to illustrate the relative effect of the presence or absence of incident shortwave radiation on them:

CENTRAL SIERRA SNOW LABORATORY

REGRESSION COEFFICIENTS

		Radiation		Conv. $(T_a - T_s)v$	Cond./Conv. Ratio	Cond. $(e_a - e_s)v$	Coeff. of Det. D
		$I_{net} - kaI_i$	k				
Lysimeter	1954	0.0054	0.24	0.00044	6.82	0.0030	0.92
Castle Creek	1954	0.0036	0.28	0.00038	6.84	0.0026	0.94
	1952	0.0042	0.63	0.00023	8.26	0.0019	0.75
	1951	0.0031	0.49	0.00018	9.44	0.0017	0.93
		I_{net}					
Lysimeter	1954	0.0047		0.00040	8.00	0.0032	0.89
Castle Creek	1954	0.0028		0.00035	8.00	0.0028	0.90
	1952	0.0029		0.00029	8.28	0.0024	0.65
	1951	0.0022		0.00030	8.33	0.0025	0.90

It can be readily seen that the convection and condensation coefficients are in closer agreement among years for the function which omits incident shortwave radiation. A reason for the more extreme variation among convection and condensation coefficients, when shortwave incident is substituted for longwave loss in the open, is that incident shortwave is an index of longwave radiation in the open. By itself, shortwave incident explains only about twelve percent of the variance of the longwave loss, but with convection and condensation, the explained variance is about 54%. Thus, the convection and condensation parameters take on the additional function of contributing to the estimation of longwave exchange in addition to their normal job of indexing convection and condensation melt. The net effect of this double duty is felt in the magnitudes of the convection and condensation coefficients, which no longer bear the same relation to one another as in the case of the complete thermal budget index. Due to the relatively weak determination of longwave loss by incident shortwave, convection and condensation, there is a large sampling variation in the regression coefficients for these variables when they are used as a substitute for longwave loss. This accounts for the erratic variation of "k" and the unstable ratio of the convection and condensation coefficients in the upper portion of the above table. In view of these effects, it is doubtful that the coefficients of any one of the years for the function including incident shortwave radiation would be satisfactory for other years. Consequently, it appears better to sacrifice some of the degree of determination in individual cases for the better over-all agreement among the other coefficients by omission of shortwave incident radiation. It is emphasized that such comparisons are possible only because of the precision afforded by the use of hourly data in the convection and condensation parameters.

6-03.15 Radiation coefficients for densely forested areas. - As mentioned earlier in the discussion of the regression analysis schedule, shortwave radiation in a densely forested area is nonsignificant. It appears that the longwave component, which is essentially a temperature function in dense forest, is adequately described by the convection parameter. In the analysis of the 1949 data at UCSL (85% effective forest cover) addition of maximum temperature as a separate independent variable reduced the convection parameter by 30% but had no effect on the condensation parameter and no effect on the over-all coefficient of determination for the function. The same treatment of the 1950 UCSL data showed the addition of maximum temperature as a separate variable to be non-significant and to have no effect whatever on the coefficients for the convection and condensation parameters. Reasons for this will be discussed under relation of wind effects to the convection and condensation parameters in later paragraphs. It is mentioned here to emphasize that in densely forested areas where it is expected that longwave radiation will be important and shortwave radiation unimportant, results of regression analysis are compatible with thermodynamic considerations.

6-03.16 Condensation and convection. - Parameters for convection and condensation are generally discussed together since they are both jointly associated with wind travel. Although in the past it has been thought by some investigators that convection and condensation parameters are sufficient to describe melt, work of the Snow Investigations has demonstrated that this is so only for limited conditions of weather and vegetative cover. The only situations where convection and condensation adequately describe the thermal budget are those where the direct influence of solar radiation on melt is inhibited either by dense forest canopy or by dense cloud cover such as may occur during storm conditions. The importance of heat exchange by longwave radiation exchange likewise must be assessed for specific conditions, and consideration should be given as to the adequacy of a convection parameter to index longwave exchange. Snow Investigations studies have been concerned primarily with clear-weather melt to assess the relative importance of convection and condensation in areas having different degrees of forest cover. Examination of coefficients of determination for three regression functions answers the questions:

1. What is the best that can be done with all three variables?
2. How well do convection and condensation by themselves explain melt runoff?
3. How well does radiation alone explain the melt-runoff without the aid of the convection and condensation parameters?

The answers to these questions may be seen in the following table which summarizes coefficients of determination for regression analyses on three areas having different degrees of forest cover as shown:

Year	Area	Effective forest cover, percent	Function		
			(1) Rad, conv, cond.	(2) Conv. cond. (w/o rad.)	(3) Rad. (w/o conv. cond.)
1954	Lysimeter*	0	.97	.46	.94
1954	Castle Cr.*	30	.90	.55	.80
1949	Skyland Cr.**	85	.89	.90	.29

* Allwave net radiation and hourly convection-condensation parameters used.

** Daily values of convection-condensation parameters and daily absorbed shortwave radiation.

Examination of the relative magnitudes of the coefficients of determination for the open area in the above table shows that the function suffers a serious loss of determination without radiation and suffers hardly any if radiation is used without convection and condensation. This is strong evidence of the unimportance of the convection and condensation parameters in open areas where radiation is the controlling variable. It is important to bear in mind, however, that these results apply to clear-weather conditions only. In open areas the situation could be easily reversed during stormy or overcast conditions when convection and condensation, combined with longwave radiation, might well become more important than shortwave radiation. The coefficients of determination for the lysimeter and Castle Creek were obtained from functions including allwave radiation and hourly convection and condensation parameters to emphasize the effect of radiation and to give the convection and condensation parameters the best possible advantage in the open and partly forested categories. In the forested category (Skyland Creek basin, UCSL) neither allwave radiation nor hourly convection and condensation parameters were available. In this case, however, absorbed shortwave radiation and daily convection and condensation parameters adequately demonstrate the importance of convection and condensation relative to radiation. In Skyland Creek basin the presence or absence of indexes of radiation had essentially no effect on the coefficient of determination, but omission of convection and condensation parameters caused the relation to suffer a serious loss of determination. This clearly demonstrates the inadequacy of radiation alone as a melt index in a forested area. For the forested category then, convection and condensation parameters by themselves explain all of the accountable variance in clear-weather snowmelt runoff. It is to be remembered, however, that for any degree of forest cover during clear weather, solar radiation is the primary source of heat supply, and consequently it is important in thermal budget analyses for all areas. Statistical analyses, on the other hand, relegate solar radiation to a place of no importance for forested areas because there is little detectable association between the day-to-day changes in radiation absorbed by snow in the open and the day-to-day variations in generated snowmelt runoff.

6-03.17 Regression coefficients for convection and condensation. - Coefficients obtained in multiple regression analyses vary both with magnitude and kinds of indexes used for the various components of the melt budget. Different values of convection and condensation coefficients are obtained, for example, when daily parameters are substituted for the hourly parameters of the preliminary analyses. Coefficients are influenced by the presence or absence of other variables such as radiation and wind, and the particular index used for these. For example, the magnitudes of the lysimeter convection and condensation coefficients were different when the shortwave and longwave components of radiation were substituted as separate independent variables for allwave radiation. The wind index (12 hr wind, 24 hr wind, etc.) will also affect the magnitude of the regression coefficients. An effort was made to apply the same indexes of convection and condensation to each of the areas studied, but as work progressed, it became apparent that the 1400 vapor pressure would be more representative for UCSL than the 1800 vapor pressure used in the CSSL analyses. More specific differences in magnitudes of derived coefficients are attributable to height of wind measurement, (UCSL: 31 feet; CSSL: 1 foot in 1954, 50 feet in 1951 and 1952). Even if the power law for temperature and wind variation with height as used at CSSL did apply in UCSL (doubtful because of the greater density of forest cover), coefficients would still be expected to differ by virtue of the differing elevation ranges of the two areas and the different locations of the index stations in their respective areas. Regression coefficients for the lysimeter (unforested site) represent melt occurring at a point (lysimeter area = 600 sq. ft.) close to the index station (150 feet from lysimeter to Station 3) and thus are not called upon to integrate the thermal budget of an entire basin several square miles in area as is the case for the other categories of forest cover. The other categories, part forest, forest, and dense forest exhibit varying quantities of transpiration loss and this loss is taken into account by the regression coefficients, while such is not the case for the lysimeter, where loss by evaporation from the snow surface is accounted for by the condensation parameter. All these considerations are possible sources of differences among derived coefficients. Nonetheless, it is to be expected that convection and condensation melt quantities will retain the same relative proportions in a given area, from year to year for any one function. To make such comparisons, the following table summarizes convection and condensation coefficients derived for the lysimeter, Castle Creek and Mann Creek and shows, in addition, the ratio of the condensation coefficient to the convection coefficient in each case, for equations involving hourly parameters. Convection and condensation coefficients for UCSL are excluded from the table because the results were obtained with daily parameters only.

Laboratory	Year	Equation No.	Table	Coefficients		Ratio
				Conv.	Cond.	cond./conv.
Lysimeter, CSSL	1954	(1)	6-1	.00011	.00105	9.5
Castle Creek, CSSL	1954	(1)	6-2	0.00018	0.00148	8.2
	1954	(7)	6-2	0.00024	0.00187	7.8
	1952	(9)	6-2	0.00012	0.00097	8.1
	1951	(11)	6-2	0.00011	0.00089	8.1
Mann Creek, WBSL	1951	(5)	6-4	0.024	0.085	3.5
	1950	(6)	6-4	0.036	0.112	3.1
	1949	(7)	6-4	0.039	0.094	2.4
	1949	(8)	6-4	0.048	0.147	3.1

The consistency of the ratios of condensation to convection, for each environment, leads to confidence in proper weightings of the condensation and convection parameters by the statistical analysis. Differences in the ratio among areas are mainly due to the dual role of the convection term in indexing the effect of longwave heat exchange in the forested areas. In section 6-4, in connection with the derivation of a general expression for snowmelt during rain-on-snow, the effect of longwave radiation is separated from the convection parameter and the proportional effects of condensation and convection show remarkable consistency between laboratories. Direct comparisons of regression coefficients as shown above can be made only when hourly parameters of convection and condensation are used, and where the melt resulting from direct shortwave radiation is adequately indexed by a separate variable for open areas.

6-03.18 Wind. - Assessment of the importance of wind in the heat transfer processes involving convection and condensation has been based on the results of regression analyses in which wind travel was either used jointly in the convection and condensation parameters or omitted entirely. The following table shows coefficients of determination from analyses with daily parameters for the partly forested and forested areas (Castle Creek, CSSL; Skyland Creek, UCSL). Radiation has been excluded to emphasize the effect of the presence or absence of wind on the coefficients of determination. The following coefficients of determination are abstracted from Tables 6-2, and 6-3:

Area	Table	Eq.No.	Independent variables	Coeff of Determination
Castle Creek CSSL, 1954	6-2	(13)	Convection, condensation (including wind)	0.47
"	6-2	(16)	Convection, condensation (excluding wind)	0.14
Skyland Creek UCSL, 1949	6-3	(4)	Convection, condensation (including wind)	0.90
"	6-3	(6)	Convection, condensation (excluding wind)	0.60

From the coefficients of determination in the above table it is apparent that exclusion of wind from the regression function results in a serious loss of determination. The loss of determination by excluding winds for individual periods is a function of the variance of wind within the period. For periods other than the ones shown above, the loss of determination by omission of wind is less. Admittedly the convection and condensation parameters by themselves are weak for the partly forested category (Castle Creek, CSSL) but they are considerably weaker without wind than with it. By induction we may infer also that the joint effect of wind will be important for estimation of convection and condensation melt at open sites. Analyses made on densely forested area (Mann Creek, WBSL) did not fully assess the importance of wind for this category of forest cover, for two fundamental reasons. First, although laboratory observations of wind were not available, surface winds in a dense forest are apt to be small and have little variance due to the stilling effect of the dense forest canopy on air movement. Therefore, although it is not conclusive, it may be said that wind is relatively unimportant for the estimation of clear-weather snowmelt runoff from densely forested areas. Secondly, in preliminary correlations, upper-air winds were found non-significant.

6-03.19 Temperature and vapor pressure bases. - The question of what base to use for convection and condensation parameters has long been a matter of conjecture. Thirty-two degrees has been a commonly used base but with no more justification than that it is the temperature at which ice melts. A melt index involving maximum air temperature alone would obviously need a base greater than 32°F. by reason of the diurnal temperature variation. Where air temperature is indexing solar radiation melt, however, the temperature base tends to be well below 32°. Variation of basin to station temperature (as, for example, when the temperature station is above or below the mean basin elevation), causes a displacement of the temperature base. Rational bases may be deduced for mean temperatures and, in the absence of other criteria will give acceptable results. If, however, regression analyses are being performed to evaluate melt-runoff coefficients, it is not necessary to rationalize or choose the base in advance. The base which is appropriate not only to the index station, but to the index itself (mean temperature, maximum temperature, etc.) with or without wind data may be computed from the derived constants of the regression equation.

6-03.20 Statistically derived bases for parameters excluding wind. - The concept of statistically derived bases was originated for studies of clear-weather melt in WBSL, as presented in Research Note 19. The general regression function for that area is

$$Q_{gen} = A(T_a - T_b) + B(e_a - e_b) \qquad (6\text{-}5a)$$

where Q_{gen} is the daily generated Mann Creek snowmelt runoff in inches over the snow-covered area of the basin, and T_a and e_a are the temperature and vapor pressure respectively at Station 6 in the Mann Creek basin. The coefficients A and B, and the bases T_b and e_b were to be evaluated by regression. By expanding equation 6-5a, the following is obtained:

$$Q_{gen} = AT_a + Be_a - (AT_b + Be_b) \qquad (6\text{-}5b)$$

Now, if the regression of Q_{gen} on T_a and e_a is computed by the usual least squares technique, the equation obtained will be

$$Q_{gen} = AT_a + Be_a + c \qquad (6\text{-}5c)$$

Having derived regression constants, A, B, and c in 6-5c, it is a matter of simple algebra to find T_b and e_b in 6-4b by writing the equation:

$$c = -(AT_b + Be_b) \qquad (6\text{-}6a)$$

which may be solved (by trial and error because of the non-linearity of the relationship between air temperature and saturation vapor pressure) to find a value of T_b and the corresponding saturation vapor pressure, e_b, which will satisfy equation 6-6a.

6-03.21 Statistically derived bases for parameters including wind. - Having developed the concept of derivation of bases from regression constants, as described in the preceding paragraph, it is a relatively simple matter to amplify the technique to apply to parameters which include wind, as in the following function:

$$Q_{gen} = A(T_a - T_b)v + B(e_a - e_b)v + c \qquad (6\text{-}7a)$$

If, as before, we expand the right hand member,

$$Q_{gen} = AT_a v + Be_a v - (AT_b + Be_b)v + c \qquad (6\text{-}7b)$$

where the quantity in parenthesis may be lumped into a single constant, C, the coefficient of v. Thus, for parameters containing wind, the least squares analysis is performed in the regression of runoff on T_a, e_a, and v, to obtain the coefficients

A, B, and C. As before, T_b and e_b are obtained by trial solution of

$$C = -(AT_b + Be_b) \qquad (6\text{-}6b)$$

with the important difference that, in this case, C (big "C") is the derived coefficient of the wind term and not the regression constant, c, (little "c") as in the case of no wind. In the case with wind there will also be a regression constant, c, which is the Y-intercept and an integral part of the regression equation. It is emphasized that, in order to compute coefficients and bases correctly when convection and condensation parameters have wind as a factor, wind must be carried as a separate independent variable in the regression function. It is also important, however, to discard the wind term in writing the final regression equation, if the computed bases are written into the parameters. The coefficients for wind have been included in tables 6-1, 6-2, and 6-3, where appropriate, only to provide complete information on derivation of the bases.

6-04. ESTIMATES OF SNOWMELT DURING RAIN

6-04.01 General. - Evaluation of snowmelt during rain represents a special condition for which certain simplifying assumptions can be made in the snowmelt equation. As in the case for clear-weather snowmelt, the form of the equation is dependent somewhat upon the type of area to which it is to be applied. Heat transfer to the snowpack during rain involves the following basic considerations in application of indexes:

1. Shortwave radiation is relatively unimportant and can be evaluated as a constant amount.
2. Longwave radiation exchange between forest or low clouds and the snowpack may be adequately indexed linearly by air temperature.
3. Air is assumed to be saturated, so that air temperature (combined with wind) may be used to index both convection and condensation melt. By assuming a linear relationship between air vapor pressure and dewpoint, for the range normally experienced under these conditions, a linear expression of convection and condensation melt may be assumed as a function of air temperature and wind.
4. Wind is important and should be evaluated for open or partly forested basins. On heavily forested basins, however,

wind variation is so reduced beneath the forest canopy that an average wind condition may be assumed, thereby eliminating the wind variable.

5. Rain melt may be evaluated simply as a function of rainfall intensity and air temperature.

6. Ground melt is unimportant and may be estimated as a constant amount.

7. Water lost by evapotranspiration is negligible.

6-04.02 Melt rates during rain may be determined from clear-weather melt coefficients derived for the laboratories by applying conditions set forth in the preceding paragraph and evaluating separately the convection-condensation melt for the basin. These coefficients integrate basin characteristics and conditions of measurement for the particular laboratory to which they apply, but they may be used as a guide for general application to other basins. Coefficients of convection-condensation melt derived for the Lower Meadow lysimeter at CSSL are directly applicable to open areas. Adjusted coefficients for WBSL may be applied generally to heavily forested areas. Coefficients for partly forested areas may be estimated for the specific conditions of exposure and instrumentation.

6-04.03 In the following paragraphs a generalized snowmelt equation for computing point or basin snowmelt during rain is developed from theoretical considerations of heat transfer and derived coefficients of convection-condensation melt. Separate melt equations are presented for areas having different forest cover. For basin application, the general equation must be interpreted in terms of average conditions, considering the areal distribution of each variable. The basin may be divided into sub-areas or elevation zones in computing the snowmelt, but cognizance should be given to variability of forest cover and exposure to wind in each sub-area.

6-04.04 Project basin coefficients for heat indexes can be derived from analysis of rain-free melt data by methods set forth in section 6-03 for the snow laboratories, and extended to rain-on-snow conditions, with due consideration for particular type of environment involved. Such a procedure gives indexes of snowmelt runoff for a particular basin and condition of observation. When it is impractical to derive basin coefficients, a generalized rational equation must be used.

6-04.05 Coefficients of melt during rain at laboratories. - Melt coefficients during rain were derived from a combination of statistically and rationally determined melt coefficients for clear-weather melt, by separation of terms in the thermal budget. For this condition, melts by longwave shortwave radiation exchange, as well as rain melt and ground melt, are treated adequately from theoretical general equations or assumed average rates of energy transfer. Convection and condensation resulting from turbulent exchange of energy between the atmosphere and the snowpack is an important source of melt and must be evaluated for the specific condition of environment. Comparative coefficients of convection and condensation melt for varying environments are presented from the convection-condensation coefficients derived rationally for the lysimeter, and from statistically derived coefficients for the lysimeter, Castle Creek at CSSL and Mann Creek at WBSL.

6-04.06 <u>Convection-condensation melt coefficients.</u> - The basic equation for convection-condensation melt set forth in chapter 5 may be simplified and reduced to a function involving air and dewpoint temperatures and wind, on the assumption of linear variation of vapor pressure and dewpoint for the range between 32°F and 50°F, and for a constant snow surface temperature of 32°F. The equation may be written in the general form

$$M_{ce} = K (v) (AT_a + BT_d - 32) \qquad (6\text{-}8a)$$

where M_{ce} is convection-condensation melt, $\underline{v}$ is the wind speed, T_a and T_d are the air and dewpoint temperatures, $\underline{K}$ is the point or basin coefficient of convection-condensation melt, and $\underline{A}$ and $\underline{B}$ are the effective respective weights of air temperature and dewpoint temperature in producing convection-condensation melt. The sum of $\underline{A}$ and $\underline{B}$ is unity, and in the case of saturated air, air temperature and dewpoint are equal, so that the expression becomes

$$M_{ce} = K (v) (T_a - 32) \qquad (6\text{-}8b)$$

The coefficients $\underline{K}$, $\underline{A}$, and $\underline{B}$ have been evaluated for the 1954 observations at Lower Meadow lysimeter, CSSL, on the basis of the rational coefficients presented in chapter 5, as well as for statistical weightings of the data, in which net longwave, net shortwave, and hourly parameters of convection and condensation were evaluated separately in a multiple linear regression analysis. Coefficients of convection-condensation melt for Castle Creek were derived for the 1954 melt period by statistical weightings using the same parameters as for the lysimeter. For Castle Creek, the longwave radiation exchange in the forest was indexed by the convection parameter. The longwave portion of the convection parameter coefficient was separated by utilizing the ratio of longwave exchange to combined longwave and convection in forested areas of 0.72, as derived in Research Note 11, (see figure 2, plate 6-2) and applying this ratio to the area of forest canopy effective in longwave radiation exchange for CSSL, estimated to be 30%. For example, the convection parameter coefficient for CSSL in 1954 was 0.00018 (equation 1, table 6-2). With 30% of the basin forested and 72% of combined longwave and convection representing longwave exchange in the forest, the longwave-in-forest part of the convection coefficient is 0.72 x 0.30 x 0.00018 or 0.00004 and the true convection amount is (0.00018 - 0.00004) = 0.00014. With convection isolated in this way, it is possible to compare relative proportions of convection and condensation for Castle Creek with those for the lysimeter. The manner in which this is accomplished is illustrated by the following computation. Having isolated the convection coefficient as described above, an expression for convection and condensation melt may be written (equation 1, table 6-2):

$$M_{ce} = 0.00014\ (T_a - T_s)v + 0.00148\ (e_a - e_s)v \qquad (6\text{-}9a)$$

Converting the condensation coefficient for use with dewpoint in °F instead of vapor pressure in millibars (multiply vapor pressure coefficient by 0.34),

$$M_{ce} = 0.00014\ (T_a - T_s)v + 0.00050\ (T_d - T_s)v \qquad (6\text{-}9b)$$

By factoring the sum of the convection and condensation coefficients, the following is obtained:

$$M_{ce} = 0.00064\ (0.22T_a + 0.78T_d - T_s)v \qquad (6\text{-}9c)$$

which shows that 22% of the combined convection-condensation melt is due to convection and 78% due to condensation. The coefficient 0.00064 is for hourly melt amounts for winds at 1 foot and temperatures at 10 feet above the snow surface. The coefficient must be multiplied by 24 for daily melt amounts and divided by 1.9 to correct winds to the 50-foot level. The corresponding coefficient is 0.008, which is the value shown in the table below for 1954 Castle Creek with net shortwave and net longwave as the radiation variables. It should be remembered that wherever net longwave is included as a separate variable, it represents only longwave radiation exchange in the open and should be distinguished from longwave exchange in the forest indexed by the convection parameter described above. Since there is no forest on the lysimeter, the convection coefficient derived for the open site is a pure convection coefficient and the above technique for separation of longwave in the forest does not apply in that case. The convection-condensation coefficients are presented below for CSSL, elevation 7200 feet msl, with measurements of temperature and dewpoint at the 10-foot level and wind at the 50-foot level at the Lower Meadow: (see figure 3 (b) plate 6-2)

CONVECTION-CONDENSATION MELT RATES, CSSL, IN/DAY

$$M_{ce} = K(AT_a + BT_d - T_b)v$$

Radiation variables	DATA (METHOD)	K*	A	B
Net shortwave Net longwave	1954, Lysimeter (Rational)	0.0084	0.20	0.80
	1954, Lysimeter (Statistical)	0.0058	0.24	0.76
	1954, Castle Creek (Statistical)	0.0080	0.22	0.78
Net shortwave only	1954, Castle Creek (Statistical)	0.0104	0.23	0.77
	1952, Castle Creek (Statistical)	0.0102	0.22	0.78
	1951, Castle Creek (Statistical)	0.0093	0.22	0.78

* Values of K for M_{ce} in inches per day in equation 6-8b.

It is seen that coefficients derived independently show remarkable consistency. In the upper part of the table it may be seen that the convection-condensation melt rate (K) for Castle Creek is represented closely by the rationally derived convection-condensation melt rate for the lysimeter, which seems reasonable considering the exposure to wind of the Lower Meadow in comparison with the Castle Creek basin as a whole. This concept is further supported by comparisons in the lower portion of the above table, which represents results of three clear-weather melt periods from different seasons (1954, 1952, and 1951, equations 2, 5, and 7 in table 6-2). The 1954 coefficients have been adjusted for use with winds measured at the 50-foot level, (in 1952 and 1951 recorded 50-foot winds were used in the derivations), longwave loss in the open is not a variable in the regression model for the lower portion of the table, but its average effect is felt through interaction with other variables and in the regression constant, which is remarkably uniform among the three years. Here the melt rate for convection and condensation is slightly higher than was obtained from the 1954 data when longwave loss in the open was included in the regression function. This difference may be attributed to possible calibration errors in the shortwave and allwave radiation instruments. (Net longwave radiation exchange was not separately measured but was computed as the difference between allwave and shortwave radiation observations). Thus the estimate of longwave loss in the open may be in question and the higher melt rates should be used as a guide when extrapolating to areas similar to Castle Creek.

6-04.07 Mean daily temperatures and vapor pressures were used in deriving total melt coefficients at WBSL. There, however, wind effects are greatly reduced because of the heavy forest which covers nearly the entire basin. Although no continuous wind measurements were obtained at WBSL, attempts to improve determination of melt by adding wind parameters were unsuccessful, and the degree of determination without wind was consistently high. Therefore, it was concluded that convection and condensation within heavy forest are adequately represented by an average wind amount, implicit in the total coefficient of melt. Coefficients of convection and condensation melt, shown in table 6-4, derived from mean daily ai_ temperatures and vapor pressures, provide a means for determining the basin coefficients of K, A, and B in equation 6-8a, modified by exclusion of the wind term, which can be compared with CSSL coefficients. The longwave exchange between the snow and forest was subtracted from the temperature coefficient. Values of K, A, and B for Mann Creek, WBSL, are tabulated below for each of the four periods studied, with adjustments for height of measurement of temperature and vapor pressure to 10 feet above the snow surface:

CONVECTION-CONDENSATION MELT RATES, WBSL, IN/DAY

$$M_{ce} = K\ (AT_a + BT_d - T_b)$$

Period	K*	A	B	T_b
April, 1949	0.043	0.22	0.78	31
May, 1949	0.039	0.26	0.74	33
May, 1950	0.048	0.22	0.78	30
April, 1951	0.036	0.20	0.80	29
Mean	0.042	0.22	0.78	31

* K for melt rates expressed in inches per day.

Adjusting the melt coefficients above to a theoretical 32°F base, the mean daily convection-condensation melt for Mann Creek, WBSL, is

$$M_{ce} = 0.045\ (.22T_a + .78T_d - 32), \qquad (6\text{-}9d)$$

where M_{ce} is expressed in inches per day. (see figure 3a, plate 6-2) The tabulation of coefficients above shows the stability of the relationship between the relative weights of convection and condensation melts, expressed by the coefficients A and B. The proportional weights given in the preceding paragraph for CSSL, although at a different elevation level, are in general agreement with WBSL. The magnitude of the coefficient K for the heavily forested WBSL corresponds to an average wind of approximately 5 miles per hour at the 50-foot level, or between 2 and 3 miles per hour at the 1-foot level. This is a reasonable order of magnitude for conditions in the forest.

6-04.08 Shortwave radiation melt. - Snowmelt by shortwave radiation, M_{rs}, is relatively unimportant during periods of rain-on-snow. Studies of incident radiation during these periods show that it is reasonable to assume a constant daily average of 40 ly for an open area with an average albedo of the snow surface of 65 percent. The resulting net snowmelt is 0.07 inch per day. For forested areas it may be less, depending on the areal extent and density of forest cover.

6-04.09 Longwave radiation melt. - Longwave radiation during periods of significant precipitation can be adequately estimated by the theoretical exchange of blackbody radiation between the snow surface and the forest canopy or low clouds. During storm conditions, turbulent mixing in the lower layers of the atmosphere establishes an equilibrium between air temperature measured at the normal instrument height and the temperature of the forest or low clouds. When the cloud base is less than 1000 feet above the ground, air temperature lapse rate corrections may be ignored. A linear relationship of net longwave radiation exchange closely approximates the theoretical exchange expressed by equation 5-12. The net melt by longwave radiation for rain-on-snow conditions, expressed in terms of air temperature and with a snow surface temperature of 32°F is

$$M_{rl} = 0.029\ (T_a - 32) \qquad (6\text{-}10)$$

where $\underline{M_{rl}}$ is melt in inches per day resulting from net longwave radiation exchange, and $\underline{T_a}$ is the air temperature in degrees F.

6-04.10 Rain melt. - Snowmelt by the transfer of heat from rain, as discussed in chapter 5, may be expressed in terms of average daily rainfall rate and free air temperature as in the following equation:

$$M_p = 0.007\ P_r\ (T_a - 32) \qquad (6\text{-}11)$$

where $\underline{M_p}$ is the daily snowmelt from rain, $\underline{P_r}$ is the daily precipitation in inches, and $\underline{T_a}$ is the air temperature in degrees F.

6-04.11 Ground melt. - Snowmelt from ground heat, $\underline{M_g}$, may be estimated at 0.02 inch per day (see section 5-10).

6-04.12 Generalized convection-condensation melt equation. - It was shown in paragraph 6-04.06 that for saturated air, convective melt is only approximately 20 percent of the total convection-condensation melt, as shown by the value of the coefficient $\underline{A}$ determined from both rational and statistical evaluations for several different conditions of environment. It was explained in chapter 5 that convective heat transfer is a function of air density, and that differences in convective heat due to elevation may be expressed as an elevation or pressure function. The magnitude of the elevation correction for convective melt, in terms of total convection-condensation melt for saturated air, is relatively small, and for an elevation difference between sea level and 7,000 feet, the correction represents only 5 percent of the total melt. Considering the accuracy of the over-all melt coefficient, the elevation correction for convective melt is not warranted. The coefficients derived for the laboratories, therefore, may be applied without regard to elevation differences. The following generalized equations represent convection-condensation melt in inches per day during rain, for varying environments:

(1) for melt at a point in the open:

$$M_{ce} = .0084\ v\ (T_a - 32) \qquad (6\text{-}12a)$$

(2) for basin melt from open or partly forested areas:

$$M_{ce} = (k)\ .0084\ v\ (T_a - 32) \qquad (6\text{-}12b)$$

(3) for heavily forested areas:

$$M_{ce} = .045\ (T_a - 32) \qquad (6\text{-}13)$$

where $\underline{T_a}$ is the temperature of saturated air at the 10-foot level in ^{o}F, $\underline{v}$ is the wind speed at the 50-foot level in miles per hour, and $\underline{k}$ is a basin constant, considering the conditions of measurement with respect to average basin topographic characteristics and exposure to wind. Conversion to different observation levels of temperature and wind from those specified in the above equations may be accomplished according to the power law variation explained in chapter 5, with the reservation that the exponent $\underline{n}$, may vary from one area to another. Increased turbulence due to rain should tend to increase $\underline{M_{ce}}$. Experiments are needed to determine the effect of rain on both the temperature and wind profiles near the surface.

6-04.13 <u>General equation for total basin melt during rain.</u> - Components of melt may now be combined to form a general equation for total basin melt during rain. Since total melt, $\underline{M}$, is expressed by the relationship,

$$M = M_{rs} + M_{rl} + M_{ce} + M_g + M_P \qquad (6\text{-}14)$$

the terms may be combined for environmental conditions as follows:

(1) for open or partly forested basin areas,

$$M = (0.029 + 0.0084kv + 0.007P_r)\ (T_a - 32) + 0.09 \qquad (6\text{-}14a)$$

(2) for heavily forested areas,

$$M = (0.074 + 0.007P_r)(T_a - 32) + 0.05 \qquad (6\text{-}14b)$$

where M is total daily snowmelt in inches per day, T_a is the temperature of saturated air at the 10-foot level in degrees F, v is the wind speed at the 50-foot level in miles per hour, P_r is the rate of precipitation in inches per day, and k is the basin constant as defined in the previous paragraph. The value of k varies from about 0.2 for densely forested areas to slightly over 1.0 for exposed ridges or mountain passes. It is emphasized that total basin melt can be computed from the above equations only by use of values of wind and temperature which are representative of average conditions over the snow-covered area of the basin or by integration of melts computed from representative zonal averages of temperature and wind.

6-05. PROJECT BASIN APPLICATION

6-05.01 General. - Previous sections of this chapter have dealt with analyses of laboratory data to demonstrate the essential elements of the thermal budget and the kinds of meteorological data required for snowmelt indexes in drainage areas having various degrees of forest cover. While coefficients derived in these analyses are strictly applicable only to the areas for which the investigations were made, the basic principles which have been demonstrated may be used to establish clear-weather snowmelt-runoff relations for other areas. A study of this kind has already been made for a densely forested area and published as Supplement to Research Note 19 (North Santiam River, Willamette Basin, Oregon). This section will deal with investigations for a project basin in the partly forested category, namely, Boise River basin above Twin Springs, Idaho. Evaluation of basin snow cover and a hydrograph reconstitution for this stream will be discussed in chapters 7 and 9.

6-05.02 Basin characteristics. - The Boise River above Twin Springs, Idaho, drains an area of 830 square miles in the upper watershed of the Boise River. Situated in the Sawtooth Mountains, the area has deep valleys, steep slopes, and narrow sharp-top ridges. It ranges in elevation from about 3000 to 9000 feet. The stream system and instrumentation are shown in figure 3, plate 9-5. Forest cover consists principally of conifers which are estimated to have a shading effect on 30% of the basin area.

Practically the entire runoff of the Boise River is contributed from headwaters areas, 3/ and spring floods on this river result primarily from melting snow. Consequently, it is of paramount importance for optimum use of storage in Boise River reservoirs to have a reliable and accurate technique of estimating the basin's snowmelt contribution to spring runoff.

6-05.03 Scope. - Exploratory analyses for selecting indexes best suited to this basin are limited to study of clear-weather days in May and June 1955. Final indexes selected on the basis of the 1955 study are used for independent derivation of a clear-weather snowmelt-runoff equation for the 1954 season and for the combined data of both seasons. Selection of the Boise River basin and the 1955 and 1954 melt seasons in particular for this application was based primarily on the availability of snow-cover information from several aerial reconnaissance flights over the area during these seasons, performed by personnel from the Walla Walla District Office of the Corps of Engineers.

6-05.04 Melt components. - It will be recalled that the primary thermal budget components affecting snowmelt in a partly forested area are shortwave radiation, longwave radiation loss in the open, convection, and condensation. The following paragraphs will discuss the data available for estimating each of these components in the Boise basin. The analysis shows that available humidity data did not satisfy the requirement of a condensation-melt index; that maximum temperature alone served as a better convection-melt index than a temperature-wind product; and that an estimate of longwave loss in the open from 700 mb and surface minimum temperatures significantly improved the overall runoff estimate.

6-05.05 Snowmelt runoff. - By application of a standard recession curve to the continuous discharge hydrograph of the Boise River above Twin Springs, separation of daily generated snowmelt-runoff amounts was accomplished after the manner described in Research Note 19. Number of available clear days and hydrograph base flow are shown for each season in the following table:

Month and year	Clear days	Base flow - cfs
May - June 1955	26	0
Apr - May 1954	21	1500

Daily runoff quantities were expressed in inches depth on the snow-covered portion of the basin. These runoff amounts were used as the dependent variable in all regression analyses of this section.

6-05.06 Area of snow cover. - The estimation of areal extent of snow cover was based on aerial reconnaissance flights in 1954 and 1955. Day-to-day variation of the snow-covered area was determined as part of the material in chapter 7 and is fully discussed therein. In general, the estimate of snow cover appears to be too high at the start of the 1955 period of study and too low at the end. If this is actually the case, the computed values of runoff (depths over snow-covered area) are too low at the beginning and too high at the end. The net effect of this error would be to cause derived melt coefficients to be too high, resulting in melt estimates that are too high in the early part of the period and too low at the end. These errors are clearly seen in the reconstitution of the 1955 hydrograph in chapter 9. No refinements in snow cover were made, however, for derivation of the melt coefficients, since the primary purpose of this study was the demonstration of the method. The present results, even as a first approximation, show that the parameters used explain a large portion of the runoff variance and are superior to those obtained with a temperature index alone.

6-05.07 Shortwave radiation. - Pyrheliometric observations of incident shortwave radiation were available at Boise. These were used for the computation of absorbed shortwave radiation in conjunction with estimates of snow albedo based on decay curves of albedo versus age of snow surface (figure 4, plate 5-2) by methods described in Technical Bulletin 6, taking into account the occurrence of new snowfalls during the period. Albedo versus time is shown in plate 6-3, figure 1.

6-05.08 Longwave radiation. - Net longwave exchange within the forested portions of the basins is considered to be adequately described by the temperature index. Longwave loss in the open, however, was estimated (for the latter studies) from a graphical relationship as shown on figure 2, plate 6-3. It is emphasized that this relation was devised expressly for the Boise basin study and is not intended for general application. Time limitations do not permit detailed analyses for the establishment of a universally applicable relation of this kind. The parameter for net allwave radiation in the open was obtained by adding together absorbed shortwave radiation and estimated longwave loss.

6-05.09 Convection and condensation. - Required data for convection and condensation parameters are:

1. Convection - mean or maximum temperature and daytime wind.
2. Condensation - mean or some instantaneous dewpoint (or vapor pressure) and daytime wind.

In this study, temperature records were available for five stations in or near the basin (Boise, el. 2842; Idaho City, el. 3940; Lowman, el. 3794; Atlanta Summit, el. 7590; and Bald Mountain, el. 8700)*. Humidity and wind records were available only at Boise. The data selected for trial convection and condensation parameters were: Boise maximum temperature; Boise mean daytime dewpoint temperature (average of 1100 and 1700 observations); and Boise mean daytime wind (average of 1100 and 1700 observations).

6-05.10 Analytical procedure. - The following paragraphs will show the variables which were tested in regression analyses for estimation of Boise River snowmelt runoff and will present some of the intermediate results to demonstrate the process by which the final results were achieved. The following variables were tested for use as indexes of components in the thermal budget of this basin; the table shows the combinations of these variables which were studied and the coefficient of determination computed for each combination:

X_1 Absorbed shortwave radiation, ly

X_2 Incident shortwave radiation, ly

X_3 Convection parameter ($T_{max} \cdot v$), (T_{max} and v at Boise, in ^{o}F and in mph, respectively)

X_4 Condensation parameter ($T_d \cdot v$)

(T_d = mean Boise daytime dewpoint, average of obs. at 1130 and 1730 MST, in ^{o}F)

X_5 Mean Boise daytime wind, v (average of obs. at 1130 and 1730 MST, in mph)

X_6 Boise maximum temperature, (eqs. 1-10), Idaho City maximum temperature (eq. 11); ^{o}F

X_7 Boise 700 mb temperature (0800 MST), ^{o}C

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* Elevations in feet above m.s.l.

X_8 Boise 700 mb dewpoint (0800 MST), °C

X_9 Longwave loss in open (estimated from Boise 700 mb temperature and Idaho City minimum temperature), ly

X_{10} Estimated allwave radiation (X_1 + X_9), ly

Eq. No.	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	D
(1)	*	*	*	*	*						0.82
(2)			*	*	*						0.82
(3)	*		*		*						0.83
(4)			*		*						0.82
(5)	*										0.58
(6)	*		*		*		*	*			0.87
(7)	*					*					0.86
(8)						*					0.75
(9)	*					*			*		0.89
(10)						*				*	0.89
(11)						*				*	0.86

6-05.11 Sequence of analyses. - The table of the previous paragraph shows not only the different combinations of variables tested, but also the sequence or order of progress from one function to the next. The first four equations demonstrated that convection and condensation parameters alone were as good as convection and condensation parameters with absorbed and incident radiation added. Furthermore, the convection parameter alone, in equation 4, was as good a determinant of the snowmelt runoff as any combination shown by the first three equations. Without the condensation parameter, shortwave radiation and convection were slightly better than the convection parameter alone (eqs. 3 and 4). However, the first order relation of runoff to absorbed shortwave radiation had a determination of 0.58 (eq. 5) approximately the same order of magnitude as obtained for the partly-forested laboratory area (Castle Creek, CSSL). The weakness of the radiation variable in the presence of the convection parameter indicates interaction of radiation and local climate at a valley station where the ground is bare of snow.

6-05.12 Upper air indexes. - Of the first five derived equations, equation 3 was best with a coefficient of determination of 0.83. The question of how much improvement could be gained by addition of 700 mb temperatures and dew points was answered in equation 6. (D = 0.87) Here, both absorbed shortwave radiation and the 700 mb temperature were nonsignificant, while the convection parameter continued to be highly significant, and the 700 mb dewpoint was acceptably significant. The coefficient of the 700 mb dewpoint had a negative sign, indicating that it was not performing the desired index function, namely that of representing condensation melt. For this reason, 700 mb dewpoint was dropped as a condensation index. Thus, even though this function (eq. 6), improved noticeably over equation 3, it was decided to abandon the condensation index, and to further explore modifications of equation 3 by omission of wind from the convection parameter and by addition of an estimate of longwave radiation loss in the open.

6-05.13 Wind. - Equation 7 was set up with a view to examining the relative importance of wind in the convection parameter. This function, equation 7, contained only two independent variables, absorbed shortwave radiation and Boise maximum temperature, and had a coefficient of determination of 0.86 as contrasted with equation 3 which had only 0.83. With omission of wind, absorbed shortwave radiation became highly significant, apparently due to a lesser degree of dependence between absorbed radiation and maximum temperature at Boise than between radiation and the convection parameter (X_3 = product of maximum temperature and wind). This appears reasonable for a valley station where the air temperature is not measured over snow. The importance of absorbed shortwave radiation in equation 7, is emphasized by equation 8, which shows that Boise maximum temperature without shortwave radiation is far less effective than with it. Although there is little difference in over-all effectiveness between equation 4 (which uses the Boise max temp-wind product) and equation 7 (which omits wind but includes absorbed shortwave radiation), the latter is favored because rationally it is better suited to the general theoretical thermal budget of the area. It is well to bear in mind, however, that a temperature-wind index may be better than temperature alone in situations where radiation estimates are desirable but not available.

6-05.14 Longwave radiation in the open. - Thus far, all components of the thermal budget have been accounted for, with the exception of longwave loss in the open. Examination has been made of absorbed shortwave radiation, convection, and condensation, with decisions to retain absorbed shortwave radiation, to discard Boise wind from the convection parameter, and, for lack of adequate data, to abandon completely the condensation index. The only remaining component which has not yet been examined is longwave radiation exchange in the open. Since longwave loss in the open has been demonstrated by laboratory studies to be a major component of the thermal budget for this kind of area, attention is now focussed on examination of indexes for this component.

6-05.15 A graphical relation for estimating longwave loss as a function of 700 mb and minimum surface temperatures was devised, using Boise upper-air data and Idaho City minimum temperatures. Construction of the chart is based on the concept, that, for a given airmass condition, minimum temperature is a function of the amount of nighttime cooling by longwave radiation. Therefore, the temperature condition of the airmass, as indexed by the 700 mb temperature, may be combined with the minimum nighttime surface temperature to represent the total nighttime loss by longwave radiation, which in turn may be used to represent the loss for the 24-hour period. Surface winds also affect minimum temperatures, but inclusion of a wind parameter in the chart for the Boise River basin was not required. Idaho City (rather than Boise) minimum temperatures were used in order to provide a more representative index of local climate in the basin. The adopted relation for this study is shown in figure 2, plate 6-3. It is again emphasized that this relation was specially derived as an expedient for this particular study and may not be applicable to other areas without modification.

6-05.16 The effectiveness of the longwave loss index as estimated from 700 mb and minimum surface temperatures when tested in equation 9 (D = 0.89) showed a significant improvement over equation 7. Since the coefficients for absorbed shortwave, and the longwave-loss index derived in equation 9 were nearly equal, the longwave-loss estimate was combined with absorbed shortwave to give an estimate of net allwave radiation effective in producing snowmelt. This estimate was tested in equation 10 with a coefficient of determination of 0.89 (equal to that for equation 9). Equation 10 represents the final result of this series of analyses and explains all but approximately ten percent of the variance of clear-weather snowmelt runoff from the Boise River basin above Twin Springs, Idaho. Daily runoff estimated from this equation is plotted against observed runoff in figure 3, plate 6-3.

6-05.17 <u>Regression equations for 1955 and 1954</u>. - To assess the universality of application of the snowmelt equation derived for this basin from 1955 data (eq. 10a, table 6-5) a similar derivation was made with data from the 1954 season and with data of both seasons combined. 1954 and 1955 snowmelt runoff coefficients are in close agreement. All coefficients, and statistical measures of accuracy are shown in table 6-5.

6-05.18 For the purpose of reconstitution of streamflow hydrograph (presented in chapter 9), a melt equation was derived, with Idaho City maximum temperatures rather than Boise maximum temperatures (eq. 11, table 6-5) because Idaho City is at a higher elevation and is nearer the basin, and because Idaho City minimum temperatures had been used for the estimation of longwave radiation loss in the open. The coefficient of determination, however, was lower than that for the case where Boise maximum temperatures were used.

6-05.19 Summary. - This section has presented an investigation of clear-weather snowmelt runoff from the Boise River basin above Twin Springs, Idaho. The basin is partly forested and suitable indexes were applied to represent the thermal-budget components of melt essential to this category of forest cover. It was found that allwave radiation was an essential item in the melt budget of the area; that a combination of temperature and wind at a valley station was less effective than temperature alone; that condensation is not adequately indexed by any presently available data; and, incidentally, that a quite satisfactory estimate of longwave radiation loss from snow in the open could be made from 700 mb temperature and surface minimum temperature. The final melt equation, (10c, in table 6-5) is

$$Q_{gen} = 0.00238\ G + 0.0245\ (T_{max} - 77) \qquad (6\text{-}15)$$

where Q_{gen} is daily generated snowmelt runoff of Boise River above Twin Springs, Idaho in inches over snow-covered area, G is estimated daily net allwave radiation exchange (snow and sky) in the open, in langleys, and T_{max} is Boise daily maximum temperature, in degrees F. The high temperature base of 77°F reflects the adjustment necessary in using data from a valley station bare of snow. The equation explains 90 percent of the runoff variance and gives runoff estimates that are correct within 0.11 inch of the observed daily values of generated runoff, approximately 67 percent of the time.

6-05.20 This example of the Boise River was primarily intended to illustrate the method of approach and the kind of problems which confront the hydrologist seeking to establish snowmelt runoff rates for project basins. The problems are as follows:

(1) Determination of physical characteristics of the basin with regard to topography, forest cover, soil, and ground-water conditions.

(2) Separation of daily increments of snowmelt runoff by hydrograph analysis.

(3) Availability of adequate meteorological data for basin representation of air temperature, humidity, wind speed, and allwave radiation.

(4) Determination of snow-surface albedo.

(5) Evaluation of snow-covered area.

6-05.22 To the hydrologist accustomed to using degree-day indexes for estimating snowmelt, the procedures presented thus far in this chapter may seem complex and cumbersome. It is important to bear in mind, however, that the best indexes of snowmelt are those which describe as closely as possible the thermal budget of the drainage area concerned. The degree of closeness sought and the availability of data both influence the choice of method. There are situations in which it is desirable to use a temperature index only. The following section deals with the applicability and effectiveness of temperature data alone as a snowmelt index.

6-06. TEMPERATURE INDEXES

6-06.01 General. - In many areas where snowmelt is an important factor in runoff, air-temperature measurements are the only data available from which snowmelt can be computed. Moreover, air temperature is a simple index of snowmelt, and, as was demonstrated in the preceding section, is the best single index of snowmelt for forested areas. For these reasons, temperature indexes are the most widely used method of computing snowmelt. Much work has been done in relating snowmelt amounts to temperature indexes; the most commonly used index is degree-days above freezing, that is, mean daily temperature in excess of 32°F. Mean temperature is usually taken as the mean of the daily maximum and minimum temperatures, those two measures of temperature being generally available. The 32°F base follows from the idea that most snowmelt results directly from the transfer of sensible heat from the air in excess of 32°F. While it is now known that air temperature is not the primary cause of snowmelt in most areas, 32°F is still a good average base value for use with mean temperatures. The use of a time period of one day results from the diurnal pattern of snowmelt; in most areas each day's melt may be identified by a drop in the discharge hydrograph associated with considerable reduction or even cessation of melt during the night. Time periods other than one day have been used under special circumstances with appropriate temperature indexes of degree-half days, degree-hours, etc. Also temperatures other than mean daily temperature are used for temperature indexes (e.g., maximum daily temperature), and bases other than 32°F are often used. These other temperatures, temperature bases and time periods will be examined later. For the moment, only the common index of degree-days above freezing will be considered.

6-06.02 Point melt rates. - Whereas snowmelt runoff is determined from hydrograph analysis, as in the preceding sections, snowmelt or snowpack ablation rates are determined from the analysis of snow survey data. This is done by noting the change in water equivalent on the snow course (or point within the snow course) over a period of several days, and relating it to the accumulated temperature index during the period. The period selected should be long enough and have a change in water equivalent large enough to make the errors of measurement small, relative to the total change in water equivalent. Where data from the entire snow course are used, care must be taken that all points remain snow covered. If any of the points become bare, a lesser melt rate than actually occurred is indicated.

6-06.03 It should be noted that snowmelt defined in this manner—the change in water equivalent of the snowpack—may differ from the melt equivalent of the heat supply to the snowpack at the snow surface, especially early in the snowmelt season. Before the pack has been thoroughly ripened, some of the melt water from the snow surface may refreeze within the pack and still more may go to satisfy the liquid-water-holding capacity of the pack (see chapter 8). Furthermore, the snow-surfaces albedo decreases as the season progresses. Assuming a temperature index to be a good indicator of heat supply, then a changing relationship between the index and snowmelt is indicated while the snowpack is being ripened and snow-surface albedo is changing.

6-06.04 Early investigations of temperature indexes of snowmelt were mostly concerned with point melt rates. In 1914, Horton 6/ performed experiments wherein cylinders of snow were cut from the snowpack and melted under laboratory-controlled temperature conditions. He found the melt rate to be about 0.04 to 0.06 inch of water per 24 hours for each degree above 32°F for the conditions of the experiment. In 1931, Clyde 2/ performed similar experiments and determined average melt rates of 0.05 to

0.07 inch per degree-day above freezing. However, these laboratory experiments are not representative of actual melt conditions, since the radiation exchange was certainly not typical of field conditions. In addition, since the snow samples stood on a table in the laboratory, the air which became cooled by contact with the snow could drain away and be replaced by warmer air, as pointed out by Horton in subsequent article. 7/ This condition does not exist over snowfields where the air cooled by the snow tends to stagnate over the snow surface. Due to this effect alone, a smaller degree-day factor than those cited above, would be indicated; however, the inclusion of allwave radiation would indicate a larger factor.

6-06.05 Clyde 2/ also determined spring snowmelt rates from a field study made at Gooseberry Creek, Utah, over a period of 17 days. Using snow-course data, he related the change in water equivalent to degree-days and arrived at a degree-day factor of 0.054 inch per degree-day using mean daily temperatures above freezing. Church 1/ compared snowmelt at Soda Springs, California with the "mean of temperatures above freezing during month" (equals one-half mean maximum temperature above 32°F for month) and arrived at a degree-day factor of 0.051 inch per degree-day. His data were for the month of April and covered the years 1936 through 1941. The foregoing factors represent melt rates per degree-day only for a given site and for a specified time of year. Obviously, there must be a considerable variation in point melt rates at different sites within a basin during the same period, and also a variation in the relationship with time of temperature indexes and point melt rates at a given site. Degree-day factors derived for just one site and for a single melt season are of limited significance in determining basin snowmelt. A more firm basis for the relationship between degree-days and point melt rates can be had from an analysis of the data from a single snow course over a number of years and from the analysis of a large number of different courses having different exposures. Such an analysis has been made using the considerable snow course data from the three snow laboratories for their years of operation. Mean degree-day factors for all the years of record of each snow course were computed. Also, a mean degree-day factor was determined for each of the snow laboratory basins for all of the years of record by averaging all snow courses within the basin. These data are summarized in the table below:

POINT MELT RATES: DEGREE-DAY FACTORS*

(Based on mean daily temperature)

Laboratory	Maximum Melt Station	Minimum Melt Station	Mean All Stations
CSSL	.128	.066	.106
UCSL	.131	.054	.090
WBSL	.108	.026	.060
Mean	.122	.049	.085

* inches of melt per degree-day above 32° F.

It is emphasized that the factors given in the table above are mean values for the several years of operation of each of the laboratories. Individual values for each year and for within-year periods exhibited a wide range of values for the individual snow courses. Deviations of the individual degree-day factors from the mean factor, computed for each snow-course, showed the more sheltered sites to have more constant factors. This bears out findings of the previous section on statistical determination of snowmelt indexes, which showed temperature indexes to be more accurate in determination of snowmelt in more heavily-forested areas. With regard to the degree-day factors for the maximum melt stations, it is pointed out that these factors are greater than those that would be observed at a horizontal, unforested site. Each of the maximum stations had a decided southerly exposure in addition to being unforested. As regards the minimum melt stations, the considerable difference in the magnitudes of these factors may be attributed to differences in forest cover. The WBSL site was especially conducive to low melt rates, being in a small clearing surrounded by high and dense trees. While solar radiation was effectively excluded from the site, longwave radiation loss from the snowpack was not reduced to the extent it would be under a solid forest canopy. The mean all-station factor for each of the laboratories represents an average in time as well as space. The mean degree-day factor gives a higher melt rate than the true melt rate over the laboratory area since they are for snow courses, which, on the whole, are in more open areas than the mean forest cover for the basin. The temperatures used in computing the degree-day factors were daily maximum and minimum values as determined by mercury-and-alcohol thermometers at the headquarters stations of each of the laboratories. A fixed lapse-rate correction of 3°F per 1000 feet was used to adjust this temperature to the elevation of the snow course being considered. Changes in water equivalent were means for the entire snow course, all points remaining snow covered throughout.

6-06.06 Temperatures. - While daily mean temperature is the most commonly used index of snowmelt, many other temperature indexes have been tried in an attempt to improve the index relationship (see Snyder, 9/ p.24). Most of these are based on daily maximum and daily minimum temperatures because of the wide availability and simplicity of use of these measures. Daily maximum temperature by itself, has been extensively used by the Snow Investigations as an index of snowmelt. When used by itself, maximum temperature has been found to be a more accurate index than daily mean temperature, and, in addition, is even simpler to use. Tabulated below are degree-day factors relating point snowmelt amounts to daily maximum temperatures in excess of 32°F. The factors are based on the same data used in computing the degree-day factors of the table of paragraph 6-06.05.

POINT MELT RATES: DEGREE-DAY FACTORS*

(Based on maximum daily temperature)

Laboratory	Maximum Melt Station	Minimum Melt Station	Mean All Stations
CSSL	.054	.029	.045
UCSL	.041	.020	.035
WBSL	.060	.015	.034
Mean	.052	.021	.038

* inches of melt per degree-day above 32° F.

The factors given here are roughly half those based on mean daily temperature. No general conclusions can be drawn regarding the relative accuracy of the two indexes even with the extensive data used in this study. The wide scatter in computed melt rates for individual snow courses obscured the relative effectiveness of the temperature parameters in computing melt.

6-06.07 It would seem that some measure of possible nocturnal snowpack heat deficit should appear in the temperature index, yet it is felt that the inclusion of minimum temperature at an equal weight with maximum temperature gives undue emphasis to this effect. On the other hand, the use of maximum temperature only, excludes this effect entirely. The use of an index such as $(2T_{max} + T_{min})/3$ would seem to offer a superior index to either maximum or mean temperature. However, in view of the slight difference in goodness of fit between maximum and mean temperatures, it appears unlikely such a refinement is warranted. Temperature indexes based on wet-bulb or dewpoint temperatures have also been suggested as being superior to dry-bulb temperatures. From the correlations presented in section 6-03, it may be seen that air temperature is a better index to snowmelt runoff than is vapor pressure. In view of the approximate linear relationship between dewpoint and vapor pressure over the limited ranges of these variables ordinarily encountered over melting snow, it follows that dewpoint temperature alone is not as good an index of snowmelt as is the dry-bulb temperature. Still another temperature index of snowmelt that has been considered is upper-air temperature. In favor of its use, it is argued that this is a temperature truly representative of the basin as a whole, being unaffected by local influences. However, studies by the Snow Investigations have shown that for small-to-moderate-sized drainage basins, upper-air temperatures by themselves are not sensitive-enough indicators of heat supply to represent melt variations adequately. Upper-air temperature variation is small compared to the daily variation of snowmelt. Much of the heat energy which goes to produce snowmelt is generated and consumed within the surface layers of the atmosphere and thus is not manifest in the upper-air temperature. It may be that for larger basins (greater than, say, 10,000 square miles), this may prove to be an adequate index, since the sensitivity required in smaller basins is not so important here.

6-06.08 <u>Temperature bases</u>. - The 32°F base used so far in this section is the most commonly used temperature base. While its use stems largely from a lack of knowledge concerning bases and their variations, it is, nevertheless, a good average base value for mean temperature indexes. Where maximum temperatures are used, higher bases and somewhat lower degree-day factors are generally indicated. The tendency is for the melt to become more independent of the temperature index as the amount of cover decreases. The temperature bases and degree-day factors for the point melt rates of this section, are given in figure 1, plate 6-4 for the extremes of forest cover. The graphs in this figure were determined by plotting the point melt data as functions of the average temperatures (both mean and maximum) for the period, for both open and forested snow courses, from data representing all three laboratories for several melt seasons. There is, of course, wide variation in melt rates between periods, because air temperature alone does not adequately represent the entire melt process, particularly for open sites. The curves do, however, represent the average relationship between air temperature and snowmelt during the active spring snowmelt period, for the extremes of forest cover. It should be noted that the temperature base decreases with decreasing forest cover, which conforms to the statistically-derived temperature bases described in section 6-03. The increase in temperature bases when maximum temperatures are used instead of mean temperatures should be noted. There is also a change in the degree-day factor. The below-freezing temperature bases for open sites do not necessarily indicate that snowmelt occurs with air temperatures below 32°F, but rather that there is included in the melt equations an average component of melt (principally solar radiation) which is independent of air temperature. Because of this, the melt equations are applicable only to average springtime melt for conditions as experienced at the snow laboratories and only for the approximate range of temperatures shown on the diagrams.

6-06.09 Basinwide snowmelt. - So far this section has been restricted to the consideration of point melt rates. Basinwide snowmelt rates present further complications. For one thing, variations in areal snow cover complicate the problem, while at the same time the progressive retreat of the snowline results in a change in the mean elevation of the snow-covered area. In addition, only a part of the snow-covered area may be contributing to snowmelt and the southerly exposed open areas become bare of snow first, leaving the more sheltered areas to produce the last of the snowmelt. As a result of these complications, basinwide snowmelt is most difficult to evaluate. While apparent point melt (ablation) rates can be determined from snow survey data and basin snowmelt runoff from hydrograph analysis, there is no single satisfactory measure of basinwide snowmelt. The mean change in water equivalent of all snow courses within the basin, in itself, is not adequate even for such densely-sampled basins as those of the snow laboratories, since snow courses are generally located in clearings and have higher than average basin melt rates. In order to evaluate basinwide snowmelt properly, it is necessary that a complete water balance be made for the area such that the snowmelt can be determined relative to the other causes of runoff. Moreover, it is necessary that the areal extent of the snowpack be known. The climatological data of chapter 2, the water balance of chapter 4, and the snow-cover depletion data of chapter 7, for each of the three laboratory basins afford the opportunity for such a determination. A study of basinwide snowmelt was made, based on these data using all of the years of record at each of the three snow laboratories. Basinwide snowmelt amounts corrected for areal snow cover, were related to temperature indexes (both mean and maximum temperatures), the temperatures being corrected to the mean height of the snow-covered area by means of a standard lapse rate of 3°F per 1000 feet. Results are given in the table below for the standard temperature base of 32°F. Monthly values for the months of April and May only are given. During June the areal extent of the snow cover was not well enough known to permit accurate computation.

BASINWIDE SNOWMELT RUNOFF: DEGREE-DAY FACTORS *

Basin	Mean temperature		Maximum temperature	
	April	May	April	May
CSSL	.089	.100	.024	.043
UCSL	.037	.072	.010	.031
WBSL	.039	.042	.021	.025

* inches of melt over the snow-covered area per degree-day above 32°F.

The values given in the above table are mean values for the several years of record at each of the laboratories. They reflect the general decrease in melt rates with increasing forest cover and also show the increase in the melt rates as the melt season progresses. Since, on the average, some of the heat transferred to the snowpack during April goes to ripen the pack, the resultant melt for this month is less than for subsequent months. Other things also influence this change in factor with time; they will be discussed in a subsequent paragraph. For comparison with the above, reference is made to a study of basinwide snowmelt by Horton. 7/ He found melt rates varying from 0.088 to 0.058 inches per degree-day (mean temperature greater than 32°F) for thinly forested and fully forested areas in western Pennsylvania during March and April.

6-06.10 Using temperature bases for snowmelt, appropriate to the degree of forest cover as previously discussed, degree-day factors for basinwide snowmelt were also computed for the three snow-laboratory areas. These were as follows:

BASINWIDE SNOWMELT: TEMPERATURE BASES AND DEGREE-DAY FACTORS *

Basin	Mean temperature			Maximum temperature		
	Base °F	Degree-day factor April	May	Base °F	Degree-day factor April	May
CSSL	26	.036	.062	29	.020	.038
UCSL	32	.037	.072	42	.109	.064
WBSL	32	.039	.042	42	.046	.046

* inches of melt over the snow-covered area per degree-day above indicated temperature base

The same average temperature base was used for both months for each of the laboratories since the variation with time in the base value is slight. As before, the temperatures were corrected to the mean height of the snow-covered area.

6-06.11 Degree-day factors. - In the foregoing paragraphs of this section, degree-day factors for both point and basinwide melt rates have been given. The variation in these factors with density of forest cover and with time has been shown. Here the reasons for the variations will be discussed and some general conclusions will be drawn concerning them. Regarding the increase in the degree-day factors for basinwide snowmelt from April to May, it is to be pointed out that this increase is largely fictional, the result of using monthly means in the computation. The typical April has alternate periods of snowmelting and deposition of new snow (cf. tables 4-1, 4-2, and 4-3). Even though corrections are made for additions of snow in computing the total ablation for the month, in each instance of new snowfall, this snow must first be ripened before it can be melted. Considerable heat is thus consumed which would otherwise go to produce snowmelt, and the resultant degree-day factor is accordingly lowered. During May, the occurrences of new snowfall are much less frequent; hence the degree-day factor is higher. If only periods of actual melting were considered, rather than monthly totals, the difference between the degree-day factors for the two months (April and May) would be much less. This was done in the determination of degree-day factors for point melt rates for snow known to be ripe. Only periods of active melt between two snow surveys were used in arriving at the degree-day factors. As a result, there was no apparent seasonal increase in these factors. While it would seem that there should be some increase due to the increasing quantities of solar radiation through the season, apparently this increase was adequately reflected by the temperature index. This is discussed in the next paragraph.

6-06.12 The place and method of air temperature measurement has a secondary effect upon the variation of the degree-day factor with time. If temperatures are measured at or near the basin outlet, as is quite often the case, it is usual for the ground to become bare in the vicinity of the temperature station fairly early in the melt season when considerable snow cover still remains on the basin. This change from snow-covered to snow-free ground results in a measureable increase in air temperature over what it would have been, had the ground remained snow covered throughout. This effect is further heightened if temperature measurements are made at a fixed level with respect to the ground surface. As the melt season progresses, the height of the temperature measurement with respect to the snow surface increases until the ground is bare of snow. Because of the usual inversion over the snowpack, this results in a greater increase in temperature with time than would have been the case had no snow existed or had the thermometer remained at a fixed height relative to the snow surface. In this situation, the additional temperature gain tends to offset any actual seasonal increase in the degree-day factor. For temperature index stations that remain snow-free throughout the melt season this effect is, of course, non-existent.

6-06.13 The causes of the normal increase in the degree-day factors with time are (1) increasing ripeness of the snowpack, (2) decrease of snow-surface albedo, (3) depletion of snow cover, (4) increase in insolation, (5) increase in percentage of sheltered snow-covered area, and (6) the increase in the mean elevation of the snow-covered area. These are even more important in larger basins having considerable ranges in elevation than in the examples of the snow laboratories. Failure to make adjustment for these variations results in a net decreasing degree-day factor with time. If corrections are made for the effects of snow-cover depletion and mean elevation of the snow-covered area, such minor effects as the increase in insolation and the progressive increase in shelter of the residual snow cover as the melt season progresses, tend to cancel one another, making for a more constant degree-day factor for basinwide snowmelt.

6-06.14 The usual temperature increase through the melt season suggests an empirical scheme which may be used to approximate the observed increase in degree-day factors with time as the melt season progresses. If, for example, the degree-day factor is taken as $K(T_a - T_b)^n$, then

$$M = K(T_a - T_b)^{(n + 1)} \tag{6-16}$$

The value of n may be determined from analysis of snowmelt data. This form of the melt equation has been used, with good results, in several studies of melt rates, using n = 0.25. Not only does it approximate the seasonal increase in degree-day factors through the seasonal temperature increase, but it allows also for such decreases in the factors as usually follow springtime frontal passages. While the decrease in degree-day factors may be, physically, the result of the high albedo and thermal quality of newly-deposited snow, they are empirically reflected in the degree-day factor in consequence of the usual colder airmass following the frontal passage. At the present writing, this method has not been extensively tested, and it is not known whether it is generally applicable to the computation of snowmelt. Consequently, it should be used only in the sense in which it is presented here, namely, as an empirical device for increasing the degree-day factor with time in situations where such an increase has been shown to exist.

6-06.15 Snowmelt runoff. - Actually, as was pointed out previously, measurements of basinwide snowmelt are not ordinarily available. Lacking a water balance, all that are available for most basins are point melt rates and basin snowmelt-runoff rates. Hence, for a measure of basinwide melts, recourse is usually made to basin snowmelt runoff. For large drainage basins, it is impossible to separate daily increments of flow for purposes of analysis as was done in the preceding section of this chapter for the small laboratory areas and the moderate sized Boise River basin above Twin Springs, Idaho, where a marked diurnal snowmelt rise and fall made identification of daily melts possible. For large basins it is possible to determine the snowmelt runoff per degree-day by plotting double mass curves of snowmelt runoff as a function of degree-days. This technique was used by Snyder 9/ in studies of the Susquehanna River Basin, by Miller 8/ in the Missouri River Basin and by Wilson 10/ for

Gardiner River, Wyoming. Inasmuch as observed mean daily runoffs rather than the actual daily generated runoff are accumulated, during periods of increasing flows, too flat a curve results and too low a degree-day factor, while during periods of receding flows the reverse is true. Periods of sub-freezing temperatures result in irregularities in the curve since the recession of the runoff values continues even though no temperature index values are accumulated. However, if the melt season is taken as a whole, such irregularities are slight and the general relationship between snowmelt runoff and the temperature index is readily apparent. Corrections must be made in the runoff hydrograph, of course, for any rainfall runoff that occurs. As an example of the double-mass curve approach to the determination of the degree-day factor for snowmelt runoff, computations of the factor were made for the 1949 snowmelt season at the UCSL. Both maximum and mean temperature indexes were used; the previously determined temperature bases were used. The results are given in figures 2 and 3 of plate 6-4. Shown on each of the figures is: (a) the snowmelt runoff in inches over the basin (not corrected for contributing area) as a function of the unadjusted temperature index; (b) the snowmelt runoff in inches depth over the contributing area as a function of the unadjusted temperature index; and (c) the snowmelt runoff corrected for contributing area as a function of the temperature index adjusted to the mean height of the contributing area.

6-06.16 The foregoing method of double-mass curve analysis was presented only as an illustrative example of the method, giving data for one year only from one of the snow laboratories. Other years and other laboratories were not analyzed because the relationships between the temperature indexes and the snowmelt runoff have already been determined by the statistical studies of the preceding sections of this chapter. The two approaches in computing degree-day factors for snowmelt runoff for this one year at the UCSL gave results which are in close agreement. In this analysis, as in the basinwide snowmelt analysis based on the monthly water balance data, it is to be emphasized that the early-season melt rates are of little significance, reflecting as they do the frequency and quantity of new snowfall. Moreover, in the case of snowmelt runoff, additional snowmelt water goes to satisfy soil moisture and depression storage (pondage) requirements early in the melt season; this fact further affects the relationship between the temperature index and the snowmelt runoff.

6-07. SUMMARY - THE GENERALIZED BASIN SNOWMELT EQUATION

6-07.01 Basin snowmelt coefficients are most accurately determined by statistical analysis of past runoff records correlated with appropriate indexes of snowmelt. Statistically derived coefficients relate snowmelt to the conditions of observation of meteorologic variables at fixed points, give proper weight to features of the physical environment of the basin (i.e., percent of forest cover, slope, orientation, loss, etc.), and allow relatively unimportant melt processes to be indexed by major melt parameters. The application of statistically derived coefficients from daily snowmelt runoff records is particularly suited to short-term streamflow forecasting, for cases where adequate past record is available for study and reconstitution. Logically, the coefficients so derived apply only to the conditions for which they were developed. For many cases, particularly in connection with design floods, it is impractical to derive basin melt coefficients, and a general snowmelt equation is required. In order to meet this requirement, the rational analysis of snowmelt presented in chapter 5 may be combined with the statistical weightings of the variables developed in this chapter to arrive at simplified general snowmelt equations which are applicable to all conditions of environment over project-sized basins. The general solution for snowmelt during rain on snow, as described in section 6-04, serves as a guide to a more general snowmelt equation applicable to rain-free conditions. The principal requirement of the general equation is to express snowmelt in terms of ordinarily available meteorologic data which most reliably represent the physical processes of melt. Simplifying assumptions which are well within the accuracy of the derived melt coefficients may be applied in order to obtain a workable snowmelt formula.

6-07.02 The following equations for rain-free periods have been developed on the basis of the above-stated requirements, for varying conditions of forest environment:

Heavily forested area:

$$M = 0.074\ (0.53T'_a + 0.47T'_d) \qquad (6\text{-}17)$$

Forested area:

$$M = k(0.0084v)\ (0.22T'_a + 0.78T'_d) + 0.029T'_a \qquad (6\text{-}18)$$

Partly forested area:

$$M = k'(1 - F)(0.0040\ I_i)\ (1 - a) +$$
$$k(0.0084v)(0.22T_a' + 0.78T_d') + F(0.029T_a') \qquad (6\text{-}19)$$

Open area:

$$M = k'(0.00508\ I_i)\ (1 - a) + (1-N)(0.0212T_a' - 0.84)$$
$$+ N(0.029T_c') + k(0.0084v)(0.22T_a' + 0.78T_d') \qquad (6\text{-}20)$$

where:

M is the snowmelt rate in inches per day.

T_a' is the difference between the air temperature measured at 10 feet and the snow surface temperature, in ^{o}F.

T_d' is the difference between the dewpoint temperature measured at 10 feet and the snow surface temperature, in ^{o}F.

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

I_i is the observed or estimated insolation (solar radiation on horizontal surface) in langleys. (See figures 4, 5 and 6, plate 5-1.)

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

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

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

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

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

k is the basin convection-condensation melt factor, as defined in paragraph 6-04.12. It depends on the relative exposure of the area to wind.

The melt coefficients given in the above equations represent daily melt amounts in inches. For those cases where a convection-condensation term with wind is included in the melt expression, it may be necessary to subdivide the day into smaller time increments where there is marked variation in both wind and temperature or dewpoint. The coefficients also express melt for a ripe snowpack (isothermal at $0^{\circ}C$ and with 3 percent initial free water content - see chap. 8). Except that they account for loss by transpiration from forested areas, the melt coefficients represent the actual melt of the snowpack averaged over a basin area, expressed as daily ablation in inches of water equivalent. The equations are based on linear approximations between saturation air-vapor pressure and dewpoint, and also on longwave radiation as a linear function of the temperature of the radiating surface. These approximations provide values which are close to the theoretical amounts for the range of temperatures and dewpoints experienced in snow hydrology, as shown in figures 1 and 5, plate 6-2. Functions involving air temperature and dewpoints are expressed as the difference between snow surface temperature and the value for a given level of observation. For a melting snowpack, subfreezing snow-surface temperatures are experienced usually only as the result of nighttime cooling in open areas (see chapter 8). Therefore, except under this condition, the temperature and dewpoint values are equal to increments above $32^{\circ}F$. The following paragraphs summarize the derivation of the general melt equations.

6-07.03 The snowmelt runoff equation for heavily forested areas directly evaluates melt by convection, condensation, and longwave radiation. Implicit in the relationship is an average wind (estimated to be between 2 and 3 miles per hour at the 1-foot level) which is required for the transfer of heat and water vapor to the snow by turbulent exchange in the atmosphere. The air temperature term includes the evaluation of heat transfer by longwave radiation and convection. The proportional effects of convection and condensation and their appropriate melt coefficients were derived as explained in paragraph 6-04.07. Direct melt by absorbed shortwave radiation is assumed to be equal to the basin loss of water by forest transpiration, as was explained in Research Note 19.

6-07.04 The general melt equation for less densely forested areas is derived in a similar manner, except that convection and condensation are evaluated separately from longwave radiation in order to include a wind variable. The value of k, the basin coefficient, depends on the conditions of measurement of wind with respect to the basin average, and its value is 1.0 for plains areas with no forest cover. It may be slightly greater than 1.0 for exposed mountain ridges, and for heavily forested areas it approaches a minimum value of 0.2. The 50-foot level wind value for forested areas is assumed to be the average wind in an open area resulting from the general airmass circulation prevailing at the time.

6-07.05 For partly forested areas, a term for shortwave radiation exchange in the unforested portions is included in the melt equation. The theoretical melt coefficient for absorbed shortwave radiation melt is reduced from 0.00508 to 0.0040, to account partly for longwave radiation loss in the open and partly for loss by evapotranspiration from the forest. The effective forest canopy cover, F, represents the average percent of the basin shaded by the forest from direct solar radiation, expressed as a decimal fraction. For partly forested basins, longwave loss in the open is considered to be adequately expressed by the reduction of the shortwave radiation melt coefficient for the open portions of the area.

6-07.06 The expression for snowmelt in open areas becomes more complex because of the requirement for direct evaluation of longwave radiation exchange. Incident shortwave radiation is presently observed at approximately 90 stations in the United States. For areas where observations are not available, shortwave radiation may be estimated by duration of sunshine or diurnal temperature rises. Longwave radiation, on the other hand, is not regularly measured, and although many expressions have been developed to evaluate it from both surface and upper-air meteorologic data, they are mostly too complex or cumbersome to incorporate in a generalized melt expression. From observations of longwave radiation made at CSSL, it has been found that for the condition of clear skies, the downward longwave radiation from the atmosphere over snow can be expressed simply as 0.75 of the theoretical blackbody radiation corresponding to surface air temperature measured at instrument height. The limited variation of the water-vapor content of the air usually experienced over snow, does not produce significant changes in downward longwave radiation. Therefore, in the general melt equation, with clear skies (N equal to 0), the net longwave radiation loss is expressed simply as a linear function of the surface air temperature. The net longwave radiation exchange for cloudy skies is expressed as the theoretical blackbody radiation, as approximated by a linear relationship, for the difference in temperature between the snow surface and the cloud base; cloud base temperatures may be determined either from soundings made by radiosonde, or by applying appropriate temperature lapse-rate corrections to known surface air temperatures and cloud heights. Estimates of longwave exchange under cloudy skies by this method are considered to be realistic for low or middle clouds. Convection and condensation melt for open areas is estimated by a general equation as discussed in section 6-04. It is not considered necessary to evaluate the effects of elevation in the convection term (due to decreased air density with elevation), because of the relatively small order of magnitude of this correction in comparison with the other components of melt.

6-08. REFERENCES

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TABLE 6-1

SUMMARY OF RESULTS OF REGRESSION ANALYSIS

SNOWMELT RUNOFF FROM UNFORESTED AREA

Lower Meadow Lysimeter, CSSL

1954

EQUATION NUMBER	DATA	SNOWMELT RUNOFF COEFFICIENTS												REGRESSION CONSTANT	STANDARD ERROR OF ESTIMATE	COEFFICIENT OF DETERMINATION
		Radiation		Convection and Condensation												
		I_{net} Shortwave	R_{net} Longwave	Convection parameter		Condensation parameter		Wind	Maximum temperature		Mean temperature					
		X_1	X_2	X_3	Base °F	X_4	Base mb	X_5	X_6	Base °F	X_9	Base °F		c	$s_{y.x}$	D
(1)	1954 hourly	0.00544	0.00445	0.00011	T_s 2/	0.00105	e_s 2/							-0.10	0.05	0.97
(2)	daily	0.00617	0.00758	-0.000038	78	-0.00411	33.1	0.00139						0.71	0.07	0.95
(3)	daily	0.00747	-0.00183 1/	0.00019	32	0.00056	6.1	-0.00939						0.31	0.18	0.67
(4)	daily	0.00576	0.00649											0.07	0.07	0.94
(5)	daily	0.00504												-0.03	0.18	0.65
(6)	hourly			0.00060	T_s	0.00238	e_s							0.37	0.24	0.46
(7)	hourly			0.00035	T_s									0.75	0.29	0.16
(8)	hourly					0.00116	e_s							1.22	0.30	0.09
(9)	daily								0.0334	22				-0.73	0.22	0.23
(10)	daily										0.0364	8		-0.31	0.29	0.08

Notes:

Definitions of variables and units are given in paragraph 6-03.02.

1/ Incident shortwave radiation substituted for longwave radiation loss in the open.

2/ T_s and e_s are temperature and vapor pressure of the snow surface.

TABLE 6-3

SUMMARY OF RESULTS OF REGRESSION ANALYSIS

SNOWMELT RUNOFF FROM FORESTED AREA

Skyland Creek - UCSL

1950, 1949

EQUATION NUMBER	DATA	SNOWMELT RUNOFF COEFFICIENTS											REGRESSION CONSTANT	STANDARD ERROR OF ESTIMATE	COEFFICIENT OF DETERMINATION
		Radiation		Convection and Condensation											
		I_{net} Shortwave	I_1 Index of longwave loss in open	Convection parameter		Condensation parameter		Wind	Maximum temperature		1400 vapor pressure				
		X_1	X_2	X_3	Base °F	X_4	Base mb	X_5	X_6	Base °F	X_7	Base mb	c	$s_{y.x}$	D
(1)	1949 daily	0.00056	0.00041	0.00028	41	0.00155	8.8	-0.02521					0.11	0.07	0.88
(2)	1949 daily	0.00004		0.00029	41	0.00141	8.8	-0.02420					0.15	0.07	0.89
(3)	1950 daily			0.00040	39	0.00128	8.0	-0.02536					0.27	0.17	0.81
(4)	1949 daily			0.00029	42	0.00139	8.9	-0.02441					0.16	0.07	0.90
(5)	1950 daily								0.03629	36	0.07849	7.2	-1.87	0.19	0.77
(6)	1949 daily								0.01962	38	0.07225	7.6	-1.28	0.13	0.60
(7)	1949 daily	0.00380	-0.00169										0.36	0.18	0.29
(8)	1949 daily	0.00130											0.15	0.18	0.23
(9)	1950 daily			0.00048	56			-0.02647					0.52	0.25	0.59
(10)	1949 daily			0.00037	54			-0.02015					0.22	0.11	0.73
(11)	1950 daily					0.00176		-0.00469					0.28	0.31	0.36
(12)	1949 daily					0.00220	6.5	-0.01425					0.39	0.15	0.48
(13)	1950 daily								0.04254	43			-1.84	0.24	0.62
(14)	1949 daily								0.02497	44			-1.02	0.14	0.54
(15)	1950 daily										0.11641		0.03	0.32	0.33
(16)	1949 daily										0.14076	3.6	-0.50	0.17	0.35

Note:

Definitions of variables and units are given in paragraph 6-03.02.

TABLE 6-4

SUMMARY OF RESULTS OF REGRESSION ANALYSIS

SNOWMELT RUNOFF FROM HEAVILY FORESTED AREA

Mann Creek, WBSL

1951, 1950, 1949

EQUATION NUMBER	DATA	SNOWMELT RUNOFF COEFFICIENTS								REGRESSION CONSTANT	STANDARD ERROR OF ESTIMATE	COEFFICIENT OF DETERMINATION
		Maximum Temperature		Max. Vapor Pressure		Mean Temperature		Mean Vapor Pressure				
		X_6	Base °F	X_7	Base mb	$\overline{X}_6$	Base °F	$\overline{X}_7$	Base mb	c	$s_{y.x}$	D
(1)	April 1951	0.027	36	0.045	7.2					-1.30	0.14	0.77
(2)	May 1950	0.031	35	0.070	6.9					-1.57	0.12	0.80
(3)	May 1949	0.030	37	0.057	7.5					-1.54	0.14	0.87
(4)	April 1949	0.027	34	0.094	6.6					-1.53	0.16	0.74
(5)	April 1951					0.024	29	0.085	5.3	-1.15	0.13	0.80
(6)	May 1950					0.036	30	0.112	5.6	-1.70	0.18	0.77
(7)	May 1949					0.039	33	0.094	6.3	-1.88	0.10	0.93
(8)	April 1949					0.048	31	0.147	5.8	-2.34	0.14	0.80
(9)	April 1951	0.034	38							-1.29	0.16	0.70
(10)	May 1950	0.038	35							-1.33	0.19	0.72
(11)	May 1949	0.030	37							-1.11	0.19	0.73
(12)	April 1949	0.034	35							-1.19	0.17	0.70
(13)	April 1951					0.040	30			-1.20	0.18	0.65
(14)	May 1950					0.043	28			-1.20	0.23	0.61
(15)	May 1949					0.044	31			-1.36	0.22	0.64
(16)	April 1949					0.051	30			-1.53	0.22	0.49

Note: Definitions of variables and units are given in paragraph 6-03.02.

TABLE 6-5

SUMMARY OF RESULTS OF REGRESSION ANALYSIS

SNOWMELT RUNOFF, BOISE RIVER

above Twin Springs, Idaho

1955, 1954

1/ EQUATION NUMBER	SNOWMELT RUNOFF COEFFICIENTS											REGRESSION CONSTANT	STANDARD ERROR OF ESTIMATE	COEFFICIENT OF DETER-MINATION
	Radiation				Convection and Condensation									
	I_{net} Shortwave	I_1 Index of longwave loss in open	LW loss in open $f(T_{700}, T_{min})$	G_{net} Allwave $X_1 + X_9$	Convection parameter	Condensation parameter	Wind	Maximum Temp.	700 mb Temp.	Dewpoint	Temperature Base °F			
	X_1	X_2	X_9	X_{10}	X_3	X_4	X_5	X_6	X_7	X_8	T_b	c	$s_{y.x}$	D
(1)	0.00123	0.00024			0.00245	0.00005	-0.163				66.5	-0.31	0.16	0.82
(2)					0.00313	-0.00024	-0.195				67.0	0.11	0.16	0.82
(3)	0.00153				0.00234		-0.158				67.4	-0.17	0.15	0.83
(4)					0.00303		-0.196				64.7	0.11	0.16	0.82
(5)	0.00451										----	-0.86	0.24	0.58
(6)	0.00102				0.00268				0.0124	-0.0150	66.1	-0.30	0.14	0.87
(7)	0.00239							0.0274			83.5	-2.29	0.14	0.86
(8)								0.0375			62.4	-2.34	0.19	0.75
(9)	0.00237		0.00228					0.0200			81.4	-1.63	0.12	0.89
*(10a)				0.00233				0.0236			76.7	-1.81	0.12	0.89
*(10b)1954				0.00271				0.0267			80.2	-2.14	0.10	0.87
*(10c)'54&55				0.00238				0.0245			76.9	-1.89	0.11	0.90
(11) 2/				0.00227				0.0267 2/			75.0	-2.00	0.14	0.86

Notes:

Definitions of variables and units are given in paragraph 6-05.10

1/ All equations for 1955 data unless otherwise indicated.

2/ For reconstitution of hydrograph in Chap. 9. (X_6 = Idaho City Max. Temp.).

* In 10a, n = 26; in 10b, n = 14; and in 10c, n = 40.