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An Analysis of Climate and Runoff Events for Peyto Glacier, Alberta

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INLAND WATERS DIRECTORATE,
WATER RESOURCES BRANCH,
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Contents

Illustrations

Illustrations (cont'd)

Tables

Abstract

As part of the I.H.D. glacier research program, this study investigates some basic hydrometeorological relationships for Peyto Glacier, Alberta, and develops and tests some autoregressive models applicable to various climate and runoff events of 1968 and 1969. The existing hydrometeorological data are critically evaluated in relation to their use in statistical or physical models. A detailed discussion of rainfall-runoff relations and subsequently the type of analysis best suited to the data available is presented.

Multiple regression equations, allowing for autocorrelative effects, are developed for the 1968 runoff season. A detailed discussion of the assumptions, problems, and solutions involved in the statistical modelling process is outlined. Such considerations include intercorrelation of predictor variables and the effect of serial correlation within data sets. A season model and several "weather" period models are developed using 1968 data and are tested with 1969 data. The results are encouraging and suggest that further modification and improvement of the models will improve the possibility of short-term runoff prediction.

This study by B. Goodison was undertaken in the summer of 1969. It is one of a series to analyse data obtained during glaciological studies at Peyto glacier, a research basin included in the Canadian contribution to the International Hydrological Decade.

Introduction

PURPOSE OF THE STUDY

As part of the International Hydrological Decade (I.H.D.) Program (1965-1974), glaciological research is being undertaken on selected glaciers along chains throughout the world. In Canada emphasis is being placed on five glaciers (Ram River, Peyto, Woolsey, Place and Sentinel) located in an east-west profile across the western mountain ranges, on one glacier in northern British Columbia (Berendon), and on one glacier on Baffin Island (Decade). These studies will include measurements of mass balance, meteorological observations on or near the glacier, and measurements of discharge and sediment content in outflow streams (Østrem and Stanley, 1969, p. 2).

The program does not involve just the collection of data; useful analysis must be forthcoming. The value and usefulness of the results depend not only on the type of analysis, but also on the quality of data available.

The purpose of this report is to investigate some basin hydrometeorological relationships by means of an autoregressive technique; to evaluate the applicability of the data collected from 1965 to 1968 for use in statistical analysis; to test the 1968 runoff model with 1969 data; and to discuss changes which will facilitate more sophisticated analysis.

PREVIOUS RESEARCH AND ANALYSIS

Previous analysis of data that have been collected for Peyto Glacier has been necessarily preliminary, and detailed hydrometeorological studies have not been carried out. In determining the type of analysis that should be tested, however, several factors were considered.

First, a predictive model for runoff was desired. Such a model could later be related to more comprehensive and applied hydrologic analysis of the North Saskatchewan River. Secondly, only simple, standard meteorological observations recorded during each ablation season (May-October) at Peyto Glacier would be available for analysis. Thirdly, existing data do not lend themselves to a complete heat balance study; also, the measurements required for this method, if it is to be applied over a long period of time, require a considerable amount of experience, equipment, care, field work, and evaluation. In this study a more flexible model was being sought than the specific heat balance model.

Allowing for the above considerations it was deemed desirable to test the applicability of a statistical model of some form. Physical models used for snowmelt analysis have been tested before in both glacierized and non-glacierized basins by other researchers. These models include the energy balance approach, Light's (1941) equation, and the U.S. Army Corps of Engineers equations (1956; 1960). The latter two methods are strictly applicable to snowmelt. Light's equation is derived from Sverdrup's eddy conductivity equation based on a theory of atmospheric turbulence, while the Corps of Engineers equations evaluate snowmelt on the theoretical basis of heat transfer involving radiation, convection, and conduction. Both methods require adjustments for variable basin characteristics.

It has been only recently, however, that statistical modelling of hydrological and hydrometeorological processes has been attempted. In this study an attempt is made to develop a statistical model capable of predicting the daily discharge of Peyto Creek from meteorological variables measured at Peyto Glacier base camp. The technique of autoregression was selected as the statistical method to be tested.

Regression and correlation analysis has been applied recently to climate-runoff relations of glacier basins. Rannie (1966) investigated simple correlations between temperature and runoff for the Decade Glacier, Baffin Island. To avoid undue complexity, periods of rainfall of over 0.05 inches were excluded from the analysis. Goodison (1968) extended this type of research to a non-glacierized Arctic basin, studying snowmelt and runoff using multiple regression analysis. Slight modification of the method of analysis has been deemed necessary, and these changes are employed in this report. Pysklywec (1966), Pysklywec et al., (1968), and Gross (1968) have compared the use of multiple regression analysis with various physical approaches in the investigation of snowmelt in a non-glacierized basin in New Brunswick. Generally, they conclude that the use of experimental index-snowmelt plots and computerized regression equations offer possibilities for reliable estimates of point-snowmelt rates that may be used in determination of basin snowmelt and hydrograph synthesis (Pysklywec et al., 1968, p. 945).

The application of this statistical approach in glacier basin research has been limited. Analysis based only on the graphical correlation of variables is still being attempted (Brunger et al., 1967; Faber, 1969), but results from these analyses should be carefully examined before being accepted. Further, predictive regression equations should not be formulated on the basis of the best visual graphical correlation between variables as was done by Faber (1969). Poor statistical methods can only produce results which are questionable from a physical point of view.

Østrem (1966; 1969; 1970) is attempting to apply regression analysis in his glacier basin studies in Norway. His latest report (1970) indicates work is progressing on the determination of the most useful meteorological parameters for predicting discharge from five Norwegian glaciers. Following his previous analysis (1966), predictive regression models are being developed. In the earlier analysis the use of the regression model to show the influence of the lag effect of meteorological events is well handled, but the presentation of the results is deceiving, in that the multiple correlation coefficient rather than the coefficient of determination is presented as a measure of the model's variance explanation.

Lang (1967; 1969) has made a very useful contribution to the statistical analysis of hydrometeorological events on glaciers. He has analyzed both hourly and daily variations in meltwater runoff as related to the meteorological variables of global radiation, temperature, vapor pressure, wind speed, and precipitation. The intention of the author was to find out how much information standard meteorological data could provide to the regression analysis; there was no intention of explaining the results with consideration of the physical meaning of the meteorological factors to the meltwater runoff. Unfortunately, the decision not to present regression equations and the associated regression coefficients and significance levels of the initial work limits the study to primarily a multiple correlation analysis.

In the above studies the necessity of determining the delay or lag in runoff resulting from certain meteorological events is an important aspect in developing a runoff model for the glacier basins. As in the present study, the situation was usually handled by using the lag parameters as additional predictor variables. Another approach is that of Mathews (1964), who studied the weather-discharge relationship by considering the effect of air temperature for a number of days before the day on which discharge was measured.

For the Athabasca Glacier he found that a "recession" equation of the form

$$Q_o = a + b \sum_{i=o}^{n} \bar{T}_i k^i$$

gave the best explanation of daily discharge (Q_o), where a and b are regression coefficients, T_o is the mean temperature for the day in question, n is the number of days previous to that day and k is a recession coefficient with a range of $0<k<1$. By testing various combinations of lag period and recession coefficients a "best recession coefficient" may be determined. This approach was applied to preliminary Peyto Creek data; the results gave trends similar to Mathews, but more data will be necessary to confirm the pattern of coefficient variation. Consequently, the results are neither presented nor discussed in this report.

CHAPTER 2

Available Hydrometeorological Data for Peyto Glacier

Meteorological observations commenced in 1965 at Peyto Glacier, but a reliable runoff record is available only since 1968. For this reason hydrometeorological analysis is limited to the 1968 and 1969 ablation period. The meteorological instuments were set up at the base camp (2,225 m a.s.l.) on the land north of the tongue of the glacier (Fig. 1). The stream gauge is located about 0.7 km downstream from the ice front. In 1969 a micro-meteorological site was established on the glacier (2,280 m a.s.l.) to study the energy balance over a small area. Interesting data have been obtained, but these data are not applicable to the present analysis.

AIR TEMPERATURE AND RELATIVE HUMIDITY MEASUREMENTS

Since 1965, continuous temperature and relative humidity measurements have been obtained during the ablation season by a thermohygrograph placed in a Stevenson Screen, 1.5 m above the ground. Minimum, maximum and standard mercury thermometers supplemented the continuous records (Fig. 2). Consequently, the standard measures of air temperature — minimum, maximum, and mean (from which "melting

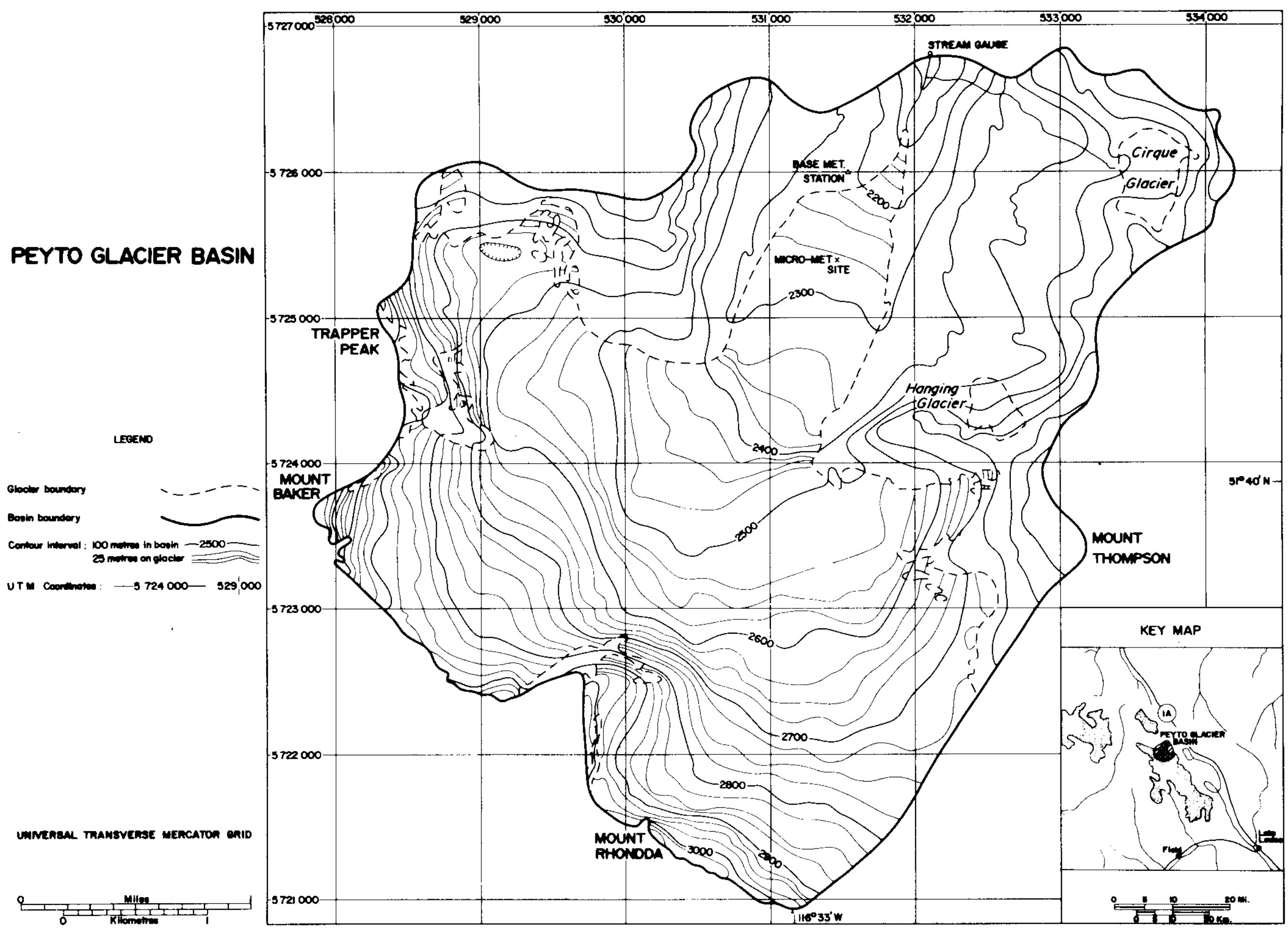


Figure 1. Peyto Glacier Basin

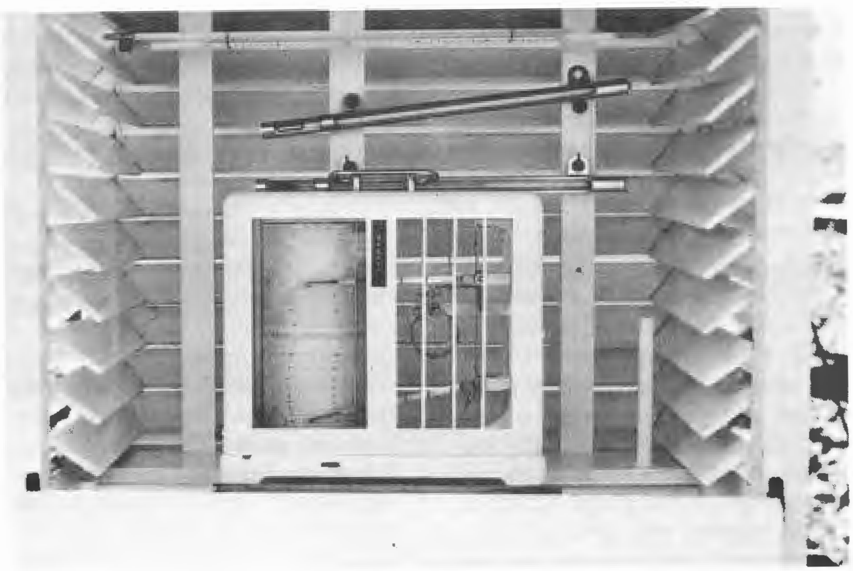


Figure 2. Thermohygrograph and thermometers in Stevenson Screen

degree-days" is calculated) — are reliably recorded for 1965-1970 inclusive.

Lacking temperature data at higher elevations, a pseudoadiabatic lapse rate of 0.55°C/100 m was assumed to apply during periods of precipitation. Such a value is very important in the estimation of rainfall over the basin as it is necessary to determine the form precipitation will take.

In the subsequent analysis, then, mean temperature (°C), as recorded by the thermograph for the daily period 0001-2400, the daily maximum temperature (°C) recorded by a maximum thermometer and checked with the thermograph record to ensure it corresponded to the 0001-2400 time period, and mean daily relative humidity (%) calculated from the continuous hygrograph trace for 0001-2400 h, were three of the predictor variables entered into the analysis of 1968 data. Their corresponding lag values for the previous time period were also used in the analysis.

WIND MEASUREMENTS

Records providing total daily run of wind are available for the 1967 to 1970 ablation periods. The totalizing anemometer is located at the base meteorological site, 5 m above the ground surface. The instrument is read daily at 0800, 1200, 1600 and 2000 h; the daily total in this study applies to the 2001-2000 period.

The wind values are for a 24-hour period, preceding the other variables by four hours. The other alternative was 0801-8000, but this would mean the runoff period would end 8 h before the predictor variable's period. Physically, the effect of wind would be delayed so it was better to end its "daily" total before the runoff total than to have it extend beyond. Analytically, the time periods of the variables should be the same, but this was not possible in this case.

CLOUD, SUNSHINE, AND RADIATION RECORDS

Estimates of cloud cover have been recorded since 1965, but the more precise and useful records of hours of sunshine and incoming solar radiation are available only since 1967. Cloud cover estimates are rather subjective and imprecise measures are limited to four instantaneous observations at 0800, 1200, 1600 and 2000 h. Quantitatively, these data are virtually useless and for this reason no attempt was made to incorporate this variable into the analysis.

A more reliable method of obtaining a measure of cloudiness or sunshine is to install a sunshine recorder. At Peyto Glacier a Campbell-Stokes recorder (Fig. 3) was in use during the summer observation period to obtain continuous daily values for periods of sunshine. Since the instrument site is located in an area of maximum shadow, in any quantitative analysis it is necessary to express the measured daily total of sunshine hours as a percentage of possible hours of sunshine. This method of expression also facilitates month-to-month comparisons, and allows for easy computation of the duration of cloudiness for any selected period.

The third meteorological variable in this group is incoming shortwave or global radiation; physically, it is a significant variable as it is an integral part of the energy

Figure 3. Campbell-Stokes sunshine recorder

Figure 4. Horizontally-installed pyranometer

Figure 5. Steven's type A–35 water-level recorder, Peyto Creek

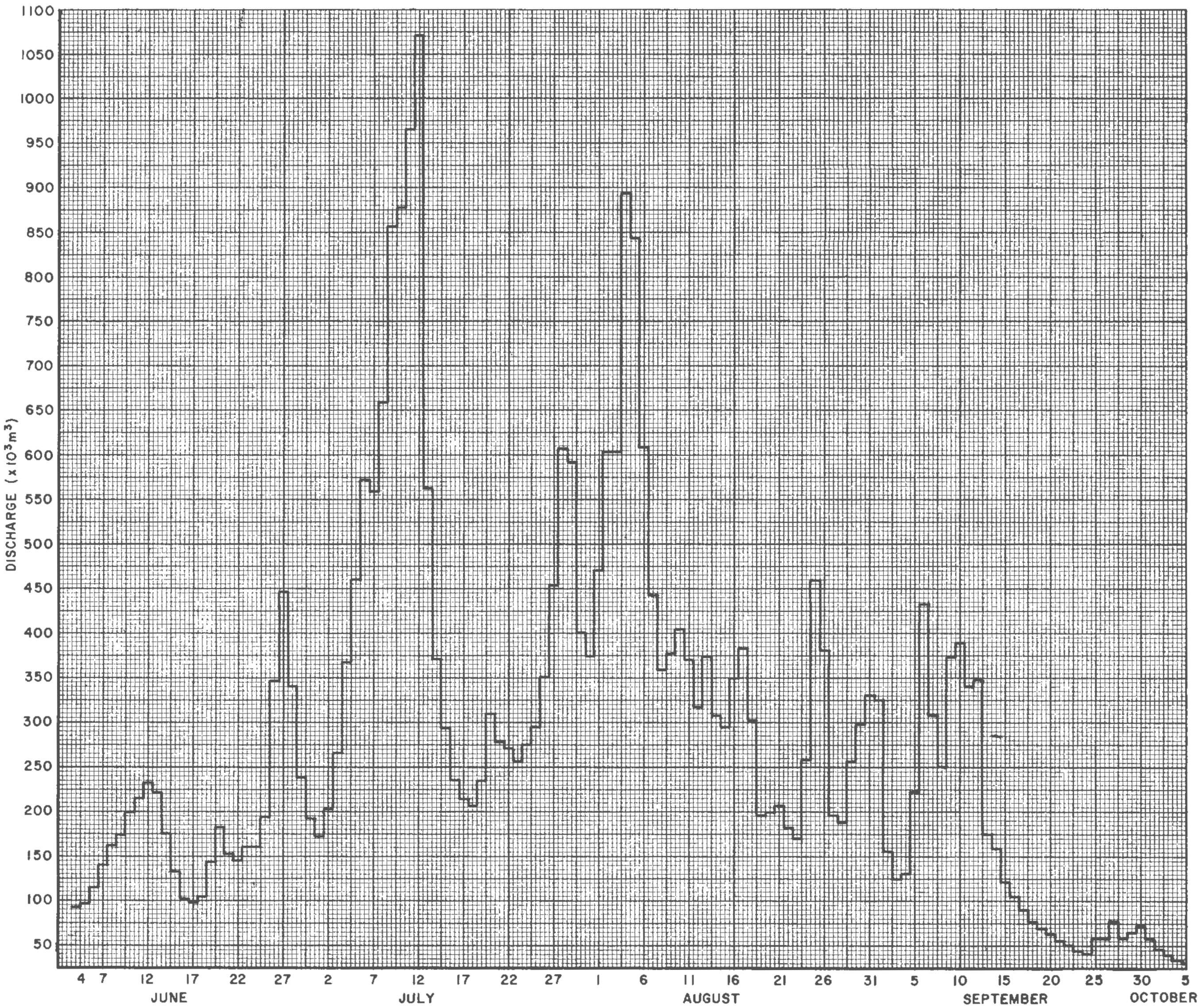


Figure 6. Peyto Creek hydrograph, 1968 (measured discharge)

balance near the surface of the earth. Records of global radiation, as measured by a horizontally installed pyranometer (Fig. 4) are available from the 1967 summer season onwards. However, a continuous record is not provided and only accumulated totals for each observation interval are available. With the sun setting before the 2000 h observation, only a negligible amount of diffuse solar radiation is received after this time; consequently, the period 2001-2000 provides the daily total for global radiation at the camp location. These totals are thus applicable to the 0001-2400 time period, as are the percentage sunshine values. It is important to remember that both these variables are measuring the same effect, but in a different manner.

PRECIPITATION MEASUREMENTS

The accurate measurement of precipitation, especially rainfall, is one of the most important meteorological parameters to be recorded at Peyto Glacier Point. Precipitation totals, as measured by a Pluvius rain gauge, are available from the base camp meteorological site for the summer season; point values for varying locations on the glacier tongue (i.e., below 2,460 m) provide additional information concerning precipitation distribution, but there are no records for the upper basins.

Since point precipitation totals (mm) are available only for the four observation periods, a 0001-2400 daily total cannot be calculated. As in the case of the wind measurements the 2001-2000 h time period has been used as the "daily" time period in this study.

DISCHARGE MEASUREMENTS

Since 1965 an attempt to obtain continuous stage records and to establish a reliable rating curve for Peyto Creek has been hindered by an unstable cross section, a problem common to flashy proglacial streams. In 1968 a Stevens type A-35 water-level recorder (Fig. 5) was installed by the Water Survey of Canada. Several direct discharge measurements using a current meter for low flows and the salt dilution method (Østrem, 1964) or the constant injection dye method for higher flows were used to establish a graph of water level vs. discharge, i.e., the rating curve. Using the results of the actual discharge measurements at different river stages, Water Survey of Canada constructed a rating curve for Peyto Creek for 1968; the curve is rated as fair (Ozga, 1968, p. 62). The main limitation was that there were no direct measurements of the stream at a flow above 260 m^3s^{-1}; consequently, the rating curve has been extended to higher water levels using a straight line log-log plot.

Following standard procedures, the rating curve has been used to determine the total daily (0001-2400) discharge (m^3) from the continuous stage records. Figure 6 shows the graph of daily discharge for Peyto Creek from June 5 to October 5, 1968. Daily discharge data have been worked up for 1967 based on the existing stage records and on the 1968 rating curve. Since a major flood in August 1967 washed the gauge out, a major channel realignment undoubtedly occurred; under such circumstances the 1968 rating curve cannot be applied to the 1967 record. Consequently, the 1967 discharge records are not considered reliable and are not used in this study.

Rainfall-Runoff Relations

THE AREAL DETERMINATION OF RAINFALL

To supplement the single totalizing rain gauge at the camp, a single line of Pluvius rain gauges were located at selected stakes on the tongue of the glacier (Fig. 7) during the 1965-1968 ablation seasons. These covered an altitudinal range from about 2,175 m to about 2,460 m, but the location and number of gauges were inconsistent from year to year. The gauges were positioned at varying times throughout each season, rather than all at the beginning, and consequently the accuracy and comparability of the records vary. The problem then is to estimate precipitation totals for the higher elevations which comprise about 75% of the total area of Peyto Basin. The distribution of area within the basin and the glacier itself may be readily seen in Figure 8.

Figure 7. Pluvius rain gauges located at selected stakes on Peyto Glacier

To establish a best estimate of this value, precipitation totals were corrected for elevation after computation of an altitudinal correction factor. Derikx (1969) used the 1967-68 winter accumulation values to establish the correction factor. In this study an attempt was made to use the existing Pluvius rain gauge records for the 1965, 1967 and 1968 seasons; from these records a correction factor based on seasonal rainfall totals was calculated.

A line of best fit, based on subjective interpretation of its position, was fitted to each year's totals (see Fig. 9). The observed base camp value was adjusted to the theoretical 2,300 m level and the correction factor was computed. Based on the slope of the line any desired altitudinal correction can then be calculated from the observed base value. The correction factors for the altitudinal zones are listed in Table 1.

Table 1. Altitudinal correction factors for rainfall

Elevation (m)	Correction Factors			Average Correction Factor
	1968	1967	1965	
<2400*	1.20	1.16	1.13	1.16
2400-2500	1.35	1.33	1.29	1.32
2500-2600	1.45	1.43	1.40	1.43
2600-2700	1.54	1.54	1.50	1.53
2700-2800	1.64	1.65	1.60	1.63
>2800**	1.83	1.86	1.86	1.85

*<2400: The base value is raised to the equivalent theoretical rainfall at 2300 m.

**>2800: 2950 m is used as the computational elevation; in the other cases the midpoint of the zone was used.

The lines of best fit may not be statistically precise, but the results have proven consistent and reasonable. Two likely sources of error exist. First, the correction factors are based on seasonal totals; for any particular storm they may not be correct. Secondly, the rainfall curve has been extended linearly to apply to the upper reaches of the basin. There are no data to confirm this assumption; hopefully future data will help solve this problem.

The next step was to determine the form of the precipitation. The differentiation between rain and snow was estimated from air temperatures by assuming rain to occur whenever the air temperature is 1.66°C (35°F) or

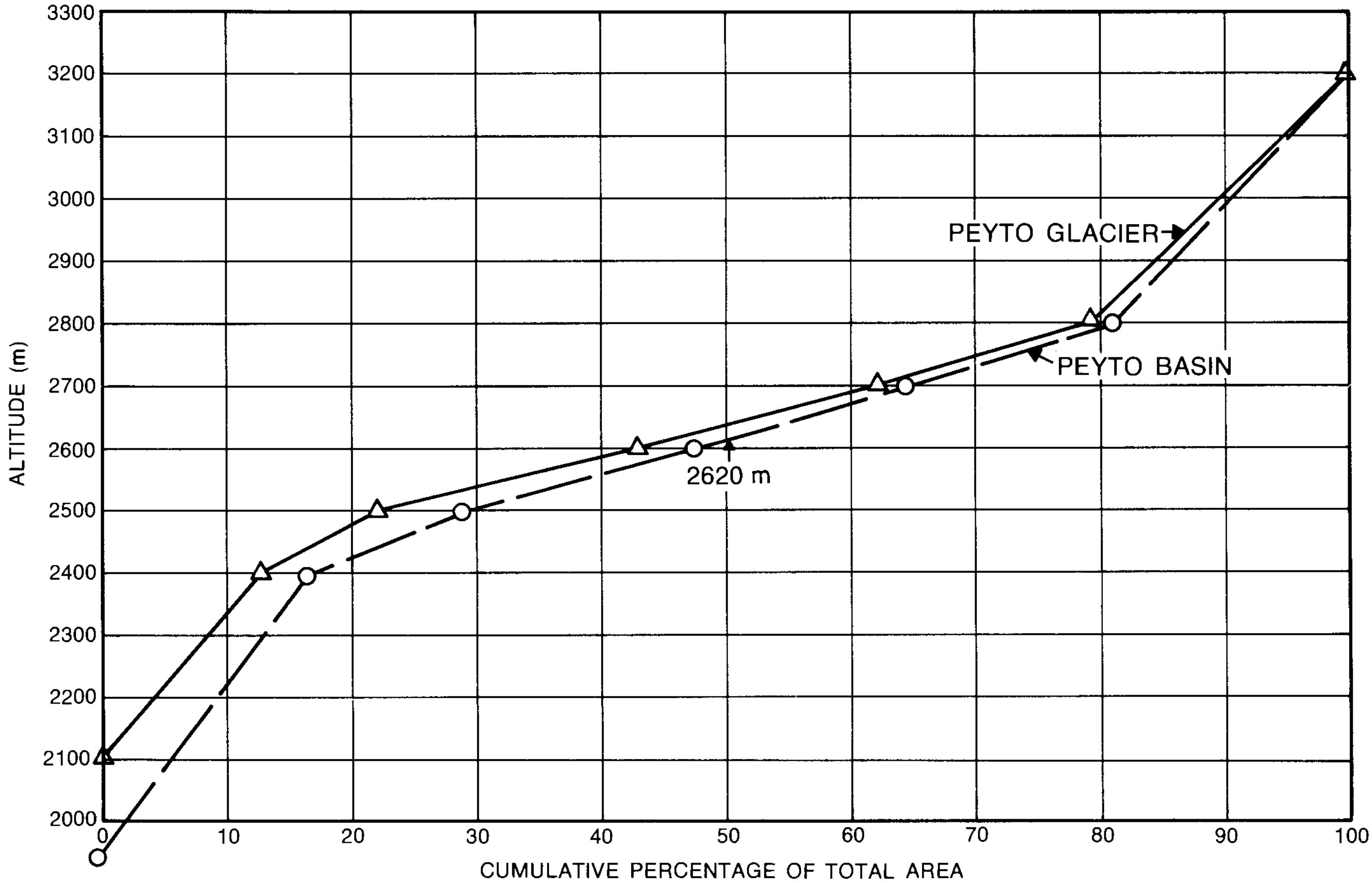


Figure 8. Hypsometric curves of Peyto Basin and Peyto Glacier

greater, and assuming snow to occur when it is less than 1.66°C (U.S. Corps of Engineers, 1965, p. 55). With this division about 90% of all cases would be correctly designated. Independent study by Denisov (1967, pp. 310-311) confirmed this division as he found 1.5°C (34.7°F) to be the dividing level. He also assumed a linear increase in precipitation with height as done in this study.

To determine the level, and thus the altitudinal zone in which snow might fall, a pseudoadiabatic lapse rate of 0.55°C/100 m was assumed to apply when precipitation occurred. A significant departure from this value during any storm will produce a significantly different result of the total rainfall distribution over the basin. At present, however, this method provides a best estimate of daily (2001-2000) precipitation over the basin.

RAINFALL-RUNOFF ANALYSIS

The hydrometeorological study of glacier runoff is constantly complicated by the addition of precipitation, particularly rain. The problem is that there is always going to be ice melt when there is rain; it is necessary to try to determine the time distribution of runoff of rain alone, so that this component can be extracted from total runoff to facilitate study of meltwater runoff alone.

The initial problem is that there are seasonal changes in the glacier-runoff characteristics influenced primarily by snowpack conditions. In spring a deep pack is present over all of Peyto Basin; the winter accumulation is measured before melt begins. This pack, however, does subdue and delay any runoff which would occur from direct rainfall. One reason for this is the effect the snowpack has in storing rain and snowmelt; this basically involves the fulfillment of the liquid water requirements of the snowpack. This apparent "loss" of water input in conditioning the snowpack before runoff begins is the sum of the equivalent cold content of the snowpack and its liquid water deficiency. From snow pit data at selected basin sites, the snowpack was recorded as being isothermal at 0°C during the early part of the ablation season; apparently the cold content requirements had been met earlier in the spring, at least in the accessible parts of the glacier.

Conditioning of the snowpack will have to occur only once provided there is no freezing weather subsequent to the addition of water. For Peyto Glacier it was assumed that the liquid-water-holding capacity of the snowpack was

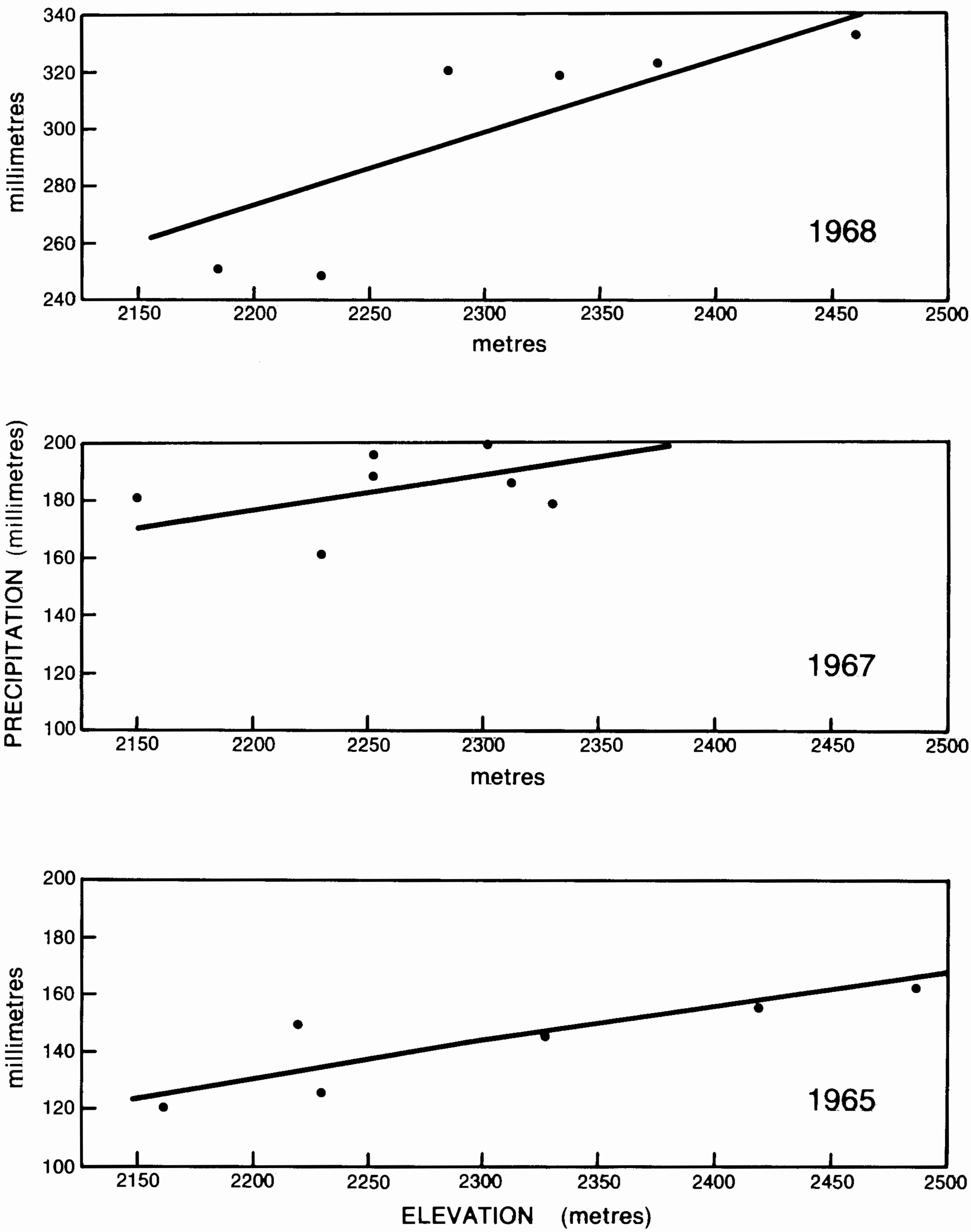


Figure 9. Distribution of rainfall with altitude

Figure 10. Surface drainage network developing during late June 1969 at 2500-2700 m elevation

about 4% of the water equivalent. However, the free water content of the pack is not measured, and liquid water deficiency values at any particular time are only estimates. It is reasonable, though, to assume that a liquid water deficiency of some order of magnitude did exist in the upper basins during the early part of the ablation period.

In a previous analysis (Goodison, 1969) of a rain-on-snow event from June 25 to June 30, 1968 the liquid water deficiency problem was considered and subsequent allowances were made for it. For the present study involving the entire season there is not enough information to allow daily calculations to be made; analytically, it is necessary to assume the liquid-water-holding capacity was near 4% throughout the entire season. To have information on the free water content would also be useful in analyzing changes in the delay of runoff from direct precipitation. Not only is water lost because of the liquid-water-holding capacity, but it is estimated that for deep mountain snow pack water in transit could be up to 6% of the snowpack water equivalent once inflow and outflow were in equilibrium (U.S. Army Corps of Engineers, 1960, p. 23).

Another factor influencing the delay in runoff is that meltwater channels are not well developed in the spring. On Peyto Glacier it appears that runoff is subglacial, englacial and superglacial; in spring these channels are still frozen or have not developed on the surface because of a deep snow cover. With no indication of a jökulhlaup opening the subsurface channels (Meier, 1964, pp. 16-31), it appears that the channels progressively develop and result in a gradual reduction of the delay or lag period involved in the runoff process.

The travel time for surface or subsurface meltwater to reach the gauge from various elevations is another unknown. Without this information lag times for rain and melt are even more difficult to calculate. As an example, Figure 10 shows a surface drainage network developing during late June 1969 at the 2500-2700 m level. However, there is no information regarding the travel time for water from here to the stream gauge. Some estimate of this time is necessary in any calculation of the lag time of meltwater and rainfall runoff on the glacier. Naturally, these times change as the surface and subsurface conditions change. Meier (1964, pp. 16-19) summarizes the characteristics of direct precipitation-runoff as follows: spring, it is subdued and delayed; summer, there is a slight delay; and fall (before a snowpack accumulates), there is no delay and the runoff is very "flashy". In 1968 Peyto Creek runoff during periods of precipitation followed the spring and summer characteristics.

The above discussion emphasizes reasons for runoff delay and its subsequent changes, but as for most glaciers being studied there is a limited quantitative assessment of the lag period available. In a non-glacierized basin the unit-hydrograph method is used to study the distribution of runoff over succeeding days after an initial rainfall input. For a glacier basin, however, one cannot derive a unit-hydrograph for rain alone since there will always be snow or ice melt when there is rain; the flow components remain unseparated.

To obtain an estimate of runoff times for Peyto Basin, a snowmelt-rainfall recession curve was derived based on the combination of data from periods throughout the summer of 1968 (Fig. 11). Data used were for periods when the air temperature over the ice was 0°C or lower, so that melt would be nil or at least limited to a small amount of radiation melt. Overlapping of values from different periods facilitated the positioning of points on the graph and the

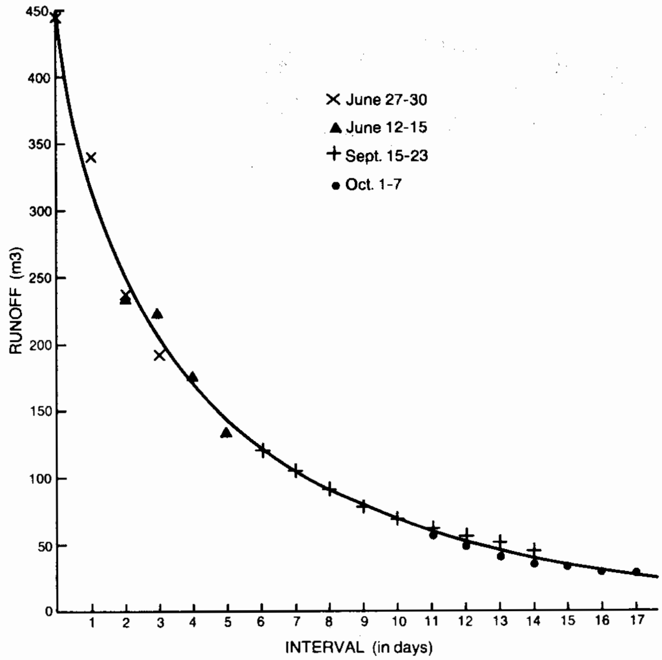


Figure 11. Calculated recession curve for Peyto Creek

subsequent drawing of a smooth curve. From the recession values it was determined that for daily flows above 150 m^3 the recession constant is 0.76 and for recession flows less than this it is 0.88. In the transition range of 150 m^3, 0.82 is applicable. This recession curve can then be applied to total daily flows to estimate the daily runoff distribution (Goodison, 1969, p. 25). In this study, a lack of continuous precipitation readings limited the accuracy of melt and rainfall estimates and thus affected the calculated distribution. It is clear, though, that a runoff delay period involving five days existed in late June 1968, a period characterized by an extensive snow cover and cool, wet weather. Of significance is that for any day's melt and rainfall, when there was a deep snow cover over the basin, there was more runoff on each of the second, third and fourth days than on the first day. This presumes rainfall to be equally distributed throughout the day or somewhere around midday. If rain falls very early or very late in the day the same percentage distribution cannot be expected to hold true. The calculated distribution would also not apply later in the season when the glacier tongue and ice-free parts of the basin are not snow-covered.

Using the available data and subjective interpretation, a percentage distribution of any day's rainfall was calculated. The values listed in Table 2 were applied to the daily rainfall totals (as calculated by the above method), and the adjusted values were then extracted from daily runoff to give runoff totals which would approximate those from snow and ice melt alone. For a completely snow-covered basin it takes about five days for most of any day's rainfall to pass through the system; naturally, there are adjustments

Table 2. Runoff distribution resulting from rain*

I BASIN IS SNOW-COVERED:	
Rain over entire basin	total rainfall, %
a) rain all day or mid-day:	15 – 30 – 25 – 20 – 10
b) rain in last 8 hours only:	8 – 32 – 27 – 22 – 11
c) rain in first 8 hours only:	23 – 28 – 23 – 18 – 8
Snow at higher elevations	
d) rain all day below 2500 m:	45 – 35 – 20
rain all day below 2600 m:	40 – 35 – 25
rain all day below 2700 m:	30 – 35 – 25 – 10
rain all day above 2700 m:	as in a)
II TONGUE OF GLACIER IS BARE ICE, BASIN IS FREE OF SNOW:	
Rain over entire basin	total rainfall, %
e) rain all day or mid-day:	60 – 30 – 10
f) rain in last 8 hours only:	50 – 35 – 15
g) rain in first 8 hours only:	67 – 33
Snow at higher elevations	
h) rain all day below 2500 m:	80 – 20
rain all day below 2600 m:	75 – 25
rain all day below 2700 m:	70 – 25 – 5
i) rain in first 8 hours only below 2500 m:	100
rain in first 8 hours only below 2600 m:	90 – 10
rain in first 8 hours only below 2700 m:	80 – 20

*The values give the percentage of total rainfall that runs off on same first day, second day, third day, etc., after a rainfall.

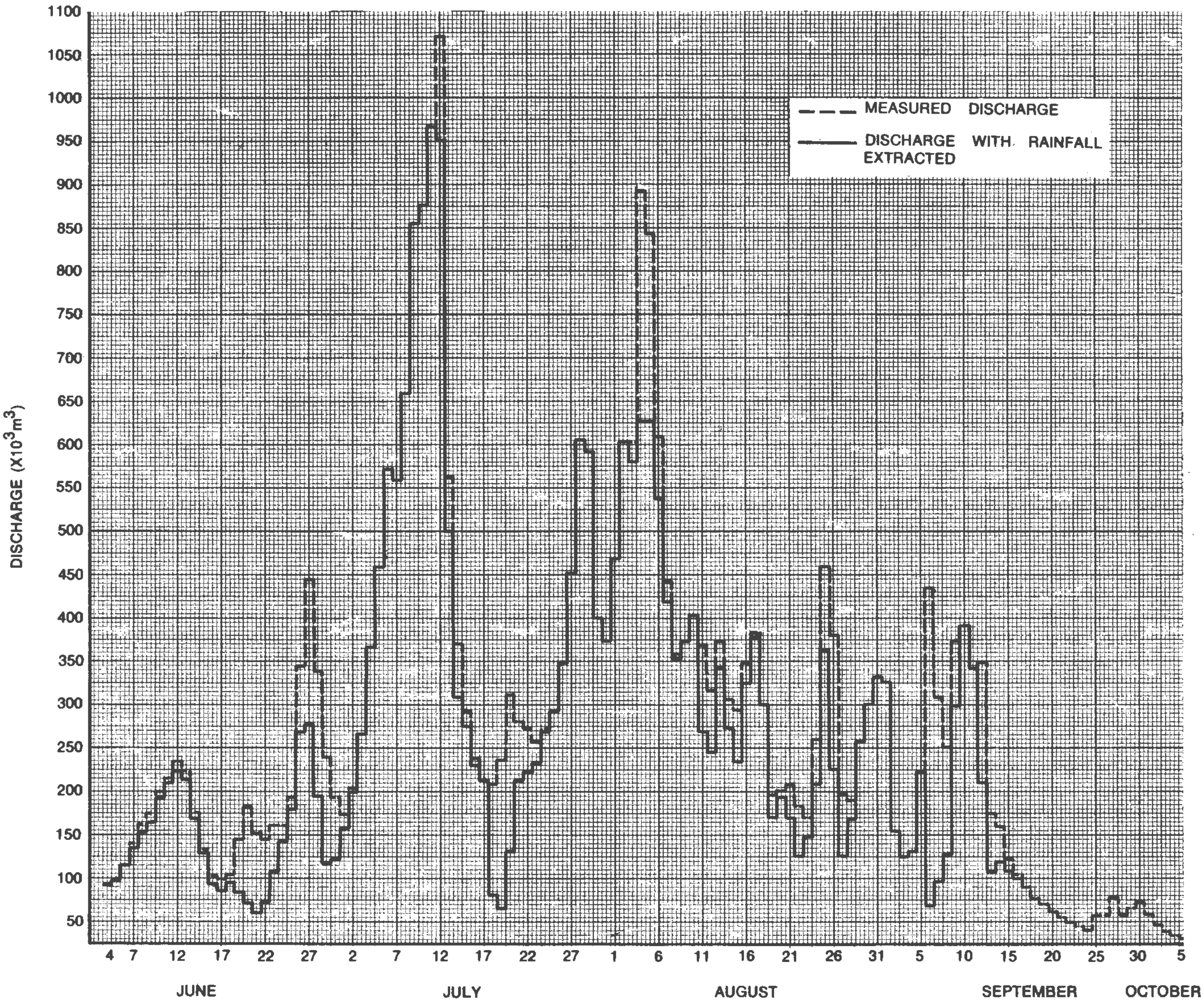


Figure 12. Peyto Creek hydrograph, 1968

necessary if rain falls only at the lower levels with snow falling at higher levels. A faster flow-through time is expected as the season progresses, while late in the season a combination of the two distribution sets is applied, depending on whether a fresh snowfall occurred between rainfalls.

Figure 12 shows the daily runoff totals both before and after rainfall has been extracted by the above method. At the moment, there is no way of establishing the accuracy of these distribution estimates; other members of the Glaciology Division concerned with this problem agree the estimates are reasonable. It is desirable to be able to extract the contribution of rainfall in order to have only melt runoff to analyze, either by the energy balance equation or by statistical analysis.

From the above discussion it is evident that it is difficult to forecast the runoff which will result from any given rainstorm. Meier and Tangborn (1961, p. B-14) had the same problem with glaciers in the western United States and they concluded that the following factors affected the rate of runoff following a rainstorm: a) the amount of basin area covered by snow, b) the thickness and density of the snowpack (i.e., the liquid-water-holding capacity), c) the snow temperature, and d) whether the snow has been channeled by previous rain or periods of high melt rate. As discussed above, a normal seasonal pattern of these factors does exist for Peyto Glacier, but they may change rapidly and unpredictably in the fall. It is unfortunate that in the last 10 years more quantitative information has not been collected which would allow a more detailed assessment of these factors and their effect on the rate of runoff.

A Statistical Analysis of Hydrometeorological Events on Peyto Glacier

MULTIPLE REGRESSION ANALYSIS

As pointed out at the beginning of this paper, limited research has been carried out in applying multiple regression analysis to glacier runoff. Although results are encouraging, it is not clear yet how successful the technique will be in providing a predictive runoff model. As in most models, there are certain inherent problems which first must be understood. A discussion of the mathematics of regression analysis will not be provided here. Instead reference is made to Johnston (1963), to Ezekiel and Fox (1959), or to Draper and Smith (1966) for theoretical discussions. Solomon (1966) and Stammers (1966) provide technical discussions with reference to hydrological problems.

As with most modelling schemes, several requirements or assumptions are involved in the regression method. Sharp *et al.* (1960, pp. 1284-1286) and Tywoniuk and Wiebe (1970) discuss the assumptions which can lead to difficulty. Multiple regression assumes that there are no errors in the independent variables, as error occurs only in the dependent variable. With hydrometeorological data this is not entirely true as there is error in all variables simply because of the nature of the data being measured. Another assumption is that the population of the dependent variable is normally distributed about the regression line and has the same variance for all fixed levels of the independent variables being considered. In hydrology, however, over a short time period, there are not enough large events on record to afford reliable information about the distribution of the dependent variable about the regression line. Finally, it is assumed that the observed values of the dependent variable (in this case, runoff) are uncorrelated random values. Needless to say, this is not the case in hydrology; this problem of serial correlation will be discussed further in relation to the present study.

If the above assumptions are seriously invalidated then one must be careful in accepting the regression results as correlation coefficients, t-tests, and other significance tests may prove misleading. Since many of the above problems are linked to the normality of the distribution, it may be decided to use some form of transformation to normalize the original distribution. However, it must be decided whether transformation of the variables is physically meaningful. If logarithmic transformations of the independent variables are deemed necessary, do they actually reflect the exponential relation which should exist between the variables? In other words should the model be additive or multiplicative? The question is whether one should transform to obtain normality and linearity despite the physical interpretation or be used to help indicate if a transformation is necessary? Goodison (1968, pp. 108-111; 1968, pp. 27-36) studied the effect different types of transformations had on the results of regression models and how the physical interpretation of the model would differ. Using hydrometeorological data similar to that available for this study, it was found that the results were not significantly improved when different transformations were employed and that transformed variables did not provide physically meaningful results. Based on this earlier work, no transformations were applied in this study.

It is necessary, however, to consider the effects of serial correlation of a hydrologic time series. A time series is a sequence formed by the values of a variable at increasing points in time. The series may be composed of the sum of two components: a random element and a non-random element. If the values of the series are not independent of each other, the non-random element exists, and the values are said to be serially dependent (Matalas, 1963). The serial nature of some hydrological and meteorological events is commonly observed, and has been used in the study of trends and cycles inherent in the data.

Autocorrelation analysis is a long established technique, but it has tended to be overshadowed by spectral analysis. In respect to streamflow analysis Matalas (1963), Fiering (1964), Dawdy and Matalas (1964), and Matalas (1966) have contributed greatly to this type of analysis, while Quimpo (1968a; 1968b) provides a review of the theory and the application of autocorrelation analysis in the study of hydrologic events.

Being concerned with daily flows in this study, it is realized that basin storage of rain and meltwater (i.e., in the snowpack, in the channel, or as "groundwater" and interflow) significantly influences the runoff process. A lag effect of some order of magnitude will exist, and the runoff sequence will be non-random. To permit statistical modelling of such hydrologic series, an autoregression process is used.

Table 3. Serial correlation coefficients for selected variables, 1968 and 1969

Lag (in days)	Runoff		Mean Temperature		Maximum Temperature		Sunshine Hours		Rainfall	
	1968	1969	1968	1969	1968	1969	1968	1969	1968	1969
0	1.000*	1.000*	1.000*	1.000*	1.000*	1.000*	1.000*	1.000*	1.000*	1.000*
1	0.903*	0.866*	0.804*	0.697*	0.798*	0.616*	0.540*	0.292*	0.111*	0.403*
2	0.753*	0.639*	0.574*	0.376*	0.606*	0.322*	0.287*	0.216*	−0.084	0.177
3	0.628*	0.610*	0.469*	0.254*	0.506*	0.210*	0.300*	0.138	0.014	0.110
4	0.517*	0.515*	0.412*	0.141	0.413*	0.081	0.236*	0.181	0.086	0.081
5	0.440*	0.420*	0.291*	0.010	0.320*	−0.050	0.071	0.071	−0.012	0.073
6	0.389*	0.394*	0.175*	−0.005	0.218*	−0.033	0.009	0.068	0.013	0.005
7	0.332*	0.369*	0.153	0.061	0.177*	0.086	0.178	−0.024	0.050	0.026
8	0.274*	0.315*	0.118	0.100	0.139	0.095	0.150	0.239	−0.070	0.090
9	0.204*	0.318*	0.061	0.173	0.061	0.107	−0.035	−0.034	−0.161	0.092
10	0.149	0.338*	0.023	0.233	−0.018	0.138	−0.097	−0.039	−0.128	0.129
11	0.145	0.293*	0.054	0.337	0.002	0.192	−0.088	−0.033	−0.046	0.165
12	0.156	0.258*	0.103	0.311	0.056	0.103	−0.124	−0.104	−0.073	−0.013
13	0.151	0.275*	0.148	0.321	0.056	0.129	−0.157	−0.042	−0.128	−0.089

These correlation coefficients are based on the entire summer record for Peyto Glacier.
*Significant at the 95% level.

The general model for the autoregressive scheme is

$$Q_t = \sum_{i=1}^{n} \alpha_i Q_{t-1} + \epsilon_t$$

where Q_t is discharge at time t

$\sum_{i=1}^{n} \alpha_i Q_{t-1}$ is the effect of n autoregressive terms which have been found to contribute significantly to the estimation of Q_t and ϵ_t is a random component

In this study a first order process was used in the runoff analysis of Peyto Creek. This process alone may be represented by

$$Q_t = r_1 Q_{t-1} + \epsilon_t$$

where $r_1 = \alpha_1$, the first order serial correlation coefficient.

However, other components in addition to the basin lag effect which will affect the daily runoff are the daily heating input which will determine a particular day's contribution of snow and ice melt; precipitation, in particular rainfall, which will add to the total runoff; and, other meteorological parameters which will operate in conjunction with the heat inputs to affect the daily melt contribution.

To combine the above factors in a physically meaningful and useful model involves careful consideration of the use of lag variables and serially correlated variables. Not only is there the problem of runoff being serially correlated, but there are serial effects present for most of the weather elements. The effect of previous day's events is especially marked in relation to the heat inputs. Often the ability of a given input to produce melt will depend on the previous events; for example, is there a heat deficit which must be overcome before melting can occur? As discussed earlier in this report there is the problem of liquid-water deficiencies occurring; heat inputs in some form or other must be used to overcome this deficiency before runoff from melt will occur.

The degree of serial correlation present in hydrometeorological data is evident in Table 3. The effects are pronounced for discharge and temperature but progressively decrease for sunshine, and precipitation variables.

Statistically, the significant number of lags varies for each variable and during each year. Physically, the previous day's effects diminish rapidly and are largely determined by the persistence of short-term weather patterns. In the subsequent analysis, it was deemed sufficient to employ only a one-day lag in the model, and to avoid statistical and physical interpretation difficulties which could result from a multivariate multi-lag model. The type of analysis most suited to this particular problem (given the data previously outlined) was step-wise multiple regression which considered lag variables as additional predictor parameters and discharge as the dependent variable. The inclusion of the previous day's discharge as a predictor variable allows for the development of an autoregressive model. The variables entered into this analysis are:

Q_0 – Total daily (0001-2400) discharge (m^3); the dependent variable,

Q_1 – total daily discharge (m^3) for previous day,

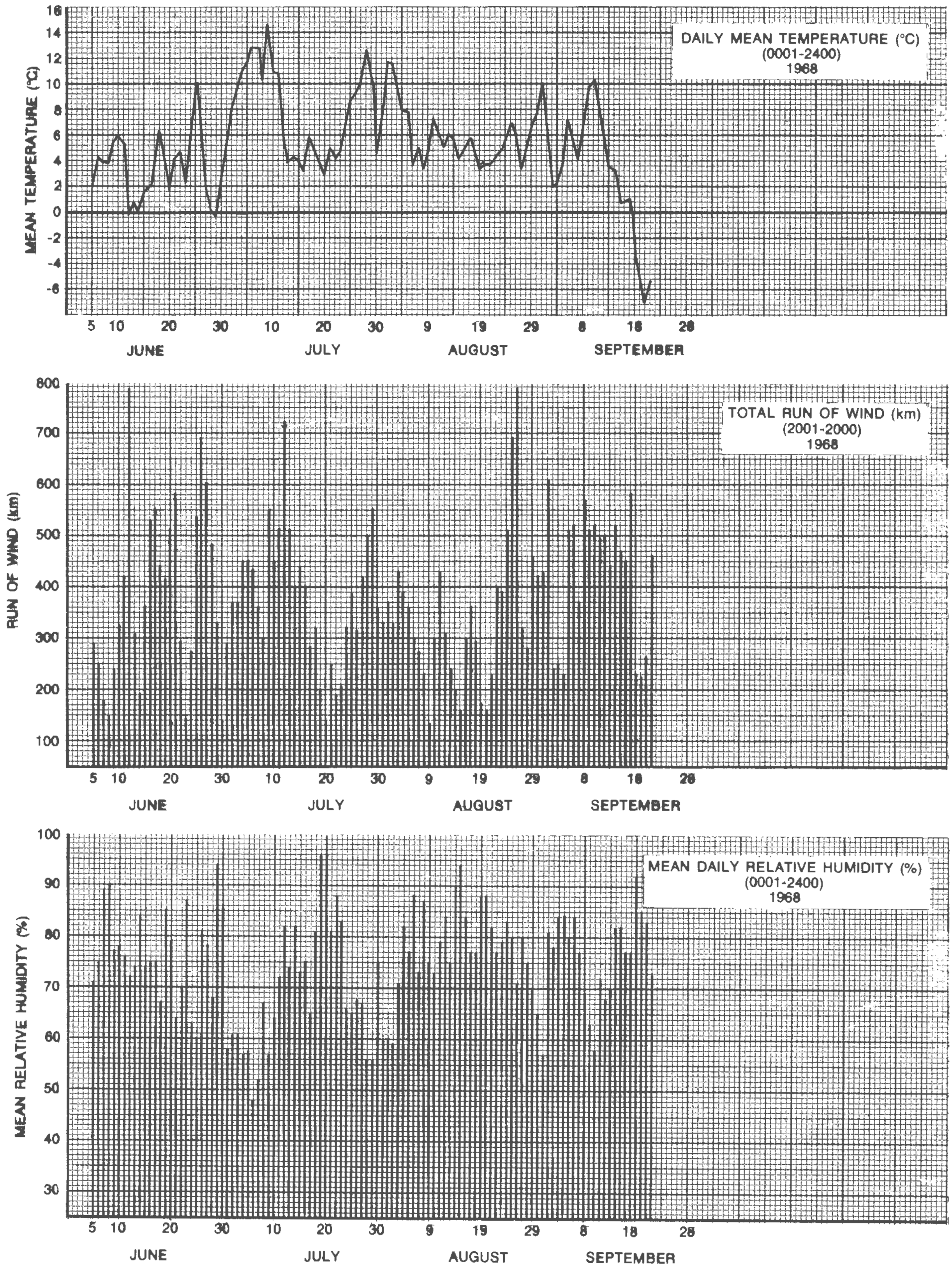
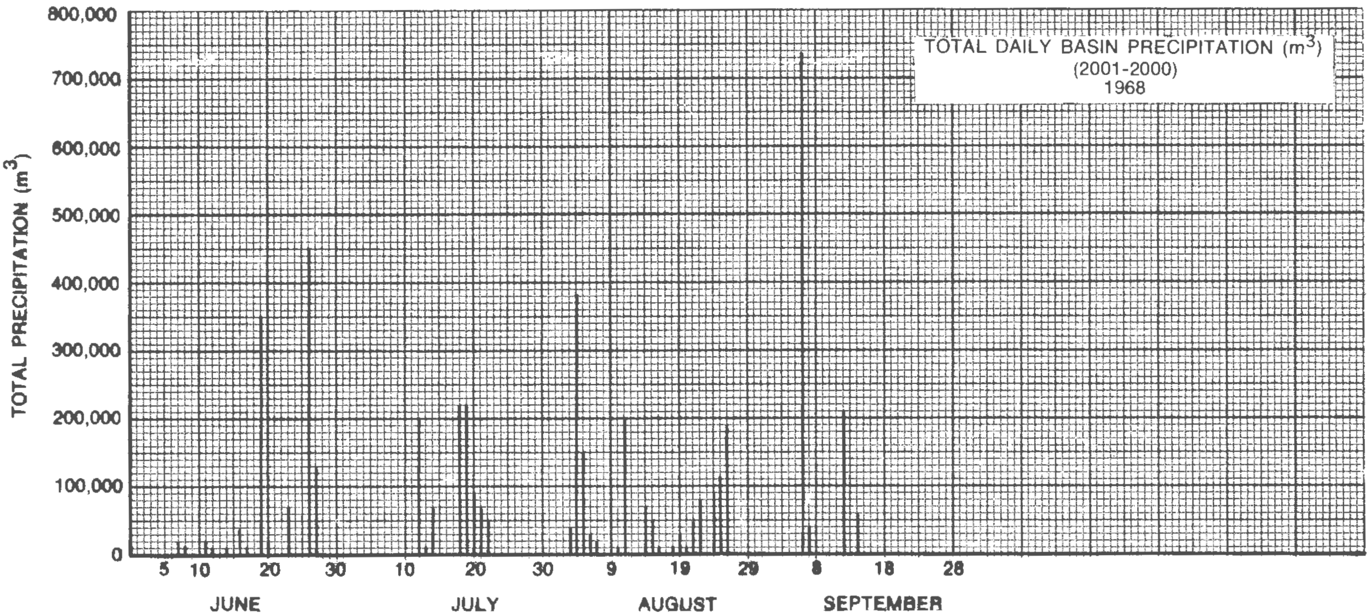
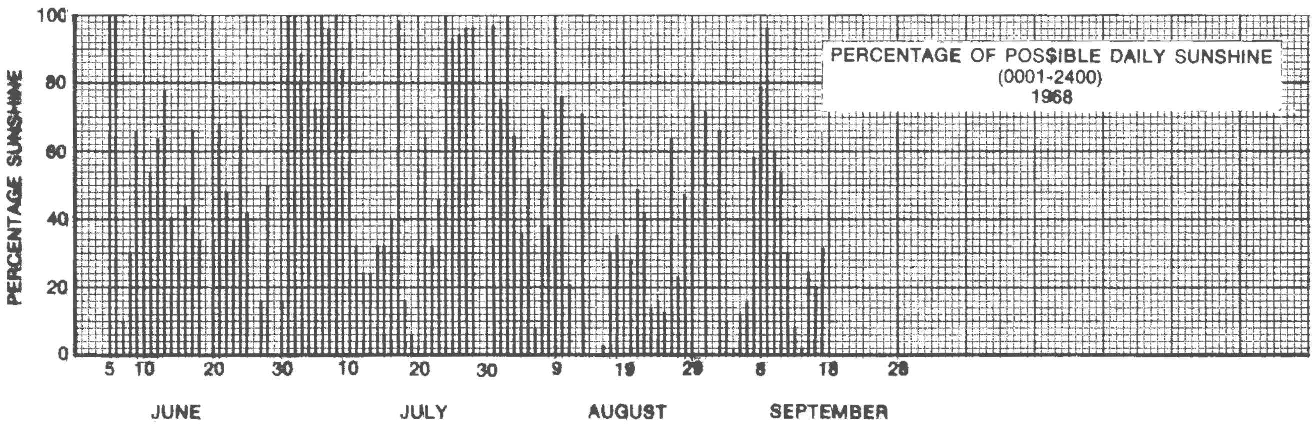


Figure 13. Daily values of measured weather elements, Peyto Glacier, 1968





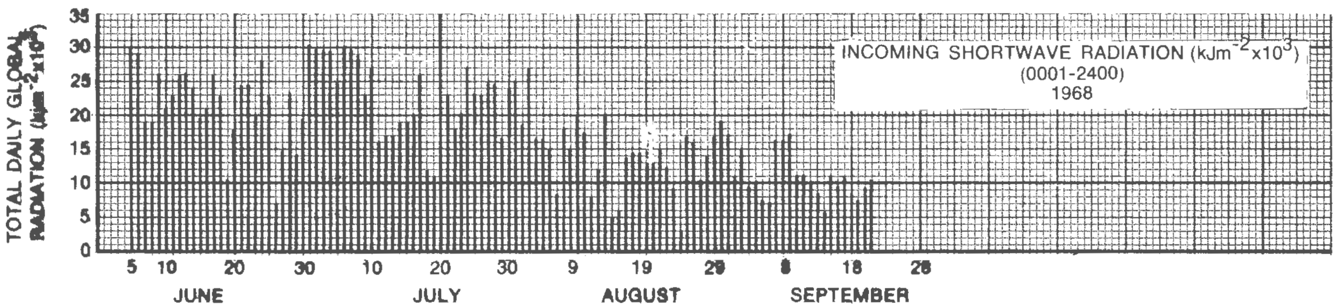


Figure 13. (Cont.) Daily values of measured weather elements, Peyto Glacier, 1968

Table 4. Intercorrelation matrix for 1968 model (June-September)*

	Q_1	T_o	T_1	T_{max_o}	T_{max_1}	RH_o	RH_1	H_o	H_1	V_o	V_1	R_{swo}	R_{sw_1}	Q_o
Q_1	1.00	0.48	0.67	0.47	0.66	−0.25	−0.38	0.19	0.32	0.21	0.06	0.12	0.23	0.90
T_o		1.00	0.82	*0.97*	0.83	−0.65	−0.56	0.58	0.61	0.22	0.02	0.38	0.48	0.67
T_1			1.00	0.79	*0.97*	−0.41	−0.66	0.35	0.55	0.32	0.12	0.18	0.35	0.75
T_{max_o}				1.00	0.82	−0.69	−0.58	0.67	0.64	0.16	−0.01	0.50	0.55	0.67
T_{max_1}					1.00	−0.47	−0.71	0.42	0.66	0.25	0.09	0.28	0.48	0.73
RH_o						1.00	0.53	−0.77	−0.53	−0.38	0.02	−0.62	−0.49	−0.39
RH_1							1.00	−0.39	−0.78	−0.34	−0.08	−0.29	−0.62	−0.44
H_o								1.00	0.53	0.07	−0.08	*0.82*	0.55	0.31
H_1									1.00	0.08	−0.06	0.44	*0.81*	0.42
V_o										1.00	0.25	−0.03	−0.01	0.24
V_1											1.00	−0.15	−0.14	−0.05
R_{swo}												1.00	0.67	0.23
R_{sw1}													1.00	0.31
Q_o														1.00

*Based on 109 continuous daily observations.

T_o — mean daily (0001-2400) temperature (°C),

T_1 — mean daily temperature for previous day,

T_{max_o} — maximum daily (0001-2400) temperature (°C),

T_{max_1} — maximum daily temperature during previous day,

RH_o — mean daily (0001-2400) relative humidity (%),

RH_1 — mean daily relative humidity during previous day,

H_o — percentage sunshine hours (%),

H_1 — percentage sunshine hours during previous day,

R_{swo} — daily incident shortwave radiation (kJm^{-2}),

R_{sw1} — daily incident global radiation during previous day,

V_o — daily (2001-2000) run of wind (km),

V_1 — daily run of wind during previous day.

In some models tested, rainfall was used as an independent variable instead of extracting it from discharge. When this was done the following were used:

P_o — total daily (2001-2000) rainfall (m^3) over Peyto Glacier,

P_1 — total daily rainfall for the previous 24-hour period.

These variables are illustrated graphically in Figure 13.

In a step-wise procedure a number of intermediate regression equations are obtained, as well as the complete multiple regression equation. These equations are obtained by adding one variable at a time; the variable added is that one which makes the greatest improvement in "goodness of fit". The important property of the step-wise method is that a variable may be indicated to be significant early in the operation but after several other variables are added to the regression equation, the initial variable may be indicated to be insignificant and will be removed before others are added. Thus only significant variables are included in the final regression (Efroymson, 1960, pp. 191-192).

For all of the test runs, based on 1968 data, additive rather than multiplicative models were used, as on the basis of physical and statistical reasoning transformations were not desired. Initial runs used precipitation as an independent variable, without it being extracted from the runoff records. For rainy periods this is a suitable method, if there are few zero events to destroy the relationship of the rainfall-runoff process. June 1968 at Peyto was a rainy period with some rain on 50% of the days; in August there was rain on 65% of the days. Models for these rainy periods produced good results with a variance explanation and standard error as a percentage of the mean of 93.2% and 12.4%, and 94.5% and 12.5%, respectively. Lang (1967) also found precipitation to be a useful predictor for wet periods; in his analysis rain occurred 73% of the time. In such cases variations in runoff are determined largely by the number and persistence of rainfall events. However, when radiation inputs dominate the melt and runoff process, scattered rainfalls are not detected in a multiple regression analysis, and statistically, precipitation becomes an insignificant predictor variable. In order to account for the effect of precipitation on discharge, precipitation must first be extracted from the runoff record by some physically meaningful method. This was done for Peyto Creek discharge for June-September, 1968, by the method outlined above. Results suggest this extraction was successful, except for the month of September, when fresh snow and rain caused problems in selecting the best percentage distribution.

A further complication, which one must be aware of, is the problem of inter-correlation among predictor variables. Hydrometeorological data is particularly prone to this problem. Table 4, is a correlation matrix for all variables (excluding rainfall) over the time period June 6 to September 21, 1968. Two sets of inter-correlations are particularly significant: one between mean and maximum temperature (and their lag complements), and the other between sunshine hours and radiation.

If all these predictor variables are entered into the regression analysis, negative regression coefficients usually result, suggesting the existence of an inverse relationship with the dependent variable. In general, these results are physically misleading as some of the negative, partial correlation coefficients are caused by high intercorrelations between predictor variables.

Table 5, illustrates how sensitive the partial correlation coefficient can be. In the first case all variables are forced into the model and several negative coefficients are present. These in turn result in negative regression coefficients. Reasonable physical intuition suggests that these are not true relationships. In reality, one variable is trying to explain variations already accounted for by the other, i.e. they are not "independent" of each other.

In analyzing the intercorrelation matrix, a decision must be made concerning mean and maximum temperature and sunshine and radiation. Either the variables can be combined in some manner, perhaps through the use of principal component analysis, or one of the two variables must be dropped. In this study maximum temperature and radiation were dropped. The use of mean temperature is a standard procedure, but one would not expect the important physical variable of global radiation to be

Table 5. Comparison of partial correlation coefficients

	A	B	C	D
Q_1	0.891	0.872	0.868	0.891
T_o	−0.084	0.396	0.364	0.508
T_1	0.169	−0.063	−0.017	–
T_{max_o}	0.353	–	–	–
T_{max_1}	−0.261	–	–	–
RH_o	0.123	0.122	0.084	0.066
RH_1	0.054	0.002	0.035	–
H_o	−0.090	−0.006	0.101	0.100
H_1	0.191	0.111	−0.003	–
V_o	0.200	0.164	0.147	0.057
V_1	−0.333	−0.323	−0.314	–
R_{swo}	0.114	0.152	–	–
R_{sw1}	−0.161	−0.181	–	–
R^2	91.9	90.4	90.1	88.9
$\frac{S_{Q_o}}{\bar{Q}_o}$	0.219	0.236	0.238	0.246

Table 6. Results of selected multiple regression analyses for 1968.

RUN	Constant a (x10^5)	Regression Coefficients									R^2	$\frac{S_{Q_o}}{\bar{Q}_o}$
		Q_1	T_o	T_1	RH_o	RH_1	H_o	H_1	V_o	V_1		
Monthly Models												
1. June	– 0.2	0.875	5520.8	6440.3							86.9	0.160
2. July	– 3.7	0.738	35260.3	12086.5	3655.0			−1205.2	358.8	−520.7	96.7	0.117
3. Aug.	– 3.2	0.731	41262.8		2596.5			−1082.2			91.2	0.127
4. Sept.	5.6		8826.1			−5630.1					70.9	0.280
Weather Period Models												
5. June	– 0.2	0.875	5520.8	6440.3							86.9	0.160
6. July 1 – Aug. 5	– 4.0	0.705	38040.0	11871.9	3816.4			−1442.4	346.7	−445.9	96.4	0.118
7. Aug. 6 – Sept. 21	0.9	0.588	12195.0							−142.9	76.6	0.266
Season Model												
8. June – Sept.	0.06	.787	14266.7						94.1	−156.3	89.6	0.238
Models Without Q_1												
9. June	1.1		10968.6								21.3	0.378
10. July – Aug. 5	– 11.5			68833.3		10263.6			842.2		84.1	0.233

Table 6. (Cont'd) Results of selected multiple regression analyses for 1968

2 Day Running Mean	Constant a (x 10^5)	Regression Coefficients						R^2	$\frac{S_{Q_o}}{\bar{Q}_o}$
		Q_1	T	RH	H	R_{sw}	V		
11. June – Sept.	0.13	0.732	17555.7				–91.9	88.1	0.392
12. June	–0.78	0.973	14976.7		606.3			89.6	0.158
13. July 1 – Aug. 5	–11.20	0.643	52497.9	10013.3		7.4		93.5	0.151
14. Aug. 6 – Sept. 21	0.96	0.542	13006.2				–147.7	71.8	0.291

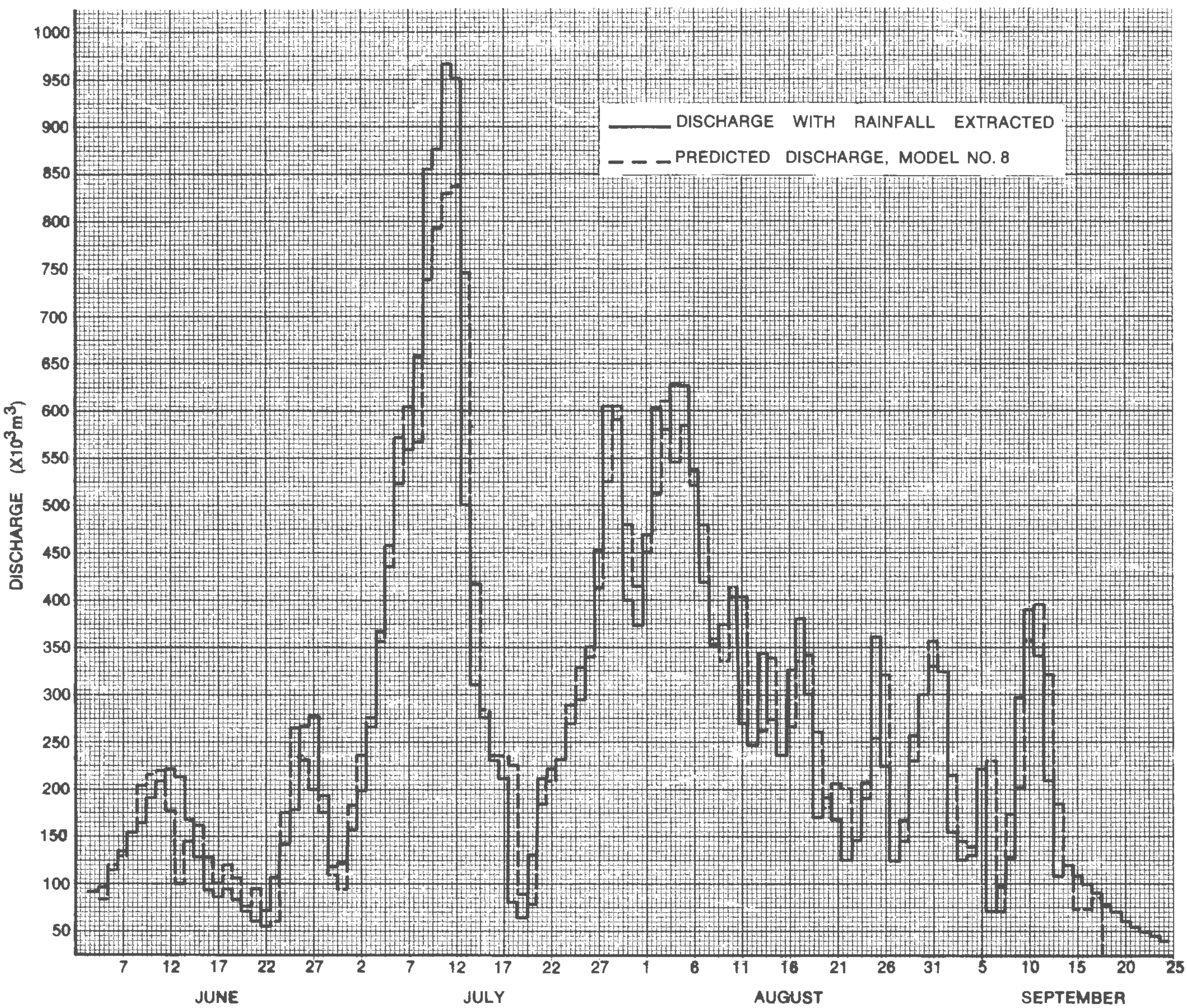


Figure 14. Observed and predicted discharge, 1968 (model no. 8)

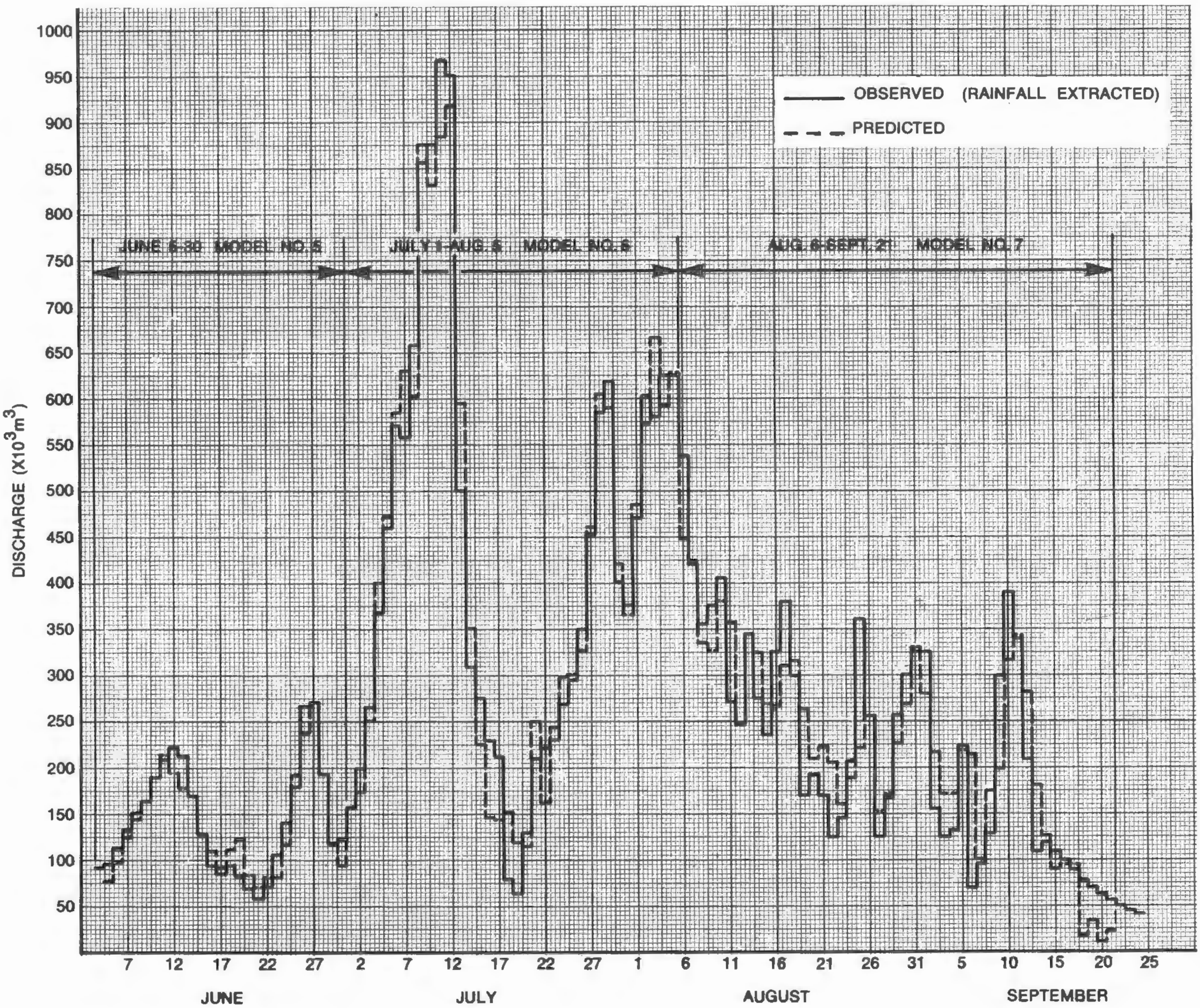


Figure 15. Observed and predicted discharge, 1968 (models no. 5, no. 6 and no. 7)

eliminated. In this case, however, it is a question of sunshine hours being the easier variable to measure. Practicality is of prime importance in this case.

Steps B and C in Table 5 show the effects of removing those two variables; lag variables become negative, except for relative humidity. Again, high intercorrelation (>0.6) appears to be the cause, except in the case of wind lagged (V_1), which in all runs is a negative coefficient. The physical reason for this is in doubt, but may be related to convective turbulence. Step D eliminates the variables with moderately high collinearity, and positive partial coefficients result. It must be remembered that these steps are not taken just to obtain positive relations. In other cases negative relations may be the true ones.

From this discussion the reasons for maximum temperature and radiation not being included in the final regression model is clear. Precipitation is the other weather element removed before the commencement of the analysis.

The results of several regression analyses of 1968 data are presented in Table 6. Figures 14-17 compare the observed and predicted discharge for several of these models. The question is which model or combination of models is most useful.

Practically, one model for the entire ablation period, such as No. 8, would be most useful, but in reality a single model for Peyto Glacier tries to combine several different

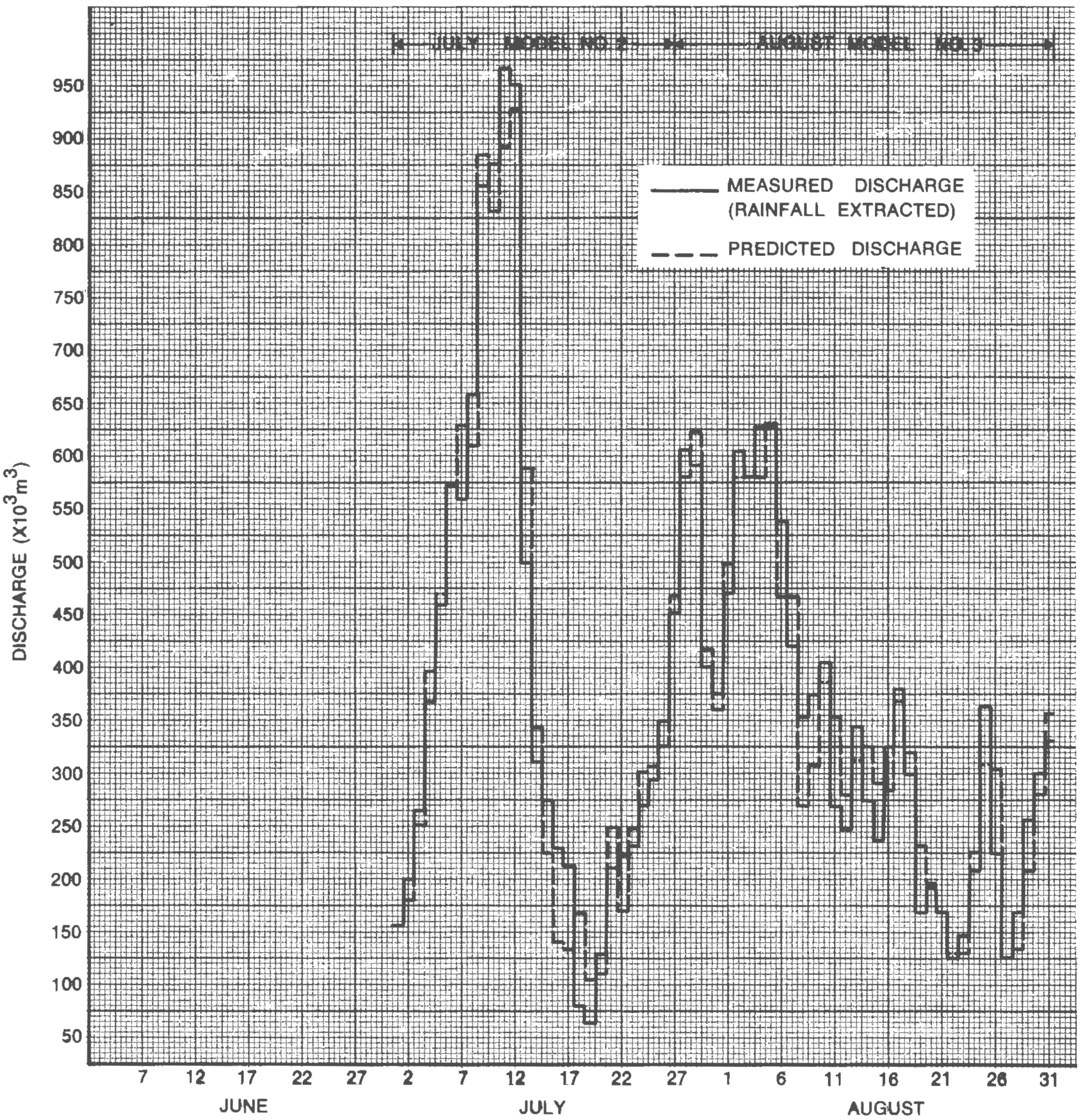


Figure 16. Observed and predicted discharge, July-August 1968 (models no. 2 and no. 3)

weather and hydrologic periods. This results in a slightly lower variance explanation and a higher standard error for discharge than the models for shorter time periods. The model is particularly weak for the low-flow rainy month of June. Undoubtedly the variables in the model were an expression of the July-August hydrometeorological events, as evidenced by the reasonably good fit for this period (Fig. 14). Overall, this model is acceptable if a single seasonal model is desired.

Models 1-7 are an attempt to improve the prediction of discharge by considering the varying hydrometeorological conditions of 1968. June (models 1 and 5) was a cool wet month - with precipitation extracted, temperature both previous and same day, becomes the dominant meteorological parameter. The lag effect is particularly significant for this model which represents a period in which a fresh winter snow cover is ripening.

The weather period of July 1-August 5 (model 6) was warm with occasional days of rain. Temperature, relative humidity, sunshine and wind all contributed to the variance reduction. Considering the variability of discharge over the period the model's explanation is very good (Fig. 15). A model for the month of July (#2) yields virtually identical results, indicating that similar hydrometeorological conditions exist (compare Figures 15 and 16). Two lag variables, sunshine and wind, suggest an inverse relation with discharge. Reasons for this have not been found.

Representing the latter part of the 1968 melt season, which was cool and wet with intermittent snow, three models were tested: two monthly and a combined one. The latter model is not as good as #5 and #6 in its explanation of events; this is a result of poor relationships during the month of September as indicated in model 4. Fresh snow in parts of the basin is suspected to create these complications. For August alone a good model (#3) is obtained (Fig. 16) suggesting August and September hydrometeorological events are not similar. A colder, snowy September presents a different hydrologic situation to a cool, rainy August.

From the above results, the importance of lag parameters is evident; why negative relationships should exist is not clear. In an attempt to overcome the need of using two independent variables to represent two succeeding time periods, models were tested using the two-day running mean for each variable. The results are given in models 11-14.

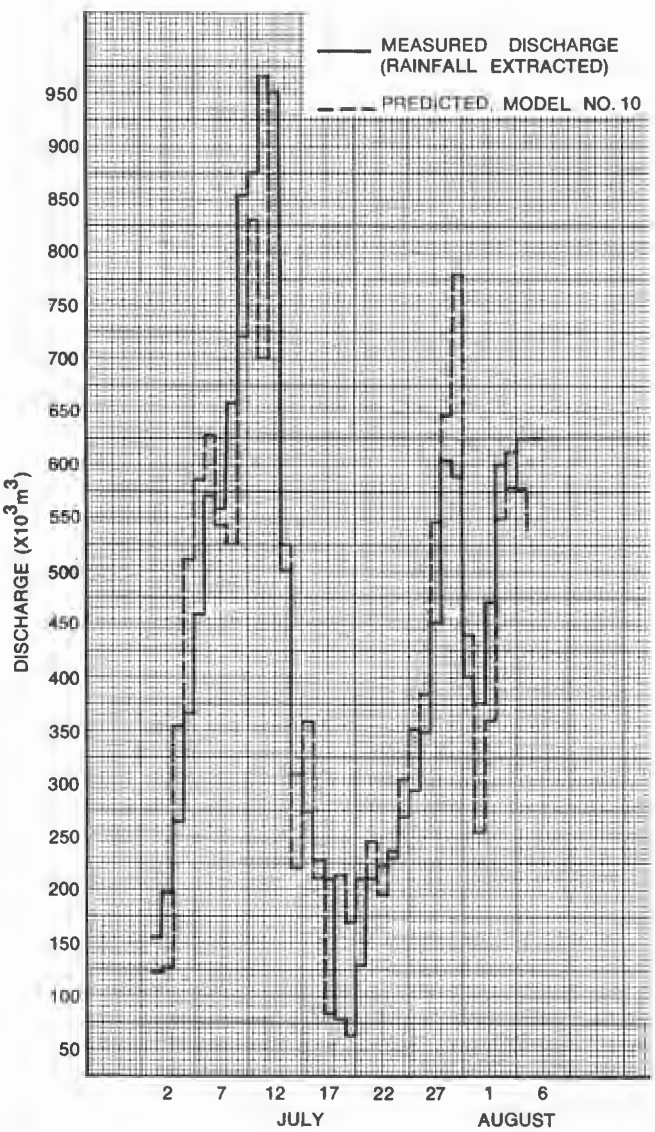


Figure 17. Observed and predicted discharge, July 1–August 5, 1968 (model no. 10)

The seasonal model (#11) is very similar to seasonal model (#8). Although it has a slightly higher explanation of variance, it also has a higher standard error of the estimate. The July-August (#13) and August-September (#14) models do not represent the events as well as those using individual daily values, but the June model (#12) is slightly better. However, it is this month which is in least need of improvement. Because of the lack of improvement provided by these models, the use of the two-day running mean is not advantageous in this analysis.

Of greater significance in the analysis is the need to have discharge from the previous time period (Q_1) as a predictor variable. Runoff from Peyto Glacier is not a random event; it is quite the opposite, and for this reason the previous day's runoff was included as a predictor variable. In addition to the points previously presented, the usefulness of Q_1 in the model is evident in an analysis of the residuals. Draper and Smith (1966) provide a good discussion on the tests applied to residuals. Basically, one must avoid trends, runs, and serial correlation of these values. It is in the elimination of these undesirable properties that the necessity of Q_1 is best seen.

Models 9 and 10 were run without using the previous day's discharge as an independent variable. The model for June is a complete failure; the July-August model (Fig. 17) has a reasonable explanation of variance but a higher standard error of the estimate. However, the residuals of these models provide very interesting comparisons to those which include discharge, Q_1 (models #5 and #6).

The test for the presence of any autocorrelated disturbances was the Durbin-Watson "d" Statistic (Johnston, 1963). Letting e_t ($t = 1, \ldots n$) denote the residuals from the fitted-least-squares regression, then

$$d = \frac{\sum_{t=2}^{n} (e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^2}$$

The serial correlation coefficients of the residuals for models 1 or 5 and 9 (June) are 0.33 and 0.82 respectively, while for July 1 - August 5, models 6 and 10 had residual autocorrelation coefficients of -0.02 and +0.35. The results for June clearly show that without discharge for the previous day included in the model, the unexplained values are anything but random. For the July-August period the residuals are random when runoff is included although without it the Durbin-Watson test was inconclusive, suggesting the model could be used if desired.

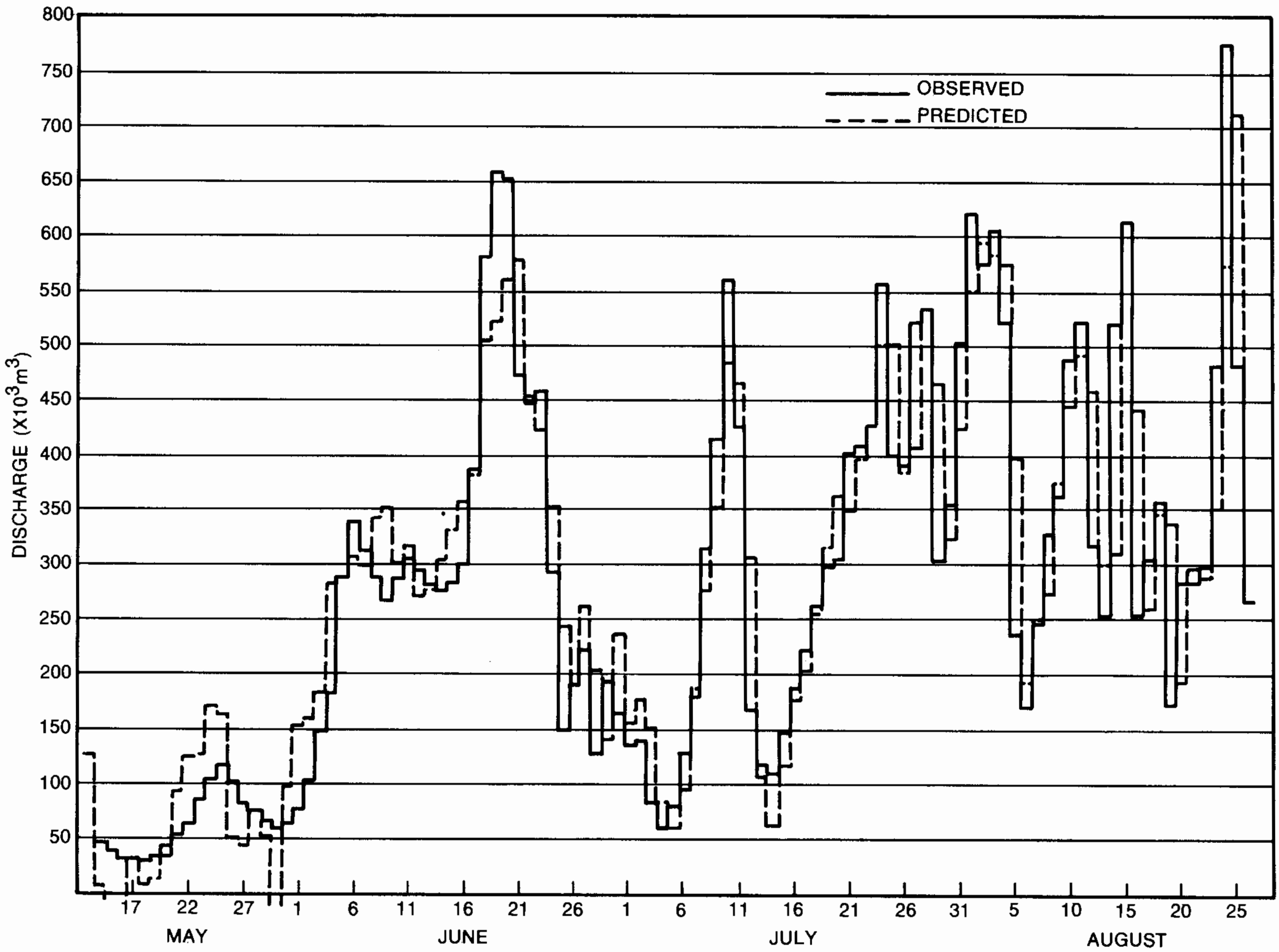


Figure 18. Peyto Glacier, application of the 1968 season model (no. 8) to the 1969 hydrograph

These comparisons show the type of checks that must be made on this type of model. The end result is a model which is both physically and statistically stable. For 1968, models 1, 2, 3, 5, 6 and 8 are good models; models 1, 2, 3 and 6 are the best.

In all the above models, previous day's discharge (Q_1) and the temperature parameters (T_0 and T_1) are the dominant variables. The other meteorological parameters are less significant and more variable in their entry or exit either to or from a particular model, depending on the weather conditions. The models discussed above have been developed and tested on one and the same year's data - not an entirely desirable situation. Therefore, the better models were tested using 1969 data. Precipitation totals were calculated by the same method as outlined previously: extraction of the totals from the discharge record produced the revised hydrograph.

Results of the test were very encouraging. Application of the 1968 season model (#8) to the 1969 hydrograph (Fig. 18) accounted for 82.4% of the variation in discharge, and provided a particularly good fit to the June-July runoff period. As in 1968, the early and late part of the season does not provide as good a fit as might be hoped. However, considering the different weather conditions between the two years, the discharge prediction is good.

Better results were obtained when the period models (#5, #6, #7) were applied although the actual dates differed, the period models were used when the climatic conditions were similar to the 1968 conditions. Model #5, applied to the early part of the season when there was an extensive snow cover over the basin, produced excellent results (Fig. 19) as it accounted for more of the variation than it did for the original 1968 data from which the equation was derived. The other two-period models did not hold up as well in testing as did the one for the first of the season. Model #6 predicts well on many days, but was in error for one brief period in July (Fig. 19). Model #7 for

Table 7. Comparison of regression models for Peyto Glacier

1968 Models			1968 Models Applied to 1969			1969 Models	
Model	% Variation accounted for	Standard error as a % of mean	Model	% Variation accounted for	Standard error as a % of mean	% Variation accounted for	Standard error as a % of mean
SEASON (#8) Q_1, T_o, V_1, V_o	89.6	24	SEASON (#8A)	82.4	27	85.8 Q_1, T_o, RH_1	24
#5 5-30 June Q_1, T_1, T_o	86.9	16	#5A May 13 to June 17	93.7	19	97.4 Q_1, T_o, T_1	13
#6 1 July-5 Aug. $Q_1, T_o, V_1, RH_o, SH_1, V_o, T_1$	96.4	12	#6A June 18 to Aug. 4	73.4	28	91.1 Q_1, T_o	16
#7 Aug. 6 to Sept. 21 Q_1, T_o, V_1	76.6	27	#7A Aug 5 to Aug. 26	41.2	33	80.3 T_o, Q_1	20
August Model (#3) Q_1, T_o, SH_1, RH_o	91.2	13	August (#3A)	74.5	21		

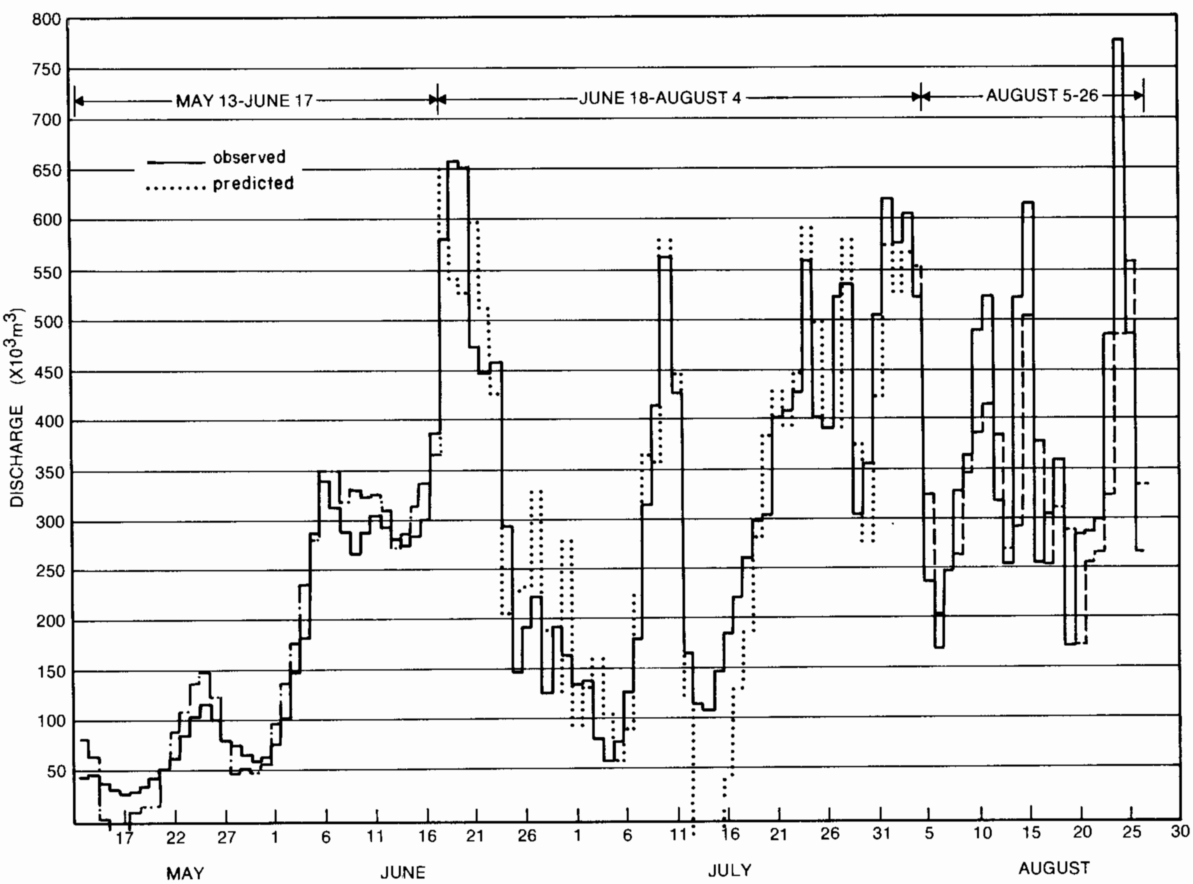


Figure 19. Peyto Glacier, application of the 1968 season models (no. 1, 2 and 3) to the 1969 hydrograph

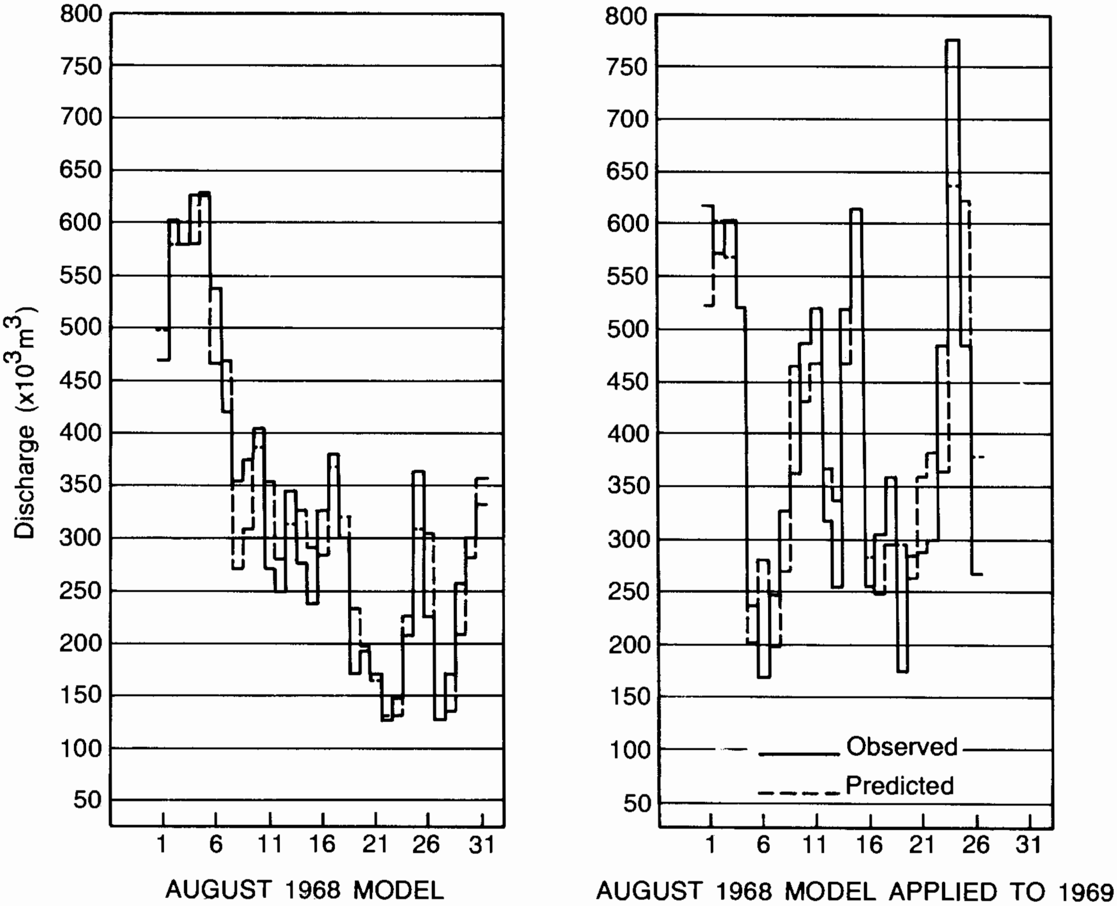


Figure 20. Peyto Glacier, application of the 1968 August model (no. 3) to the August 1968 hydrograph

August 5-26 was not at all satisfactory, but the 1968 August-September model tested, was not one of the best 1968 models. Instead, a better discharge prediction is obtained if the August 1968 model (#3) is applied to the August 1969 data (Fig. 20). The result is even more encouraging when one considers the much greater daily variation in discharge in 1969 than 1968. From the above results it is clear that the season model in general, provides a more accurate estimation of discharge from June 18 onwards than do the two weather period models tested.

A comparison and summary of all these results is tabulated in Table 7. In four of the five models tested, (#8A, 6A, 7A, 3A) variance explanation decreases from 7% to 35%, while the percentage standard error increases 3% to 16%. These percentage changes are to be expected in such a testing of a multivariate model. To compare the test models for 1969, new 1969 models were derived in the same manner as the original 1968 models. The same time periods were used as were employed in testing the 1968 models. Table 7 compares the variables, variance explanation and standard error for these new 1969 models with models 5A, 6A, 7A, and 8A.

In all cases the new 1969 models give slightly better results than those obtained from the application of the 1968 equations. Particularly encouraging is the small improvement in the 1969 season model and the early season model over models 8A and 5A, respectively. This suggests that the Peyto Creek hydrograph can be predicted using multiple regression models which consider auto-correlative effects. The dominant predictor valuables are the temperature and discharge parameters in both 1968 and even more in 1969; as pointed out earlier there are less significant meteorological parameters which change from period to period and year to year; generally their influence is minor. Overall, then, it is evident that the testing of the 1968 models have been reasonably successful; subsequent years' data will allow further testing and modification of these initial predictive models. Hopefully, by the end of the I.H.D. program a series of more stable workable predictive models will be developed to apply to different weather and hydrologic periods for Peyto Glacier.

Discussions and Conclusions

Although the present models are quite promising, modifications and improvements both in the model and in the accuracy of the data will be sought. A limitation of the present approach is the need to include discharge as a predictor variable, although physically and statistically this makes sense. The problem is a practical one - discharge may not be measured in the future and only simple meteorological variables may be available. If discharge is to be included it remains to find a method of generating it from say an initial known event at the beginning of the season.

Very preliminary analysis of this problem was attempted. Using the known hydrologic characteristics of the stream, a Monte Carlo generation technique was used. However, predictions were not in line with the observed discharge. Another thought was to use the predicted runoff of one day as the independent variable for the next, but continued over- or under-prediction resulted. One, instead requires, or at least desires, alternating over- and under-predictions so that random deviations result. These particular approaches will require much further study by the author before a final conclusion may be made about their usefulness.

Modifications or additions to the data collected up to 1969 will also be of use in future Peyto Glacier studies which are concerned with detailed study of the hydro-meteorological relations. Temperature data for higher elevations are available for the 1970 season. This additional information should eliminate the need of using an average lapse rate, and will improve the precipitation estimates for the basin. This new information should also improve the estimate of that portion of the basin which is effectively contributing to runoff either through rainfall or snow and ice melt.

This additional temperature data, collected over the glacier, should provide information on temperature variations over ice as compared to over land. Preliminary analysis (Goodison, 1969) of data at the micro-meteorological site suggested that air temperature over the land is significantly higher during the day than that over the ice. This has since been confirmed by additional data from the micrometeorological site. Noteworthy is that differences are not constant all day and are minimal during the night. Comparison of these diurnal fluctuations and the diurnal runoff regime would be a study of interest.

Coincident with the additional Stevenson Screens are more rain gauges which will greatly improve the knowledge of areal distribution of precipitation over the glacier. The expanded rain-gauge network is anchored by a digital recording gauge at the new micrometeorological site. By using the isohyetal or Thiessen polygon method (Bruce and Clark, 1966, pp. 167-169; Goodison, 1968, pp. 76-84) areal totals will now be determinable, as the data for 1970 becomes available. Certainly, a measured total for different reaches of the basin should be much more accurate than a total extrapolated from a single gauge value. An improved estimate of precipitation (rain and snow) and its distribution will allow calculation of a more accurate "revised discharge value" (discharge minus rainfall) used in this statistical study.

Useful data should also be forthcoming from the long-term temperature humidity and wind recorders installed at a high elevation in the glacier basin. These 6-month recorders will provide new data during fall and winter periods in addition to the continuous summer records. All these improvements in data acquisition will certainly help reduce that portion of error attributable to field measurement.

Needless to say, error may also be reduced by improvements and refinements of the method of statistical analysis. Cross-correlation or spectral analyses may suggest the use of a longer lag period for some of the predictor variables. By using a longer lag, perhaps the previous day's discharge may not be required as a predictor variable.

To make the model more applicable to other basins in the North Saskatchewan headwaters region, models could be compared with those using Lake Louise data or other stations' data which will be recorded continuously in the future. There is no reason to expect good results in such a comparison because there is great variability in a mountain region and the further one goes from the study area, the greater will be the temporal and spatial variation of events. Physically a model could lose its significance, but statistically the model may provide a satisfactory result. Caution in the interpretation of results must be taken, when such a study is undertaken. It is the author's feeling that statistical modelling in hydrology must be based on sound physical reasoning. Lately, some research seems to have drifted from this idea.

The results of this study have been in line with results of other researchers, in particular Østrem (1969; 1970) and Lang (1967; 1969). The present study has attempted to go past the stage of correlation to develop regression equations. At this stage of the study, the development of a statistical runoff model has been very encouraging; future data should allow modification and improvement of the models presented, hopefully permitting prediction of short-term runoff events for Peyto Glacier.

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