A STUDY OF THE GRID SQUARE METHOD FOR ESTIMATING MEAN ANNUAL RUNOFF

by

WILLIAM OBEDKOFF

B.A.Sc., University of British Columbia, 1967

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in the Department

of

Civil Engineering

We accept this thesis as conforming to the

required standard

THE UNIVERSITY OF BRITISH COLUMBIA

April, 1970

Department of Civil Engineering

The University of British Columbia
Vancouver 8, Canada

Date April 1, 1970

ABSTRACT

With the increasing importance of network planning for water resource management and inventory of supply of water there is need for new analytical methods of estimating flows from sparsely gauged regions. A new approach to estimating mean annual runoff was proposed by Solomon et al. and reported in "Water Resources Research" journal, Volume 4, October 1968. In this technique both meteorological and hydrological information are used to assess the mean annual precipitation, temperature and runoff distribution over large areas. The study area is broken up into a large number of squares and physiographic parameters are determined for each square; available meteorological data are used to derive multiple linear regression equations which relate precipitation and temperature to physiographic parameters and from these equations precipitation, temperature and evaporation are estimated for each square; runoff is obtained by subtracting evaporation from precipitation for each square and the runoff from all the squares is summed to obtain an estimate of the runoff for the entire basin; if the computed runoff disagrees with the recorded runoff, the precipitation for each square is adjusted and the procedure is repeated until the computed runoff approaches the observed runoff to the desired degree.

The method has already been applied to a region in British Columbia with promising results. In the following study, use of the available basic data have been made to develop a seasonal estimate approach to the "grid square" method and in particular to consider the evaporation component and the possible incorporation of snow course data, two components which have not yet been adequately developed for use in the method under British

Columbia conditions. Considering the evaporation component, it was found that apart from Turc's formula, used in the original grid square method, the Thornthwaite evapotranspiration method was the only other practical method for estimating evapotranspiration over wide areas as required by the grid square method. An attempt at an independent comparison of the two methods on an evaporation basis alone proved to be inconclusive due to the lack of adequate data but a comparison in actual computer trials of the grid square method showed that on basis of the first estimate of runoff distribution the Thornthwaite approach gave significantly better results. To incorporate the snow course data into the grid square method several approaches were taken in which an attempt at estimating on a seasonal basis the melt prior to April 1st, the date of snow surveys, was unsuccessful but showed insignificant melt which was subsequently ignored and an attempt at estimating annual precipitation at snow courses to supplement the meteorological station data was also unsuccessful. However, an attempt in which the snow course data was added to a segregated winter precipitation estimate at the meteorological stations proved to be successful and gave a small but significant improvement to the first estimate of regional precipitation and runoff distribution thus amplifying the potential use of snow course data in supplementing meteorological data for defining more clearly the regional variation of precipitation.

TABLE OF CONTENTS

LIST OF APPENDICES

LIST OF TABLES

ACKNOWLEDGMENT

The author wishes to express his sincere thanks to Mr. S.O. Russell for his guidance throughout the course of work of this study and his valuable criticism during the write up.

The author also wishes to thank T. Ingledow and Associates for providing the data for this study, without which the study could not have been accomplished.

CHAPTER 1 INTRODUCTION

With the increasing importance of long range planning for water resources development there is an urgent need for an inventory of the available supply of water. However, in British Columbia there are very few water sheds which are adequately gauged. This results mainly from the size and diversity of the province but also to some extent from the fact that there has been little regional network planning and in general the network just "grew" to meet immediate needs. Obviously, it would be very useful to be able to regionalize hydrologic information in British Columbia to reduce the need for stream gauging stations which have high capital costs. Unfortunately most available regionalizing techniques are either not applicable due to the shortage of data or inadequate for the rugged terrain which prevails in most of British Columbia. Hence, there is need for new analytical methods of estimating flows from sparsely gauged regions.

A new approach to estimating mean annual runoff was proposed by Solomon et al. and reported in "Water Resources Research" journal, Vol. 4, October 1968. In this technique both meteorological and hydrological information are used to assess the mean annual precipitation, temperature and runoff distribution over large areas. The study area is broken up into a large number of squares and physiographic parameters are determined for each square; available meteorological data is used to derive multiple linear regression equations which relate precipitation and temperature to physiographic parameters and from these equations precipitation, temperature and evaporation are estimated for each square; runoff is obtained by subtracting evaporation from precipitation for each square and the runoff from all the squares is summed to obtain an estimate of the runoff for the entire basin; if the computed runoff disagrees with the recorded runoff, the precipitation for each square is adjusted and the procedure is repeated until the computed runoff approaches the observed runoff to the desired degree. A summary of the method is given in Chapter 2 and a more detailed description is given in Reference 3.

An attempt has already been made to apply the method to a region in British Columbia (Reference 3) with promising results and it is planned to use the method to estimate the areal variation of runoff in the Nicola-Kamloops area as part of a comprehensive study of water resources in British Columbia now under way in the Department of Civil Engineering at the University of British Columbia. However, there are two potential weaknesses which need to be carefully assessed before the method is widely used in British Columbia. One is the use of Turc's formula, a widely used empirical formula for evaporation but one which has not yet been verified for British Columbia conditions. The other potential weakness is that the precipitation equation is defined for the whole basin only on the basis of existing precipitation data. In British Columbia nearly all meteorological stations are located in the valleys whereas most of the precipitation occurs in the mountains. An obvious improvement would be to use snow course data which give practically the only information on precipitation at the higher elevations.

The aim of this study is to develop a seasonal estimate approach to the Solomon or "grid square" method and in particular to consider the evaporation component and the possible incorporation of snow course data into the method. An attempt to apply the grid square method to the South Thompson drainage area has been made by T. Ingledow and Associates as part of a study of hydrometric network planning in British Columbia and the basic data have been made available (Reference 3). Since assembly of the basic data for each of the grid squares involves considerable effort it was decided to make use of the available data and use the South Thompson area as the test area for the study. Chapter 2 describes the grid square method, gives details of the size and number of squares, the type of physiographic data considered and describes the adaption of the method to the available computing facilities at U.B.C. In Chapter 3 a review of literature establishes the Thornthwaite method as the only other practical method of estimating evapotranspiration within the scope to which evaporation methods are used in the grid square method (water balance approach in which runoff is equivalent to precipitation minus evapotranspiration) and an attempt is described to make an independent comparison of the Turc and Thornthwaite methods on an evaporation basis. Chapter 4 describes an attempt to estimate the melt prior to April 1st, the date of snow surveys (snow course data), and shows that the snow melt model assumed was inadequate on a seasonal basis but that the melt was insignificant. Chapter 5 describes the trial runs of the experimental grid square method in which both the Turc and Thornthwaite evaporation approaches are compared on the basis of the first estimate of runoff and in which the snow course data are incorporated. The results are discussed throughout the course of the text and recommendations for further work are given where appropriate. Final conclusions are given in Chapter 6.

CHAPTER 2 GRID SQUARE METHOD

2.1 Description of the Method

In the original grid square method the study area is first divided into a grid consisting of a series of uniform squares, the size of which determines to a large extent the accuracy of the representation. (A finer grid would result in greater accuracy on the one hand, but would increase computer costs of extracting and processing information on the other hand.) Physiographic data for each square are then extracted from available maps and climatological data for meteorological stations are obtained from available published records. Physiographic data are also determined for each meteorological station. The grid system permits the storage and retrieval of basic data for future processing by means of simple computer operations. The characteristics of the overall area or sub-basins can be obtained by combining the characteristics of each square which lies wholly or partially within the boundaries of the drainage area. The procedure for the iterative computation to develop equations for mean annual runoff at any point within a basin is summarized as follows:

(1) Establish a preliminary relationship between mean annual precipitation at meteorological stations and the corresponding physiographic parameters by a standard linear multiple regression technique.

(2) Similarly, establish a relationship for mean annual temperature at meteorological stations.

(3) Compute evaporation as a function of precipitation and temperature (using a formula such as that derived by Turc) for each square.

(4) Make an initial estimate of runoff for each square in the study area by estimating precipitation (Step 1), evaporation (Steps 2 and 3) and subtracting evaporation from precipitation.

(5) Compute the mean annual runoff for the drainage area above the streamflow gauging station by summing runoff of each square within the watershed.

(6) Compute for the overall drainage basin the ratio

$$K = \frac{\text{recorded mean annual runoff}}{\text{computed mean annual runoff}}$$

(7) Adjust the precipitation value for each square by the following formula:

$$\text{Precipitation (adjusted)} = (K)(R_1) + E_1$$

where R_1 represents runoff and E_1 represents evaporation obtained from the previous estimates.

(8) Using the adjusted value of precipitation for each square and the precipitation data at meteorological stations, establish a new correlation between precipitation and physiographic parameters with the meteorological station data given a weight ten times that given to the estimated precipitation in each square.

(9) Compute a second estimate of runoff for each square as in Step 4.

(10) Compute a new value of K by repeating Steps 5 and 6.

(11) Re-iterate steps 7, 8, 9 and 10 until a value of K as close to unity as practicable is obtained.

(12) Obtain the final regression equation between mean annual precipitation and physiographic parameters by repeating steps 7 and 8.

(13) Correlate the final estimate of the runoff in each of the squares with the physiographic characteristics to establish a final equation relating runoff to physiographic parameters. At this stage, additional physiographic parameters such as area of lakes, which may be correlated with runoff, can be introduced into the regression analysis.

The iterative technique described above can only be applied when the grid square method gives a good runoff distribution and all sub-basins are either overestimated or underestimated. Thus when iteration is applied in these cases the new estimate of sub-basin runoff would approach the actual values with each iteration. For cases in which the first estimate gave both positive and negative sub-basin errors, iteration would increase some sub-basin errors as it decreased the overall basin error by virtue of step 7, above. To circumvent this situation the iterative technique could be adjusted to compute sub-basin K ratios and apply these individual ratios to adjust the precipitation in each square of the respective sub-basin. The errors of runoff estimates will then decrease in each sub-basin as well as in the overall basin with each iteration. Iteration in this sense is a useful tool, in that, all available hydrologic information is efficiently used and successive runs tend to eliminate some of the inherent errors in the regression technique as well as errors of measurement in meteorological observations.

The main strength of the grid square method lies in the simultaneous use of meteorological and hydrometric data, two types of data that have not previously been used together. The method also has the advantage that it makes use of direct correlation of meteorological data with physiographic data for each square rather than average values for entire basins. It can thus cope with physically diverse regimes, an important consideration in an area such as British Columbia. Another advantage of the method is that the process of determining the physiographic characteristics and compiling the hydrologic estimates for each square provides an extremely simple computerized method of information storage and retrieval for large drainage areas. The method, however, has the disadvantage that when there are large errors in the first estimate of flows, the precipitation in each square has to be adjusted and the iteration process destroys the statistical independence of the first estimate. The only meaningful correlation is that of the first multiple correlation of temperature and of precipitation; all subsequent correlations are statistically meaningless because they are derived from functions which have already been defined by a least squares fit. Standard statistical tests therefore cannot be applied. However, the physical meaning of this approach can be preserved if an independent check is made of the areal distribution of runoff by comparing the computed values with those measured in the subbasins of the total basin.

2.2. UBC Trip

The University of British Columbia Computing Center, in one of their many computer services, provides a subroutine package (Reference 2), called UBC Trip, which performs a series of statistical tests and manipulations on observed data. One of the routines, called Stpreg, in this package makes use of a standard stepwise regression technique for linear multiple correlation analysis. During the regression analysis Stpreg considers the significance of each independent variable in turn and either includes or excludes that variable from the regression equation depending on the significance level defined by the user. If desired, an independent variable can be included in the regression equation regardless of its significance. The independent variables to be considered in the regression equation can be fed into Stpreg in any desired form by the user. For example, if the user wanted a curvilinear component of a variable he would feed in the square of the variable in addition to the variable itself and may obtain squared independent variables in the resultant regression equation (e.g., Equation 5.1 of section 5.2). This routine was used to define the regression equations that were used in the programs in the study of the grid square method. At the present time there is no provision for iteration in this routine package.

2.3 Data Used in Grid Square Method

The South Thompson River Basin was used in the development of the grid square method since data from this basin was processed and compiled by T. Ingledow and Associates Limited in a hydrometric network study in which they applied the grid square method in its original form. The South Thompson River Basin is also one of the few areas in British Columbia where there are adequate meteorologic and hydrologic data to perform the regression analysis. The drainage basin, with a catchment area of approximately 6,350 square miles, is shown in Figure A-1 of Appendix A. The grid system covering the study area has a 10 kilometer interval (standard on the 1:250,000 scale maps used in Canada) with a total of 212 squares which fall within or on the boundaries. The grid square system is shown in

Figure A-2 and the areas of squares in each sub-basin are listed in Table A-3 of Appendix A.

The time base period used for the study was 10 years (1956-1966) since adequate streamflow records are available from four gauging stations for this period. The location of these stations are shown in Figure A-1 and station data are as follows:

Station No.	Station Name	Drainage Area Above Station (sq. mi.)	Ten Year Mean Flow (cfs)
8LC-3	Shuswap River near Lumby	776	1,800
8LC-19	Shuswap River at Mable Lake	1,560	2,890
8LD-1	Adams River near Squilax	1,156	2,560
8LE-69	South Thompson River near Monte Creek	6,350	10,700

Adequate precipitation records for the selected time base period are available from 37 meteorological stations in the general area of the South Thompson River Basin. However, only 15 of these stations are located within the study basin, while the remaining 22 are peripheral stations which presumably reflect climatic conditions in the basin. Adequate temperature data are available for 28 of the 37 meteorological stations. The locations of these stations are shown in Figure A-1 and the 10 year mean values of precipitation and temperature at these stations are listed in Table A-1 of Appendix A. Detailed description of compilation of data is given on page 6-6 of Reference 3.

The physiographic characteristics that were considered are:

(a) Elevation: The mean elevation of a square was obtained by averaging the elevations at the grid square corners, the center and the intermediate 5 kilometer points.

(b) Land Slope: Slope is determined by Horton's method which consists of counting the number of contour lines crossing two perpendicular center lines of the square which are parallel to the sides.

(c) Distance to Barrier: The index that was adopted was the distance from the center of a square to a straight line drawn along the divide of the Coast Mountains, measured in a west-southwest direction, the predominant wind direction of moisture inflow for the area.

(d) Latitude: The latitude index was defined as the distance measured from the U.S. border to the center of a grid square.

(e) Shield Effect: The shield effect was determined by summing the average barrier heights along the center line of each square extending for 28 kilometers in a west-southwest direction.

The physiographic data for the meteorological stations were extracted from 10 kilometer squares centered over each station. The published elevation characteristic for each station was used instead of the average elevation of the square. A more detailed description of the physiographic characteristics and their measurement are given on pages 6-6 through 6-9 of Reference 3.

CHAPTER 3 EVAPORATION

3.1 Introduction

Evaporation theory can be used for estimating the runoff from ungauged watersheds by using the water balance approach. Water balance can be defined as the balance between the income of water from precipitation and the outflow of water by evapotranspiration. The general procedure is to estimate the evapotranspiration loss E, subtract it from the precipitation P and consider the "moisture surplus" (P-E) as representative of the runoff. This procedure is better suited for climatological rather than hydrological use where time-lag influences (e.g., ground-water storage and snow melt) predominate. However, this water balance procedure can be satisfactorily applied to hydrological estimates of mean monthly and mean annual water balances in which time lag effects are of little influence.

For the evaporation component of water balance estimates two estimates of evaporation are generally made, that of potential evaporation and actual evaporation. Potential evaporation is defined as the evaporation that would occur were there an adequate moisture supply at all times. Actual evaporation is equal to potential when the precipitation exceeds the potential evaporation but is less than the potential evaporation when precipitation falls below potential evaporation.

In the original grid square method mean annual evapotranspiration is calculated by Turc's evaporation formula which was developed on the basis of a statistical study of 254 watersheds in all climates of the world.

The formula is very simple to apply and is given as follows:

$$L(t) = 300 + 25t + 0.05t^3 \qquad \text{....(3.1)}$$

$$E = \frac{P}{\sqrt{0.9 + \frac{P^2}{L(t)^2}}} \qquad \text{....(3.2)}$$

where

E = Actual annual evaporation (mm)

P = Annual Precipitation (mm)

t = Mean annual temperature (°C)

A translation of the résumé of Turc's original paper (which is in French) is given in Appendix D.

A brief review of research literature was made to determine which methods were widely used to estimate evapotranspiration in water balances of watersheds. It was concluded that Penman's method produced the most accurate results but required data which are not readily available over wide areas for which the grid square method is proposed. For the available data, Thornthwaite's evapotranspiration method was found to be the one most widely used. R.C. Ward, in his paper on potential evapotranspiration, compares the Penman and Thornthwaite methods with an evapotranspirometer (Reference 11). His study showed that there was generally close similarity among the results of the three methods. Both the Penman and Thornthwaite methods showed slight discrepancies in the spring and autumn but the discrepancies were complementary in each case and the annual results were similar.

The Thornthwaite method was derived from a statistical study of available observations in the central and eastern United States. The method involves first calculating potential evapotranspiration and then, on the basis of a series of assumptions and empirical rules (formulas or tables), monthly runoff from rainfall and snowmelt. The monthly water balance is calculated with regard to a running total of soil moisture storage from which calculations of moisture deficit and surplus as well as runoff are derived. Basic data used in the method are mean monthly temperature and precipitation and estimates of water holding capacity of the soil.

The Thornthwaite formulae used in the computer programs of this study are:

$$i_k = \left[\frac{t_k}{5}\right]^{1.514} \qquad \text{....(3.3)}$$

$$I = \sum_{k=1}^{12} i_k \qquad \text{....(3.4)}$$

$$F = \frac{0.93}{2.42 - \log I} \qquad \text{....(3.5)}$$

$$E_k = C_k \text{ antilog}\left[0.204 + F(1 - \log I) + F \log t_k\right] \qquad \text{....(3.6)}$$

$$M = \text{antilog}\left[\log S - (A)(PE)\right] \qquad \text{....(3.7)}$$

where:

E_k = adjusted potential evapotranspiration for month k (cm)

C_k = coefficient depending on the month and the latitude (Reference 8)

t_k = mean monthly temperature (°C)

M = soil moisture retained in the soil (in.)

S = water holding capacity of the soil (in.)

A = rate of change of M with different amounts of PE (dimensionless)

i.e., when S = 16, A = 0.02719

S = 14, A = 0.03106

S = 12, A = 0.03628

S = 10, A = 0.04331

PE = potential evapotranspiration (in.)

The first four formulae were taken from G.S. Cavadias' paper on evaporation (Reference 4). The last formula was developed from Thornthwaite's tables starting on page 245 of Reference 9. In the programs of the study of the grid square method Formula 3.7 was used with S = 14 inches only since a preliminary study showed essentially no difference in evapotranspiration estimates using the four different values of S (see Program C-1 of Appendix C).

The extent to which the water balance method of Thornthwaite was used, was in calculation of actual evapotranspiration (see Reference 9). A simplified version of surface runoff was then estimated from precipitation minus actual evapotranspiration for each month and summed to obtain the annual runoff estimate. Thornthwaite determines surplus runoff in a more detailed analysis in which moisture deficit and surplus are both estimated and detention periods are used for both water and snow runoff estimates. However, this analysis is beyond the present scope of the grid square method.

3.2. Comparison of Evaporation Methods

For the comparison of the Turc and Thornthwaite methods of estimating evapotranspiration under British Columbia conditions, several attempts were made. A preliminary examination was first made for a wide range of meteorological stations with mean annual precipitation ranging from 8.15 inches to 179.50 inches. Precipitation data and Thornthwaite evaporation estimates were obtained from Thornthwaite's published results (Reference 1) and temperature data were obtained from the U.B.C. Geography Department. The meteorological stations considered and the results that were obtained are given in Table 3.1.

TABLE 3.1

PRELIMINARY COMPARISON OF TURC AND THORNTHWAITE EVAPORATION METHODS

(All figures are mean annual)

Station	Temp. (°F)	Precip. (in.)	Turc Actual Evapotrans. (in.)	Thorn. Actual Evapotrans. (in.)	Difference between Thorn. and Turc
OKANAGAN					
Okanagan Centre	48	12.75	11.46	12.75	1.29
Oliver	49	8.65	8.46	8.65	0.19
Kelowna	47	12.20	10.99	12.20	1.21
Keremeos	49	9.75	9.37	9.75	0.38
SOUTH THOMPSON DRAINAGE AREA					
Ashcroft	45	9.45	8.89	9.45	0.56
Kamloops	47	10.20	9.58	10.20	0.62
Salmon Arm	46	19.05	14.31	18.00	3.69
Vavenby	43	14.65	11.80	14.65	2.85
Chinook Cove	44	16.50	12.82	16.50	3.68
Tappen	46	21.10	15.03	18.55	3.52
Tranquille	47	8.15	7.96	8.15	0.19
WEST COAST AND VANCOUVER ISLAND					
Alberni	49	66.75	21.66	22.70	1.04
Anyox	44	78.40	18.48	20.95	2.47
Britannia Beach	50	75.85	22.65	23.60	0.95
Clayoquot	49	106.50	22.31	24.45	2.14
Estevan Point	48	107.80	21.54	24.15	2.61
Holberg	46	101.80	20.03	23.70	3.67
Ocean Falls	47	179.50	21.02	24.40	3.38
Ucluelet	48	102.80	21.51	23.70	2.19

Upon examination of the Difference column it can be seen that Turc's method gives consistently lower estimates of actual evapotranspiration than Thornthwaite, especially in the South Thompson region.

In a second examination a program was written for calculating actual evapotranspiration by the Turc and Thornthwaite methods (see Program C-1 of Appendix C). Two meteorological stations were chosen for the trial runs, one for high and one for low precipitation (Reference 7). The results obtained are given in Table 3.2.

TABLE 3.2

PROGRAMMED COMPARISON OF TURC AND THORNTHWAITE EVAPORATION METHODS

(All figures are mean annual)

Station	Temp. (°F)	Precip. (in.)	Turc Actual Evapotrans. (in.)	Thorn. Actual Evapotrans. (in.)
Armstrong	44.5	17.2	13.2	17.2
Glacier	36.2	57.1	13.8	18.7

The difference between the two methods again appears to be rather significant.

In an evaporation study of the Carrs Landing area in the Okanagan, the British Columbia Water Resources Services has determined some evaporation data based on the Penman method. Using these data as a base (assuming that the data represented true evaporation), the methods of Turc and Thornthwaite were compared in the third examination in an attempt to establish which method gave better evaporation results for British Columbia conditions. The results of the comparison of two sites for 1967 are given in Table 3.3.

TABLE 3.3

CARRS LANDING STUDY COMPARISON

(All figures are mean annual)

Station No.	Temp. (°F)	Precip. (in.)	Thorn. Evapotrans. Potential (in.)	Thorn. Evapotrans. Actual (in.)	Turc Actual Evapotrans. (in.)	Penman Evapotrans. Potential (in.)	Penman Evapotrans. Actual (in.)
1	51.0	8.9	27.8	8.9	8.9	27.5	6.3
3	42.4	12.9	21.9	12.9	10.8	22.9	9.0

The Penman "annual" figures are aggregates of summer period only (April-October), therefore may be underestimates of total annual evapotranspiration. Calculations for only one year at two sites with the highest observed precipitation were made since further examination of the Penman data revealed that in no trial did precipitation exceed evapotranspiration. In both trials shown above the precipitation was so much lower than the potential evapotranspiration that both the Thornthwaite and Turc methods (except Turc at Station 3) simply showed that actual evapotranspiration was equal to the precipitation. Hence the comparison of the two methods with the Penman method proved to be inconclusive in the third evaporation examination.

Although the first two attempts (Tables 3.1 and 3.2) at comparing the Turc and Thornthwaite methods indicated a significant difference in their estimates, no conclusion could be drawn on an evaporation basis alone as to which method gave better results for British Columbia conditions. Hence there was a need for an experimental grid square approach to establish which method gave better results in water balance estimates. The comparison of the two evaporation methods using a grid square approach is presented in Chapter 5.

CHAPTER 4 SNOW

4.1 Snow Courses

The British Columbia Water Resources Service conducts a snow survey program for purposes of forcasting volumes of snowmelt runoff. Most of the snow courses in operation are located at elevations above 4,000 ft. Since most of the meteorological stations are situated in valleys at elevations below 4,000 feet, the snow survey data provide practically the only observed information on precipitation at the higher elevations. In the study area, all meteorological stations are located below 4,100 feet (except one which is at 4,100 feet) and all snow courses are located at or above 6,000 feet. Hence, the snow course data should provide additional valuable information in the seasonal development of the grid square method.

4.2. Melt Prior to Snow Survey

The British Columbia Water Resources Service is also undertaking snowmelt studies in which they have so far, collected two years of snow pillow data at two different sites. This data was examined and a very simplified model was developed to determine the melt prior to the 1st of April, the date of the snow surveys. The method consisted of a program (see Program C-2 of Appendix C) which read in daily average values of temperature and water equivalent of snow pack, compiled the accumulated degree days (base 32°F) against the accumulated incremental water equivalent losses and plotted the relationship with degree days as the independent variable and the water equivalent loss as the dependent variable. In each computer run of a set of data, four plots were produced where time lags of zero, one, two and three days were observed. The best plot was determined and from it a seasonal average melt (accumulated melt from start of snowfall to April 1st) was estimated using a season average temperature multiplied by the length of season for the seasonal average degree day estimate (see Figure 4.1). With this approach it was hoped to estimate the seasonal premelt and to combine it with the snow course data for an estimate of winter precipitation.

The program was tested out on three complete sets of data from Blackwall (1967-68 and 1968-69) and Barkerville (1968-69). The resulting graphs were examined for shape and lags of one and two days were found to give the best plots. A seasonal value of melt was required since a daily estimate is beyond the scope of the grid square method. When a seasonal estimate of degree days was made (season average temperature multiplied by the length of season in days) the seasonal melt was found to be 77% in error for Barkerville (1968-69) while the seasonal melts for the other two sets of data were found to be meaningless since the seasonal average temperature was below 32°F. The best plot was that of Barkerville which is shown in Figure 4.1. Since the melt in each case was below 1.5 inches, it was ignored in subsequent use of snow course data. This approach did not prove to have any significant results due most likely to unexplained factors affecting snow melt (e.g., antecedent moisture in soil affecting heat from the ground and effect of humidity), and perhaps the limitation in measuring equipment.

The results of the model when applied to snow pillow data on a daily basis showed melt graphs which displayed smooth plots for lag times of one

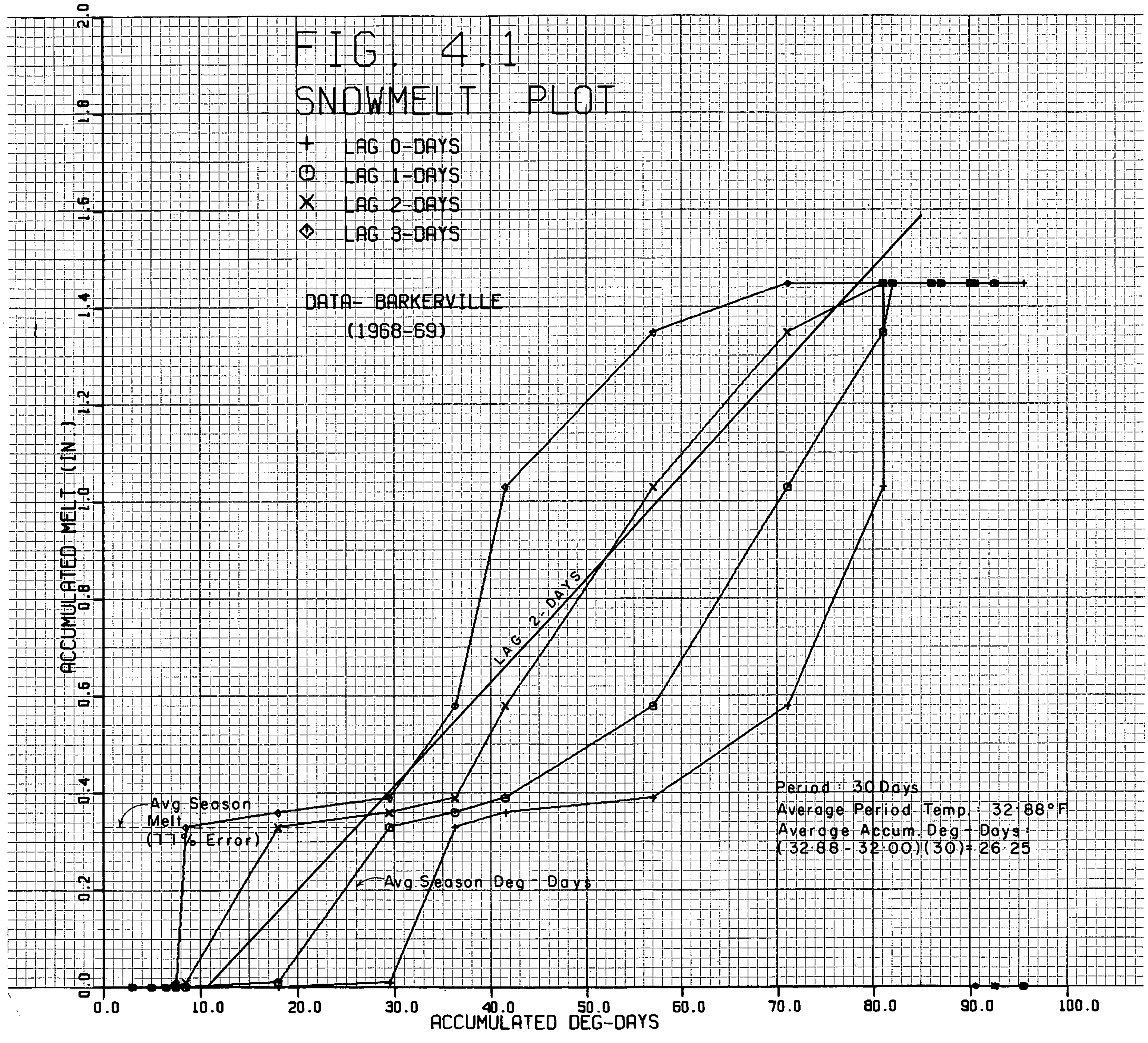
FIG. 4.1
SNOWMELT PLOT
LAG 0-DAYS
LAG 1-DAYS
LAG 2-DAYS
LAG 3-DAYS
DATA- BARKERVILLE
(1968-69)
LAG 2-DAYS
Avg Season
Melt
(77% Error)
Avg Season Deg - Days
Period : 30 Days
Average Period Temp. : 32·88°F
Average Accum. Deg - Days :
(32·88 - 32·00)(30)= 26·25
ACCUMULATED MELT (IN.)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
ACCUMULATED DEG-DAYS

and two days. These plots suggest the existence of a melt function or a snow melt variation with average accumulated degree days. In further development of the method it is suggested that the same model be applied to the data but with maximum daily temperatures as a basis for a heat index. This would give positive seasonal melt estimates (see section 4.2, page 20) which may or may not be significant on a seasonal basis. Other aspects to be considered would be the effect of antecedent moisture conditions (can be estimated from the rain hydrograph prior to snowfall and the soil conditions), the effect of the snow pillow interfering with the actual natural melt process (e.g., may have a shielding effect from heat from the ground) and the comparison of the precipitation hydrograph with the snow pillow hydrograph to determine the difference between the actual snow melt runoff and the ripening and storage processes. Dr. Quick of the Civil Engineering Department of U.B.C. is now collecting snow pillow data on Mount Seymour and should have sufficient data for such modelling in the near future.
It is also suggested that rain gauges be installed on a yearly basis at the snow pillow sites of the British Columbia Water Resources Services to obtain information which could lead to the development of snow melt models and thus make wider use of the many snow course data that have been collected to date.

CHAPTER 5 EXPERIMENTAL GRID SQUARE METHOD

5.1 Programming

Computer programs, using UBC Trip, were initially set up to define regional temperature and precipitation regression equations. Stpreg (see section 2.2, page 7) was used to establish the relationships between temperature and precipitation at meteorological stations (dependent variables) and the corresponding physiographic parameters (independent variables). Mean annual temperature and precipitation equations were used in the Turc approach but mean monthly equations were derived for the Thornthwaite approach. The results of these programs are given in the following sections 5.2 and 5.3. A program was then written for estimating mean annual runoff by the grid square method using Turc's formula for estimating mean annual evaporation. Another program was written for estimating mean annual runoff, using the Thornthwaite approach for estimating mean annual evapotranspiration. Several modified trial runs were made with this program and the modifications and the results are presented in section 5.4. A sample program of one of the trial runs is given in Appendix C (Program C-3). In the Thornthwaite programs both potential and actual evapotranspiration were estimated but only the latter was used in estimating runoff. Mean annual runoff was determined by adding the twelve estimates of mean monthly runoff (precipitation minus actual evapotranspiration). In both the Turc and the Thornthwaite programs mean annual runoff was determined for each square and summed to obtain the total mean annual runoff for the basin. Provision was made in both programs for checking the areal distribution of the first estimate of basin runoff by dividing the total basin into four sub-basins for which published hydrometric data were available. A final set of programs was written to incorporate the snow course data into the grid square system. These trial runs are described in part c of section 5.5 and a sample program is given in Appendix C (Program C-4).

5.2 Estimation of the Temperature Distribution

Using data at 28 meteorological stations, a correlation was established between the mean annual temperature and the corresponding physiographic characteristics (elevation, land slope, distance to barrier, latitude index, barrier height, and shield effect). The resulting regression equation is:

$$T = 50.8308 - 0.003107E - 0.00003754L^2 \qquad \ldots.(5.1)$$

where, T is mean annual temperature in°F, E is station elevation in feet, and L is the latitude index in kilometers. The coefficient of correlation is 0.96 which is significant at the one percent level and the standard error estimate is 1.0°F. The coefficients of the variables included in the equation have signs corresponding to their expected physical influence on the mean annual temperature.

For the Thornthwaite approach in the grid square method twelve mean monthly temperature equations were needed. Since monthly temperature data were not available in Reference 3, the twelve mean monthly values for each station were obtained from References 5 and 7, and were adjusted to the time base period of Reference 3. The correlations were established as for Equation 5.1 and twelve regression equations were obtained, one for each month. The equations are similar in form and are shown in Appendix B, section B.1 (Equations B.1 through B.12). For example, the equation for the mean monthly temperature for January is:

$$T1 = 28.1903 - 0.002675E - 0.00006324L^2 \qquad \text{....(B.1)}$$

where E is station elevation in feet and L is the latitude index in kilometers. The coefficient of correlation ranges from a low of 0.81 for T2 (February) to a high of 0.94 for T4 (April), with a significance at the one percent level. The standard error of estimate ranges from a low of 1.1°F for T10 (October) to a high of 2.2 for T1 (January). The smaller coefficients of variation for the monthly equations suggest that less variation was explained in these than in the annual equation, which was expected since the time base for correlation was shortened.

5.3 Estimation of the Precipitation Distribution

Using data at 37 meteorological stations, a correlation was established between the mean annual precipitation and the corresponding physiographic characteristics (elevation, land slope, distance to barrier, latitude index, barrier height and shield effect). The resulting regression equation is:

$$P = 11.7765 - 0.0956L + 0.0000005127E^2 + 0.0005778DB^2 - 0.00000002558SE^2 \qquad \text{....(5.2)}$$

where P is mean annual precipitation in inches, L is the latitude index in kilometers, E is elevation in feet, DB is distance to barrier in kilometers and SE is shield effect in feet. The coefficient of correlation is 0.97 which is significant at the one percent level and the standard error of estimate is 3.59 inches.

For the Thornthwaite approach in the grid square method twelve mean monthly precipitation equations were required. As in the case of the monthly temperature data, the data for the twelve mean monthly precipitation values for each station were obtained from References 5 and 7 and adjusted to the common time base period (1956-1966). As with the temperature equations, twelve correlations were established for mean monthly precipitation. The equations are similar in form and are shown in Appendix B, section B.2 (Equations B.13 through B.24). For example, the corresponding equation for the mean monthly precipitation for January is:

$$P1 = 5.3639 - 0.0474DB + 0.0001803DB^2 - 0.00003784L^2 \quad \ldots(B.13)$$

The coefficient of correlation ranges from a low of 0.68 for P8 (August) to a high of 0.96 for P3 (March), with a significance at the one percent level. The standard error of estimate ranges from a low of 0.25 inches for P4 (April) to a high of 0.80 inches for P12 (December).

Of the independent variables used in correlation in this study, the variable of elevation was considered the most important since it is the only common characteristic that all land areas share which influences the variation of weather phenomenon. The stepwise regression technique (Stpreg, described in section 2.2) that was used in the correlation analysis includes in the regression equations only those independent variables which are significant to the level defined by the user. Seven of the above twelve regression equations did not retain elevation as a significant variable and were defined by other significant independent variables. By using UBC Trip with the elevation variable included regardless of significance, into the regression equations, twelve additional correlations were established and are shown in Appendix B, section B.3 (Equations B.25 through B.36). Elevation was forced into the regression equations as E^2 since previous examination of Stpreg revealed that E^2 resulted in higher significance than E and was generally more readily accepted into a regression equation than was E. The corresponding equation for the mean monthly precipitation for January is:

$$P1 = - 0.2672 + 0.00000008047E^2 + 0.00007911DB^2 - 0.00003614L^2 \qquad \text{....(B.25)}$$

The coefficient of correlation ranges from a low of 0.70 for P8 (August) to a high of 0.96 for P3 (March), with a significance at the one percent level, the exceptions being the elevation variables in equations of P8, P10 and P12 where the variable significance is 5.5%, 9.15% and 1.2% respectively. The standard error of estimate ranges from a low of 0.25 inches for P4 (April) to a high of 0.76 inches for P12 (December).

5.4 Estimation of the Runoff Distribution

Regression equations for temperature and precipitation that had been derived from the meteorological observations were used to calculate actual evapotranspiration which was then subtracted from the corresponding precipitation to obtain runoff for each square. The runoff values for each square were then summed for each sub-basin (partial areas of squares within sub-basins were accounted for) and the total basin. The sub-basin runoff totals then represented the first estimate of the grid square technique and were therefore used to compare the Turc and Thornthwaite methods of estimating evaporation. A runoff regression equation comparison was of no benefit since the correlation coefficient of any runoff regression equation would be 0.999

due to the nature of derivation of runoff values (observations would be derived from functions which had already been fitted by a least squares method).

In the program for calculating runoff with the Turc approach the mean annual regression equations for temperature and precipitation, Equations 5.1 and 5.2, were used since the Turc formula uses only annual values. The resulting first estimates and their corresponding recorded flows for the sub-basins and total basin are given in Table 5.1.

TABLE 5.1

FIRST RUNOFF ESTIMATES USING TURC'S METHOD

River	Stream Gauge Station	Sub-Basin Drainage Area (sq. mi.)	Recorded Flow (cfs)	Estimated Flow (cfs)	Percentage Difference
Shuswap	8LC-3	776	1800	1940	+ 7.8
Shuswap	8LC-19	784	1090	1548	+ 42.0
Adams	8LD-1	1156	2560	3281	+ 28.2
S. Thompson	8LE-69	3634	5250	7063	+ 34.6
Total		6350	10,700	13,831	+ 29.2

In the program for calculating runoff with the Thornthwaite approach the twelve mean monthly regression equations for temperature, Equations B.1 to B.12 inclusive of Appendix B, and precipitation were used since the Thornthwaite approach uses monthly values. One trial runoff estimate was made with the precipitation Equations B.13 to B.24 inclusive, derived with normal stepwise regression (elevation not included in all regression equations) and another runoff estimate was made with the precipitation Equations B.25 to B.36

inclusive, derived with the modified stepwise regression (elevation variable included in all the regression equations regardless of its significance). The resulting first estimates and their corresponding recorded flows are given in Table 5.2.

TABLE 5.2

FIRST RUNOFF ESTIMATES USING THORNTHWAITE'S METHOD

River	Stream Gauge Station	Sub-Basin Drainage Area (sq. mi.)	Recorded Flow (cfs)	Estimated Flow Normal Stpreg (cfs)	% Diff.	Estimated Flow Modified Stpreg (cfs)	% Diff.
Shuswap	8LC-3	776	1800	1262	-29.2	1775	- 1.4
Shuswap	8LC-19	784	1090	990	- 9.2	1369	+25.6
Adams	8LD-1	1156	2560	2612	+ 2.0	3021	+18.0
S. Thompson	8LE-69	3634	5250	4633	-11.8	6040	+15.0
Total		6350	10,700	9498	-11.2	12,204	+23.4

Examination of the coefficients of correlation of the two sets of twelve precipitation equations of section 5.3 on pages 27 and 28 will show that the two sets of equations essentially show identical statistical significance. However, the results shown in Table 5.2 show a significant difference between the two trial runs in which the normal regression equations underestimate and the modified regression equations overestimate the flow. This result is interpreted as being due to the fact that the meteorological stations are mostly situated in the valley bottoms while the grid squares cover fairly large areas which generally include parts of the higher elevation mountain slopes. This fact was investigated further when in a program, the precipitation for each square was printed out for each trial of the normal and the modified regression. Upon examination of the squares with the lowest elevations, it was found that both sets of equations gave the same precipitation estimates but at the squares with the highest elevations the normal regression equation set underestimated while the modified regression set overestimated the precipitation. This result was inferred from the results of Table 5.2 in which runoff estimates are underestimated in the first trial and overestimated in the second. The reasoning was further substantial when the runoff estimates were printed out for each square for both trials and the higher elevation squares were examined to compare the runoff estimates with the precipitation and evaporation estimates. The precipitation values were found to be much larger than the corresponding evaporation values in most cases. Temperature distribution did not affect either of these trials because elevation was significant in all twelve mean monthly temperature regression equations and one set of temperature equations was therefore used in both trials. The conclusion to be drawn from this analysis is that the meteorological stations, being located in the valley bottoms, do not adequately explain the precipitation variation, in terms of elevation at least. This point is well brought out in the next section when snow course data is used to supplement the meteorological data to define a better precipitation variation.

It appears that the Thornthwaite approach to the grid square method gives better results than Turc's evaporation approach since it gives a better first estimate of runoff distribution. Obviously both estimates could be improved by iteration to progressively reduce the discrepancies between estimated and recorded runoff (see discussion on page 6 of section 2.1) and this would normally be the next step. However, at other than the first estimate there would be no basis for comparison between alternative techniques. Hence in this research study the grid square method was not taken beyond the first estimate.

5.5 Incorporation of Snow Course Data

To incorporate the snow course data into the grid square system several approaches were made as follows:

(a) The closest related (considering location and physiographic characteristics) meteorological station was chosen for each snow course station and the percentage of annual precipitation that the winter precipitation (October-March) represented was determined at the meteorological station. The two independent estimates, percentage of winter precipitation and the April 1st snow pack water equivalent were combined for an estimate of annual precipitation at each snow course station. These independent (of the precipitation stations) average annual precipitation estimates were combined with the average annual precipitation station observations and data was then available for 50 meteorological stations. A correlation was established between the mean annual precipitation and the corresponding physiographic characteristics. The resulting regression equation is:

$$P = - 30.9787 + 0.005885E + 0.2302DB - 0.0001832L^2 \qquad \ldots .(5.3)$$

where P is mean annual precipitation in inches. The coefficient of correlation is 0.93 which is significant at the one percent level and the standard error of estimate is 7.6 inches. When compared with Equation 5.2, Equation 5.3 with the snow courses added, shows a slightly lower statistical significance and adds no refinement to the original precipitation regression Equation 5.2. As an added check, Equation 5.3 was used in place of Equation 5.2 in the Turc method of the grid square system and the results obtained were much worse than those shown in Table 5.1 for Equation 5.2.

(b) Mean annual precipitation at each snow course station was computed from the regression equation developed from meteorological stations only, Equation 5.2, and the percentage of these values represented by the April 1st snow course data was determined. The percentage values were then correlated with physiographic parameters and the regression equation thus derived was used to recompute the percentages at the snow course locations. The recomputed percentage values were combined with the snow course data to estimate an average annual precipitation value at the snow course locations. These annual precipitation estimates were then combined with the mean annual precipitation station observations and another set of data was available for 50 meteorological stations. A correlation was again established between the mean annual precipitation and the corresponding physiographic characteristics. The resulting regression equation is:

$$P = -\ 3.2011 + 0.003910E + 0.0005573DB^2 - 0.0002471L^2 \qquad ....(5.4)$$

The coefficient of correlation is 0.95 which is significant at the one percent level and the standard error of estimate is 6.3 inches. When compared with Equation 5.2, Equation 5.4 with the snow courses added, shows a slightly lower statistical significance and, just as Equation 5.3, adds no refinement to the original precipitation regression Equation 5.2. It should be noted, however, that the regression equation of percentages had a correlation coefficient of 0.36 and a standard error of 13.7% and this trial is, hence, of very little significance.

The attempts to use snow course data to estimate annual precipitation at the snow courses by assuming that the percentage of annual precipitation was the same as that at the nearest meteorological station (part a) and by recomputing from a correlation equation the percentage that the snow course represented of annual precipitation (part b) were not successful. The resultant precipitation regression equations (Equations 5.3 and 5.4) did not improve upon the precipitation distribution as estimated by the meteorological stations only (Equation 5.2).

(c) Mean monthly temperatures for every grid square were calculated by the twelve temperature regression equations (B.1 to B.12 of Appendix B) and then examined to define the winter period. It was observed that virtually all squares had mean monthly temperatures greater than 32°F for the period of April to October and the winter period was therefore defined as November to March. Actual observed precipitation for this period was compiled for each meteorological station making available data for 37 winter season observations. A correlation was established between winter season precipitation and the corresponding physiographic characteristics. The resulting regression equation is:

$$P_{(n-m)} = 27.6898 - 0.0605L - 0.2073DB + 0.0007837DB^2 \qquad \ldots.(5.5)$$

where $P_{(n-m)}$ is the mean winter seasonal (November-March) precipitation in inches. The coefficient of correlation is 0.96 which is significant at the one percent level and the standard error of estimate is 2.6 inches. The elevation variable was not retained in the regression equation as being significant. A duplicate correlation at the five percent level did not automatically produce elevation as a significant variable. UBC Trip was then used with elevation forced at the one percent level into the regression equation (the variable E^2 was included without regard to significance as discussed at the end of section 5.3) and the following result was obtained:

$$P_{(n-m)} = -\ 2.1805 + 0.0000004381E^2 + 0.0003352DB^2 - 0.0001476L^2 \qquad \ldots.(5.6)$$

The coefficient of correlation is 0.96 which is significant at the one percent level and the standard error of estimate is 2.6 inches.

By compiling winter monthly precipitation data into lumped five month season estimate for each meteorological station, an opportunity was created in which snow course data could be added in its unaltered form and in a comparable sense. Thus, with snow courses included, data were then available for 50 mean winter seasonal observations for correlation with their corresponding physiographic characteristics. The resulting regression equation is:

$$P_{(wint)} = -\ 21.5062 + 0.1647DB + 0.0000005143E^2 - 0.0001474L^2 \qquad \ldots.(5.7)$$

where $P_{(wint)}$ is the mean winter seasonal (with snow courses added) precipitation in inches. The coefficient of correlation is 0.94 which is significant at the one percent level and the standard error of estimate is 4.8 inches. It can be noted that the elevation variable was retained in the correlation equation at the usual level of significance without forcing a fit as in the case of Equation 5.6. However, a comparison of the statistical significance of the above formulae shows that Equations 5.5 and 5.6 are very slightly better than Equation 5.7. The three equations are again compared after they were applied in the grid square method.

Runoff distribution was estimated by the grid square method using the Thornthwaite approach for each of the winter seasonal precipitation equations. In the main program each of these regression equations was used as a lumped five month season runoff estimate (no evaporation because all temperatures were below 32°F) together with seven separate monthly estimates of runoff to produce an average annual runoff estimate for each square. The results of the trial runs of the grid square method using Equations 5.5 and 5.6 as the winter season estimates are given in Table 5.3.

TABLE 5.3

FIRST RUNOFF ESTIMATES USING THORNTHWAITE'S METHOD

WITH WINTER SEASON PRECIPITATION ESTIMATES

River	Stream Gauge Station	Sub-Basin Drainage Area (sq. mi.)	Recorded Area (cfs)	Estimated Flow Normal Stpreg (cfs)	% Diff.	Estimated Flow Modified Stpreg (cfs)	% Diff.
Shuswap	8LC-3	776	1800	1161	-35.5	1782	- 1.0
Shuswap	8LC-19	784	1090	901	-17.4	1365	+25.2
Adams	8LD-1	1156	2560	2569	+ 0.4	3012	+17.7
S. Thompson	8LE-69	3634	5250	4538	-13.6	6077	+15.8
Total		6350	10,700	9169	-14.3	12,235	+14.3

The results obtained above, basically show the same trends as those of Table

5.2 where mean monthly precipitation regression equations were used. The same argument, that of precipitation variation not being explained by the low elevation meteorological stations, can be applied.

Runoff distribution was then estimated using Equation 5.7, with added snow course data, and the results are given in Table 5.4.

TABLE 5.4

FIRST RUNOFF ESTIMATES USING THORNTHWAITE'S METHOD WITH SNOW COURSES ADDED TO THE WINTER SEASON PRECIPITATION ESTIMATES

River	Stream Gauge Station	Sub-Basin Drainage Area (sq. mi.)	Recorded Flow (cfs)	Estimated Flow (cfs)	% Diff.
Shuswap	8LC-3	776	1800	1748	- 2.9
Shuswap	8LC-19	784	1090	1361	+24.9
Adams	8LD-1	1156	2560	2852	+11.4
S. Thompson	8LE-69	3634	5250	6142	+17.0
Total		6350	10,700	12,103	+13.1

Comparison of these results with those of Table 5.3 shows that the runoff distribution estimate using the snow course data is slightly better than, and falling within the range of, the previous estimates which did not use snow course data. This improvement is slight but real despite the fact that the precipitation Equation 5.7 used in the estimates summarized in Table 5.4 is statistically inferior (again slightly) to Equation 5.5 used as a basis of Table 5.3. As pointed out previously, the supporting statistics for Equation 5.7 is that the elevation variable was retained in the correlation at the usual level of significance without forcing a fit as in the case of

Equation 5.6. Snow course data thus appear to add additional valuable information to the meteorological stations located in the lower elevations.

Comparison of the errors of the first estimates in the final run shown in Table 5.4 with those of the first estimates of the original method shown in Table 5.1 will show that the Thornthwaite method with the snow course data gives a significantly better first estimate with errors that approach those inherent in the observed values of runoff. This can be supported by the fact that hydrometric Stations 8LC-3 and 8LC-19 measure small drainage areas with relatively small annual runoffs and thus the observed values of runoff for these stations would probably tend to have larger errors than the observed values for say Stations 8LD-1 and 8LE-69. The results of Table 5.4 are similar to those of the second trial of Table 5.2 and both estimates could be improved by the application of an iterative technique as described in section 2.1.

CHAPTER 6 CONCLUSIONS

This study using data for the South Thompson River Basin has demonstrated that a seasonal estimate approach to the grid square method is feasible and that the revision of the evaporation component and the incorporation of snow course data into the precipitation component have improved significantly the areal runoff distribution estimate on the basis of the first estimate, giving the grid square method a more sound physical basis.

Considering the evaporation component it was found that apart from Turc's formula, the Thornthwaite evapotranspiration method was the only other practical method for estimating the evapotranspiration over wide areas as required by the grid square method. An attempt was made at an independent comparison of the two methods of estimating evapotranspiration on an evaporation basis alone but it was found inconclusive due to lack of adequate data. A comparison of the two methods in actual trials of the grid square method showed that on the basis of the first estimate of runoff distribution the Thornthwaite approach gives significantly better results lowering on the average the error of estimate in the total basin from approximately 30% to 15%.

To incorporate the snow course data into the grid square method several approaches were made. An attempt was made at estimating on a seasonal basis, the melt at the snow courses prior to April 1st, the date of snow surveys, with the aim of adding the estimate to the measured water equivalent of snow pack to give estimates of the total winter precipitation. The attempt was unsuccessful but showed that the melt prior to April 1st was not significant and was therefore ignored in subsequent calculations. Attempts were made to compute annual precipitation at the snow courses by first estimating the percentage of annual precipitation that the April 1st water equivalents represented and then extrapolating the seasonal to annual estimates. The attempts were not successful and did not improve the precipitation distribution as estimated by the meteorological stations only. A final attempt was then made to break the annual precipitation into winter and summer season components and to use the snow course data (from the higher mountain elevations) together with meteorological data (from the lower valley elevations) for the winter precipitation estimates and the meteorological data alone for the summer estimates. This approach of incorporating snow course data when applied to the grid square method gave a small but significant improvement to the first estimate of regional precipitation and runoff distribution. The potential use of the snow course data is thus amplified in its additional value of information for the existing meteorological stations in defining more clearly the regional variation of precipitation.

The grid square method, from its original development and from the study presented here, has demonstrated a feasible regression technique for estimating mean annual flows for sparsely gauged regions. The study has also demonstrated that the method is flexible for development on a mean monthly and seasonal approach (mean annual runoff was calculated from a sum of mean monthly values in the Thornthwaite approach). Potential development therefore, exists for application of the method to annual flows in particular years and ultimately to seasonal and monthly flows in any period of a year. This development would have to be supplemented by a modelling technique to distribute the seasonal or monthly volume estimates over a time basis (e.g., daily). In such modelling, considerations will have to be given to such physical aspects as snow-melt runoff lagging the actual melt process (e.g., estimated by some heat index), basin response to precipitation input (e.g., unit hydrograph) and dependence or independence of events which influence runoff (e.g., in the Thornthwaite approach monthly flows are interrelated). Hence, it is recommended that further studies be undertaken to develop the potential of this apparently powerful technique.

REFERENCES

1. Average Climatic Water Balance Data of the Continents. C.W. Thornthwaite Associates, Laboratory of Climatology, Publications in Climatology, Volume 17, Number 2. 1964.

2. Bjerring, J.H., J.R.H. Dempster and R.H. Hall. UBC Trip (Triangular Regression Package). The University of British Columbia, Computing Center. February 1969.

3. British Columbia Hydrometric Network Study. T. Ingledow and Associates Limited, Consulting Engineers, Volumes I and II. April 1969.

4. Cavadias, G.S. Evaporation Applications in Watershed Yield Determination. Proceedings of Hydrology Symposium No. 2, Evaporation, National Research Council of Canada. March 1961.

5. Climate of British Columbia, Tables of Temperature, Precipitation and Sunshine. Province of British Columbia, Department of Agriculture. 1965.

6. Solomon, S.J., J.P. Denouvilliez, E.J. Chart, J.A. Woolley and C. Cadou. The Use of a Square Grid System for Computer Estimation of Precipitation, Temperature and Runoff. Water Resources Research, The American Geophysical Union, Volume 4. October 1968.

7. Temperature and Precipitation Tables for British Columbia. Canada, Department of Transport, Meteorological Branch. 1967.

8. Thornthwaite, C.W. An Approach Toward a Rational Classification of Climate. Geographical Review, Volume 38. January 1948.

9. Thornthwaite, C.W. and J.R. Mather. Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance. Drexel Institute of Technology, Laboratory of Climatology, Publications in Climatology, Volume 10, Number 3. 1957.

10. Turc, L.C. Calcul du Bilan de L'Eau, Evaluation en Fonction des Precipitations et des Temperatures. International Association of Scientific Hydrology, General Assembly of Rome, Volume 38. 1954.

11. Ward, R.C. Observations of Potential Evapotranspiration (PE) on the Thames Floodplain 1959-1960. Journal of Hydrology, Volume 1. 1963.

APPENDIX A

DATA

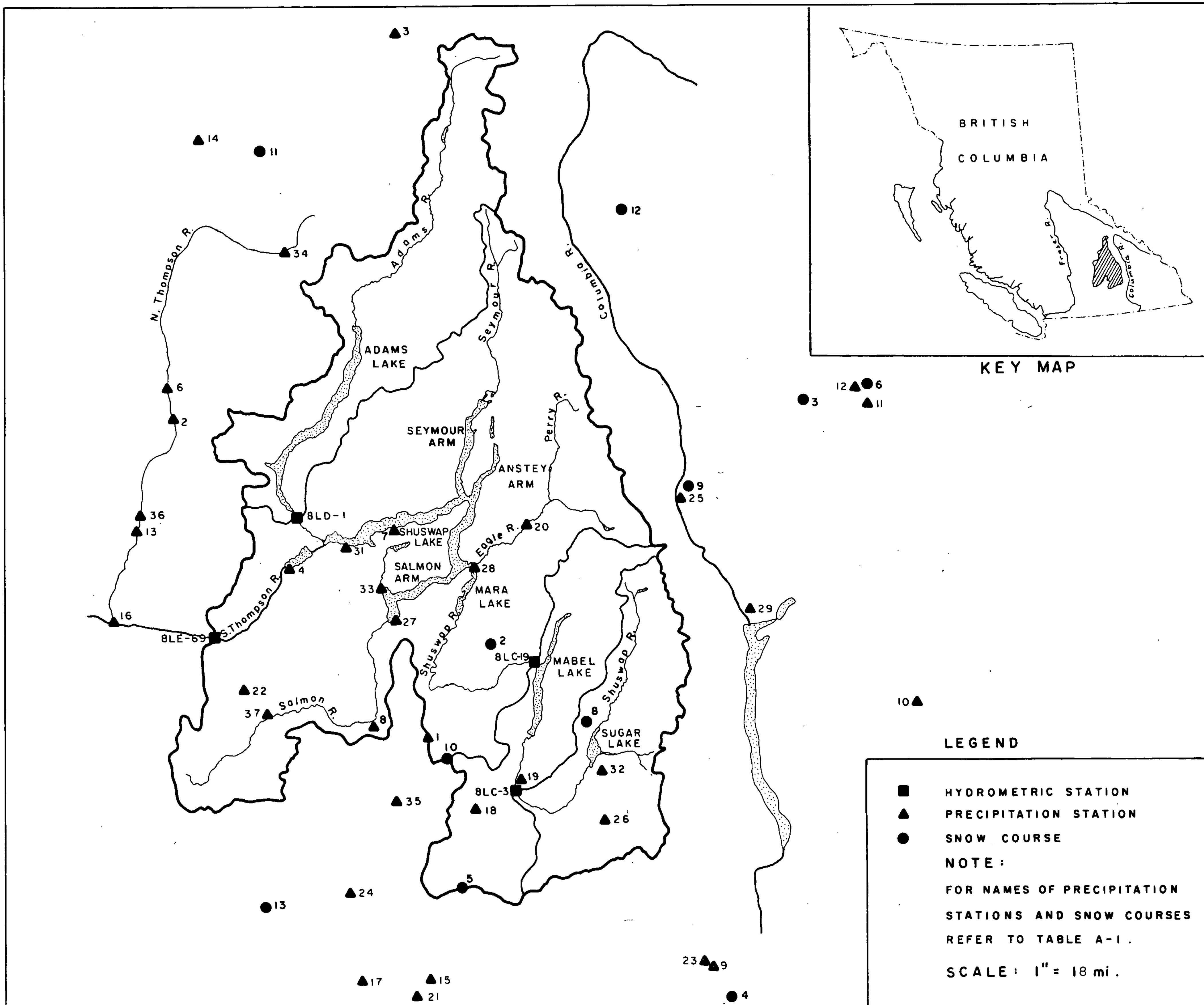

FIGURE A-1 SOUTH THOMPSON RIVER BASIN AND HYDROMETEOROLOGICAL STATIONS.

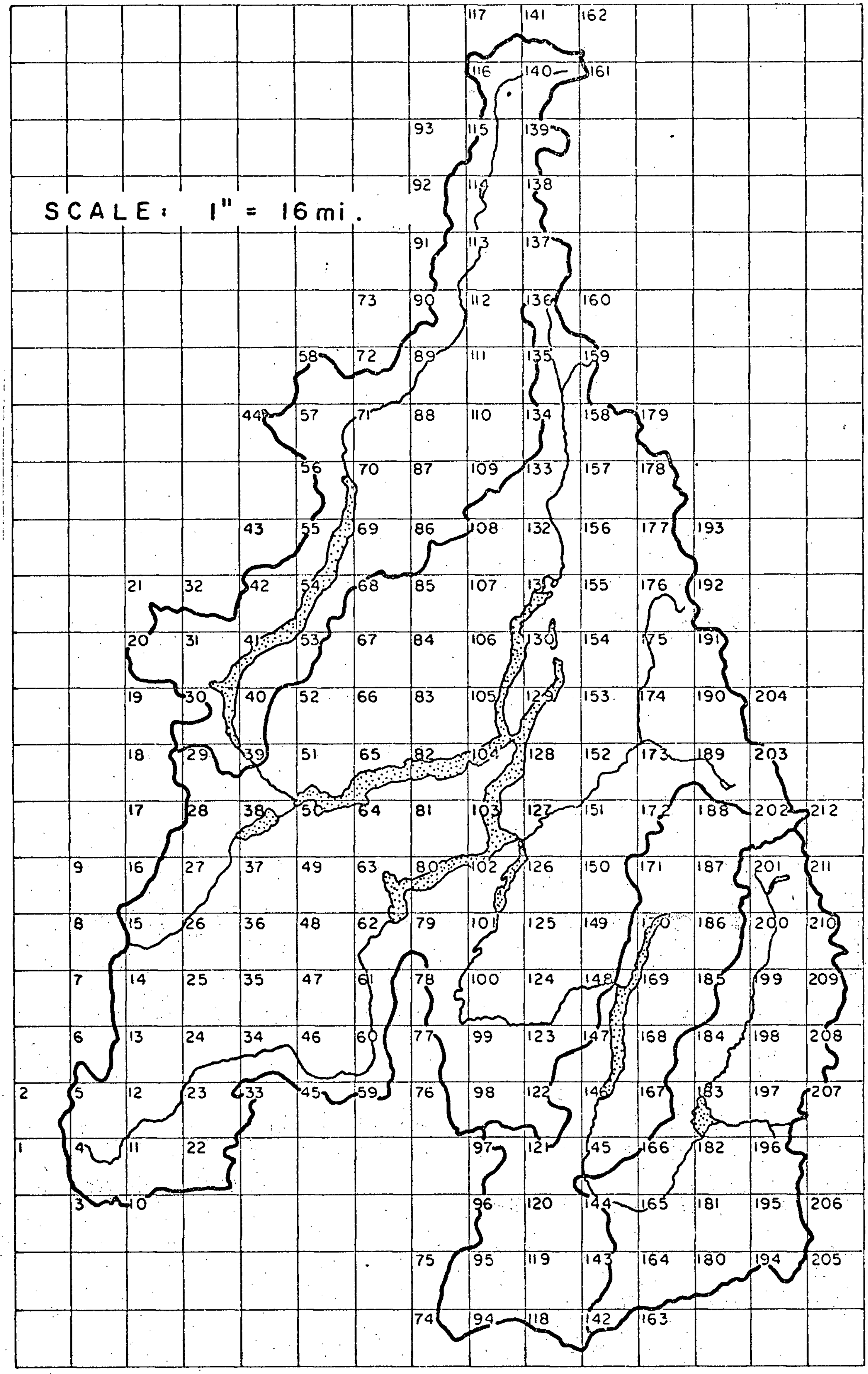

FIGURE A-2 GRID SQUARE LAYOUT.

TABLE A-1 METEOROLOGICAL STATION DATA

Station	Mean Annual Temp. (F.)	Mean Annual Precipitation (inch)	Station Elevation (ft.)	Land Slope (ft./mi.)	Distance to Barrier (km.)	Latitude Index (km.)	Barrier Height (ft.)	Shield Effect (ft.)
1 Armstrong	45.0	18.82	1,190	506	201	151	4,790	9,600
2 Barriere	44.5	14.23	1,280	695	217	235	6,690	11,100
3 Blue River	40.0	48.67	2,240	822	333	335	6,430	10,300
4 Chase	45.9	15.36	1,160	822	208	193	7,420	7,400
5 Chute Lake	39.1	23.29	3,920	885	127	73	3,380	8,000
6 Darfield	-	16.40	1,250	695	225	249	6,600	11,500
7 Eagle Bay	-	24.14	1,180	822	241	204	7,320	7,400
8 Falkland (Salmon R.)	44.6	18.39	1,500	758	194	153	5,210	10,300
9 Faquier	45.8	25.07	1,600	1,454	208	85	4,010	16,400
10 Gerrard	43.2	34.37	2,350	2,149	299	155	4,290	18,100
11 Glacier	37.2	57.11	4,090	2,402	350	239	3,320	12,500
12 Glacier Avalanche	36.5	69.71	3,860	2,655	348	237	3,440	7,400
13 Heffley Creek	42.1	12.87	2,240	442	184	199	6,830	8,300
14 Hemp Creek	39.5	23.77	2,100	822	277	314	7,390	9,600
15 Joe Rich Creek	40.3	22.92	2,870	885	154	86	3,300	7,600
16 Kamloops A	47.4	10.05	1,130	632	164	182	7,510	7,600
17 Kelowna	46.2	11.54	1,590	316	141	86	5,030	6,700
18 Lumby	44.0	17.33	1,700	758	195	128	4,080	7,300
19 Mable Lake	-	21.20	1,310	1,138	210	136	3,560	10,600
20 Malakwa	-	35.02	1,200	1,074	261	204	5,940	7,500
21 McCulloch	37.0	25.08	4,100	253	147	77	2,920	8,900
22 Monte Lake	-	14.51	2,240	822	176	160	5,660	9,000
23 Needles	-	26.06	1,420	822	207	85	5,330	16,400
24 Okanagan Centre	48.0	12.66	1,155	506	155	107	4,600	7,300
25 Revelstoke	45.1	43.17	1,500	1,264	295	201	6,470	7,200
26 Richland	43.8	25.53	2,350	948	215	126	3,480	9,600
27 Salmon Arm	46.0	21.29	1,660	822	217	179	7,340	11,000
28 Sicamous	46.0	25.93	1,400	885	243	193	7,240	11,000
29 Sidmouth	43.0	43.16	1,410	1,074	284	180	6,210	17,400
30 Shuswap Falls	-	21.10	1,450	1,011	206	133	3,990	7,600
31 Sorrento	-	21.15	1,280	442	223	199	7,500	7,400
32 Sugar Lake	43.0	30.53	2,000	1,390	224	139	2,700	10,600
33 Tappen	45.1	20.13	1,450	822	221	188	7,030	10,400
34 Vavenby	43.4	17.05	1,465	1,138	269	279	6,310	16,000
35 Vernon (Coldstream)	45.4	15.28	1,580	1,074	182	131	3,810	7,800
36 Vinsulla	-	12.90	1,170	948	190	206	6,590	9,400
37 Westwold	43.6	12.63	2,025	1,074	176	154	5,290	8,800

TABLE A-1 SNOW COURSE DATA

Station	April 1 Water Equivalent (inch)	Elevation (ft.)	Land Slope (ft./mi.)	Distance to Barrier (km.)	Latitude Index (km.)	Barrier Height (ft.)	Shield Effect (ft.)
1 Albreda Mountain	26.8	6,300	2,971	373	381	7,100	14,800
2 Enderby	32.0	6,250	1,201	227	172	4,200	14,800
3 Fidelity Mountain	52.5	6,150	3,097	336	235	5,500	11,000
4 Koch Creek	29.3	6,100	2,402	206	83	6,000	16,400
5 Mission Creek	19.7	6,000	632	174	104	4,300	10,200
6 Mount Abbot	45.5	6,800	2,465	352	241	5,500	11,000
7 Mount Cook	54.1	6,000	2,149	335	345	6,800	12,300
8 Park Mountain	33.3	6,200	1,327	231	151	4,900	14,200
9 Revelstoke Mountain	45.6	6,000	1,833	300	216	5,400	10,300
10 Silver Star Mountain	23.0	6,050	1,138	200	141	4,900	14,200
11 Trophy Mountain	25.0	6,250	1,643	285	304	6,600	15,400
12 Upper Goldstream	43.3	6,300	2,339	340	288	6,600	22,300
13 White Rock Mountain	19.6	6,000	758	137	103	3,000	5,800

TABLE A-2 GRID SQUARE PHYSIOGRAPHIC DATA

Square No.	Average Elevation (ft.)	Land Slope (ft./mi.)	Distance to Barrier (km.)	Latitude Index (km.)	Shield Effect (ft.)	Area of Lake in Square (sq. km.)	Area of Square in Basin (sq. km.)
1	3,944	190	160	135	6,722	1.00	4.37
2	4,233	316	168	145	6,712	0.00	6.25
3	3,689	126	160	125	6,466	1.05	9.37
4	3,500	126	168	135	6,589	7.26	96.87
5	4,233	695	176	145	6,744	2.42	96.87
6	4,533	316	184	155	6,722	2.42	35.62
7	3,478	695	193	165	7,000	7.66	22.50
8	2,333	632	201	175	7,066	0.80	9.37
9	3,500	506	209	185	7,466	0.00	2.50
10	4,878	885	168	125	6,267	0.80	5.62
11	4,111	1,011	176	135	6,755	0.80	95.62
12	3,700	1,138	184	145	11,211	1.61	100.00
13	3,756	1,264	192	155	6,789	3.63	100.00
14	3,178	695	201	165	6,789	0.00	100.00
15	2,100	506	209	175	7,200	6.45	97.50
16	3,189	885	217	185	7,311	3.63	66.25
17	3,744	1,391	225	195	7,611	2.82	13.75
18	4,578	1,138	234	205	8,234	0.00	7.50
19	4,533	1,327	242	215	8,522	0.00	7.50
20	3,733	1,138	250	225	11,200	0.80	70.50
21	3,433	569	258	235	10,677	2.82	21.70
22	5,111	1,580	184	135	6,400	1.21	77.50
23	4,211	948	192	145	11,422	1.21	99.37
24	3,011	1,075	200	155	11,068	0.00	100.00
25	3,489	759	209	165	6,789	0.80	100.00
26	3,000	1,075	217	175	7,045	1.21	100.00
27	2,444	1,075	225	185	7,356	10.08	100.00
28	2,856	253	233	195	7,556	9.68	94.37
29	3,889	1,264	241	205	7,900	0.00	95.62
30	3,578	1,327	250	215	8,411	14.11	81.87
31	3,422	2,023	258	225	8,389	17.74	100.00
32	3,933	1,138	266	235	11,100	5.65	37.50
33	4,411	948	200	145	11,289	2.82	13.75
34	3,322	1,391	208	155	6,744	0.00	93.12
35	3,844	1,327	216	165	10,966	2.02	100.00
36	3,867	1,580	225	175	6,867	0.00	100.00
37	3,322	1,643	233	185	7,122	0.00	100.00
38	2,022	632	241	195	7,477	21.77	100.00
39	2,633	1,770	249	205	7,833	5.65	100.00
40	4,056	1,454	258	215	8,278	2.42	100.00
41	3,100	1,201	266	225	8,345	25.00	100.00
42	3,278	948	274	235	10,999	7.50	93.12
43	4,278	1,201	282	245	10,711	0.00	20.00
44	5,256	1,201	299	265	14,333	1.21	21.87
45	3,511	1,643	208	145	11,522	0.00	25.62
46	3,322	1,707	216	155	11,211	0.80	100.00
47	4,211	1,075	224	165	11,089	4.44	100.00
48	4,222	948	233	175	7,000	1.61	100.00
49	3,689	1,138	241	185	7,156	1.61	100.00
50	2,178	1,327	249	195	7,311	4.44	100.00
51	2,200	1,075	257	205	7,655	18.54	100.00
52	4,067	1,011	265	215	8,167	0.00	100.00
53	4,000	1,201	274	225	8,522	0.00	100.00
54	3,089	759	282	235	11,200	28.63	100.00
55	3,222	1,327	290	245	10,633	30.24	88.12
56	4,711	948	298	255	13,411	6.45	53.75
57	3,589	1,580	307	265	14,477	0.00	96.87
58	4,189	1,011	315	275	11,200	1.21	74.37
59	2,256	695	216	145	11,278	2.02	18.50
60	2,544	758	224	155	11,288	1.21	66.87
61	2,911	1,327	232	165	11,134	1.21	75.00
62	2,600	948	241	175	10,888	1.61	95.62
63	2,422	948	249	185	10,901	24.19	100.00
64	2,211	695	257	195	7,389	2.82	100.00
65	1,767	442	265	205	7,556	34.27	100.00
66	3,200	2,212	273	215	7,900	0.00	100.00
67	4,489	1,643	282	225	8,411	0.00	100.00

TABLE A-2 GRID SQUARE PHYSIOGRAPHIC DATA

Square No.	Average Elevation (ft.)	Land Slope (ft./mi.)	Distance to Barrier (km.)	Latitude Index (km.)	Shield Effect (ft.)	Area of Lake in Square (sq. km.)	Area of Square in Basin (sq. km.)
68	5,311	2,023	290	235	8,389	1.21	100.00
69	3,567	1,138	298	245	10,677	6.85	100.00
70	3,078	1,391	306	255	10,441	8.87	100.00
71	3,156	1,580	315	265	13,767	2.42	100.00
72	4,200	1,454	323	275	14,734	1.61	71.25
73	4,000	1,011	331	285	14,499	0.00	0.62
74	4,578	190	191	105	7,011	10.48	21.75
75	4,378	253	198	115	7,456	12.90	32.50
76	2,911	1,075	224	145	11,345	1.21	25.62
77	1,622	569	232	155	11,289	1.21	46.62
78	2,144	759	240	165	11,289	5.65	61.75
79	2,433	859	248	175	10,966	1.61	88.12
80	2,489	1,011	257	185	10,723	24.19	100.00
81	3,000	1,327	265	195	7,122	3.63	100.00
82	2,178	822	273	205	7,589	30.65	100.00
83	4,078	1,643	281	215	7,889	0.00	100.00
84	5,078	1,391	290	225	8,322	0.00	100.00
85	5,500	1,327	298	235	8,345	0.00	100.00
86	3,656	1,327	306	245	10,999	4.03	100.00
87	4,100	1,580	314	255	10,488	2.42	100.00
88	3,889	1,011	322	265	13,767	4.84	100.00
89	3,300	1,264	331	275	14,333	2.82	100.00
90	3,867	1,517	347	285	14,733	0.00	71.87
91	3,733	1,580	347	295	14,678	0.80	40.62
92	3,989	1,580	355	305	15,300	4.84	21.25
93	4,089	1,264	364	315	12,156	2.82	3.12
94	4,978	506	199	105	6,966	3.23	31.10
95	4,289	759	207	115	7,355	9.68	100.00
96	2,744	822	215	125	7,667	0.40	72.50
97	3,378	695	223	135	10,833	0.40	48.12
98	3,933	1,391	232	145	11,223	0.00	95.00
99	2,633	1,201	240	155	11,389	0.00	100.00
100	2,567	1,454	248	165	11,045	5.24	100.00
101	3,189	1,138	256	175	11,144	4.84	100.00
102	2,444	1,327	265	185	11,022	22.18	100.00
103	2,144	379	273	195	7,156	33.87	100.00
104	2,089	442	281	205	7,444	37.09	100.00
105	2,711	569	289	215	7,877	23.39	100.00
106	3,489	1,264	297	225	8,145	17.34	100.00
107	3,633	1,264	306	235	8,522	4.84	100.00
108	3,500	1,201	314	245	8,034	5.65	100.00
109	4,522	1,327	322	255	10,633	2.02	100.00
110	4,400	1,011	330	265	13,411	1.61	100.00
111	4,811	1,770	339	275	14,477	6.45	100.00
112	4,544	3,224	347	285	11,200	2.42	100.00
113	4,856	2,844	355	295	14,778	0.00	100.00
114	4,378	2,149	363	305	14,955	3.63	100.00
115	4,700	1,517	371	315	12,156	3.63	83.12
116	5,000	2,212	380	325	12,444	2.42	64.37
117	5,378	2,212	388	335	12,133	4.44	20.62
118	5,722	506	207	105	6,956	4.84	49.25
119	4,656	1,327	215	115	7,267	0.80	100.00
120	2,889	569	223	125	7,489	1.61	100.00
121	2,567	948	231	135	10,578	0.80	100.00
122	2,933	632	240	145	10,001	1.21	100.00
123	2,800	1,264	248	155	11,278	0.00	100.00
124	3,078	1,517	256	165	11,288	3.23	100.00
125	4,944	1,517	264	175	11,134	0.00	100.00
126	4,678	1,327	272	185	10,888	2.82	100.00
127	3,167	1,517	281	195	7,200	5.24	100.00
128	3,567	1,075	289	205	7,311	3.63	100.00
129	3,356	1,391	297	215	7,556	20.16	100.00
130	2,356	1,517	305	225	7,900	18.95	100.00
131	2,489	1,011	314	235	8,322	16.93	100.00
132	2,800	1,011	322	245	8,389	1.61	100.00
133	3,989	1,770	330	255	10,677	1.61	100.00
134	5,200	1,264	338	265	10,411	1.61	100.00

TABLE A-2 GRID SQUARE PHYSIOGRAPHIC DATA

Square No.	Average Elevation (ft.)	Land Slope (ft./mi.)	Distance to Barrier (km.)	Latitude Index (km.)	Shield Effect (ft.)	Area of Lake in Square (sq. km.)	Area of Square in Basin (sq. km.)
135	5,433	2,781	346	275	13,756	5.24	100.00
136	5,422	1,580	355	285	14,734	4.44	83.75
137	6,133	2,465	363	295	14,555	0.80	87.50
138	5,756	2,718	371	305	14,900	1.61	47.50
139	6,189	2,908	379	315	15,244	1.61	63.12
140	5,867	2,908	388	325	12,555	1.61	71.25
141	6,033	2,592	396	335	12,267	0.80	35.00
142	5,633	190	215	105	7,289	4.84	38.70
143	4,456	758	223	115	7,011	4.03	100.00
144	3,422	1,138	231	125	7,456	4.84	100.00
145	3,200	1,327	239	135	10,589	3.23	100.00
146	2,789	1,201	247	145	11,011	7.26	100.00
147	3,089	1,580	256	155	11,367	25.40	100.00
148	2,489	1,075	264	165	11,244	19.35	100.00
149	3,089	1,327	272	175	11,090	1.61	100.00
150	4,900	1,833	280	185	10,966	0.80	100.00
151	4,489	1,707	289	195	10,856	0.80	100.00
152	3,356	1,391	297	205	7,333	2.42	100.00
153	3,967	2,086	305	215	7,589	0.00	100.00
154	4,300	3,160	313	225	7,889	0.00	100.00
155	5,167	3,097	321	235	8,189	0.00	100.00
156	4,900	2,086	330	245	8,322	2.42	100.00
157	4,222	1,770	338	255	10,655	3.23	100.00
158	5,122	2,149	346	265	10,532	2.82	96.87
159	5,711	1,707	354	275	13,767	6.45	35.00
160	5,633	2,275	363	285	14,489	2.42	9.37
161	5,111	1,896	396	325	12,244	0.00	8.12
162	5,422	2,971	404	335	12,600	0.00	3.75
163	4,944	569	222	105	7,322	0.00	0.62
164	3,756	1,896	231	115	7,011	0.00	95.00
165	3,089	759	239	125	7,355	1.21	100.00
166	3,444	1,327	247	135	7,667	2.42	100.00
167	4,056	1,391	255	145	10,833	2.02	100.00
168	4,944	1,075	264	155	11,256	0.00	100.00
169	4,467	2,465	272	165	11,389	4.44	100.00
170	3,677	2,339	280	175	11,178	15.32	100.00
171	3,256	1,327	288	185	11,144	1.21	100.00
172	4,489	1,833	297	195	11,022	0.80	100.00
173	3,989	2,023	305	205	7,066	0.00	100.00
174	3,256	1,833	313	215	7,444	0.00	100.00
175	4,500	2,339	321	225	7,877	1.21	100.00
176	6,156	3,413	329	235	8,278	2.02	100.00
177	6,256	3,160	338	245	8,345	0.80	88.75
178	5,189	1,770	346	255	8,034	6.45	84.37
179	5,467	2,655	354	265	10,633	2.02	26.25
180	3,822	2,149	239	115	6,956	0.00	66.87
181	3,533	1,391	247	125	7,267	0.00	100.00
182	4,422	1,770	255	135	7,489	2.42	100.00
183	4,044	1,391	263	145	10,578	23.79	100.00
184	4,311	1,770	272	155	11,001	4.03	100.00
185	4,822	1,075	280	165	11,522	1.21	100.00
186	5,522	2,212	288	175	11,288	0.80	100.00
187	4,856	1,896	296	185	11,011	1.61	100.00
188	4,144	1,833	304	195	10,922	2.42	100.00
189	4,200	2,086	313	205	7,200	3.23	100.00
190	4,889	1,707	321	215	7,311	2.02	96.87
191	5,956	2,275	329	225	7,556	3.23	65.62
192	7,067	2,149	337	235	8,234	0.00	12.50
193	6,489	2,465	346	245	8,522	0.80	6.25
194	5,178	1,770	247	115	7,289	0.00	38.12
195	5,200	2,592	255	125	7,344	0.00	97.50
196	4,756	1,580	263	135	7,456	0.40	89.37
197	5,089	2,275	271	145	10,589	1.21	93.75
198	4,478	1,707	279	155	11,011	2.02	100.00
199	4,467	2,781	288	165	11,278	0.40	100.00
200	4,756	1,770	296	175	11,422	2.02	100.00
201	5,578	2,212	304	185	11,068	4.03	100.00

TABLE A-2 GRID SQUARE PHYSIOGRAPHIC DATA

Square No.	Average Elevation (ft.)	Land Slope (ft./mi.)	Distance to Barrier (km.)	Latitude Index (km.)	Shield Effect (ft.)	Area of Lake in Square (sq. km.)	Area of Square in Basin (sq. km.)
202	5,344	3,097	312	195	10,922	2.02	92.50
203	4,878	1,959	321	205	10,856	1.61	55.00
204	4,633	2,149	329	215	7,333	0.00	1.87
205	4,711	1,959	254	115	7,322	0.00	1.25
206	5,667	3,540	263	125	7,011	2.42	5.00
207	4,900	2,023	279	145	7,667	0.80	10.00
208	6,244	1,580	287	155	10,922	6.00	47.50
209	5,744	3,287	296	165	11,366	2.02	69.37
210	5,911	2,592	304	175	11,289	4.43	56.25
211	5,467	2,465	312	185	11,233	0.00	20.62
212	4,200	2,592	302	195	10,966	0.80	3.75

TABLE A-3 GRID SQUARE SUB-BASIN AREAS

	Area of Square in Sub-Basin (sq. km.)				
Sq. No.	8LC-3 Sugar Lake	8LC-19 Mable Lake	8LD-1 Adams Lake	8LE-69 Shuswap Lake	Total
1	-	-	-	4.37	4.37
2	-	-	-	6.25	6.25
3	-	-	-	9.37	9.37
4	-	-	-	96.87	96.87
5	-	-	-	96.87	96.87
6	-	-	-	35.62	35.62
7	-	-	-	22.50	22.50
8	-	-	-	9.37	9.37
9	-	-	-	2.50	2.50
10	-	-	-	5.62	5.62
11	-	-	-	95.62	95.62
12	-	-	-	100.00	100.00
13	-	-	-	100.00	100.00
14	-	-	-	100.00	100.00
15	-	-	-	97.50	97.50
16	-	-	-	66.25	66.25
17	-	-	-	13.75	13.75
18	-	-	0.62	6.88	7.50
19	-	-	7.50	-	7.50
20	-	-	70.50	-	70.50
21	-	-	21.70	-	21.70
22	-	-	-	77.50	77.50
23	-	-	-	99.37	99.37
24	-	-	-	100.00	100.00
25	-	-	-	100.00	100.00
26	-	-	-	100.00	100.00
27	-	-	-	100.00	100.00
28	-	-	-	94.37	94.37
29	-	-	20.62	75.00	95.62
30	-	-	81.87	-	81.87
31	-	-	100.00	-	100.00
32	-	-	37.50	-	37.50
33	-	-	-	13.75	13.75
34	-	-	-	93.12	93.12
35	-	-	-	100.00	100.00
36	-	-	-	100.00	100.00
37	-	-	-	100.00	100.00
38	-	-	-	100.00	100.00
39	-	-	18.75	81.25	100.00
40	-	-	56.25	43.75	100.00
41	-	-	98.13	1.87	100.00
42	-	-	93.12	-	93.12
43	-	-	20.00	-	20.00
44	-	-	21.87	-	21.87
45	-	-	-	25.62	25.62
46	-	-	-	100.00	100.00
47	-	-	-	100.00	100.00
48	-	-	-	100.00	100.00
49	-	-	-	100.00	100.00
50	-	-	-	100.00	100.00
51	-	-	-	100.00	100.00
52	-	-	-	100.00	100.00
53	-	-	35.62	64.38	100.00
54	-	-	87.50	12.50	100.00
55	-	-	88.12	-	88.12
56	-	-	53.75	-	53.75
57	-	-	96.87	-	96.87
58	-	-	74.37	-	74.37
59	-	-	-	18.50	18.50
60	-	-	-	66.87	66.87
61	-	-	-	75.00	75.00
62	-	-	-	95.62	95.62
63	-	-	-	100.00	100.00
64	-	-	-	100.00	100.00
65	-	-	-	100.00	100.00
66	-	-	-	100.00	100.00
67	-	-	-	100.00	100.00
68	-	-	5.63	94.37	100.00
69	-	-	4.37	95.63	100.00
70	-	-	100.00	-	100.00
71	-	-	100.00	-	100.00

TABLE A-3 GRID SQUARE SUB-BASIN AREAS

	Area of Square in Sub-Basin (sq. km.)				
Sq. No.	8LC-3 Sugar Lake	8LC-19 Mable Lake	8LD-1 Adams Lake	8LE-69 Shuswap Lake	Total
72	-	-	71.25	-	71.25
73	-	-	0.62	-	0.62
74	-	21.75	-	-	21.75
75	-	32.50	-	-	32.50
76	-	-	-	25.62	25.62
77	-	-	-	46.62	46.62
78	-	-	-	61.75	61.75
79	-	-	-	88.12	88.12
80	-	-	-	100.00	100.00
81	-	-	-	100.00	100.00
82	-	-	-	100.00	100.00
83	-	-	-	100.00	100.00
84	-	-	-	100.00	100.00
85	-	-	-	100.00	100.00
86	-	-	55.63	44.37	100.00
87	-	-	100.00	-	100.00
88	-	-	100.00	-	100.00
89	-	-	100.00	-	100.00
90	-	-	71.87	-	71.87
91	-	-	40.62	-	40.62
92	-	-	21.25	-	21.25
93	-	-	3.12	-	3.12
94	-	31.10	-	-	31.10
95	-	100.00	-	-	100.00
96	-	72.50	-	-	72.50
97	-	48.12	-	-	48.12
98	-	13.12	-	81.88	95.00
99	-	-	-	100.00	100.00
100	-	-	-	100.00	100.00
101	-	-	-	100.00	100.00
102	-	-	-	100.00	100.00
103	-	-	-	100.00	100.00
104	-	-	-	100.00	100.00
105	-	-	-	100.00	100.00
106	-	-	-	100.00	100.00
107	-	-	-	100.00	100.00
108	-	-	3.75	96.25	100.00
109	-	-	46.87	53.13	100.00
110	-	-	100.00	-	100.00
111	-	-	100.00	-	100.00
112	-	-	100.00	-	100.00
113	-	-	100.00	-	100.00
114	-	-	100.00	-	100.00
115	-	-	83.12	-	83.12
116	-	-	64.37	-	64.37
117	-	-	20.62	-	20.62
118	-	49.25	-	-	49.25
119	-	100.00	-	-	100.00
120	-	100.00	-	-	100.00
121	-	93.75	-	6.25	100.00
122	-	36.25	-	63.75	100.00
123	-	20.00	-	80.00	100.00
124	-	-	-	100.00	100.00
125	-	-	-	100.00	100.00
126	-	-	-	100.00	100.00
127	-	-	-	100.00	100.00
128	-	-	-	100.00	100.00
129	-	-	-	100.00	100.00
130	-	-	-	100.00	100.00
131	-	-	-	100.00	100.00
132	-	-	-	100.00	100.00
133	-	-	1.25	98.75	100.00
134	-	-	37.50	62.50	100.00
135	-	-	33.13	66.87	100.00
136	-	-	28.13	55.62	83.75
137	-	-	87.50	-	87.50
138	-	-	47.50	-	47.50
139	-	-	63.12	-	63.12
140	-	-	71.25	-	71.25
141	-	-	35.00	-	35.00
142	26.20	12.50	-	-	38.70

TABLE A-3 GRID SQUARE SUB-BASIN AREAS

	Area of Square in Sub-Basin (sq. km.)				
Sq. No.	8LC-3 Sugar Lake	8LC-19 Mable Lake	8LD-1 Adams Lake	8LE-69 Shuswap Lake	Total
143	48.13	51.87	-	-	100.00
144	50.62	49.38	-	-	100.00
145	40.00	60.00	-	-	100.00
146	-	100.00	-	-	100.00
147	-	87.50	-	12.50	100.00
148	-	46.87	-	53.13	100.00
149	-	11.25	-	88.75	100.00
150	-	3.75	-	96.25	100.00
151	-	-	-	100.00	100.00
152	-	-	-	100.00	100.00
153	-	-	-	100.00	100.00
154	-	-	-	100.00	100.00
155	-	-	-	100.00	100.00
156	-	-	-	100.00	100.00
157	-	-	-	100.00	100.00
158	-	-	-	96.87	96.87
159	-	-	-	35.00	35.00
160	-	-	-	9.37	9.37
161	-	-	8.12	-	8.12
162	-	-	3.75	-	3.75
163	.62	-	-	-	0.62
164	95.00	-	-	-	95.00
165	100.00	-	-	-	100.00
166	93.75	6.25	-	-	100.00
167	38.13	61.87	-	-	100.00
168	21.81	78.19	-	-	100.00
169	-	100.00	-	-	100.00
170	-	100.00	-	-	100.00
171	-	93.75	-	6.25	100.00
172	-	56.25	-	43.75	100.00
173	-	6.25	-	93.75	100.00
174	-	-	-	100.00	100.00
175	-	-	-	100.00	100.00
176	-	-	-	100.00	100.00
177	-	-	-	88.75	88.75
178	-	-	-	84.37	84.37
179	-	-	-	26.25	26.25
180	66.87	-	-	-	66.87
181	100.00	-	-	-	100.00
182	100.00	-	-	-	100.00
183	100.00	-	-	-	100.00
184	98.75	1.25	-	-	100.00
185	48.12	51.88	-	-	100.00
186	8.75	91.25	-	-	100.00
187	13.13	86.87	-	-	100.00
188	1.25	95.00	-	3.75	100.00
189	-	11.25	-	88.75	100.00
190	-	-	-	96.87	96.87
191	-	-	-	65.62	65.62
192	-	-	-	12.50	12.50
193	-	-	-	6.25	6.25
194	38.12	-	-	-	38.12
195	97.50	-	-	-	97.50
196	89.37	-	-	-	89.37
197	93.75	-	-	-	93.75
198	100.00	-	-	-	100.00
199	100.00	-	-	-	100.00
200	100.00	-	-	-	100.00
201	96.87	3.13	-	-	100.00
202	30.62	45.62	-	16.26	92.50
203	-	-	-	55.00	55.00
204	-	-	-	1.87	1.87
205	1.25	-	-	-	1.25
206	5.00	-	-	-	5.00
207	10.00	-	-	-	10.00
208	47.50	-	-	-	47.50
209	69.37	-	-	-	69.37
210	56.25	-	-	-	56.25
211	20.62	-	-	-	20.62
212	1.87	1.88	-	-	3.75
					16,447.00

APPENDIX B

MONTHLY REGRESSION EQUATIONS FOR THE THORNTHWAITE APPROACH OF THE GRID SQUARE METHOD

B.1 Estimation of Monthly Temperature Distribution

B.2 Estimation of Monthly Precipitation Distribution

B.3 Estimation of Monthly Precipitation Distribution

B.1 Estimation of Monthly Temperature Distribution

As discussed in section 5.2, page 25, the twelve regression equations for mean monthly temperature are:

$$T1 = 28.1903 - 0.002675E - 0.00006324L^2 \quad \text{....(B.1)}$$

$$T2 = 29.9052 - 0.0000005027E^2 - 0.00004295L^2 \quad \text{....(B.2)}$$

$$T3 = 41.1399 - 0.003314E - 0.00003267L^2 \quad \text{....(B.3)}$$

$$T4 = 54.5055 - 0.003337E - 0.0170DB \quad \text{....(B.4)}$$

$$T5 = 60.3414 - 0.003647E \quad \text{....(B.5)}$$

$$T6 = 66.2320 - 0.003410E \quad \text{....(B.6)}$$

$$T7 = 71.4715 - 0.003342E \quad \text{....(B.7)}$$

$$T8 = 70.1207 - 0.003307E - 0.00003050L^2 \quad \text{....(B.8)}$$

$$T9 = 61.2753 - 0.002820E - 0.00003509L^2 \quad \text{....(B.9)}$$

$$T10 = 50.0519 - 0.002385E - 0.00003762L^2 \quad \text{....(B.10)}$$

$$T11 = 41.7830 - 0.003236E - 0.0182L \quad \text{....(B.11)}$$

$$T12 = 35.8599 - 0.003191E - 0.0229L \quad \text{....(B.12)}$$

where, T1 through T12 inclusive, are mean monthly temperatures for January through December inclusive, E is station elevation in feet, L is latitude index in kilometers and DB is distance to barrier in kilometers.

B.2 Estimation of Monthly Precipitation Distribution

As discussed in section 5.3, page 27, the twelve regression equations (using normal Stpreg routine of UBC Trip) for mean monthly precipitation are:

$$P1 = 5.3639 - 0.0474DB + 0.0001803DB^2 - 0.00003784L^2 \quad \text{....(B.13)}$$

$$P2 = 6.0267 - 0.0473DB - 0.0111L + 0.0001632DB^2 \quad \text{....(B.14)}$$

$$P3 = 0.3673 - 0.009609L + 0.00005179DB^2 + 0.00000009314E^2 - 0.0000002140HS^2 \quad \text{....(B.15)}$$

$$P4 = 0.6401 - 0.005257L + 0.00003020DB^2 + 0.00000004901E^2 - 0.000000001840SE^2 \quad \text{....(B.16)}$$

$$P5 = 0.5333 + 0.0003027E + 0.00001089DB^2 \quad \text{....(B.17)}$$

$$P6 = 1.1550 + 0.00002069DB^2 \quad \text{....(B.18)}$$

$$P7 = 0.3615 + 0.0002073E + 0.00001713DB^2 \quad \text{....(B.19)}$$

$$P8 = 0.7460 + 0.00002041DB^2 \quad \text{....(B.20)}$$

$$P9 = 0.1776 + 0.0003149E + 0.00002154DB^2 \quad \text{....(B.21)}$$

$$P10 = 0.8348 - 0.009903L + 0.00005539DB^2 \quad \text{....(B.22)}$$

$$P11 = 5.8083 - 0.0452DB - 0.0119L + 0.0001676DB^2 \quad \text{....(B.23)}$$

$$P12 = 1.1343 - 0.0173L + 0.00009395DB^2 \quad \text{....(B.24)}$$

where, P1 through P12 inclusive, are mean monthly precipitations for January through December inclusive, DB is distance to barrier in kilometers, L is latitude index in kilometers, E is elevation in feet, HS is average land slope and SE is shield effect in feet.

B.3 Estimation of Monthly Precipitation Distribution

As discussed in section 5.3, page 27, the twelve regression equations (using Stpreg with elevation included into the regression equation regardless of significance) for mean monthly precipitation are:

$$P1 = -0.2672 + 0.00000008047E^2 + 0.00007911DB^2 - 0.00003614L^2 \quad \ldots(B.25)$$

$$P2 = -0.5433 + 0.00000009233E^2 + 0.00006207DB^2 - 0.00002806L^2 \quad \ldots(B.26)$$

$$P3 = 0.3673 - 0.009609L + 0.00000009314E^2 + 0.00005179DB^2 - 0.0000002140HS^2 \quad \ldots(B.27)$$

$$P4 = 0.6401 - 0.005257L + 0.00000004901E^2 + 0.00003020DB^2 - 0.000000001840SE^2 \quad \ldots(B.28)$$

$$P5 = 0.2283 + 0.005282DB + 0.00000006386E^2 \quad \ldots(B.29)$$

$$P6 = -0.0397 + 0.009214DB + 0.00000005461E^2 \quad \ldots(B.30)$$

$$P7 = -0.3860 + 0.008248DB + 0.00000004779E^2 \quad \ldots(B.31)$$

$$P8 = -0.4172 + 0.009190DB + 0.00000004510E^2 \quad \ldots(B.32)$$

$$P9 = -0.7209 + 0.0104DB + 0.00000007275E^2 \quad \ldots(B.33)$$

$$P10 = 0.6477 - 0.008663L + 0.00000003493E^2 + 0.00005202DB^2 \quad \ldots(B.34)$$

$$P11 = -0.6099 + 0.00000009757E^2 + 0.00006920DB^2 - 0.00002810L^2 \quad \ldots(B.35)$$

$$P12 = -0.5036 + 0.00000008138E^2 + 0.00008608DB^2 - 0.00003795L^2 \quad \ldots(B.36)$$

APPENDIX C

COMPUTER PROGRAMS

Program C-1 Comparison of Thornthwaite's and Turc's Evaporation Methods

Program C-2 Snow-Melt Model and Plot

Program C-3 Experimental Grid Square Method

Program C-4 Experimental Grid Square Method With Snow Courses Added

Program C-1 Comparison of Thornthwaite's and Turc's Evaporation Methods

Both the Thornthwaite and Turc methods were programmed and the following program gives the details involved in both methods. Data was taken from Reference 7 (Glacier, B.C.).

Lines 0005 to 0115, inclusive, comprise the Thornthwaite method of calculating evapotranspiration. The following list describes the highlights of this part of the program:

Lines	Description
10 to 21	Coefficients C_k of Equation 3.6
32 to 44	Equations 3.3 through 3.6 of section 3.1
45 to 115	Calculation of actual evapotranspiration and runoff. Operations were derived from the descriptions on pages 190 to 193, inclusive, of Reference 9
61 to 65	Equation 3.7 in which S is given four different values in each of the four trials

Lines 0116 to 0124 inclusive, comprise Turc's formula that is described in section 3.1 (Formulas 3.1 and 3.2). The output on the fourth page consists of four trial runs, one for each value of soil moisture holding capacity S (16, 14, 12 and 10 inches). The format of the output is similar to that used in Reference 9.

The notation used is as follows:

T(*F)	Temperature (degrees Fahrenheit)
P	Precipitation
PE	Potential Evapotranspiration
P-PE	Precipitation minus Potential Evapotranspiration
ACC-P-WL	Accumulated Potential Water Loss
ST	Soil Moisture Storage
CH-ST	Change in Soil Moisture
AE	Actual Evapotranspiration
P-AE	Precipitation minus Actual Evapotranspiration

```
0001            DIMENSION IX(20)
0002            READ (5,50) (IX(I),I=1,20)
0003            WRITE (6,50) (IX(I),I=1,20)
0004      50    FORMAT (20A4)
          C
          C     CALCULATION OF EVAPORATION BY THORNTHWAITE'S METHOD
          C
0005            SMCAP = 16.
0006            REAL INDEX,II
0007            DIMENSION T(12),CTEMP(12),II(12),E(12),C(12)
0008            DIMENSION P(12),PERNF(12),ACCPWL(12),ST(12),CHST(12),AE(12),
               1          AERNF(12)
0009            DIMENSION ARG(12)
0010            C(1) = 0.74
0011            C(2) = 0.78
0012            C(3) = 1.02
0013            C(4) = 1.15
0014            C(5) = 1.33
0015            C(6) = 1.36
0016            C(7) = 1.37
0017            C(8) = 1.25
0018            C(9) = 1.06
0019            C(10) = 0.92
0020            C(11) = 0.76
0021            C(12) = 0.70
0022            INDEX = 0.0
0023            TEVAP = 0.0
0024            TTOT = 0.0
0025            PTOT = 0.0
0026            READ (5,5) (T(K), K=1,12)
0027      5     FORMAT (12F6.1)
0028            READ(5,6) (P(K),K=1,12)
0029      6     FORMAT(12F6.2)
0030            DO 10 K=1,12
0031            CTEMP(K) = (T(K) - 32.)*(5./9.)
          C
          C     INPUT DATA- TEMP. (*F)
          C                 PREC. (IN.)
0032            IF (CTEMP(K).LE.0.0) II(K) = 0.0
0033            IF (CTEMP(K).LE.0.0) GO TO 10
0034            II(K) = (CTEMP(K)/5.)**1.514
0035      10    INDEX = INDEX + II(K)
0036            DO 11 K=1,12
0037            PTOT = PTOT + P(K)
0038      11    TTOT = TTOT + T(K)
0039            FAVG = TTOT/12.
0040            F = 0.93/(2.42 - ALOG10(INDEX))
0041            DO 15 K=1,12
0042            IF (CTEMP(K).LE.0.0) E(K) = 0.0
0043            IF (CTEMP(K).LE.0.0) GO TO 15
0044            E(K) = C(K)* EXP(2.303*(0.204 + F*(1. - ALOG10(INDEX)) + F*ALOG10(
               1CTEMP(K))))/2.54
          C
          C     E(K) IS COMPUTED IN CM. BUT CHANGED INTO IN.
          C
```

```
15    TEVAP = TEVAP + E(K)
1     CONTINUE
      J = 0
      AETOT = 0.0
      AERTOT = 0.0
      PERTOT = 0.0
      DO 16 K=1,12
      PERNF(K) = P(K) - E(K)
16    PERTOT = PERTOT + PERNF(K)
      IF(PERTOT.LT.0.0) GO TO 30
      DO 17 K=1,12
      IF(PERNF(K).GT.0.0) ACCPWL(K) = 0.0
      IF(PERNF(K).LT.0.0) ACCPWL(K) = PERNF(K)
17    IF(PERNF(K).LT.0.0) ACCPWL(K) = ACCPWL(K) + ACCPWL(K-1)
      DO 19 K=1,12
      IF(ACCPWL(K).EQ.0.0) GO TO 18
      IF(SMCAP.EQ.16.) ARG(K) = ALOG10(16.) - 0.02718513*(-ACCPWL(K))
      IF(SMCAP.EQ.14.) ARG(K) = ALOG10(14.) - 0.03105843*(-ACCPWL(K))
      IF(SMCAP.EQ.12.) ARG(K) = ALOG10(12.) - 0.03627738*(-ACCPWL(K))
      IF(SMCAP.EQ.10.) ARG(K) = ALOG10(10.) - 0.04330699*(-ACCPWL(K))
      ST(K) = EXP(2.303*ARG(K))
      J = J + 1
      GO TO 19
18    IF(CTEMP(K).GT.0.0) ST(K) = SMCAP
      IF(CTEMP(K).LT.0.0) ST(K) = SMCAP + PERNF(K)
      IF(K.GT.1) ST(K) = ST(K-1) + P(K)
      IF(J.GT.0) ST(K) = ST(K-1) + PERNF(K)
      IF(CTEMP(K).LT.0.0) GO TO 19
      IF(ST(K).GT.SMCAP) ST(K) = SMCAP
19    CONTINUE
      DO 20 K=1,12
      IF(K.EQ.1) CHST(K) = 0.0
      IF(K.EQ.1) GO TO 20
      CHST(K) = -(ST(K-1) - ST(K))
      IF(CTEMP(K).LE.0.0) CHST(K) = 0.0
      IF(ST(K-1).GE.SMCAP) CHST(K) = 0.0
20    CONTINUE
      DO 21 K=1,12
      AE(K) = P(K) + (-CHST(K))
      IF(CHST(K).GE.0.0) AE(K) = E(K)
21    CONTINUE
      DO 22 K=1,12
      AERNF(K) = P(K) - AE(K)
22    AERTOT = AERTOT + AERNF(K)
      DO 28 K=1,12
28    AETOT = AETOT + AE(K)
      GO TO 32
30    DO 31 K=1,12
      AE(K) = P(K)
      AERNF(K) = P(K) - AE(K)
      AETOT = AETOT + AE(K)
31    AERTOT = AERTOT + AERNF(K)
32    WRITE(6,40) (T(K),K=1,12),FAVG
      WRITE(6,41) (P(K),K=1,12),PTOT
      WRITE(6,42) (E(K),K=1,12),TEVAP
```

```
             WRITE(6,43) (PERNF(K),K=1,12),PERTOT
             IF(PERTOT.LT.0.0) GO TO 33
             WRITE(6,44) (ACCPWL(K),K=1,12)
             WRITE(6,45) (ST(K),K=1,12)
             WRITE(6,46) (CHST(K),K=1,12)
       33    WRITE(6,47) (AE(K),K=1,12),AETOT
             WRITE(6,48) (AERNF(K),K=1,12),AERTOT
       40    FORMAT('T(*F)    ',12F6.1,F8.1)
       41    FORMAT('P        ',12F6.1,F8.1)
       42    FORMAT('PE       ',12F6.1,F8.1)
       43    FORMAT('P-PE     ',12F6.1,F8.1)
       44    FORMAT('ACC-P-WL',12F6.1)
       45    FORMAT('ST       ',12F6.1)
       46    FORMAT('CH-ST    ',12F6.1)
       47    FORMAT('AE       ',12F6.1,F8.1)
       48    FORMAT('P-AE     ',12F6.1,F8.1)
       C
       C      CALCULATION OF EVAPORATION BY TURC'S METHOD
       C     INPUT INTO TURC'S EQ'N IS *C & MM.
       C
             CT = (FAVG - 32.)*(5./9.)
             PP = PTOT*25.4
             FPPT = 300. + 25.*CT + 0.05*CT*CT*CT
             EVAP = PP/SQRT(0.9 + (PP/FPPT)*(PP/FPPT))
             EVAP = EVAP/25.4
             PREC = PP/25.4
             RTUR = PREC - EVAP
             WRITE (6,60) PREC,EVAP,RTUR
       60    FORMAT(/'  PREC.=',F5.1,'  (TURC)EVAP.=',F5.1,'  RNF.=',F5.1/)
             SMCAP = SMCAP - 2.
             IF(SMCAP.EQ.8.) STOP
             GO TO 1
             END
```

```
EXECUTION TERMINATED


$RUN -LOAD#
EXECUTION BEGINS
DATA FROM GLACIER (D.O.T. PUBLICATION)
T(*F)       13.5  18.4  26.5  36.0  45.4  52.7  57.9  55.8  48.3  37.4  24.3  18.4     36.2
P            7.7   6.1   5.0   3.1   2.6   3.3   2.9   2.8   3.7   5.0   6.7   8.3     57.1
PE           0.0   0.0   0.0   0.9   2.6   3.8   4.5   3.9   2.4   0.9   0.0   0.0     19.0
P-PE         7.7   6.1   5.0   2.2  -0.0  -0.5  -1.7  -1.1   1.3   4.2   6.7   8.3     38.1
ACC-P-WL     0.0   0.0   0.0   0.0  -0.0  -0.6  -2.2  -3.3   0.0   0.0   0.0   0.0
ST          23.7  29.8  34.8  16.0  16.0  15.5  13.9  13.0  14.3  16.0  22.7  31.0
CH-ST        0.0   0.0   0.0   0.0   0.0  -0.5  -1.5  -0.9   1.3   1.7   0.0   0.0
AE           0.0   0.0   0.0   0.9   2.6   3.8   4.4   3.7   2.4   0.9   0.0   0.0     18.7
P-AE         7.7   6.1   5.0   2.2  -0.0  -0.5  -1.5  -0.9   1.3   4.2   6.7   8.3     38.4

 PREC.= 57.1   (TURC)EVAP.= 13.8   RNF.= 43.3

T(*F)       13.5  18.4  26.5  36.0  45.4  52.7  57.9  55.8  48.3  37.4  24.3  18.4     36.2
P            7.7   6.1   5.0   3.1   2.6   3.3   2.9   2.8   3.7   5.0   6.7   8.3     57.1
PE           0.0   0.0   0.0   0.9   2.6   3.8   4.5   3.9   2.4   0.9   0.0   0.0     19.0
P-PE         7.7   6.1   5.0   2.2  -0.0  -0.5  -1.7  -1.1   1.3   4.2   6.7   8.3     38.1
ACC-P-WL     0.0   0.0   0.0   0.0  -0.0  -0.6  -2.2  -3.3   0.0   0.0   0.0   0.0
ST          21.7  27.8  32.8  14.0  14.0  13.5  11.9  11.0  12.4  14.0  20.7  29.0
CH-ST        0.0   0.0   0.0   0.0   0.0  -0.5  -1.5  -0.9   1.3   1.6   0.0   0.0
AE           0.0   0.0   0.0   0.9   2.6   3.8   4.4   3.7   2.4   0.9   0.0   0.0     18.6
P-AE         7.7   6.1   5.0   2.2  -0.0  -0.5  -1.5  -0.9   1.3   4.2   6.7   8.3     38.5

 PREC.= 57.1   (TURC)EVAP.= 13.8   RNF.= 43.3

T(*F)       13.5  18.4  26.5  36.0  45.4  52.7  57.9  55.8  48.3  37.4  24.3  18.4     36.2
P            7.7   6.1   5.0   3.1   2.6   3.3   2.9   2.8   3.7   5.0   6.7   8.3     57.1
PE           0.0   0.0   0.0   0.9   2.6   3.8   4.5   3.9   2.4   0.9   0.0   0.0     19.0
P-PE         7.7   6.1   5.0   2.2  -0.0  -0.5  -1.7  -1.1   1.3   4.2   6.7   8.3     38.1
ACC-P-WL     0.0   0.0   0.0   0.0  -0.0  -0.6  -2.2  -3.3   0.0   0.0   0.0   0.0
ST          19.7  25.8  30.8  12.0  12.0  11.5  10.0   9.1  10.4  12.0  18.7  27.0
CH-ST        0.0   0.0   0.0   0.0   0.0  -0.5  -1.5  -0.9   1.3   1.6   0.0   0.0
AE           0.0   0.0   0.0   0.9   2.6   3.8   4.4   3.7   2.4   0.9   0.0   0.0     18.6
P-AE         7.7   6.1   5.0   2.2  -0.0  -0.5  -1.5  -0.9   1.3   4.2   6.7   8.3     38.5

 PREC.= 57.1   (TURC)EVAP.= 13.8   RNF.= 43.3

T(*F)       13.5  18.4  26.5  36.0  45.4  52.7  57.9  55.8  48.3  37.4  24.3  18.4     36.2
P            7.7   6.1   5.0   3.1   2.6   3.3   2.9   2.8   3.7   5.0   6.7   8.3     57.1
PE           0.0   0.0   0.0   0.9   2.6   3.8   4.5   3.9   2.4   0.9   0.0   0.0     19.0
P-PE         7.7   6.1   5.0   2.2  -0.0  -0.5  -1.7  -1.1   1.3   4.2   6.7   8.3     38.1
ACC-P-WL     0.0   0.0   0.0   0.0  -0.0  -0.6  -2.2  -3.3   0.0   0.0   0.0   0.0
ST          17.7  23.8  28.8  10.0  10.0   9.5   8.0   7.2   8.5  10.0  16.7  25.0
CH-ST        0.0   0.0   0.0   0.0   0.0  -0.5  -1.5  -0.8   1.3   1.5   0.0   0.0
AE           0.0   0.0   0.0   0.9   2.6   3.8   4.3   3.6   2.4   0.9   0.0   0.0     18.5
P-AE         7.7   6.1   5.0   2.2  -0.0  -0.5  -1.5  -0.8   1.3   4.2   6.7   8.3     38.6

 PREC.= 57.1   (TURC)EVAP.= 13.8   RNF.= 43.3


 STOP      0
EXECUTION TERMINATED
```

Program C-2 Snow-Melt Model and Plot

The simplified snow-melt model and plots described in section 4.2 are presented in the following two programs. The input of the first program, shown on the first page, consists of daily maximum and minimum temperatures and water equivalent of snow pack which are obtained from snow pillow charts. The details of the method can easily be followed by reading the Fortran statements. The Do Loop (lines 13 to 27) of statement number 30 picks out both incremental temperature rises and incremental melt but ignores temperature falls (below 32 F) and snow pack accumulations. Melt is compiled as accumulated incremental water equivalent loss with the corresponding accumulated degree-days with lags of zero, one, two and three days. An example of a trial run with data from Barkerville (1968-1969) is given on the third page.

The output of the first program is used as the input of the second program which is given on the fourth page. This program plots out the input data on graph paper. The Fortran statements conform to the available plotting routines of the Plotter of the I.B.M. 360 Computer at U.B.C. A sample plot of the results for data from Barkerville (1968-1969) is given in Figure 4.1 of section 4.1.

```
                C       SNOWMELT MODEL TO ESTIMATE MELT PRIOR TO APRIL 1 SNOW COURSE DATA.
                C       METHOD IS DERIVED FROM SNOW PILLOW DATA BY COMPILING INCREMENTAL
                C       TEMP. RISE (DEG-DAYS) WITH INCREMENTAL WATER EQUIVALENT LOSS.
                C       OUTPUT DATA IS SET UP WITH ACCUMULATED DEGREE-DAYS AS THE INDEPEN-
                C       DENT VARIABLE AND ACCUMULATED MELT (IN.) AS THE DEPENDENT VARIABLE
                C       N = NO. OF TEMP. DATA
   0001                 DIMENSION TMAX(100),TMIN(100),T(100),W(100),TACCUM(100),
               1                  WACCUM(100),TAVG(100)
   0002         1       READ (5,5) N
   0003         5       FORMAT (I3)
   0004                 IF (N.EQ.0) STOP
   0005                 NN = N + 1
   0006                 READ (5,10) (TMAX(I), TMIN(I),W(I), I=2,NN)
   0007        10       FORMAT (16X,2F6.1,6X,F7.2)
   0008                 TAV = 0.0
   0009                 W(1) = 0.0
   0010                 TACUMM = 0.0
   0011                 WACUMM = 0.0
   0012                 J = 0
   0013                 DO 30 I = 2,NN
   0014                 T(I) = 0.5*(TMAX(I) + TMIN(I))
   0015                 IF ((W(I-1) - W(I)).LT.0.005) GO TO 15
   0016                 WDELTA = W(I-1) - W(I)
   0017                 WACUMM = WACUMM + WDELTA
   0018                 GO TO 25
   0019        15       IF ((T(I) - 32.).LT.0.005) GO TO 30
   0020        25       TDELTA = T(I) - 32.
   0021                 IF  (TDELTA.LT.0.005) TDELTA = 0.0
   0022                 TACUMM = TACUMM + TDELTA
   0023                 J = J + 1
   0024                 M = J
   0025                 WACCUM(J) =WACUMM
   0026                 TACCUM(J) = TACUMM
   0027        30       CONTINUE
   0028                 WACCUM(M+1) = 0.0
   0029                 WACCUM(M+2) = 0.0
   0030                 WACCUM(M+3) = 0.0
   0031                 DO 31 I=2,NN
   0032                 TAVG(I) = 0.5*(TMAX(I) + TMIN(I))
   0033        31       TAV = TAV + TAVG(I)
   0034                 X = N
   0035                 TAV = TAV/X
   0036                 PAV = (TAV - 32.)*X
   0037                 WRITE (6,32) N
   0038        32       FORMAT (//' PERIOD N =',I5)
   0039                 WRITE (6,33) TAV
   0040        33       FORMAT (' AVERAGE TEMPERATURE FOR PERIOD IS',F7.2)
   0041                 WRITE (6,34) PAV
   0042        34       FORMAT (' PERIOD AVG. ACCUM. DEG-DAYS IS',F8.2)
   0043                 WRITE (6,35)
   0044        35       FORMAT ('   J  ACCUM.     ACCUM.    ACCUM.    ACCUM.    ACCUM.'/
               1        '        DEG-DAYS   MELT      MELT      MELT      MELT'/
               2        '                   LAG-0D    LAG-1D    LAG-2D    LAG-3D'/)
   0045                 WRITE (6,40) (J,TACCUM(J),WACCUM(J),WACCUM(J+1),WACCUM(J+2),
               1                 WACCUM(J+3),J=1,M)
```

```
0046      40    FORMAT (I3,F7.2,4F9.2)
0047            GO TO 1
0048            END
```

```
EXECUTION TERMINATED


$RUN -LOAD#
EXECUTION BEGINS

PERIOD N =    30
AVERAGE TEMPERATURE FOR PERIOD IS  32.88
PERIOD AVG. ACCUM. DEG-DAYS IS   26.25
 J  ACCUM.    ACCUM.    ACCUM.    ACCUM.    ACCUM.
   DEG-DAYS    MELT      MELT      MELT      MELT
             LAG-0D    LAG-1D    LAG-2D    LAG-3D

 1    3.00     0.0       0.0       0.0       0.0
 2    5.00     0.0       0.0       0.0       0.0
 3    6.50     0.0       0.0       0.0       0.0
 4    7.50     0.0       0.0       0.0       0.01
 5    8.50     0.0       0.0       0.01      0.33
 6   18.00     0.0       0.01      0.33      0.36
 7   29.50     0.01      0.33      0.36      0.39
 8   36.25     0.33      0.36      0.39      0.58
 9   41.50     0.36      0.39      0.58      1.03
10   57.00     0.39      0.58      1.03      1.35
11   71.00     0.58      1.03      1.35      1.45
12   81.00     1.03      1.35      1.45      1.45
13   81.00     1.35      1.45      1.45      1.45
14   82.00     1.45      1.45      1.45      1.45
15   86.00     1.45      1.45      1.45      1.45
16   87.00     1.45      1.45      1.45      1.45
17   90.00     1.45      1.45      1.45      1.45
18   90.50     1.45      1.45      1.45      0.0
19   92.50     1.45      1.45      0.0       0.0
20   95.50     1.45      0.0       0.0       0.0

 STOP      0
EXECUTION TERMINATED


$SIG
```

```
      DIMENSION T(100),W(100)
      CALL PLOTS
C
C     N = J FROM SNOWMELT MODEL
C
      N = 20
      K = 0
    5 READ (5,10) (T(I),W(I),I=1,N)
   10 FORMAT (3X,F7.2,F9.2)
   11 K = K + 1
      CALL SCALE (T,N,10.0,TMIN,DT,1)
      CALL SCALE (W,N,10.0,WMIN,DW,1)
      CALL AXIS (0.0,0.0,'ACCUMULATED DEG-DAYS',-20,10.0,0.0,TMIN,DT)
      CALL AXIS (0.0,0.0,'ACCUMULATED MELT (IN.)',+22,10.0,90.0,WMIN,DW)
      CALL SYMBOL (2.0,9.5,0.35,'FIG. 4.1',0.0,8)
      CALL SYMBOL (2.0,9.0,0.28,'SNOWMELT  PLOT',0.0,14)
      CALL SYMBOL (2.1,8.7,0.14, 3,0.0,-1)
      CALL SYMBOL (2.1,8.4,0.14, 1,0.0,-1)
      CALL SYMBOL (2.1,8.1,0.14, 4,0.0,-1)
      CALL SYMBOL (2.1,7.8,0.14, 5,0.0,-1)
      CALL SYMBOL (2.5,8.6,0.14,'LAG 0-DAYS',0.0,10)
      CALL SYMBOL (2.5,8.3,0.14,'LAG 1-DAYS',0.0,10)
      CALL SYMBOL (2.5,8.0,0.14,'LAG 2-DAYS',0.0,10)
      CALL SYMBOL (2.5,7.7,0.14,'LAG 3-DAYS',0.0,10)
      CALL SYMBOL (2.1,7.0,0.14,'DATA- BARKERVILLE',0.0,17)
      CALL SYMBOL (2.5,6.7,0.14,'(1968-69)',0.0,9)
      CALL PLOT (T(1),W(1),3)
      DO 15 I=1,N
   15 CALL SYMBOL (T(I),W(I),0.07,3,0.0,-1)
      CALL LINE (T(1),W(1),N,+1)
      CALL PLOT (T(1),W(1),3)
   16 DO 20 I=1,N
      IF (I.EQ.N) W(I+1) = 0.0
   20 CALL SYMBOL (T(I),W(I+1),0.07,1,0.0,-1)
      CALL LINE (T(1),W(2),N-1,+1)
      CALL PLOT (T(1),W(1),3)
   21 DO 25 I=1,N
      IF (I.EQ.N) W(I+1) = 0.0
      IF (I.EQ.N) W(I+2) = 0.0
   25 CALL SYMBOL (T(I),W(I+2),0.07,4,0.0,-1)
      CALL LINE (T(1),W(3),N-2,+1)
      CALL PLOT (T(1),W(1),3)
   26 DO 30 I=1,N
      IF (I.EQ.N) W(I+1) = 0.0
      IF (I.EQ.N) W(I+2) = 0.0
      IF (I.EQ.N) W(I+3) = 0.0
   30 CALL SYMBOL (T(I),W(I+3),0.07, 5,0.0,-1)
      CALL LINE (T(1),W(4),N-3,+1)
      CALL PLOTND
      STOP
      END
```

Program C-3 Experimental Grid Square Method

The following program is an example of an application of the experimental grid square method in which Thornthwaite's evapotranspiration method is used. The set of precipitation regression equations (Equations B.13 to B.24) used in this trial run were derived by the normal Stpreg routine of UBC Trip. The Thornthwaite method of calculating evapotranspiration is represented by lines 34 to 118,inclusive, and is essentially identical to Program C-1 except for adaptation into the grid square system of calculations. Lines 119 to 124 represent calculations of runoff for the sub-basin areas and total area. The fifth page shows the output printed for this run and corresponds to the results of the trial run presented in Table 5.2. Both potential and actual runoff were estimated but only actual runoff was analysed in the development of the grid square method, as discussed in section 3.1. The computer statistics print-out of this run is given on the sixth page and shows that the total computer time used is 22 seconds with a cost of slightly over $2.00. Even though Thornthwaite's method seems involved and lengthy on a grid square basis, the trial runs in this study used very little computer time and therefore presented a very efficient method of compiling information.

```
0001            REAL LAREA,L,INDEX
0002            DIMENSION  SQNO(212),LAREA(212),GSAREA(212),E(212),HS(212),
               1           SS(212),DB(212),L(212),HB(212),SE(212),
               2          CTEMP(12,212),II(12,212),INDEX(212),F(212),EV(12,212),
               3          T(12,212),P(12,212),TTOT(212),PTOT(212),TPERNF(5),
               4          PERNF(12,212),ACCPWL(21,212),C(12),TEVAP(212),A(212,5),
               5          TAERNF(5),J(212),AETOT(212),AERTOT(212),PERTOT(212),
               6          ARG(12,212),ST(12,212),CHST(12,212),AE(12,212),
               7          AERNF(12,212),PERUN(212,5),AERUN(212,5),FAVG(212),
               8          PWINT(212),PDIF(5),PEDIF(5),EVTOT(212)
0003            READ (5,5) (SQNO(I),LAREA(I),GSAREA(I),E(I),HS(I),SS(I),DB(I),
               1            L(I),HB(I),SE(I), I=1,212)
0004       5    FORMAT (I3,1X,2F8.2,16X,3F6.0,2F5.0,2F7.0)
0005            DO 6 I=1,212
0006       6    READ (5,7) (A(I,M),M=1,5)
0007       7    FORMAT (4X,5F8.2)
0008            DO 10 I=1,212
0009            T(1,I) = 28.1903 - 0.2675D-02*E(I) - 0.6324D-04*L(I)*L(I)
0010            T(2,I) = 29.9052 - 0.5027D-06*E(I)*E(I) - 0.4295D-04*L(I)*L(I)
0011            T(3,I) = 41.1399 - 0.3314D-02*E(I) - 0.3267D-04*L(I)*L(I)
0012            T(4,I) = 54.5055 - 0.3337D-02*E(I) - 0.0170*DB(I)
0013            T(5,I) = 60.3414 - 0.3647D-02*E(I)
0014            T(6,I) = 66.2320 - 0.3410D-02*E(I)
0015            T(7,I) = 71.4715 - 0.3342D-02*E(I)
0016            T(8,I) = 70.1207 - 0.3307D-02*E(I) - 0.3050D-04*L(I)*L(I)
0017            T(9,I) = 61.2753 - 0.2820D-02*E(I) - 0.3509D-04*L(I)*L(I)
0018            T(10,I)= 50.0519 - 0.2385D-02*E(I) - 0.3762D-04*L(I)*L(I)
0019            T(11,I)= 41.7830 - 0.3236D-02*E(I) - 0.0182*L(I)
0020            T(12,I)= 35.8599 - 0.3191D-02*E(I) - 0.0229*L(I)
0021            P(1,I) = 5.3639 + 0.1803D-03*DB(I)*DB(I) - 0.0474*DB(I)
               1 - 0.3784D-04*L(I)*L(I)
0022            P(2,I) = 6.0267 + 0.1632D-03*DB(I)*DB(I) - 0.0473*DB(I)
               1 - 0.0111*L(I)
0023            P(3,I) = 0.3673 + 0.5179D-04*DB(I)*DB(I) - 0.9609D-02*L(I)
               1 + 0.9314D-07*E(I)*E(I) - 0.2140D-06*HS(I)*HS(I)
0024            P(4,I) = 0.6401 + 0.3020D-04*DB(I)*DB(I) - 0.5257D-02*L(I)
               1 + 0.4901D-07*E(I)*E(I) - 0.1840D-08*SE(I)*SE(I)
0025            P(5,I) = 0.5333 + 0.1089D-04*DB(I)*DB(I) + 0.3027D-03*E(I)
0026            P(6,I) = 1.1550 + 0.2069D-04*DB(I)*DB(I)
0027            P(7,I) = 0.3615 + 0.1713D-04*DB(I)*DB(I) + 0.2073D-03*E(I)
0028            P(8,I) = 0.7460 + 0.2041D-04*DB(I)*DB(I)
0029            P(9,I) = 0.1776 + 0.2154D-04*DB(I)*DB(I) + 0.3149D-03*E(I)
0030            P(10,I)= 0.8348 + 0.5539D-04*DB(I)*DB(I) - 0.9903D-02*L(I)
0031            P(11,I)= 5.8083 + 0.1676D-03*DB(I)*DB(I) - 0.0452*DB(I)
               1 - 0.0119*L(I)
0032            P(12,I)= 1.1343 + 0.9395D-04*DB(I)*DB(I) - 0.0173*L(I)
0033      10    CONTINUE
           C
           C    CALCULATION OF EVAPORATION BY THORNTHWAITE'S METHOD
           C    INPUT DATA- TEMP. (*F)
           C                PREC. (IN.)
           C    OUT PUT-    EVAP. (CM.)
           C                PREC. (CM.)
           C                RUNOFF (CM.)
           C
```

```
0034               C(1) = 0.74
0035               C(2) = 0.78
0036               C(3) = 1.02
0037               C(4) = 1.15
0038               C(5) = 1.33
0039               C(6) = 1.36
0040               C(7) = 1.37
0041               C(8) = 1.25
0042               C(9) = 1.06
0043               C(10) = 0.92
0044               C(11) = 0.76
0045               C(12) = 0.70
0046               DO 15 I=1,212
0047               INDEX(I) = 0.0
0048               TTOT(I) = 0.0
0049               PTOT(I) = 0.0
0050         15    TEVAP(I) = 0.0
0051               DO 16 M=1,5
0052               TPERNF(M) = 0.0
0053         16    TAERNF(M) = 0.0
0054               DO 66 I=1,212
0055               DO 20 K=1,12
0056               CTEMP(K,I) = (T(K,I) - 32.)*(5./9.)
            C
            C      INPUT DATA - TEMP. (*F)
            C                   PREC. (IN.)
            C
0057               IF (CTEMP(K,I).LE.0.0) II(K,I) = 0.0
0058               IF (CTEMP(K,I).LE.0.0) GO TO 20
0059               II(K,I) = (CTEMP(K,I)/5.)**1.514
0060         20    INDEX(I) = INDEX(I) + II(K,I)
0061               DO 51 K=1,12
0062               PTOT(I) = PTOT(I) + P(K,I)
0063         51    TTOT(I) = TTOT(I) + T(K,I)
0064               FAVG(I) = TTOT(I)/12.
0065               F(I) = 0.93/(2.42 - ALOG10(INDEX(I)))
0066               DO 25 K=1,12
0067               IF(CTEMP(K,I).LE.0.0) EV(K,I) = 0.0
0068               IF(CTEMP(K,I).LE.0.0) GO TO 25
0069               EV(K,I)= C(K)*EXP(2.303*(0.204 + F(I)*(1. - ALOG10(INDEX(I))) +
                  1 F(I)*ALOG10(CTEMP(K,I))))/2.54
0070         25    TEVAP(I) = TEVAP(I) + EV(K,I)
            C
            C      EV(K,I) IS COMPUTED IN CM. BUT CHANGED INTO IN.
            C
0071               J(I) = 0
0072               AETOT(I) = 0.0
0073               AERTOT(I) = 0.0
0074               PERTOT(I) = 0.0
0075               DO 56 K=1,12
0076               PERNF(K,I) = P(K,I) - EV(K,I)
0077         56    PERTOT(I) = PERTOT(I) + PERNF(K,I)
0078               IF(PERTOT(I).LT.0.0) GO TO 64
0079               DO 57 K=1,12
0080               IF(PERNF(K,I).GT.0.0) ACCPWL(K,I) = 0.0
```

```
           IF(PERNF(K,I).LT.0.0) ACCPWL(K,I) = PERNF(K,I)
   57      IF(PERNF(K,I).LT.0.0) ACCPWL(K,I) = ACCPWL(K,I) + ACCPWL(K-1,I)
           DO 59 K=1,12
           IF(ACCPWL(K,I).EQ.0.0) GO TO 58
           ARG(K,I) = ALOG10(14.) - 0.03105843*(-ACCPWL(K,I))
           ST(K,I) = EXP(2.303*ARG(K,I))
           J(I) = J(I) + 1
           GO TO 59
   58      IF(CTEMP(K,I).GT.0.0) ST(K,I) = 14.
           IF(CTEMP(K,I).LT.0.0) ST(K,I) = 14. + PERNF(K,I)
           IF(K.GT.1) ST(K,I) = ST(K-1,I) + P(K,I)
           IF(J(I).GT.0) ST(K,I) = ST(K-1,I) + PERNF(K,I)
           IF(CTEMP(K,I).LT.0.0) GO TO 59
           IF(ST(K,I).GT.14.) ST(K,I) = 14.
   59      CONTINUE
           DO 60 K=1,12
           IF(K.EQ.1) CHST(K,I) = 0.0
           IF(K.EQ.1) GO TO 60
           CHST(K,I) = -(ST(K-1,I) - ST(K,I))
           IF(CTEMP(K,I).LE.0.0) CHST(K,I) = 0.0
           IF(ST(K-1,I).GE.14.) CHST(K,I) = 0.0
   60      CONTINUE
           DO 61 K=1,12
           AE(K,I) = P(K,I) + (-CHST(K,I))
           IF(CHST(K,I).GE.0.0) AE(K,I) = EV(K,I)
   61      CONTINUE
           DO 62 K=1,12
           AERNF(K,I) = P(K,I) - AE(K,I)
   62      AERTOT(I) = AERTOT(I) + AERNF(K,I)
           DO 63 K=1,12
   63      AETOT(I) = AETOT(I) + AE(K,I)
           GO TO 66
   64      DO 65 K=1,12
           AE(K,I) = P(K,I)
           AERNF(K,I) = P(K,I) - AE(K,I)
           AETOT(I) = AETOT(I) + AE(K,I)
   65      AERTOT(I) = AERTOT(I) + AERNF(K,I)
   66      CONTINUE
           DO 67 M=1,5
           DO 67 I=1,212
           PERUN(I,M) = PERTOT(I)*A(I,M)/35.1577
           TPERNF(M) = TPERNF(M) + PERUN(I,M)
           AERUN(I,M) = AERTOT(I)*A(I,M)/35.1577
   67      TAERNF(M) = TAERNF(M) + AERUN(I,M)
           DO 68 M=1,5
           PEDIF(M) = ((TPERNF(M) - TAERNF(M))*100.)/TAERNF(M)
   68      WRITE(6,69) M,TPERNF(M),PEDIF(M)
   69      FORMAT(' SUB BASIN =',I3,' PE RUNOFF =',F10.1,' CFS',F7.1,' PERCEN
          1T DIFF. FROM AE RUNOFF')
           DO 70 M=1,5
           IF(M.EQ.1) PDIF(M) = ((TAERNF(M) - 1800.)*100.)/1800.
           IF(M.EQ.2) PDIF(M) = ((TAERNF(M) - 1090.)*100.)/1090.
           IF(M.EQ.3) PDIF(M) = ((TAERNF(M) - 2560.)*100.)/2560.
           IF(M.EQ.4) PDIF(M) = ((TAERNF(M) - 5250.)*100.)/5250.
           IF(M.EQ.5) PDIF(M) = ((TAERNF(M) -10700.)*100.)/10700.
```

```
0135         70    WRITE(6,71) M,TAERNF(M),PDIF(M)
0136         71    FORMAT(' SUB BASIN =',I3,' AE RUNOFF =',F10.1,' CFS',F7.1,' PERCEN
                  1T DIFF. FROM ACTUAL RUNOFF')
0137               STOP
0138               END
```

```
EXECUTION TERMINATED


$RUN -LOAD# 5=DATA(51)
EXECUTION BEGINS
SUB BASIN =  1 PE RUNOFF =     1209.6 CFS    -4.2 PERCENT DIFF. FROM AE RUNOFF
SUB BASIN =  2 PE RUNOFF =      912.0 CFS    -7.9 PERCENT DIFF. FROM AE RUNOFF
SUB BASIN =  3 PE RUNOFF =     2562.8 CFS    -1.9 PERCENT DIFF. FROM AE RUNOFF
SUB BASIN =  4 PE RUNOFF =     4271.3 CFS    -7.8 PERCENT DIFF. FROM AE RUNOFF
SUB BASIN =  5 PE RUNOFF =     8955.5 CFS    -5.7 PERCENT DIFF. FROM AE RUNOFF
SUB BASIN =  1 AE RUNOFF =     1262.3 CFS   -29.9 PERCENT DIFF. FROM ACTUAL RUNOFF
SUB BASIN =  2 AE RUNOFF =      990.4 CFS    -9.1 PERCENT DIFF. FROM ACTUAL RUNOFF
SUB BASIN =  3 AE RUNOFF =     2612.5 CFS     2.0 PERCENT DIFF. FROM ACTUAL RUNOFF
SUB BASIN =  4 AE RUNOFF =     4632.9 CFS   -11.8 PERCENT DIFF. FROM ACTUAL RUNOFF
SUB BASIN =  5 AE RUNOFF =     9497.9 CFS   -11.2 PERCENT DIFF. FROM ACTUAL RUNOFF

 STOP      0
EXECUTION TERMINATED


$SIG
```

RFS NO. 779590 UNIVERSITY OF B C COMPUTING CENTRE MTS(AN059) JOB S
77

USER: OBED
DEPARTMENT: C.E.

```
**** ON AT  16:59:50
**** OFF AT 17:02:08
**** ELAPSED TIME        138.02   SEC.
**** CPU TIME USED        22.585  SEC.
**** STORAGE USED       5916.056  PAGE-SEC.
**** CARDS READ          177
**** LINES PRINTED       215
**** PAGES PRINTED         7
**** CARDS PUNCHED         0
**** DRUM READS          286
**** RATE FACTOR           0.9
**** APPROX. COST OF THIS RUN  C$2.16

**** FILE STORAGE         18 PG-HR.   C$.01
```

Program C-4 <u>Experimental Grid Square Method With Snow Courses Added</u>

The following program is an example of the application of the experimental grid square method with the Thornthwaite approach and the addition of snow course data. This trial was explained in detail in section 5.5. Individual monthly regression equations for April to November (Equations B.16 to B.23, inclusive) and a lumped winter season regression equation (Equation 5.7) were combined for the mean annual precipitation estimates. Evapotranspiration is calculated for the months of April to November and assumed to be zero in the winter season (see discussion of section 5.5). All steps are essentially the same as in Program C-3 except for the runoff estimates which are segregated in the winter period (lines 110 to 113, 117 to 122 and 127 to 130, inclusive). The fifth page shows the output printed for this run and corresponds to the results presented in Table 5.4 The computer statistics print-out, given on the sixth page, again shows very little computer time used.

```
0001              REAL LAREA,L,INDEX
0002              DIMENSION  SQNO(212),LAREA(212),GSAREA(212),E(212),HS(212),
                 1           SS(212),DB(212),L(212),HB(212),SE(212),
                 2          CTEMP(12,212),II(12,212),INDEX(212),F(212),EV(12,212),
                 3          T(12,212),P(12,212),TTOT(212),PTOT(212),TPERNF(5),
                 4          PERNF(12,212),ACCPWL(21,212),C(12),TEVAP(212),A(212,5),
                 5          TAERNF(5),J(212),AETOT(212),AERTOT(212),PERTOT(212),
                 6          ARG(12,212),ST(12,212),CHST(12,212),AE(12,212),
                 7          AERNF(12,212),PERUN(212,5),AERUN(212,5),FAVG(212),
                 8          PWINT(212),PDIF(5),PEDIF(5),EVTOT(212)
0003              READ (5,5) (SQNO(I),LAREA(I),GSAREA(I),E(I),HS(I),SS(I),DB(I),
                 1            L(I),HB(I),SE(I),  I=1,212)
0004        5     FORMAT (I3,1X,2F8.2,16X,3F6.0,2F5.0,2F7.0)
0005              DO 6 I=1,212
0006        6     READ (5,7) (A(I,M),M=1,5)
0007        7     FORMAT (4X,5F8.2)
0008              DO 10 I=1,212
0009              T(1,I) = 28.1903 - 0.2675D-02*E(I) - 0.6324D-04*L(I)*L(I)
0010              T(2,I) = 29.9052 - 0.5027D-06*E(I)*E(I) - 0.4295D-04*L(I)*L(I)
0011              T(3,I) = 41.1399 - 0.3314D-02*E(I) - 0.3267D-04*L(I)*L(I)
0012              T(4,I) = 54.5055 - 0.3337D-02*E(I) - 0.0170*DB(I)
0013              T(5,I) = 60.3414 - 0.3647D-02*E(I)
0014              T(6,I) = 66.2320 - 0.3410D-02*E(I)
0015              T(7,I) = 71.4715 - 0.3342D-02*E(I)
0016              T(8,I) = 70.1207 - 0.3307D-02*E(I) - 0.3050D-04*L(I)*L(I)
0017              T(9,I) = 61.2753 - 0.2820D-02*E(I) - 0.3509D-04*L(I)*L(I)
0018              T(10,I)= 50.0519 - 0.2385D-02*E(I) - 0.3762D-04*L(I)*L(I)
0019              T(11,I)= 41.7830 - 0.3236D-02*E(I) - 0.0182*L(I)
0020              T(12,I)= 35.8599 - 0.3191D-02*E(I) - 0.0229*L(I)
0021              P(1,I) = 5.3639 + 0.1803D-03*DB(I)*DB(I) - 0.0474*DB(I)
                 1 - 0.3784D-04*L(I)*L(I)
0022              P(2,I) = 6.0267 + 0.1632D-03*DB(I)*DB(I) - 0.0473*DB(I)
                 1 - 0.0111*L(I)
0023              P(3,I) = 0.3673 + 0.5179D-04*DB(I)*DB(I) - 0.9609D-02*L(I)
                 1 + 0.9314D-07*E(I)*E(I) - 0.2140D-06*HS(I)*HS(I)
0024              P(4,I) = 0.6401 + 0.3020D-04*DB(I)*DB(I) - 0.5257D-02*L(I)
                 1 + 0.4901D-07*E(I)*E(I) - 0.1840D-08*SE(I)*SE(I)
0025              P(5,I) = 0.5333 + 0.1089D-04*DB(I)*DB(I) + 0.3027D-03*E(I)
0026              P(6,I) = 1.1550 + 0.2069D-04*DB(I)*DB(I)
0027              P(7,I) = 0.3615 + 0.1713D-04*DB(I)*DB(I) + 0.2073D-03*E(I)
0028              P(8,I) = 0.7460 + 0.2041D-04*DB(I)*DB(I)
0029              P(9,I) = 0.1776 + 0.2154D-04*DB(I)*DB(I) + 0.3149D-03*E(I)
0030              P(10,I)= 0.8348 + 0.5539D-04*DB(I)*DB(I) - 0.9903D-02*L(I)
0031              P(11,I)= 5.8083 + 0.1676D-03*DB(I)*DB(I) - 0.0452*DB(I)
                 1 - 0.0119*L(I)
0032              P(12,I)= 1.1343 + 0.9395D-04*DB(I)*DB(I) - 0.0173*L(I)
            C
            C     PWINT(I) IS STANDARD REGRESSION PREC. EQ'N. (NOV. - MAR.)
            C     INCLUDING SNOW COURSE DATA
            C
0033              PWINT(I) = - 21.5062 + 0.5143D-06*E(I)*E(I) - 0.1474D-03*L(I)*L(I)
                 1 + 0.1647*DB(I)
0034       10     CONTINUE
            C
            C     CALCULATION OF EVAPORATION BY THORNTHWAITE'S METHOD
```

```
                C       INPUT DATA- TEMP. (*F)
                C                   PREC. (IN.)
                C       OUT PUT-    EVAP. (CM.)
                C                   PREC. (CM.)
                C                   RUNOFF (CM.)
                C
      0035              C(1) = 0.74
      0036              C(2) = 0.78
      0037              C(3) = 1.02
      0038              C(4) = 1.15
      0039              C(5) = 1.33
      0040              C(6) = 1.36
      0041              C(7) = 1.37
      0042              C(8) = 1.25
      0043              C(9) = 1.06
      0044              C(10) = 0.92
      0045              C(11) = 0.76
      0046              C(12) = 0.70
      0047              DO 15 I=1,212
      0048              INDEX(I) = 0.0
      0049              TTOT(I) = 0.0
      0050              PTOT(I) = 0.0
      0051       15     TEVAP(I) = 0.0
      0052              DO 16 M=1,5
      0053              TPERNF(M) = 0.0
      0054       16     TAERNF(M) = 0.0
      0055              DO 66 I=1,212
      0056              DO 20 K=1,12
      0057              CTEMP(K,I) = (T(K,I) - 32.)*(5./9.)
                C
                C       INPUT DATA - TEMP. (*F)
                C                     PREC. (IN.)
                C
      0058              IF (CTEMP(K,I).LE.0.0) II(K,I) = 0.0
      0059              IF (CTEMP(K,I).LE.0.0) GO TO 20
      0060              II(K,I) = (CTEMP(K,I)/5.)**1.514
      0061       20     INDEX(I) = INDEX(I) + II(K,I)
      0062              DO 51 K=1,12
      0063       51     TTOT(I) = TTOT(I) + T(K,I)
      0064              FAVG(I) = TTOT(I)/12.
      0065              DO 52 K=4,10
      0066       52     PTOT(I) = PTOT(I) + P(K,I)
      0067              PTOT(I) = PTOT(I) + PWINT(I)
      0068              F(I) = 0.93/(2.42 - ALOG10(INDEX(I)))
      0069              DO 25 K=1,12
      0070              IF(CTEMP(K,I).LE.0.0) EV(K,I) = 0.0
      0071              IF(CTEMP(K,I).LE.0.0) GO TO 25
      0072              EV(K,I)= C(K)*EXP(2.303*(0.204 + F(I)*(1. - ALOG10(INDEX(I))) +
                       1 F(I)*ALOG10(CTEMP(K,I))))/2.54
      0073       25     TEVAP(I) = TEVAP(I) + EV(K,I)
                C
                C       EV(K,I) IS COMPUTED IN CM. BUT CHANGED INTO IN.
                C
      0074              J(I) = 0
      0075              AETOT(I) = 0.0
```

```
         AERTOT(I) = 0.0
         PERTOT(I) = 0.0
         DO 56 K=1,12
         PERNF(K,I) = P(K,I) - EV(K,I)
   56    PERTOT(I) = PERTOT(I) + PERNF(K,I)
         IF(PERTOT(I).LT.0.0) GO TO 64
         DO 57 K=1,12
         IF(PERNF(K,I).GT.0.0) ACCPWL(K,I) = 0.0
         IF(PERNF(K,I).LT.0.0) ACCPWL(K,I) = PERNF(K,I)
   57    IF(PERNF(K,I).LT.0.0) ACCPWL(K,I) = ACCPWL(K,I) + ACCPWL(K-1,I)
         DO 59 K=1,12
         IF(ACCPWL(K,I).EQ.0.0) GO TO 58
         ARG(K,I) = ALOG10(14.) - 0.03105843*(-ACCPWL(K,I))
         ST(K,I) = EXP(2.303*ARG(K,I))
         J(I) = J(I) + 1
         GO TO 59
   58    IF(CTEMP(K,I).GT.0.0) ST(K,I) = 14.
         IF(CTEMP(K,I).LT.0.0) ST(K,I) = 14. + PERNF(K,I)
         IF(K.GT.1) ST(K,I) = ST(K-1,I) + P(K,I)
         IF(J(I).GT.0) ST(K,I) = ST(K-1,I) + PERNF(K,I)
         IF(CTEMP(K,I).LT.0.0) GO TO 59
         IF(ST(K,I).GT.14.) ST(K,I) = 14.
   59    CONTINUE
         DO 60 K=1,12
         IF(K.EQ.1) CHST(K,I) = 0.0
         IF(K.EQ.1) GO TO 60
         CHST(K,I) = -(ST(K-1,I) - ST(K,I))
         IF(CTEMP(K,I).LE.0.0) CHST(K,I) = 0.0
         IF(ST(K-1,I).GE.14.) CHST(K,I) = 0.0
   60    CONTINUE
         DO 61 K=1,12
         AE(K,I) = P(K,I) + (-CHST(K,I))
         IF(CHST(K,I).GE.0.0) AE(K,I) = EV(K,I)
   61    CONTINUE
         DO 62 K=4,10
         AERNF(K,I) = P(K,I) - AE(K,I)
   62    AERTOT(I) = AERTOT(I) + AERNF(K,I)
         AERTOT(I) = AERTOT(I) + PWINT(I)
         DO 63 K=1,12
   63    AETOT(I) = AETOT(I) + AE(K,I)
         GO TO 66
   64    DO 65 K=4,10
         AE(K,I) = P(K,I)
         AERNF(K,I) = P(K,I) - AE(K,I)
         AETOT(I) = AETOT(I) + AE(K,I)
   65    AERTOT(I) = AERTOT(I) + AERNF(K,I)
         AERTOT(I) = AERTOT(I) + PWINT(I)
   66    CONTINUE
         DO 92 I=1,212
         PERTOT(I) = 0.0
         EVTOT(I) = 0.0
         DO 72 K=4,10
         EVTOT(I) = EVTOT(I) + EV(K,I)
   72    PERTOT(I) = PERTOT(I) + PERNF(K,I)
   92    PERTOT(I) = PERTOT(I) + PWINT(I)
```

```
          DO 67 M=1,5
          DO 67 I=1,212
          PERUN(I,M) = PERTOT(I)*A(I,M)/35.1577
          TPERNF(M) = TPERNF(M) + PERUN(I,M)
          AERUN(I,M) = AERTOT(I)*A(I,M)/35.1577
   67     TAERNF(M) = TAERNF(M) + AERUN(I,M)
          DO 68 M=1,5
          PEDIF(M) = ((TPERNF(M) - TAERNF(M))*100.)/TAERNF(M)
   68     WRITE(6,69) M,TPERNF(M),PEDIF(M)
   69     FORMAT(' SUB BASIN =',I3,' PE RUNOFF =',F10.1,' CFS',F7.1,' PERCEN
         1T DIFF. FROM AE RUNOFF')
          DO 70 M=1,5
          IF(M.EQ.1) PDIF(M) = ((TAERNF(M) - 1800.)*100.)/1800.
          IF(M.EQ.2) PDIF(M) = ((TAERNF(M) - 1090.)*100.)/1090.
          IF(M.EQ.3) PDIF(M) = ((TAERNF(M) - 2560.)*100.)/2560.
          IF(M.EQ.4) PDIF(M) = ((TAERNF(M) - 5250.)*100.)/5250.
          IF(M.EQ.5) PDIF(M) = ((TAERNF(M) -10700.)*100.)/10700.
   70     WRITE(6,71) M,TAERNF(M),PDIF(M)
   71     FORMAT(' SUB BASIN =',I3,' AE RUNOFF =',F10.1,' CFS',F7.1,' PERCEN
         1T DIFF. FROM ACTUAL RUNOFF')
          STOP
          END
```

```
EXECUTION TERMINATED


$RUN -LOAD# 5=DATA(51)
EXECUTION BEGINS
SUB BASIN =  1 PE RUNOFF =     1694.8 CFS   -3.0 PERCENT DIFF. FROM AE RUNOFF
SUB BASIN =  2 PE RUNOFF =     1282.5 CFS   -5.8 PERCENT DIFF. FROM AE RUNOFF
SUB BASIN =  3 PE RUNOFF =     2802.7 CFS   -1.7 PERCENT DIFF. FROM AE RUNOFF
SUB BASIN =  4 PE RUNOFF =     5582.7 CFS   -9.1 PERCENT DIFF. FROM AE RUNOFF
SUB BASIN =  5 PE RUNOFF =    11362.6 CFS   -6.1 PERCENT DIFF. FROM AE RUNOFF
SUB BASIN =  1 AE RUNOFF =     1747.5 CFS   -2.9 PERCENT DIFF. FROM ACTUAL RUNOFF
SUB BASIN =  2 AE RUNOFF =     1360.9 CFS   24.9 PERCENT DIFF. FROM ACTUAL RUNOFF
SUB BASIN =  3 AE RUNOFF =     2852.4 CFS   11.4 PERCENT DIFF. FROM ACTUAL RUNOFF
SUB BASIN =  4 AE RUNOFF =     6142.0 CFS   17.0 PERCENT DIFF. FROM ACTUAL RUNOFF
SUB BASIN =  5 AE RUNOFF =    12102.7 CFS   13.1 PERCENT DIFF. FROM ACTUAL RUNOFF

 STOP      0
EXECUTION TERMINATED


$SIG
```

```
USER: OBED
DEPARTMENT: C.E.

**** ON AT  15:29:02
**** OFF AT 15:31:07
**** ELAPSED TIME        124.53   SEC.
**** CPU TIME USED        23.23   SEC.
**** STORAGE USED      5413.013   PAGE-SEC.
**** CARDS READ          194
**** LINES PRINTED       232
**** PAGES PRINTED         7
**** CARDS PUNCHED         0
**** DRUM READS          121
**** RATE FACTOR           0.9
**** APPROX. COST OF THIS RUN  C$2.23

**** FILE STORAGE           PG-HR.     .00
```

```
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
**************************************************************************************************
```

APPENDIX D

TRANSLATION OF THE RESUME OF THE PAPER, "CALCUL DU BILAN DE L'EAU EVALUATION EN FONCTION DES PRECIPITATIONS ET DES TEMPERATURES" BY L.C. TURC (REFERENCE 10).

This translation is included in the thesis to present the general nature of the formula and the following criticism should be regarded as a personal evaluation by the author only. The following translation and a brief inspection of the original paper with a French dictionary will show that the formula was derived from a general and a non-comprehensive approach. The data used is too varied and broad (i.e., climatic data of one half the world and lysimetric data of the other). The formula is probably not adequate and results in large errors when applied to small drainage areas. However, the simplicity of the formula and the relatively good approximate results that it does give is enough to justify further study of the formula in which a slight modification of the formula may give much better useable results for regionalizing hydrologic information on a smaller scale in British Columbia.

Calculation of Water Balance Evaluation as a Function of Precipitation and Temperature

by

Lucien Turc

(Laboratoire des Sols, Versailles)

Resume

Simple formulas enable the evaluation of actual evaporation at different times of the year as a function of precipitation and temperature (and data of which precise knowledge is more available).

One can estimate the amount of runoff or perculation through soil and inflow to rivers as well as the variation in humidity of soil.

These calculations provide therefore the evaluation of the availability of water, within the accuracy of stream gauge measurements; the formulas give runoff if one knows the precipitation and finally one can calculate the dry periods for which water must be adequate for irrigation.

The proposed formulas have been established after a systematic study of water balances of 254 rivers located in all climates of the globe of one part and the results of a certain number of lysimetric installations of the other part; these formulas constitute a synthesis of actual knowledge on the subject of water balance in our universe.

The relative knowledge of water balance in different lands of the earth

is by no means complete and the measured data available is sometimes grossly in error.

For example, those interested in soil science will often have insufficient data on: the periods when the soil is saturated and the quantity of water perculating through the soil; the periods of drought, the extent of droughts, the amount of water necessary for irrigation to sustain abundant crops.

To overcome these difficulties we have compared the numerical results now available in hydrologic literature in order to make a synthesis of actual knowledge; by this method we have established simple formulas which sum up the results already acquired and permit evaluation of the conditions of water balance as a function of precipitation and temperature, the magnitude of which give relatively satisfactory results for most parts of the world.

A detailed write up of this work was published in the "Annales Agronomiques" (1954); we will describe here concisely the general approach and the main results because a more complete discussion would be out of the scope of this article.

The first part presents the measures taken by the hydrologists within the overall hydrological systems constituted by the river basins, the second part presents the measures taken by the agriculturalists (agronomists) and soil scientists who made use of small artificial installations, the lysimetric cases; one will see that the proposed formulas show agreement between the results obtained in these two regions even if different in some respects.