THESIS

# SNOWMELT INDEXES FOR SMALL MOUNTAIN WATERSHEDS

Submitted by
James Elbert Reid

In partial fulfillment of the requirements
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY JAMES ELBERT REID

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BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

BC Goodell

EE Remmenga

James R Meiman
Adviser

Arthur T. Wilcox
Head of Department

Examination Satisfactory

Committee on Final Examination

BC Goodell

EE Remmenga

James R Meiman
Adviser

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# ABSTRACT OF THESIS

## SNOWMELT INDEXES FOR SMALL MOUNTAIN WATERSHEDS

The area used in this study was the Upper Hourglass watershed which is located on the Little South Fork of the Cache La Poudre River, 26 air miles west of Fort Collins, Colorado. The Upper Hourglass watershed is an area of approximately 1000 acres lying between 10,400 and 12,700 feet above msl on the north side of Comanche Peak.

The snowmelt indexes were developed using multiple correlation and regression analyses of runoff and climatic data from the study area. Two dependent variables and 23 independent variables were used in the analysis.

In the development of the independent variables the variation of solar radiation between mountain watersheds for the period July-August, 1965, was studied. This analysis showed that there were significant differences in the amount of incoming shortwave radiation between days and between the two general locations studied.

Six snowmelt indexes are presented to fit different situations that occurred during the study year. These indexes indicate that solar radiation and minimum temperature play an important role in indexing snowmelt on the Upper Hourglass watershed. The indexes using the first day's runoff as the dependent variable consistently accounted for more of the variability in snowmelt than did the indexes using total generated runoff.

The six relationships presented all appear reasonable when the factors that effect snowmelt are considered.

James Elbert Reid
Department of Recreation and
Watershed Resources
Colorado State University
Fort Collins, Colorado, 80521
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# Chapter 1

# INTRODUCTION

Today in the management of mountain watersheds more and more consideration is being given to the potentials for improving water yield regimes. From time to time different methods of accomplishing this goal have been suggested. At the same time the need and interest by management groups in application of water yield improvement practices on selected sites has increased. In several instances management decisions have led to the application, on a limited scale, of research results in water yield improvement to meet specified land management objectives. This increasing need by land managers for sound research information in all phases of water yield improvement has led to the development of research in areas that appear particularly promising for making selected changes in the runoff regime of an area.

One such area of water yield improvement is the manipulation of snow and the energy balance over the surface of large snow deposition areas to change the timing of the water yield from these areas. Several investigators of the Watershed Management Unit at Colorado State University have been investigating problems relating to snow and snowmelt as a means of improving water yields. Several recent studies have centered around the energy balance over snow deposition areas. Most of this work is aimed toward actual tests on the manipulation of water yield from a perennial snowfield in the Upper Hourglass watershed west of Fort Collins, Colorado. If such a project is undertaken it will be necessary to know what the water yield would have been if no treatment had taken place. One way this information could be obtained is through a snowmelt model that is based on measurable climatic parameters.

Other areas where such a model would prove useful are watershed studies and land management planning. An example of such a use would be in albedo modification studies. If the model adequately explained the radiation snowmelt relationship for the site where albedo modification is being proposed, then it could be used to predict the snowmelt that would be expected if the albedo modification had not taken place. In addition, such a model could be used when evaluating the potential of operational modification programs. By comparison of the computed and actual hydrographs the effect of the modification program could be determined and evaluated.

As research and management of the water resources associated with mountain watersheds progresses, procedures that can be used to help evaluate research projects and proposed management applications of research results will be needed more and more. It is to the development of such procedures that this study hopes to contribute.

## Objective.

The objective of this study was to test the relationship between climatic parameters and daily snowmelt runoff during 1965 on the Upper Hourglass watershed of the Little South Fork of the Cache La Poudre River. Inherent in this objective was the use of data temperature, precipitation, and insolation that generally can be assumed available to land managers.

## Watershed description.

The watershed area used in this study is the Upper Hourglass watershed, which is located in the Little South Fork of the Cache La Poudre watershed. These drainages are located within Larimer County, in north central Colorado, roughly 26 air miles west of Fort Collins and 14 miles north of Estes Park.

The Upper Hourglass watershed is an area of approximately 1000 acres located on the north side of Comanche Peak. Elevations within the watershed range from 10,400 feet above msl at the stream gage to 12,700 feet above msl at the summit of Comanche Peak.

The watershed area is made up of both alpine and subalpine vegetative types. The alpine vegetation varies with the three major soils which occur in the area. Vegetation on the Alpine Turf soils ranges from dense sods to areas largely void of plants except for a few forbs. The sods are dominated by sedges, bluegrass and golden avens. Alpine Meadow soils usually occupy the lower concave slopes of the alpine area and are on alluvium or glacial till. The vegetation on these soils is dominated by willows, sedges, and hairgrass. The Alpine Bog soils in the watershed are also normally occupied by willows, sedges, and hairgrass.

The subalpine area in the watershed is almost entirely forested and is commonly referred to as the spruce-fir zone. In addition to the Engelmann spruce and subalpine fir one may find lodgepole pine on some sites. The herbaceous vegetation under both types is primarily vaccinium with minor amounts of various grasses, sedges, and forbs. The subalpine type occurs only at the lower elevations in the Upper Hourglass watershed.

The climate of the watershed is typical of the climate at higher elevations in the Colorado Front Range of the Rocky Mountains. Temperatures are less extreme than on the plains to the east, but averages are lower due to the higher elevations. The temperature patterns undoubtedly show the effect of cold air drainage, especially in the cirques and glaciated valleys.

Precipitation in the watershed occurs during all months of the year. From June through September, precipitation is usually the result of intense convectional activity. During the winter months, precipitation falls as snow, generally as a result of major frontal disturbances in the atmosphere. Snow accumulates over the entire watershed during the winter although snow depths vary greatly as a result of wind transportation and redeposition.

### Source of data.

The hydrometeorological data that was utilized in this study was obtained from a weather station at Pingree Park, 4 miles east of the watershed at an elevation of 9000 feet, operated by Colorado State University, and a stream gage at the lower end of the watershed operated as a cooperative project by Colorado State University and the Roosevelt National Forest, U. S. Forest Service. In addition, some climatic data collected in the watershed from June 1965 to September 1965 by Colorado State University were utilized.

## Chapter 2

# LITERATURE REVIEW

## (Snowmelt Indexes)

Index methods of forecasting seasonal snowmelt have been developed for a wide variety of conditions and uses. Some of the indexes make no use of knowledge about the processes of melting snow, while others rely heavily on this knowledge.

Many techniques have been used in developing these indexes, most are essentially correlation analyses ranging from simple graphical correlations to complex curvilinear multiple correlations. Garstka (1964) discusses the following five techniques for the analysis of snowmelt and forecasting runoff from snowmelt.

(1) Degree-day Correlation
(2) Basin Indexes
(3) Recession Analysis
(4) Correlation Analysis
(5) Physical Equations

All these methods have been used with varying degrees of success. In actual practice most analyses seem to involve a combination of the above techniques. In this review, recession and correlation analyses will receive the emphasis as these methods appear most applicable to the index development being considered in this problem.

Throughout this review the work of the Corps of Engineers in its Cooperative Snow Investigations will be heavily relied upon as it is probably the most intensive study of the factors involved in snowmelt to date. This study dealt with the physical relationships of the processes involved in snowmelt.

Recession analysis, dependent variables.

In any index development there is an end product, the dependent variable, to index. Runoff, water equivalent of the snow pack, and snow ablation are the most common dependent variables in studies of the snowmelt processes. Water equivalent and snow ablation are commonly associated with point measurements of snowmelt while in drainage basin studies some form of runoff is the most common dependent variable.

Two recent studies (U. S. Army, 1956, and Garstka et al., 1958) used the runoff volume generated by one days' snowmelt as the dependent variable. In both cases, the runoff volumes were computed on the basis of the recession equation originally proposed by Barnes (1939):

$$Q = Q_o {K_r}^t$$

in which:

$Q$ is the flow in c.f.s. at time, t.

$Q_o$ is the flow in c.f.s. at the beginning of the computation period or when t equals 0 days.

$t$ is the time in days.

$K_r$ is the daily runoff recession coefficient.

The Corps of Engineers (U. S. Army, 1956) expressed their derived runoff volumes in terms of inches of runoff from the contributing area while Garstka et al. (1958) expressed runoff in acre feet.

Snowmelt indexes, independent variables.

Many parameters have been used to index the independent variable of the heat budget associated with melting snow. Much of the early work indexing snowmelt amounts used temperature indexes; the most commonly used index was degree-days above freezing. The reasons behind the wide use of temperature indexes center around the following three items:

(1) In many areas where snowmelt is an important factor in runoff, air temperature measurements are the only meteorological data readily available.

(2) Air temperature is a simple index of snowmelt and is one of the better indexes in forested areas.

(3) Air temperature was thought to be the best index of the heat transfer processes.

As research has progressed towards a more complete thermal budget of a drainage basin it was found that temperatures were not as good an index of snowmelt as other meteorological parameters except in heavily forested areas where temperature plays an important indexing role (U. S. Army, 1956). On this point, studies using data from different geographic areas of the west have arrived at somewhat different conclusions. Garstka et al. (1958) found that a multiple regression containing two temperature variables gave consistently good results. He stated that the "results of the statistical analysis of the factors causing snowmelt runoff lead to the conclusion that, for the data used in these cooperative snow investigations, the temperature factor is at least as good as, and in many cases better than a combination of other factors used in correlation analysis". He recognized the fact that the relative weight of factors that influence the rate of snowmelt in the high altitude Rocky

Mountain terrain could be expected to differ from the relative weight of factors in the Pacific Northwest, California Sierras, and in the Northeastern United States.

The Corps of Engineers (U. S. Army, 1956) felt that the differences in components that best indexed the snowmelt process were based more on the percent of forest cover rather than on the geographic location of the area.

Temperature indexes have been applied in practical applications with varying degrees of success depending mostly upon the size of the area, and how the indexes were used. Anderson and Crawford (1964) found that the effects of a degree-hour factor were not constant over the whole season. By using various parameters they were able to correct the index for individual years, but found that no single set of parameters could be found which would produce a consistent reasonable fit in a series of years. This problem has been pointed out by other workers as well. One source (U. S. Army, 1965) felt these changes in degree-day factors with time related to:

(1) Increasing ripeness of the snowpack

(2) Decrease of snow surface albedo

(3) Depletion of snow cover

(4) Increase in insolation

(5) Increase in percent of sheltered snow covered area

(6) The increase in the mean elevation of the snow covered area.

They felt that if items 3 and 6 could be corrected, the others would tend to cancel out. Many authors have found snowmelt evaluation difficult because of the changing location of the snowline.

Solar radiation.--The importance of shortwave radiation in the thermal budget for the direct evaluation of snowmelt has been found to depend, for the most part, on the areal extent and density of forest cover over the area of interest. There appears to be an increasing importance of shortwave radiation with decreasing forest cover. The Corps of Engineers (U. S. Army, 1956) felt that in open areas radiation should be estimated when actual measurements are not available. They also found that, in general, diurnal temperature was not as good an index of shortwave radiation as sunshine duration data. Specifically, maximum temperature alone, when measured over snow, is a poor index of solar radiation since its magnitude also reflects variations associated with other processes. Minimum temperatures are also sensitive to other variables. Diurnal temperature range is a fair index of solar radiation in heavily forested areas, but the degree of association is less for partly forested areas. Garstka et al. (1958) in work at the Fraser Experimental Forest felt that solar radiation was expressed adequately in an air temperature variable.

Unlike shortwave radiation, longwave radiation is important for all densities of forest cover although the net effect of the input does vary with forest cover. Air temperature has been found to be a fair index of downward longwave radiation for densely forested areas. In open areas the variability of snow surface temperature does not permit air temperature to act as an acceptable index of longwave exchange between snow and sky. Observations made at Central Sierra Snow Laboratory showed that for conditions of clear skies the downward longwave radiation from the atmosphere to the snow can be expressed simply as 0.75 of the theoretical blackbody radiation corresponding to the surface air temperature measured at instrument height.

Megahan et al. (1967) in a recent study of albedo modification found that only 3 percent of the variation of melt in lysimeters could be explained by changes in incoming shortwave radiation. By evaluating longwave radiation exchange between snow and air and accounting for the change in snow albedo, a net allwave radiation measurement provided an additional 88 percent explained variance. They suggest that net allwave radiation would provide a reliable index of snowmelt on a watershed basis. Since convective heat exchange and evaporation at a snow surface decrease with increasing forest cover, net radiation should provide an even better index of snowmelt under forest covers of greater density.

The omission of an allwave radiation parameter from the runoff indexes in the Corps of Engineers studies resulted in a loss of more than one half of the explained variance of the regression equations for an unforested site. They stated that: "Allwave radiation is the controlling variable for the melt regime at an open site. For the best estimates of snowmelt runoff from an open area, then, it is imperative to have good estimates for both short and longwave radiation." When longwave radiation was removed from their relations, 30 percent of the accountable variation was lost. For clear weather melt they concluded that the function suffers a serious loss of determination without radiation as a variable.

Under partly forested conditions the omission of allwave radiation from the analysis resulted in losses of from 10 to 15 percent of the amount of variation in the dependent variable accounted for by the independent variables. The Corps of Engineers (U. S. Army, 1956) in their final equation to estimate runoff decided to leave out shortwave radiation because of its extraneous effects on condensation and convection in some years. Overall, they felt they had a more consistent index without this parameter.

In the partly forested Boise River basin the Corps of Engineers (U. S. Army, 1956) used incident shortwave radiation for the computation of absorbed shortwave radiation, in conjunction with an estimate of snow albedo. Longwave radiation loss in the open was estimated as a function of 700 MB temperature and minimum surface temperatures in degrees centigrade. A parameter for net allwave radiation in the open was then obtained by adding absorbed shortwave radiation and estimated longwave loss. It was found in this analysis that allwave radiation was an essential item in the melt budget of the area.

Condensation and convection.--The Corps of Engineers (U. S. Army, 1956) used a temperature-wind function as an index for convection melt, while the condensation parameter was a vapor pressure-wind relationship.

The omission of convection and condensation parameters from the regression analysis of snowmelt on unforested areas resulted in a negligible loss in the coefficient of determination. The Corps of Engineers concluded that "convection and condensation parameters without radiation are inadequate for estimating clear-weather melt in the open, while air temperature alone is totally inadequate".

In the analysis of data from partly forested watersheds the convection and condensation parameters by themselves show a total coefficient of determination of 47 to 83 percent, while shortwave radiation by itself accounts for 22 to 71 percent of the variance of daily melt in individual years. The use of daily temperature and vapor pressure without wind accounted for 14 to 67 percent of the variance in the dependent variable. Air temperature alone was an erratic snowmelt index in these watersheds.

In the Boise River area an analysis showed that available humidity data did not satisfy the requirements of a condensation-melt index. Maximum temperature alone served as a better convection-melt index than a temperature-wind product. In this work condensation was not adequately indexed by any of the available data.

From forested areas (canopy density 80%, effective forest cover 85%) the Corps of Engineers concluded that, in general, an accurate determination of melt quantities requires parameters which include wind to express convection and condensation, but that maximum temperatures 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 complete evaluation.

The Corps of Engineers in their studies at the Willamette Basin Snow Laboratory found that maximum or mean daily temperatures when combined with vapor pressure parameters were about equally effective in estimating snowmelt runoff. In these studies there was a 10 to 20 percent loss in the coefficient of determination by the omission of the vapor pressure term. Estimates of snowmelt without vapor pressure were better using maximum temperature than mean temperature.

In summary, the Corps of Engineers found that the only situation where convection and condensation adequately described 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. For forested areas then, convection and condensation parameters by themselves explain the majority of the accountable variance in clear-weather snowmelt runoff. It should be pointed out that since these parameters are combinations of other variables they are indexing various energy sources such as longwave radiation and others which have previously been shown to be important.

## Other parameters.

From work done by the Corps of Engineers it is apparent that exclusion of wind from the regression function results in a serious loss of accountable variance, although this factor is more important on open sites than on forested sites.

Other items that must be considered in any analysis are the source of the data and the time interval to be used in the computations, although many times one must be satisfied with the interval of the data available. The Corps of Engineers (U. S. Army, 1955) showed that their best results were obtained when firsthand observations of the important melt index variables were available and when hourly data were used in the computations of the convection and condensation parameters. In dense forested areas daily values for these parameters were almost as good as hourly values. In general, some loss in reliability can be expected when daily values are used in the snowmelt runoff relations instead of hourly values.

In reviewing the literature on snowmelt and snow hydrology it is evident that there has been a wide range in the amount of variation in daily snowmelt that has been accounted for by different indexes. This is true with different periods of time and with subareas or watersheds within a study as well as between studies. These ranges are summarized in table 1.

Table 1

Range in coefficients of determination
for single variable snowmelt indexes

| Index | Range in coefficient of determination |
|---|---|
| Maximum temperature | 0.01 - 0.75 |
| Mean temperature | 0.08 - 0.65 |
| Degree day | 0.50 - 0.81 |
| Net shortwave radiation | 0.22 - 0.71 |

## Chapter 3

# THE SNOWMELT HYDROGRAPH

In order to develop indexes for a given amount of heat imput into a system it is necessary to segregate the runoff generated by that imput. This section describes the analyses made of the snowmelt hydrographs from the Upper Hourglass stream gage to develop these contributions to runoff.

### Generated runoff concept.

In most high mountain watersheds practically all of the snowmelt runoff enters the stream channels as subsurface or ground-water flow. Because of this there is quite often a significant delay in runoff. During this time it can be considered in storage. The evaluation of storage through the use of well records is not generally practical in mountainous terrain. Streamflow-recession analysis provides an indirect means of evaluating both channel and ground-water storage in a watershed.

In addition to the more or less constant physical characteristics of a given watershed, storage is dependent on other factors such as climate which varies from year to year. The use of generated runoff (the volume of water comprising a given day's contribution to the snowmelt hydrograph), as determined through streamflow-recession analysis, should then account for the average effect of storage on delayed runoff. Generated runoff volumes tend to integrate all of the factors affecting snowmelt. In addition, estimates of total seasonal water yields from snowmelt can be obtained after the snowmelt season by computing generated volumes.

From the above discussion it can be seen that generated runoff is the daily observed runoff corrected by recession analysis for transitory storage in the soil, ground, and stream channels. Generated runoff is therefore the runoff produced by a given heat imput into the watershed during a selected time interval.

Generated runoff volumes ($Q_g$) are computed from observed daily runoff volumes by means of the equation

$$Q_g = Q + Q_t - Q_i$$

where Q is the observed daily runoff, $Q_t$ is the volume of storage on the watershed at the end of the day, and $Q_i$ is the volume of storage on the watershed at the beginning of the day. The terms $Q_t$ and $Q_i$ are a function of the discharge rate, and are derived through the recession analysis of the hydrograph.

## Recession analysis.

Streamflow recession analysis provides an indirect means of evaluating storage in relation to outflow from a watershed. Assuming that all inflow to the watershed is suddenly stopped, all outflow subsequently passing the gaging station would result from depletion of ground and channel storage. A measure of the volume of this recession flow is therefore a measure of ground and channel storage within the watershed.

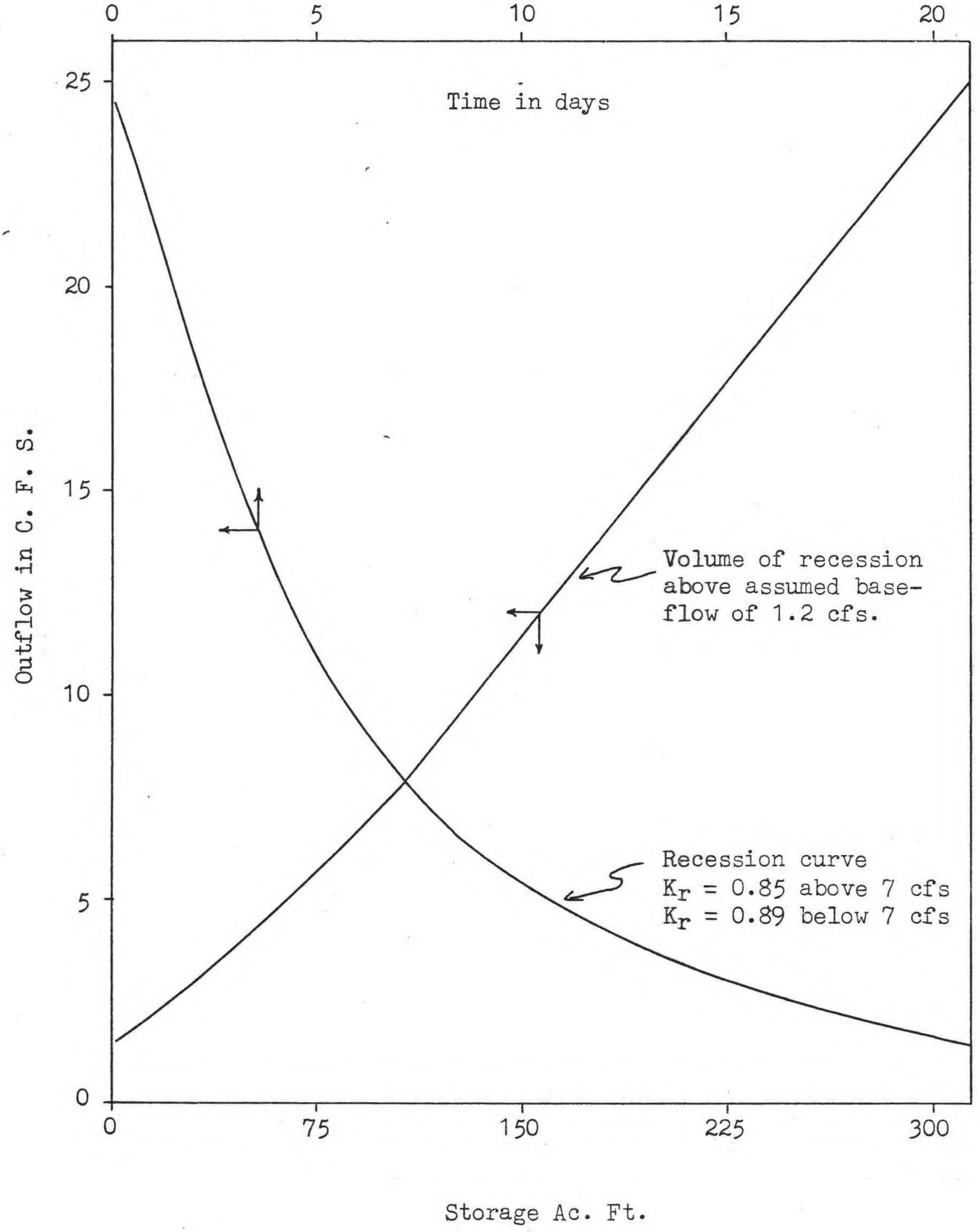
The recession curve is made up of a series of curved segments representing the various components of the recession flow. These curves follow a decay-type curve of the general form proposed by Barnes (1939)

$$Q = Q_o K_r^{\,t}$$

where Q is the flow at any time t after the initial flow $Q_o$, and $K_r$ is the recession constant, (ratio of the flow on any day to the previous day's flow). The volume of the recession flow (storage) remaining at any time on any watershed can be determined by integrating the empirically derived recession curves. In this study these curves were integrated as shown in Garstka et al. (1958). In order to facilitate these computations, volume-vs-flow curves can be developed relating the remaining runoff volume beneath the recession curve to the flow at the beginning time. A curve of this type for the Upper Hourglass watershed is shown in figure 1. This curve was developed by incrementally summing the areas beneath the recession curves to the lowest value of the recession encountered in the analysis.

Figure 1

Streamflow recession characteristics
Upper Hourglass, 1965



# Chapter 4

# RADIATION DIFFERENCES IN MOUNTAIN WATERSHEDS

Where radiation is being used as a variable in the development of snowmelt indexes it should be determined whether radiation can be extrapolated in mountainous areas, such as the Front Range of the Rocky Mountains, reliably. This is necessary for the development of indexes with general applicability, because normally there are very few radiation measurements available.

In this study the main concern was to develop an index of snowmelt in the Upper Hourglass watershed. Differences in incoming shortwave radiation that might occur between the Upper Hourglass watershed and the Pingree Park weather station were also of interest.

Since most radiation measurements are taken on a horizontal surface a watershed "lid" as proposed by Lee (1963) was developed to determine the magnitude of potential differences in solar beam irradiation between Pingree Park and the Upper Hourglass watershed.

## Variation of solar radiation between selected mountain watersheds.

Radiation data from four mountain stations, covering the period of July-August, 1965, were used to determine the variation in radiation between mountain watersheds. This period was selected as it was one of the few periods for which data were available for the four stations. It also covers two-thirds of the snowmelt period that was being studied.

The stations used in this analysis were: (1) Pingree Park (9000'), (2) Comanche Peak (11,000'), (3) Station C-1 (10,000'), and (4) Station D-1 (12,000'). Stations C-1 and D-1 are weather stations operated by the Institute of Artic and Alpine Research, University of Colorado, Boulder, Colorado. These two stations are located on Niwot Ridge west of Boulder, Colorado.

All of the data were collected using Belfort recording pyrheliometers with manufacturer's stated accuracy of ± 5 percent and precision of recording of 0.1 g. cal $cm^2$ $min^{-1}$ for 3/32" of chart width. The pyrex dome transmits approximately 90 percent of all wave lengths between 0.36 and 2.0 microns. During the period of record used in this study it is expected that the instruments were free of most of the condensation and obstruction problems which can cause poor readings when significant amounts of precipitation occur.

When all the data were analyzed it showed that there were significant differences in the amount of incoming shortwave radiation among days and between the two general locations of Pingree Park and Niwot Ridge (table 2).

The differences in incoming shortwave radiation among days is to be expected because of the ever changing cloud conditions.

The effects of the two general locations on incoming shortwave radiation are not as clear. Factors which might be contributing to these differences are:

(1) The possibility of shading on one or more of the stations. All of the instruments are located in a horizontal position with clear south horizons. The Comanche Peak station is on a NNE aspect and may have received some shading. The horizons to

## Table 2

### Variation of solar radiation between selected mountain watersheds

Analysis of Variance

| Source | Degrees of freedom | Sum of squares | Mean square | F |
|---|---|---|---|---|
| Days | 26 | 1,722,013 | 66,231 | 2.84***[1] |
| Location | 1 | 264,330 | 264,330 | 11.32*** |
| Error | 26 | 607,209 | 23,354 | |
| Elevation | 1 | 529 | 529 | N.S. |
| Elevation X Location | 1 | 76,534 | 76,534 | 4.90*** |
| Error | 48 | 743,991 | 15,500 | |
| Total | 103 | | | |

[1] Significant at the 1% level.

Mean daily solar radiation, July 23, 1965 - August 31, 1965

| Station | Mean daily solar radiation langleys per day |
|---|---|
| Pingree Park | 523 ± 32 |
| Hourglass snowfield | 476 ± 32 |
| C-1 | 369 ± 28 |
| D-1 | 430 ± 33 |

the north on Stations C-1, D-1, and Comanche Peak are open. The horizon to the north on the Pingree Park station is timbered which may produce a back radiation effect.

(2) One of the major factors in the differences in incoming shortwave radiation between the Pingree Park area and Niwot Ridge is the cloud cover. During the summer months in this area local convective clouds are a common phenomena and would be expected to affect the incoming shortwave radiation over local areas.

(3) In this study the interaction of location and elevation appears to be a significant factor. Both factors in this interaction can be expected to cause some variability in the shortwave radiation measurement. The location effect is discussed in item 2. As for elevation, Reifsnyder (1965) pointed out that as altitude increases, the length of the path of the sun's rays through the atmosphere decreases and atmospheric transmission increases. Everything else being equal the magnitude of the increase due to elevation would be the smaller effect of the two variables in this interaction.

(4) Another potential factor is instrument error. During the period from August 27, 1964, to November 7, 1964, the two instruments in the Little South were operated in adjacent positions at the Pingree Park weather

> station. An analysis of these data showed that there were significant differences in solar radiation recorded by these two pyrheliometers. The mean daily solar radiation for the test period was 400 ± 24 langleys per day for instrument No. 570 and 374 ± 19 langleys per day for instrument No. 738.

The results of this investigation seem to agree with those of Fowler (1967) in his study of the spatial distribution of solar radiation on the east side of the Cascade mountain range in the State of Washington. He found that on all the days sampled in his study, except those with continuous cloud cover and subsequent low imput, that radiative imput patterns reflected local cloud development, the passage of small disturbances, and that spatial variation was large on most days. This observation is borne out by the four stations used in this study.

Until the spatial distribution of incoming shortwave radiation has been investigated further the extrapolation of point radiation measurements any great distance in mountainous areas appears risky. For management applications of energy balance relationships over a large area, a sampling network from which an average basin imput can be developed would probably be required. An alternate would be the use of records with sufficient length that they will average the instantaneous variations which may occur.

Additional work on the determination of heat imput into a basin needs to be undertaken.

The watershed "lid".

To determine the magnitude of potential differences in solar beam irradiation between a horizontal surface and the Upper Hourglass watershed an analysis using the watershed "lid" proposed by Lee (1963) was used. The watershed "lid" attempts "to define the position of a plane surface that will effectively 'shade' the entire basin. If such a surface were found to be a near-perfect interceptor, as for example a good fitting lid, its inclination and direction of slope would serve to define the radiation index for the watershed in question."

Based on a sample of 34 points taken along the perimeter of the Upper Hourglass watershed, a theoretical intercepting surface was characterized by the regression equation, $E = 14.708 - 0.076X_1 - 0.247X_2$, $(R = 0.98)$. Where E is elevation in 1000's of feet, $X_1$ is distance east and $X_2$ is the distance north from a selected coordinate using the relations,

$$\tan b = \tan k_2 / \tan k_1$$

and

$$\tan k = \tan k_1 / \cos b$$

where $k_1$ is the slope to the north, and $k_2$ is the slope to the east, the azimuth of maximum slope has a bearing b from the $X_1$ direction, and a maximum inclination k.

For the Upper Hourglass watershed the azimuth of maximum slope is $17^{o}6'$ and it has an inclination of $14^{o}30'$. Using these characteristics the time variation of the potential solar beam irradiation for the watershed "lid" was plotted along with the time variation of the potential solar beam irradiation of the horizontal instrument site at Pingree Park (figure 2). Inspection of figure 2 shows that the radiation index, which is the ratio of potential solar beam irradiation on the watershed "lid" to that on a horizontal surface at the same latitude, increases during the early part of the snowmelt season and then decreases during the latter part. This difference in potential solar beam irradiation between the two sites reaches 13 percent during the latter part of August. Differences of this magnitude could be important in snowmelt relations when other values are measured to a comparable precision.

Because of the magnitude of this difference a daily correction factor was developed to adjust the radiation data from the horizontal pyrheliometer at Pingree Park to the radiation which would be expected on the Upper Hourglass watershed.

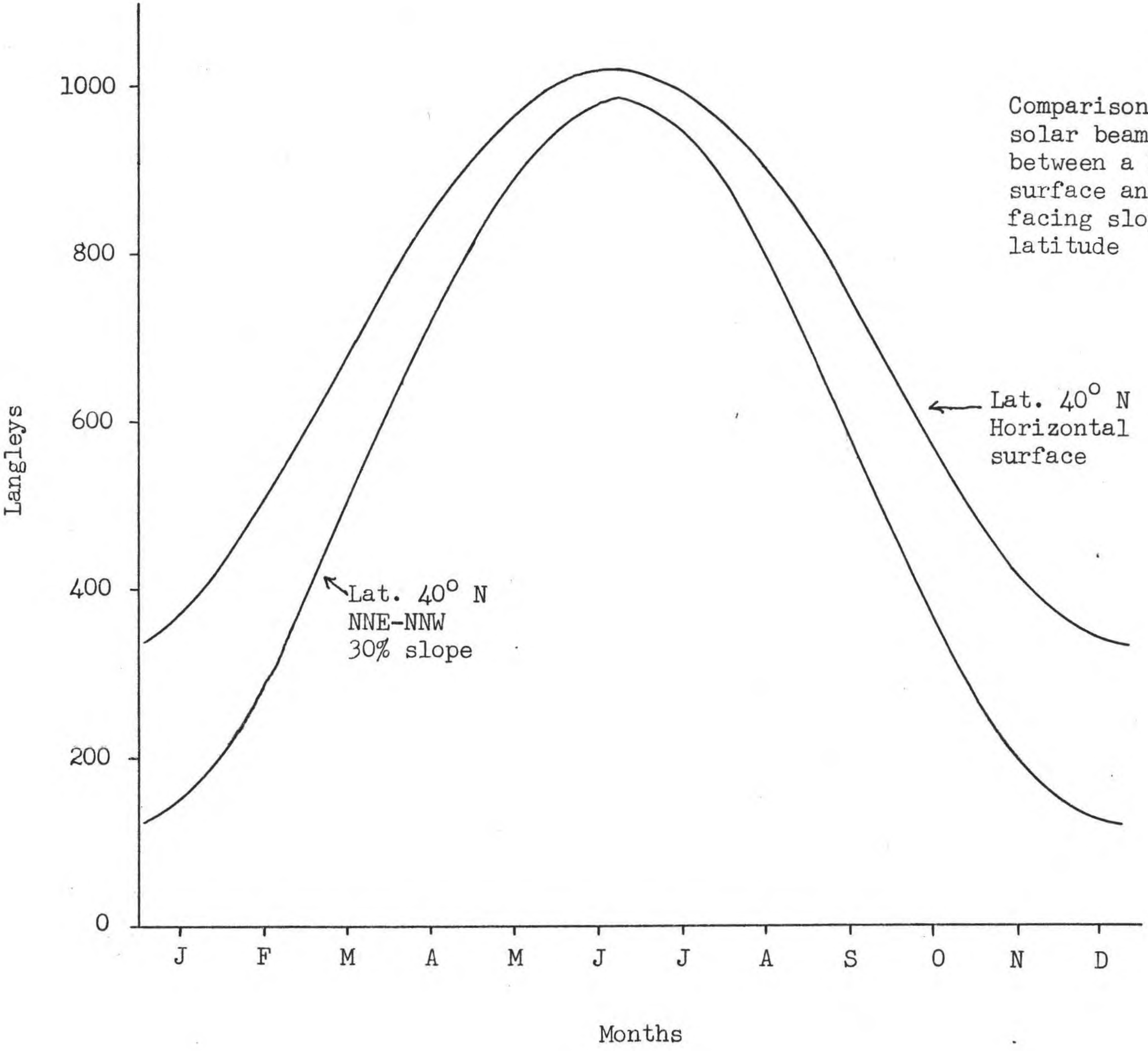


Figure 2

Comparison of potential solar beam irradiation between a horizontal surface and a 30% NNE facing slope at 40° N latitude

## Chapter 5

# ANALYSIS TECHNIQUES

In the development of indexes for relationships between factors operating in any given situation there are several methods available and commonly used. One of the most common techniques is that of developing models using variables based on the physical relations involved. The coefficients for the model are then developed by collecting data on the variables in the model and fitting the model to the collected data by statistical analysis. This method was used in this study to develop snowmelt indexes for a small mountain watershed.

Both correlation and regression analyses were used in this study. Simple and multiple correlation techniques were used: simple correlation analysis to measure the degree of linear association between pairs of sample variables; multiple correlation analysis to measure the degree of linear association among several variables.

After the correlation analyses were completed, regression analyses were used to evaluate specific models and to develop the coefficients for the final indexes.

A computer program was used to obtain simple correlations, a sequence of multiple linear regressions in a stepwise manner, and multiple correlation coefficients.

In carrying out regressions in a stepwise manner the program will choose as its first element the independent variable that has the highest simple correlation with the dependent variable. Thereafter, each successive element selected is that independent variable which will cause the greatest reduction in the unexplained variance of the dependent variable. This may be shown to be equivalent to bringing in the variable having the largest absolute partial correlation with the dependent variable after the variance of the variables already included in the regression on the dependent variable has been removed. The variables that were used in this study are discussed in the next two sections of this chapter.

Dependent variables.

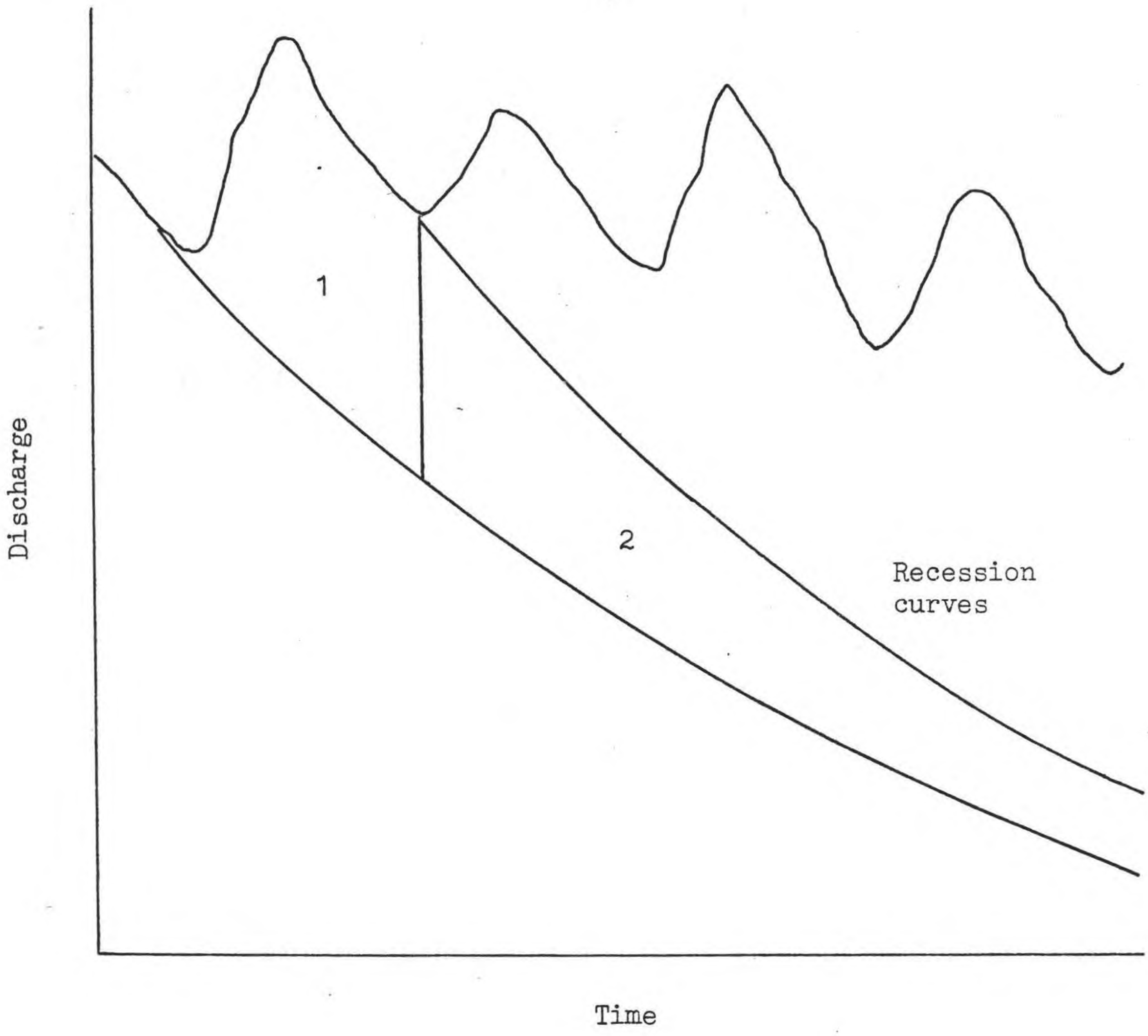
Two dependent variables were used in this study: (1) $X_1$ - the generated runoff volume occurring during the first day, and (2) $X_2$ - one day's total contribution to the snowmelt hydrograph or the total generated runoff for that given day. A schematic illustration of $X_1 + X_2$ is shown in figure 3. These values of runoff were selected because it was felt that they were a better indication of the runoff initiated on a given day than was the daily observed flow. In addition, work by Garstka et al. (1958) showed that the use of volumes computed by the recession principle offer a definite improvement over the use of daily streamflow.

Independent variables.

Selection of independent variables was limited by the climatic data currently available or variables that could be developed on a rational basis using available data and knowledge of the physical factors involved. All the variables in this study were developed to index: (1) the energy available for snowmelt, (2) the cold content of the snowpack, (3) precipitation, and (4) time of year.

Figure 3

Schematic illustration of generated runoff



Area 1 = Generated runoff volume occurring during the first day

Area 2 = Volume of a day's snowmelt in the recession flow

Total generated runoff = Area 1 + Area 2

The radiation, degree day and maximum temperature variables were used as indexes of energy available for snowmelt, while the cloud variables were used to index the reduction in energy available for snowmelt due to cloud cover over the watershed. Minimum temperature was used to index the cold content of the snowpack or the amount of energy required to raise the temperature of the snowpack to 0 degrees centigrade.

The precipitation variable was used because summer rainfall contributed to runoff during the study period. A time effect was used since there are definite changes in many of the variables as the summer progressed and it was felt that a variable, such as Julian date, would account for some of these changes over time. Other variables could be used to index this time effect, but Julian date was selected as it is commonly used with streamflow data.

The independent variables used in the study were:

(1) $X_3$ is the solar radiation received at Pingree Park. This value is the number of langleys (gram calories / $cm^2$ ) received each day on the surface of a Belfort recording pyrheliometer located at the Pingree Park forestry camp.

(2) $X_4$ is the solar radiation received at a site within the Upper Hourglass watershed during August, 1965. Solar radiation was the number of langleys (gram calories / $cm^2$ ) received each day on the surface of a Belfort recording pyrheliometer.

This variable was only used in certain analysis of the August runoff data to determine if radiation data from the watershed would better index snowmelt than that received at the Pingree Park station.

(3) $X_5$ is the number of degree days above 32 degrees Fahrenheit at Pingree Park. This variable is determined as follows:

$$N_{32} = T_{mean} - 32$$

where $N_{32}$ is the number of degree days above 32 degrees Fahrenheit, and $T_{mean}$ is the mean daily temperature as recorded on a hygrothermograph at the Pingree Park weather station.

(4) $X_6$ is the number of degree days above 50 degrees Fahrenheit at Pingree Park. This variable is computed as follows:

$$N_{50} = T_{mean} - 50$$

where $N_{50}$ is the number of degree days above 50 degrees Fahrenheit, and $T_{mean}$ is the mean daily temperature as recorded on a hygrothermograph at the Pingree Park weather station. Negative values were used where they occurred in the determination of this variable.

(5) $X_7$ is the maximum temperature during the 24-hour calendar day as recorded at the Pingree Park weather station.

(6) $X_8$ is the minimum temperature recorded during the 24-hour calendar day at the Pingree Park weather station.

(7) $X_9$ is an index of morning cloud cover based on how clouds developed over the watershed as reflected in the pyrheliograph record from Pingree Park. These indexes were designed to group the periods of complete cloud cover, scattered clouds, etc. into the same index group.

| Index | Description |
|---|---|
| 1 | Cloudy during the first half of period, clearing during the second half of period. |
| 2 | Cloudy first third of period, clear during second third of period, radiation value 0.4 of potential, cloudy last third of period. |
| 3 | Clear period, radiation value 0.4 of potential. |
| 4 | Clear period, radiation value 0.6 of potential. |
| 5 | Clear first half of period, radiation value 0.7-0.9 of potential, cloudy last half of period, radiation value 0.3-0.5 of potential. |
| 6 | Clear period, radiation value equals potential. |

(8) $X_{10}$ is an index of afternoon cloud cover developed from pyrheliograph records from Pingree Park.

| Index | Description |
|---|---|
| 1 | Cloudy, radiation value 0.2 of potential. |
| 2 | Cloudy, radiation value 0.3 of potential. |
| 3 | Cloudy during first half of period, clear second half of period. |
| 4 | Scatter clouds, radiation value 0.5 of potential. |
| 5 | Clear with a few scattered clouds, radiation value 0.9 of potential. |
| 6 | Clear period which equals potential. |

(9) $X_{11}$ is the precipitation as recorded at the Pingree Park weather station.

(10) $X_{12}$ is the Julian date corresponding to the day's observations. The Julian date is the number of the day numbering in sequence from January 1, through December 31.

(11) $X_{13}$ is the watershed index. This index was used to correct the solar radiation measurements to a "lid" fitted to the watershed (see Chapter 4). The index was computed for each day as the ratio of the potential solar beam irradiation received on the "lid" to the potential solar beam irradiation received on a horizontal surface at the same latitude. The variable was used only as an interaction term.

(12) $X_{14}$ is snow albedo estimated from the relation of the change of snow albedo over time developed by the Corps of Engineers (U. S. Army, 1956).

(13) $X_{15}$ is the daily cloud cover expressed as a decimal percent of the daylight hours with cloud cover. This was taken from pyrheliometer traces made at Pingree Park. When this variable was used the cloud indexes, $X_9$ and $X_{10}$ were not used in the analysis.

(14) $X_{16}$ is the estimated downward longwave radiation computed from the relation developed by the Corps of Engineers (U. S. Army, 1960), $R_d = 0.76 \sigma T_a^4$ (lys / min) where $R_d$ is the downward longwave radiation in langleys per minute, $\sigma$ is Stefan's constant from Stefan's Law, and $T_a$ is the temperature over the snow surface in degrees Kelvin. In estimating longwave radiation the daylight period was assumed to be 12 hours and the $R_d$ developed from the above equation was multiplied times 720 minutes. $T_a$ parameter was estimated by using the mean Pingree Park temperature minus 6° F. This was the lapse rate assumed to estimate the air temperature over the Upper Hourglass snowfield. This value was then converted to degrees Kelvin.

(15) $X_{17}$ is an estimate of incoming shortwave radiation on the Upper Hourglass watershed. It is the interaction between the watershed "lid" index and solar radiation received at Pingree Park, $X_{13}X_3$.

(16) $X_{18}$ is an interaction between the watershed "lid" index, solar radiation at Pingree Park, and snow surface albedo, $X_3X_{13}X_{14}$.

(17) $X_{19}$ is the Julian date squared.

(18) $X_{20}$ is the Julian date cubed.

(19) $X_{21}$ is the sum of the maximum and minimum temperatures recorded at Pingree Park during each 24-hour calendar day, $(X_7 + X_8)$.

(20) $X_{22}$ is the mean temperature at Pingree Park during the 24-hour calendar day, $(X_7 + X_8)/2$.

(21) $X_{23}$ is the interaction between the daily cloud cover and the average temperature, $(X_7 + X_8)/2\ (X_{15})$.

Not all of these independent variables were used in any given analysis but they were all used in at least one analysis to help define the best overall relationship for describing snowmelt runoff from climatic parameters in the Upper Hourglass watershed.

# Chapter 6

# THE DEVELOPMENT OF SNOWMELT INDEXES

The complete results of the computer analyses are on file in the Department of Recreation and Watershed Resources, College of Forestry and Natural Resources, Colorado State University. Only the summary of these results are given in this chapter.

## Correlation analysis.

As the first step in the development of the snowmelt indexes, simple linear correlations were completed. The results were then used as the basis for developing multiple correlation models of snowmelt runoff. In the initial model development two types of models were used:

(1) Models using the complete snowmelt runoff period as one unit, and

(2) Models based on dividing the runoff period into segments corresponding to streamflow hydrograph characteristics. The resulting divisions were: Period 1 - June 1 through the rising limb of the hydrograph to the peak. Period 2 - from the peak through the major part of the recession until the Hourglass snowfield was the main contributor to snowmelt in the basin, which occurred about August 1. Period 3 - the month of August.

The development of these multiple correlation models using all available variables showed that dividing the data into periods based on hydrograph characteristics consistently accounted for a higher proportion of the variability in runoff than did the models using the complete runoff period as one segment. Table 3 shows these models, the variables included, the order in which they entered the model, and the multiple correlation coefficient for each model.

The variables which entered in these relations were selected for their ability to reduce the variability of the dependent variable. The results show that the variables indexing snowmelt change from one period to the next. These changes indicate that the relationships of the variables changed between different snowmelt periods, or that unmeasured variables are having a major influence on the snowmelt runoff.

Table 3 also shows which variables were correlated with which dependent variables. The first day's runoff accounted for the highest multiple correlation coefficient for all periods except period 3 when Comanche radiation data were used.

From the analysis of the first models it was found that two cloud indexes ($X_9 + X_{10}$) and precipitation ($X_{11}$) were consistently entering the indexes. Because the heat variables were of primary interest these were tested in models differentiated on the basis of amount of precipitation received and the cloud cover. These additional models were:

(a) The total snowmelt period separated into days when more than 0.05 inches of precipitation was received at Pingree Park and days when the precipitation received at Pingree Park was 0.05 inches or less.

Table 3

Snowmelt models,
order in which variables entered
and multiple correlation coefficients

| Groups | Dependent variables $X_1$ | $X_2$ | Independent variables $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ | $X_9$ | $X_{10}$ | $X_{11}$ | $X_{12}$ | R | $R^2$ | No. obs. | Sig. level |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total data | x |  | 1 | 1/ |  |  | 5 | 2 |  |  | 4 | 3 | 0.679 | 0.461 | 63 | 0.999 |
|  |  | x |  | 1/ |  | 2 |  |  |  | 3 | 4 | 1 | 0.614 | 0.377 | 63 | 0.999 |
| Period 1 | x |  |  | 1/ |  | 1 |  |  |  |  | 2 |  | 0.741 | 0.549 | 16 | 0.900 |
|  |  | x |  | 1/ | 1 |  |  |  |  |  | 2 |  | 0.729 | 0.531 | 16 | 0.999 |
| Period 2 | x |  | 1 | 1/ | 4 |  | 3 | 2 |  |  |  |  | 0.770 | 0.593 | 25 | 0.999 |
|  |  | x |  | 1/ |  |  | 2 |  |  | 1 |  |  | 0.564 | 0.318 | 25 | 0.975 |
| Period 3a[2] | x |  |  | 1/ |  |  |  |  | 2 |  | 1 |  | 0.714 | 0.510 | 22 | 0.995 |
|  |  | x | 3 | 1/ |  |  |  |  | 2 | 1 |  |  | 0.758 | 0.575 | 22 | 0.995 |
| Period 3b[3] | x |  | 1/ | 3 |  |  |  |  |  |  | 2 | 1 | 0.612 | 0.375 | 22 | 0.950 |
|  |  | x | 1/ |  | 4 |  |  | 3 | 2 |  | 1 |  | 0.722 | 0.522 | 22 | 0.990 |

1/ Variable not allowed to enter in this relation.

2/ Pingree Park solar radiation data.

3/ Comanche solar radiation data.

Variables are described on pages 28-35

(b) The three periods based on hydrograph characteristics further separated into groups of days receiving more than 0.05 inches of precipitation at Pingree Park and those days receiving 0.05 inches or less precipitation at Pingree Park.

(c) The separation of the total runoff period into clear and cloudy days based on the extent of cloud cover, as shown on the pyrheliograph traces. When the trace was a smooth "bell shaped" curve the day was considered a clear day. When the trace was "sawtoothed" or a truncated "bell shaped" curve the day was considered cloudy.

(d) The cloudy days were further separated into days with heavy cloud and scattered cloud. When the trace was "saw toothed" the day was considered to have scattered clouds. When the trace was a truncated "bell shaped" curve the day was considered cloudy. The resulting groups based on the extent of cloud cover were: (1) clear days, (2) heavy clouds, and (3) scattered clouds. When grouped in this manner the clear days contained only six observations and were not analyzed because of the small sample.

In addition to the new models, several additional independent variables were added to better define the relationships which appeared in the first analysis. These new variables were, $X_{13}$ cloud cover as a decimal percentage, and $X_{16}$ estimated downward longwave radiation. These variables are defined in Chapter 5. The multiple correlation coefficients of these models using all variables and the order in which the variables entered the relationship are shown in table 4.

In analyzing these new models the consistency in which certain independent variables entered the relations is of particular interest. Precipitation entered over half the relations where this was not a criteria on which the data were separated. When the total snowmelt period was analyzed, a temperature variable, a solar radiation variable, and a date variable played a part in almost half the relationships. In addition there were variables which rarely entered the relationships. Some of these were estimated longwave radiation, estimated albedo, percent cloud cover, maximum temperature at Pingree Park, and the interaction of cloud cover and average temperature at Pingree Park.

Table 5 summarizes the highest multiple correlation coefficients for all correlation runs. Analysis of these models shows that when the data for the complete snowmelt period was divided according to days with rain and days without rain the relationships developed were improved only when total runoff was the dependent variable. In general the division of data based on the extent of cloud cover rather than on the amount of rain received seemed to improve the relationships. This was particularly true when first day runoff was the dependent variable.

The period 1 data were not divided because of the small sample size that would result. The multiple correlation coefficients of the period 2 data were not improved significantly by separating the days on which rain occurred. None of the period 3

## Table 4

### Snowmelt models, order in which variables entered and multiple correlation coefficients

| Groups | Dependent variables | | | | | | | | | | | | | | | | | | R | No. obs. | Sig. level |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ | $X_{11}$ | $X_{12}$ | $X_{14}$ | $X_{15}$ | $X_{16}$ | $X_{17}$ | $X_{18}$ | $X_{19}$ | $X_{20}$ | $X_{23}$ | | | |
| Total | x | | 2 | | | 3 | | | 4 | | | | | 1 | | | | | 0.782 | 63 | 0.999 |
| data | | x | | | | 2 | | | | | | | | | | | 1 | | 0.587 | 63 | 0.999 |
| Rain | x | | | | | 2 | | | | | | | | | 1 | 4 | 3 | | 0.776 | 44 | 0.999 |
| ≤0.05 | | x | | | | 2 | | | | | | | | | 3 | | 1 | | 0.727 | 44 | 0.999 |
| Rain | x | | | | | | | 1 | | | | | | | 2 | | | | 0.683 | 19 | 0.990 |
| >0.05 | | x | | | | | | | | | | | | | | | | | | | N.S. |
| Cloudy | x | | | | | | | | 4 | 2 | | | | | | 3 | 2 | | 0.717 | 36 | 0.999 |
| | | x | | | 2 | | | | | | | | | | | | 1 | | 0.538 | 36 | 0.950 |
| Heavy | x | | | | | | | 1 | 2 | | | | | 3 | | | | | 0.880 | 18 | 0.999 |
| clouds | | x | | | | | | 1 | 2 | | | 3 | | | | | | | 0.839 | 18 | 0.999 |
| Scattered | x | | | | | | | | | 2 | | | | | | 3 | 1 | | 0.811 | 17 | 0.995 |
| clouds | | x | | | | | | | | | | | | | | | 1 | | 0.564 | 17 | 0.975 |
| Period | x | | | | | | | | | | 2 | | 1 | | | | | | 0.793 | 16 | 0.995 |
| 1 | | x | | | 1 | | | | | | | | | | | | | | 0.729 | 16 | 0.995 |
| Period | x | | 1 | | | | | 2 | | | | | | | | | | | 0.686 | 25 | 0.995 |
| 2 | | x | | | | | 1 | | | | | | | | | | | | 0.417 | 25 | 0.975 |
| Period 2 | x | | 1 | | | | | | | | | | | | | | | | 0.590 | 21 | 0.995 |
| ≤0.05 | | x | | | | | 1 | | | | | | | | | | | | 0.451 | 21 | 0.950 |
| Period | x | | | | | | | | 1 | | | | 2 | | | | | | 0.717 | 22 | 0.995 |
| 3a | | x | | | | | | | 1 | | | | | | | | | | 0.610 | 22 | 0.995 |
| Period 3a | x | | | | | | | | | | | | | | | | | | | | N.S. |
| ≤0.05 | | x | | | | | | | | | | | | | | | | | | | N.S. |
| Period | x | | | | | | | | 3 | | | 2 | | 1 | | | | | 0.746 | 22 | 0.995 |
| 3b | | x | | | | | | | 1 | | | | | | | | | | 0.503 | 22 | 0.975 |
| Period 3b | x | | | | | | | | | | | | 2 | | 1 | | | | 0.712 | 15 | 0.975 |
| ≤0.05 | | x | | | | | | | | | | | | | | | | | | | N.S. |

Variables are described on pages 28-35

## Table 5

Multiple correlation coefficients of various models accounting for the greatest amount of variability in the dependent variable

| First day's runoff as the dependent variable | Total data | Rain ≤0.05 | Rain >0.05 | Clear days | Cloudy days | Heavy clouds | Scattered clouds |
|---|---|---|---|---|---|---|---|
| Total data | 0.782 | 0.776 | 0.683 | 1/ | 0.717 | 0.880 | 0.811 |
| Period 1 | 0.793 | 1/ | 1/ | 2/ | 2/ | 2/ | 2/ |
| Period 2 | 0.686 | 0.590 | 1/ | 2/ | 2/ | 2/ | 2/ |
| Period 3a | 0.717 | N.S. | 1/ | 2/ | 2/ | 2/ | 2/ |
| Period 3b | 0.746 | 0.712 | 1/ | 2/ | 2/ | 2/ | 2/ |
| **Total runoff as the dependent variable** | | | | | | | |
| Total data | 0.587 | 0.727 | N.S. | 1/ | 0.538 | 0.839 | 0.564 |
| Period 1 | 0.729 | 1/ | 1/ | 2/ | 2/ | 2/ | 2/ |
| Period 2 | 0.417 | 0.451 | 1/ | 2/ | 2/ | 2/ | 2/ |
| Period 3a | 0.610 | N.S. | 1/ | 2/ | 2/ | 2/ | 2/ |
| Period 3b | 0.503 | N.S. | 1/ | 2/ | 2/ | 2/ | 2/ |

1/ Sample size too small for analysis.

2/ Sample not broken into groups, total data only.

data sets had its multiple correlation coefficient increased by the model using only the rainy day data.

The multiple correlation analysis indicated that, using all the data, the models developed around the first day runoff as the dependent variable had the best multiple correlation coefficient. This result agrees with that found by Garstka et al. (1958) in their work using a total season's data.

The decision on whether to use models based on the complete snowmelt period or segments within the snowmelt period would depend on the objectives established. The objective in this study as discussed in Chapter 1 is to develop a snowmelt index for use in the watershed research program in the Little South Poudre watershed. Thus it was decided to develop several predictive equations to meet various needs that might occur within the Upper Hourglass watershed.

<u>Regression analysis</u>.

From the results of the correlation analysis, various models were selected for use in the actual development of the snowmelt indexes. The models chosen, the coefficient of each variable and the coefficient of determination of each equation are shown in table 6.

## Table 6

## Snowmelt models

June 1 - August 31, All days $R^2 = 0.61$

$X_1 = 0.266 - 0.0745X_3 + 0.252X_6 + 5.195X_{11} + 0.088X_{17}$

June 1 - August 31, Day with heavy clouds $R^2 = 0.77$

$X_1 = -11.572 + 0.253X_8 + 5.262X_{11} + 0.013X_{17}$

June 1 - peak runoff, All days $R^2 = 0.63$

$X_1 = -104.39 + 15.717X_{14} + 0.379X_{16}$

Peak runoff through major part of recession, All days $R^2 = 0.47$

$X_1 = -16.62 + 0.0206X_3 + 0.318X_8$

August 1-31, All days with Pingree Park solar radiation $R^2 = 0.51$

$X_1 = 13.195 + 4.56X_{11} -0.0411X_{16}$

August 1-31, All days with Hourglass snowfield solar radiation $R^2 = 0.56$

$X_1 = 4.686 + 4.395X_{11} -2.719X_{15} -0.00418X_{17}$

Variables are described on pages 28-35

# Chapter 7

# DISCUSSION AND CONCLUSION

The objective of this study was to test the relationship between climatic parameters and daily snowmelt runoff during 1965 on the Upper Hourglass watershed of the Little South Fork of the Cache La Poudre River. Several snowmelt indexes have been developed using the available climatic data. These indexes do not account for all the variability in snowmelt, but depending on the objective for using a snowmelt index, one or more of the indexes may be useful.

This report reviews the literature as it pertains to dependent variables used in other snowmelt studies and the relationships of solar radiation, condensation and convection to snowmelt. In addition, the recession characteristics of the Upper Hourglass watershed were analyzed to develop volumes of generated runoff for use as dependent variables in the study. The variation of solar radiation between four locations in the Front Range of the Rockies was also studied. Significant differences in solar radiation occurred between the four locations; this agrees with similar studies in other mountainous areas of the West (Fowler, 1967).

The snowmelt indexes in this report were developed from multiple correlation and regression analyses. Climatic data from the Little South Poudre watershed were used as independent variables and runoff from the Upper Hourglass watershed as the dependent variable.

In the analysis various groups of data were used to reduce the variability between the dependent and independent variables. Groupings used in the study include:

(1) Total snowmelt period, June 1 - August 31

(2) June 1 to the peak of the hydrograph

(3) Peak of hydrograph through the major part of the recession, about August 1

(4) August 1 - 31, days with solar radiation data available from Pingree Park

(5) August 1 - 31, days with solar radiation data available from the Hourglass snowfield

(6) Days with 0.05 inches precipitation or less at Pingree Park, June 1 - August 31

(7) Days with more than 0.05 inches precipitation at Pingree Park, June 1 - August 31

(8) Cloudy days, June 1 - August 31

(9) Days with heavy clouds, June 1 - August 31

(10) Days with scattered clouds, June 1 - August 31

(11) Days with 0.05 inches precipitation or less during the period from the peak runoff through the major part of the recession

(12) Days with 0.05 inches precipitation or less when solar radiation data was available from Pingree Park, August 1 - 31

(13) Days with 0.05 inches precipitation or less when solar radiation data was available from the Hourglass snowfield, August 1 - 31

The relationships of climatic variables to the first day's runoff were consistently better than to total generated runoff.

The models that accounted for the greatest variability in the dependent variable were:

1. June 1 - August 31, days with heavy clouds ($R^2 = 0.774$).
   First day's runoff = -11.572 + (0.253) (minimum temperature at Pingree Park) + (5.262) (precipitation at Pingree Park) + (0.013) (estimated shortwave radiation received on the Upper Hourglass watershed)
2. June 1 - peak runoff - all days ($R^2 = 0.629$).
   First day's runoff = -104.39 + (15.717) (estimated snow surface albedo) + (0.379) (estimated longwave radiation)
3. June 1 - August 31 - all days ($R^2 = 0.612$).
   First day's runoff = 0.266 -(0.074) (shortwave radiation at Pingree Park) + (0.252) (degree days above 50° F. at Pingree Park) + (5.195) (precipitation at Pingree Park) + (0.088) (estimated shortwave radiation received on the Upper Hourglass watershed)
4. August 1-31 - all days with Hourglass snowfield solar radiation ($R^2 = 0.556$).
   First day's runoff = 4.686 + (4.395) (precipitation at Pingree Park) -(2.719) (percent cloud cover) -(0.004) (estimated shortwave radiation received on the Upper Hourglass watershed)
5. August 1-31 - all days with Pingree Park solar radiation ($R^2 = 0.514$).

First day's runoff = 13.195 + (4.56) (precipitation at Pingree Park) -(0.041) (estimated longwave radiation)

6. Peak runoff through the major part of the recession, about August 1 - ($R^2 = 0.470$).

   First day's runoff = -16.62 + (0.0206) (shortwave radiation at Pingree Park) + (0.318) (minimum temperature at Pingree Park)

It is interesting to note that a radiation variable is in all six of the relationships. This indicates that solar radiation plays an important role in indexing the energy available for snowmelt on the Upper Hourglass watershed. Solar radiation corrected to the "watershed lid" entered into three of these models. This variable adjusts solar radiation to the specific watershed being studied and should provide a better index to the energy available for snowmelt on a specific watershed than the solar radiation received on a horizontal surface.

Of the temperature indexes the minimum temperature index was in two of the models and the number of degree days above 50° F. was in one model. Minimum temperature indexes the cold content of the snowpack, while degree days indexes heat input.

Many studies have found that temperature variables are the energy variables that correlate best with snowmelt when limited solar radiation data are available. In such studies the temperature data are quite often taken within the watershed being studied. In this study the only temperature data available were from Pingree Park which is outside the study watershed. Since solar radiation entered these relationships rather than the temperature variables used as heat indexes, this indicates that radiation variables may be a better index to snowmelt runoff when temperature data are not available in the immediate area of the study.

The precipitation variable plays a major role in indexing runoff after August 1, and takes part in all of the relations relevant to this period. After August 1, the snowfield is the only source of snowmelt in the Upper Hourglass watershed. Therefore, when precipitation occurs it would be expected to contribute a greater portion of the first day's runoff than during periods when snowmelt is taking place over the whole watershed.

The effect of all the variables throughout the study is surprisingly consistent between groups of data. This is borne out by the fact that the variables that entered into more than one model have coefficients of the same general magnitude in all the models. This indicates that these variables are playing important roles in indexing the snowmelt process on the Upper Hourglass watershed and not just indexing other variables.

In summary, these six relationships all appear reasonable when the factors that effect snowmelt are considered. The physical meaning of the models can only be implied since many of the variables were measured or estimated from Pingree Park data rather than from data taken on site. But the results do have a surprising consistency between groups of data and point out areas where further investigation may prove fruitful.

If more reliable indexes are needed to meet proposed objectives, there appear to be two ways to increase the reliability of the indexes. These are: (1) measure variables that have proven useful in other studies of snowmelt and snow hydrology that were not available in this study. An example of such a variable is net allwave radiation which has been significant in several studies. (2) measure the selected variables in the immediate vicinity of the study. Where snowfield melt is of particular interest these measurements should be taken in or near the snowfield.

For more generalized land management planning the models developed may prove useful. But before their widespread use they should be checked by data from other years and from other areas. If a satisfactory model were developed using total runoff rather than one day's contribution, it would probably be more applicable to most management situations.

As research and management progress it is going to become more and more desirable to develop a more complete method for evaluating the snowmelt process. Even though the first day's runoff provided the best relationship in this study, it seems reasonable that the best evaluation of the snowmelt process will be obtained through the investigation of one day's total contribution to the snowmelt hydrograph. The second factor that has shown up in this study and in studies by other workers in the field is the need for better methods of evaluating the energy balance over snow. It is to this end that I feel future investigations of snowmelt should be directed.

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