

## SNOWMELT CONTRIBUTIONS TO MAXIMUM FLOODS

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### INTRODUCTION:

Much attention has been devoted over the past few decades to developing methods of estimating the physical upper limits to floods which can occur on various rivers. Such estimates, often referred to as "maximum possible" or "probable maximum" floods are used to make decisions on spillway capacities of major dams, failure of which might result in disasters should they be overtopped. Most of the investigation and study has gone into the problem of estimating physical upper limits to rainfall over a watershed, and comparatively little to techniques for estimating contributions of snowmelt to maximum flood flows. This paper outlines several methods of estimating maximum winter snow accumulation and melt rates, and compares results obtained by the various methods for the Manicouagan and Outardes Rivers in the Quebec North Shore area, (Fig. 1).

Some of the analysis procedures followed here, were made necessary by a great lack of meteorological observations within the largely uninhabited watersheds of the Outardes and Manicouagan. Indeed, from figure 1 it can be seen that there are no observation stations within the watersheds. Weather conditions must be inferred from data around the perimeter of the area at Lake Manuan, Nitchequon, Knob Lake, Seven Islands and Baie Comeau.

This report should be of value to those concerned with maximum snowmelt investigations, particularly for watersheds with scanty observational data.

### MAXIMUM SNOW ACCUMULATIONS:

Three methods have been used to estimate the physical upper limits to snow accumulation on the watersheds. These will be referred to as the "partial season method", "the snowstorm maximization method" and the "statistical method".

#### (a) Partial Season Method:

One approach to the problem of estimating the physical upper limit of seasonal snow accumulation is to assume that one can combine the greatest amounts observed in months, or fortnights, regardless of the year of occurrence, to give a "synthetic" year of very high snowfall. For example, if November 1948 had the greatest observed snowfall in any November, December 1953, the greatest for December, January 1942 the largest for January, etc., these are combined to give a composite season

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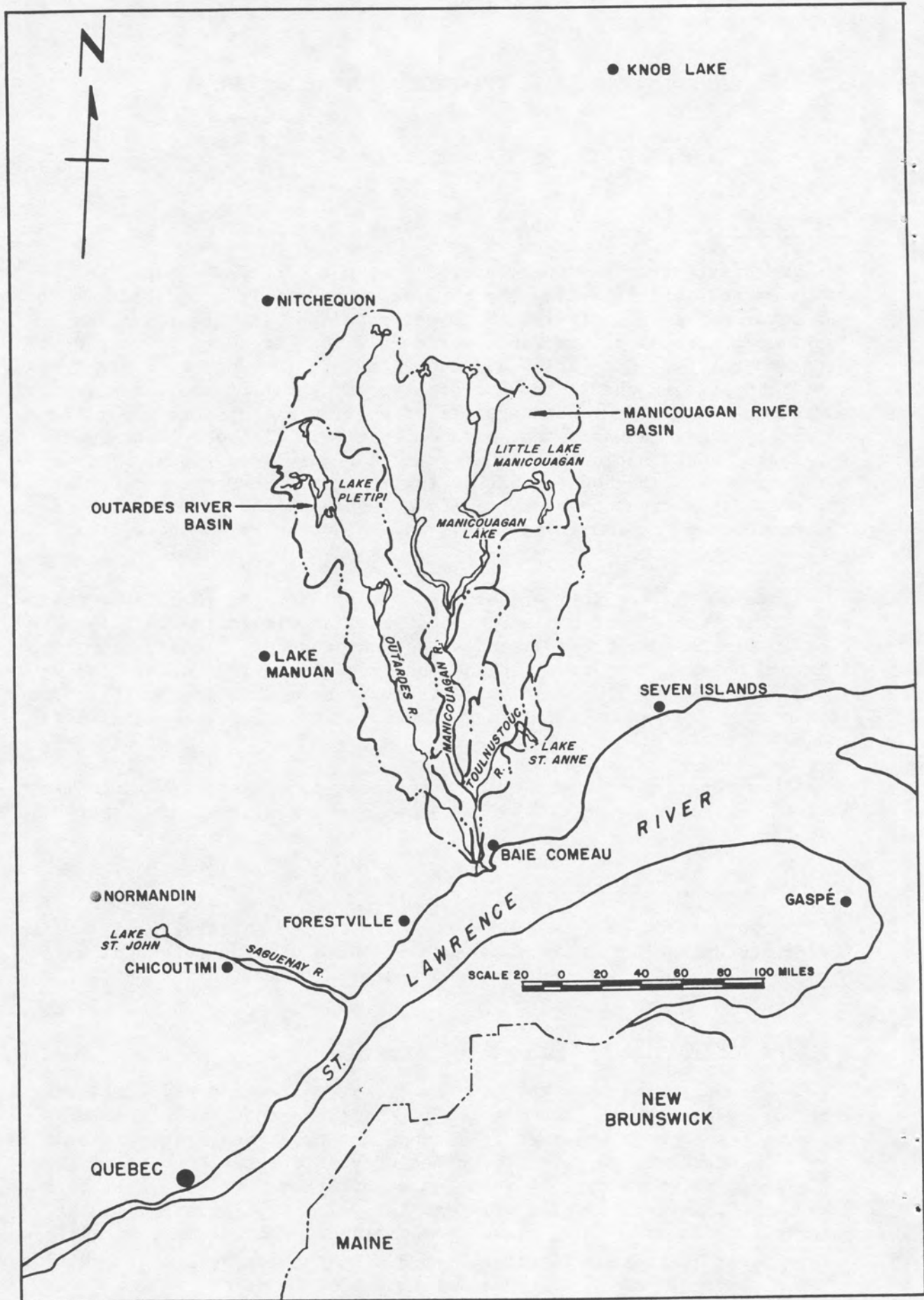


Fig. 1 Manicouagan and Outardes River Basins

of high snowfall. A similar procedure can be followed using shorter time intervals as two weeks, 1 week and 4 days, in an attempt to estimate the physical upper limit to snowfall in a season.

The curve in Fig. 2 shows the results of such a study, taking data for the station at Lake Manuan to represent the watersheds in question. Lake Manuan data were not assumed to give correct values for the watersheds in any absolute sense, but it was assumed that the percentages of greatest observed winter snowfall, obtained by combining maximum amounts for 4 day, 1 week, fortnight and monthly periods, would likely be about the same over the watersheds in question as at Lake Manuan.

The percentage of maximum observed winter snowfall (1954-1955) goes from 125% for the 1 month "synthetic" year to 198% for the 4 day period. Should one extend this analysis to include shorter time periods the percentages would continue to increase. However, from consideration of the frequency of occurrences of cyclonic storms and the time intervals between them, a period shorter than about 4 days would be completely unrealistic.

(b) Snow Storm Maximization Method:

The methods of estimating the maximum precipitation that could have been produced by a particular storm if the meteorological factors contributing to precipitation had been most critical have been reasonably well established (2, 8). In short, the procedure involves determination of the ratio of the maximum moisture content possible at that time of year in the area under consideration, and the actual moisture content of the precipitation - producing air mass in the storm. The observed storm precipitation is multiplied by this maximization ratio.

In the present study, the areal mean snowfall produced over the two watersheds combined, by each of the storms during 2 snow accumulation seasons was calculated. The precipitation production of each of these storms was maximized by the method outlined. By addition then, the total snowfall in a "maximized season" could be obtained. The two seasons studied were 1954-55, the greatest snow accumulation season of modern record, and 1960-61, another season of large accumulation. Twenty-nine and 27 storms, respectively were studied in these seasons. The 1954-55 season gave by far the largest observed and maximized amounts and will be considered further.

The 29 storms in the 1954-55 season produced 82% of the season's total snowfall. The storm maximization technique indicated that if each storm had occurred with maximum air mass moisture content, the total storm snowfall would have been 190% of the observed. It seems reasonable to assume that the total seasonal snowfall, including the 18% not accounted for by the storms studied, could also have been 190% of the observed amount.

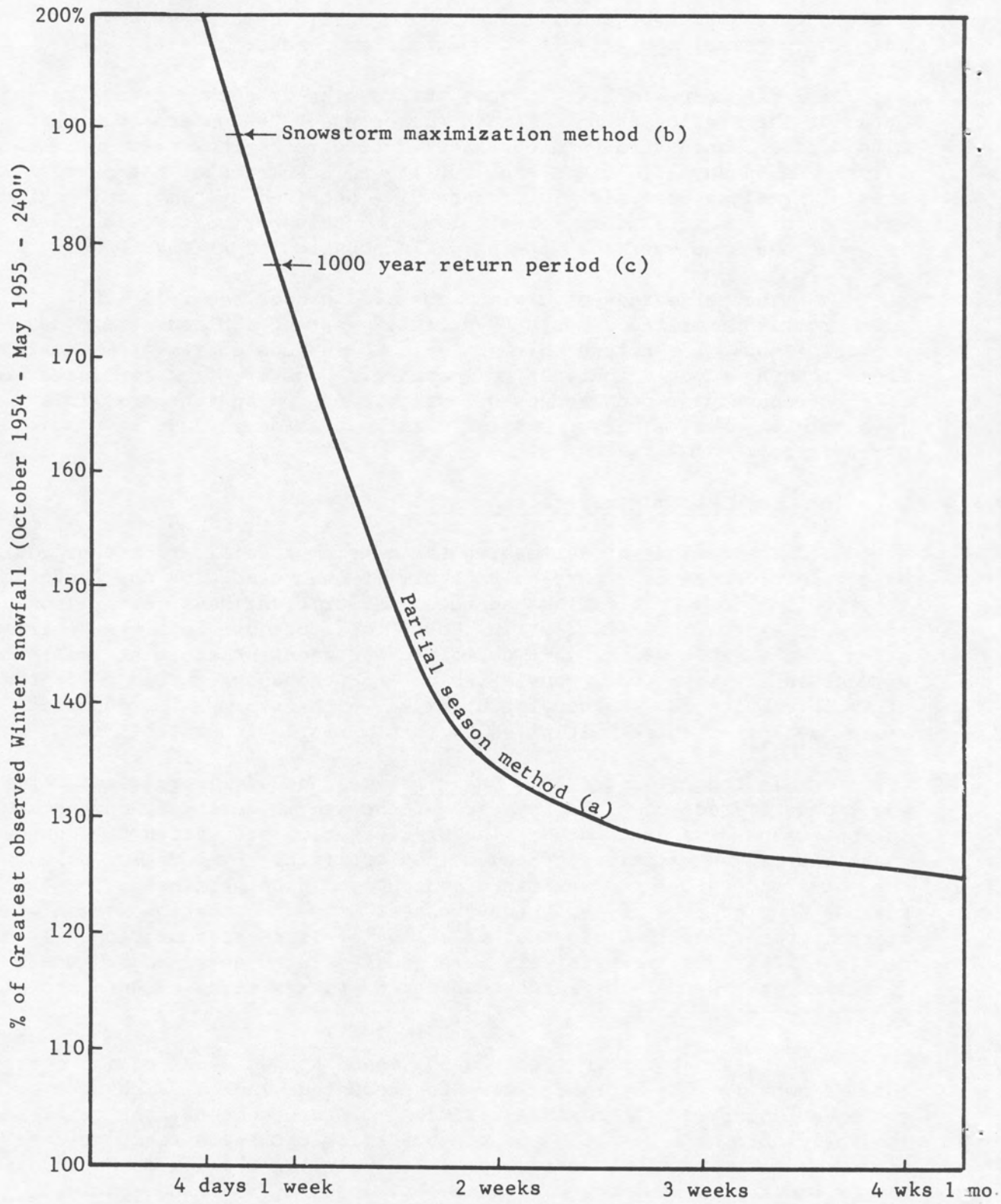


Fig. 2 Estimates of Maximum Seasonal Snowfall and Snow Accumulation



This season, (1954-55) having had the maximum snowfall on record, the snow storm maximization method result can be indicated directly on the graph of Fig. 2. The result so obtained corresponds very closely to the value derived by the "partial season method" for Lake Manuan using a four-day period.

(c) Statistical Method:

A statistical study of extreme snow depths on the ground at Canadian stations has been conducted by Boyd (1). This analysis consisted of computing by the Gumbel extreme value procedure (4) the 30-year return period maximum snow depth from 14 - 16 years of snow depth at Nitchequon, Lake Manuan, Harrington Harbour and Seven Islands, and 10 years at Knob Lake. From these data and those from other surrounding stations isolines were drawn by Boyd of 30 year-return period snow depths, which permitted estimation of such values over the Outardes and Manicouagan basins.

The dangers of extending a frequency analysis to return periods well beyond the period of record are well known. However, for the sake of comparison, and to try to determine the order of magnitude of the return period of the maximized values obtained by the methods cited above, the 1000 year return period values were computed. The average value over the Manicouagan and Outardes basins, expressed as a percentage of the maximum observed snow depth on the ground is indicated on Fig. 2.

While this value for 1000 year return period of 178% is subject to considerable doubt in itself, the two previous maximum values in the range 190-200% of maximum observed are likely well in excess of a 1000 year return period value, as they should be.

From the above analyses a figure of 200% of maximum observed amounts could reasonably be accepted as the physical upper limit to snow accumulations in this area. These three analyses, which tend to confirm each other, were based on three different types of data. The first was concerned with station precipitation, the second with precipitation over the area of the watersheds and the third with areal estimates of snow depth on the basin. The fact that the three results were reasonably compatible lends confidence to the use of the figure suggested, and supports the idea that the physical upper limit to winter snow accumulation is a realistic concept.

MAXIMUM WATER EQUIVALENT OF SNOW PACK:

The determination of maximum snow amounts by use of the two different types of data, snow cover, and snowfall, permit a further check on the calculations when maximum snow water equivalent is considered.

In the snowfall determination, the physical upper limit to snowfall at Lake Manuan would be 200% of the observed maximum of 249" or 498".

In Canadian snow measurement practice ten inches of new snow is taken as equivalent to 1 inch of liquid precipitation. By this procedure, the maximum winter precipitation in snow would be about 50 inches water equivalent at Lake Manuan. (The merits of the ten to one conversion factor are not debated here, but most evidence points to this factor as being very close to correct on the average over a season in eastern Canada). Since the mean snowfall over the Outardes basin is estimated as being 106% of the mean at Lake Manuan, and over the Manicouagan basin as being 110% of Lake Manuan snowfall, the physical upper limit of snowfall water equivalent over the two basins can be taken as 53" and 55" respectively.

The results of approaching this problem from a snow cover point of view are shown in Fig. 3. Snow survey measurements of the percentage water equivalent of the snow pack in the adjacent Lake St. John basin, were remarkably consistent from place to place and year to year, at the same date. Curve (1) in Fig. 3 represents the maximum percentage water equivalents of the snowpack at various dates from mid-March on through the snowmelt season. These maximum observed values differed only slightly from the mean values.

Curve (2) in Fig. 3 illustrates the maximum observed snow depth on the ground as the snowmelt season progresses, as a percentage of the seasonal maximum occurring between March 31 to April 15. This curve was the average of the maximum percentages at the 3 stations, Nitchequon, Lake Manuan and Seven Islands, which can be taken to represent reasonably the watersheds in question. Then by taking the physical upper limit to snow depth as being 200% of the maximum observed, and by applying the snow pack water equivalent curve (1), the upper curves (3) and (4) in Fig. 3 were obtained. They indicate the physical upper limit to snowpack water equivalent on the Outardes and Manicouagan basins.

The results obtained by the snowfall and the snow cover approaches give the maximum snow water equivalent for the Manicouagan as 55" and 60" respectively, by the two methods, and for the Outardes, 53" and 56".

As the computations based on snow cover data indicate a maximum snowpack water equivalent at the end of April, and as rain can occur in April which would not be considered in the snowfall computations, but which might well increase the water equivalent of the snowpack by a few inches, it is to be expected that the snow cover estimates would be slightly higher than the others. The agreement between the two independent results is thus remarkably good, and it seems reasonable to accept curves (3) and (4) of Fig. 3 for design flood computations.

#### Snowpack Losses

The snowpack analysis might have been expected to yield slightly lower results than the study based on snowfall, due to possible losses

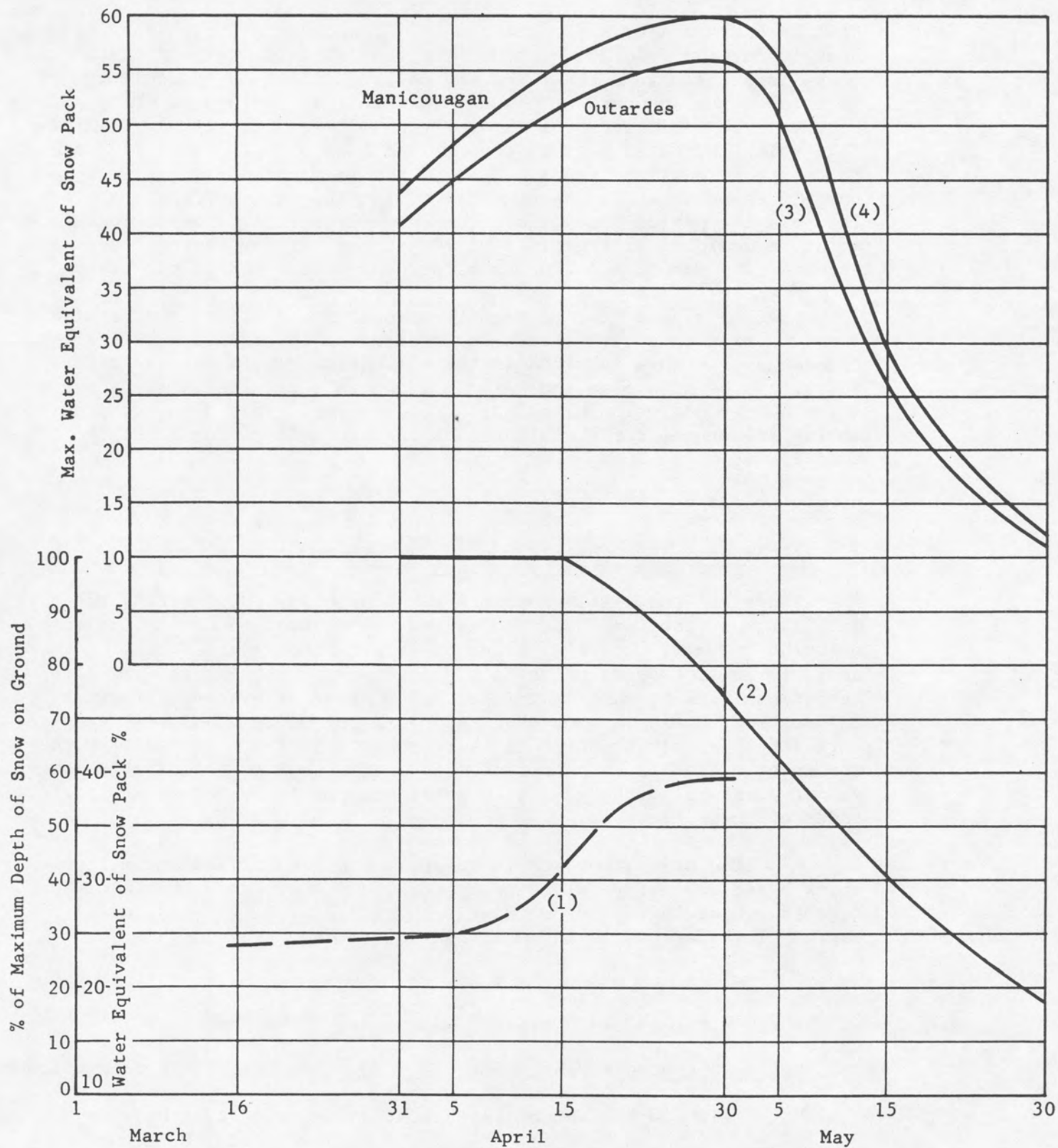


Fig. 3 Maximum Snow Pack Water Equivalent

from the snowpack by evaporation and  $\pm$  to the ground through melt from heat conduction from the ground. The results obtained suggest that these losses are very small and may well be offset by condensation of water onto the snowpack. This agrees with the findings of McKay and Blackwell in their recent work at Regina (7) and the work by Williams (12) which indicated a gross evaporation loss of only about 1/2 inch per month in eastern Canada. A loss of this magnitude might well be largely compensated for by condensation on the snow surface, particularly in the period just before the snowmelt period. Losses to soil moisture would be of the order of .02 inches per day during the snow accumulation season and thus total perhaps 3 to 4 inches per season.

In view of the difficulties inherent in the estimates of maximum winter snow accumulation, these snowpack losses are likely within the range of errors involved in the estimates. It is suggested that no deductions be made from the maximum snowpack determinations for evaporation and ground melt losses during the winter. This does not preclude making allowances for such losses during the melt period in design flood conditions.

#### SNOW MELT RATES

##### Alternative Snow Melt Computation Methods

There are two likely approaches to computing snow melting rates. One is to use the time-honoured degree-day method, and calculate snowmelt and snowmelt runoff by means of an air temperature index. Such an analysis may not be as naive as it appears at first glance, for this method has yielded excellent results for other watersheds (Simmons, 9). In addition, there is some physical basis for using a snowmelt temperature index, as air temperature is reasonably well correlated with the atmospheric factors which affect melt rates, such as solar radiation and vapour pressure, although, as we shall see, it is by no means a perfect index of these factors.

The other approach is to apply the generalized snowmelt equations based on energy balance considerations, developed in the co-operative snow hydrology studies in western U. S. (10,11). The generalized basin melt equation for snowmelt can be written as

$$M = M_{rs} + M_{rl} + M_{cc} + M_r + M_g$$

where M = total snowmelt,  $M_{rs}$  = short wave radiation melt

$M_{rl}$  = long wave radiation melt  $M_{cc}$  = convection-condensation melt

$M_r$  = melt due to heat of raindrops, and  $M_g$  = melt by heat conduction from the ground



If M is taken in inches per day the various factors can be evaluated as follows:

$$(1) \quad M_{RS} = k (1 - F) (0.0040I_i) (1 - a)$$

where k is a basin factor which depends on the predominant aspect of the slopes, and is 1.0 when north and south facing slopes are equal in area,

F is the average basin forest canopy cover, as a decimal fraction

$I_i$  is incoming solar radiation, observed or estimated in lang-leys

a is snow surface albedo, as a fraction

$$(2) \quad M_{R1} = 0.029F(T_a - 32)$$

where  $T_a$  is mean air temperature

- assuming that the snow surface is at 32°F during melt periods.

$$(3) \quad M_{CC} = K (0.0084V) [0.22 (T_a - 32) + 0.78 (T_d - 32)]$$

where k is a basin factor dependent upon relative exposure to wind and varies from 1 for an open plain to 0.3 for a heavily forested area;

V is the average daily wind speed (mph) at the 50 ft. level.

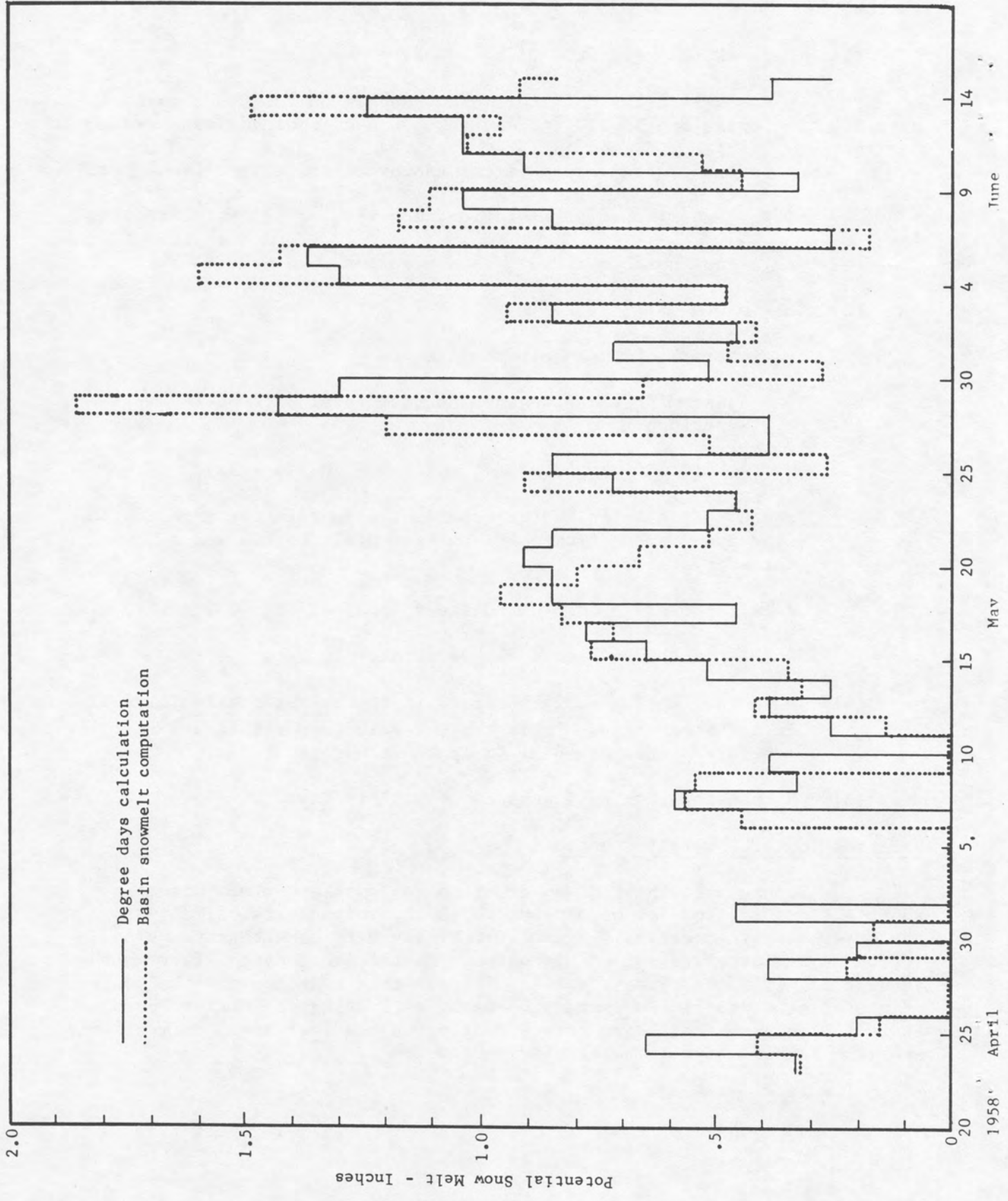
and  $T_d$  is the average daily dewpoint.

$$(4) \quad M_R = .007 P_R (T_w - 32) \text{ where } P_R \text{ is the average basin rainfall in inches per day. } T_w \text{ is the wet-bulb temperature and is generally taken as equal to } T_a \text{ on rain days.}$$

$$(5) \quad M_g \text{ can be taken as a constant} = 0.02 \text{ in/day.}$$

#### Verification of Snowmelt Equation:

Before applying such an equation to compute maximum snowmelt contributions to flood flows, it was necessary to test its validity for the watersheds in question. Hydrologic trials were made to attempt to reproduce the observed spring hydrographs on the Manicouagan River in the years 1957, 1958 and 1960. Details of these trials are beyond the scope of the present paper. However, methods of estimating the various parameters in the equations above have a bearing on the evaluation of maximum snowmelt runoff and will be briefly reviewed.



The values of  $k^1$ , K, F and "a" were originally selected from values suggested in "Snow Hydrology" and then confirmed or modified by the hydrologic trials. The albedo of the snow surface "a" was taken as 80% on a day of new snow with an exponential decrease to a minimum of 40% for a snow surface age of 18 days or longer. Due to the orientation and topography of the Manicouagan and Outardes basins a value of 1 for  $k^1$  was accepted. k was taken as 0.4 and F was estimated as 40%, based on the horizontal projection of an effective forest canopy of 80%.

In the trials, daily values of insolation were estimated for the Manicouagan basin by averaging amounts observed at Normandin and Knob Lake. Lake Manuan, Nitchequon and Seven Islands data were used to obtain daily air temperatures, dew points, wind velocities, snowfall and rainfall values.

One other factor which was difficult to evaluate but needed in the hydrologic trials was the percentage of the watershed contributing to snowmelt, particularly during the period when the contributing area decreases in the latter part of the season. This factor was determined by trial and error for the 3 years of study 1957, 1958 and 1960 using as an initial guide, values suggested in "Snow Hydrology". By plotting a factor representing the fraction of the pack already melted, (such as the potential snow melt in inches accumulated from the beginning of the melt season, divided by the water equivalent of the snow pack at the beginning of melt season) versus the fraction of area contributing to snowmelt runoff, the three years gave similar curves. The mean of these curves could be then used in reconstruction of a design flood.

By following these procedures the flood hydrographs could be excellently reproduced in each of the years under study. Thus it could be assumed that the basin snowmelt equation reproduces the natural melt rates in the watershed reasonably accurately.

#### Comparison of Methods:

The verification of snowmelt computations by the basin equation gives a standard to which snowmelt calculations by the degree-day method can be compared. Fig. 4 illustrates the "potential" snow melt, should there be an unlimited snow pack, as computed by the basin equation and by a degree-day index for the 1958 season.

The degree-day index used was 0.065 times the number of degree-days above 32°F at Lake Manuan as this factor yielded total runoff volumes of the correct magnitude.

The striking feature of the graph is the fact that the degree-day method under-estimates the melt on high melt rate days and over-estimates the melt on days of small amounts of melt as determined by the basin equation approach. For example, the seasonal maximum melting of May 28 is given as 1.86 inches by the basin equation and only 1.43 by the

degree-day calculation. The low melt rate of, say, May 30, given as 0.28 inches by the basin melt equation was estimated at 0.52 inches by the degree-day method. These are typical examples of the apparent failure of the degree-day method to indicate extremes of high and low melt rates. If this preliminary finding is verified, it may have important implications in connection with use of degree-day indices for flood forecasting as well as for design flood studies.

#### OPTIMUM MELT RATES

##### Temperature

In application of either of these methods to computation of maximum melt rates, the most critical temperature sequence must be determined. The first problem that arose in this connection was the shortness of the temperature records at stations adjacent to the two watersheds. Stations at Nitchequon, Seven Islands and Lake Manuan were all established in 1942. Baie Comeau records are broken and date only from 1939. The only reasonably long term station which might possibly represent, or be highly correlated with the temperatures in the watershed is Chicoutimi, a climatological station observing precipitation since 1876 with a maximum and minimum temperature record dating back to 1926. The mean of temperatures at Lake Manuan and Nitchequon likely give a reasonable representation of the average temperatures over the watersheds. Accordingly, correlation coefficients for maximum temperatures and mean temperatures between those observed at Chicoutimi and the average of those at Lake Manuan and Nitchequon for the period March through June 1958-1960 were computed. These indicated quite a high correlation ( $r = 0.92$ ) for maximum temperatures and regression equation relationship of

$$x = 2.7 + 0.74 y \text{ where}$$

$x$  is average daily basin maximum temperature, and

$y$  is Chicoutimi daily maximum temperature.

Similarly for mean temperatures the correlation coefficient was  $r = 0.88$  and regression equation relationship

$$x^0 = -7.5 + 0.90y^0$$

where  $x^0$  is the mean daily temperature Lake Manuan and Nitchequon

and  $y^0$  is Chicoutimi mean daily temperature.

It is possible then to proceed with an analysis of optimum temperature sequences for snowmelt at the long term station Chicoutimi, and apply the results to the Manicouagan and Outardes basin by means of these two regression equations.



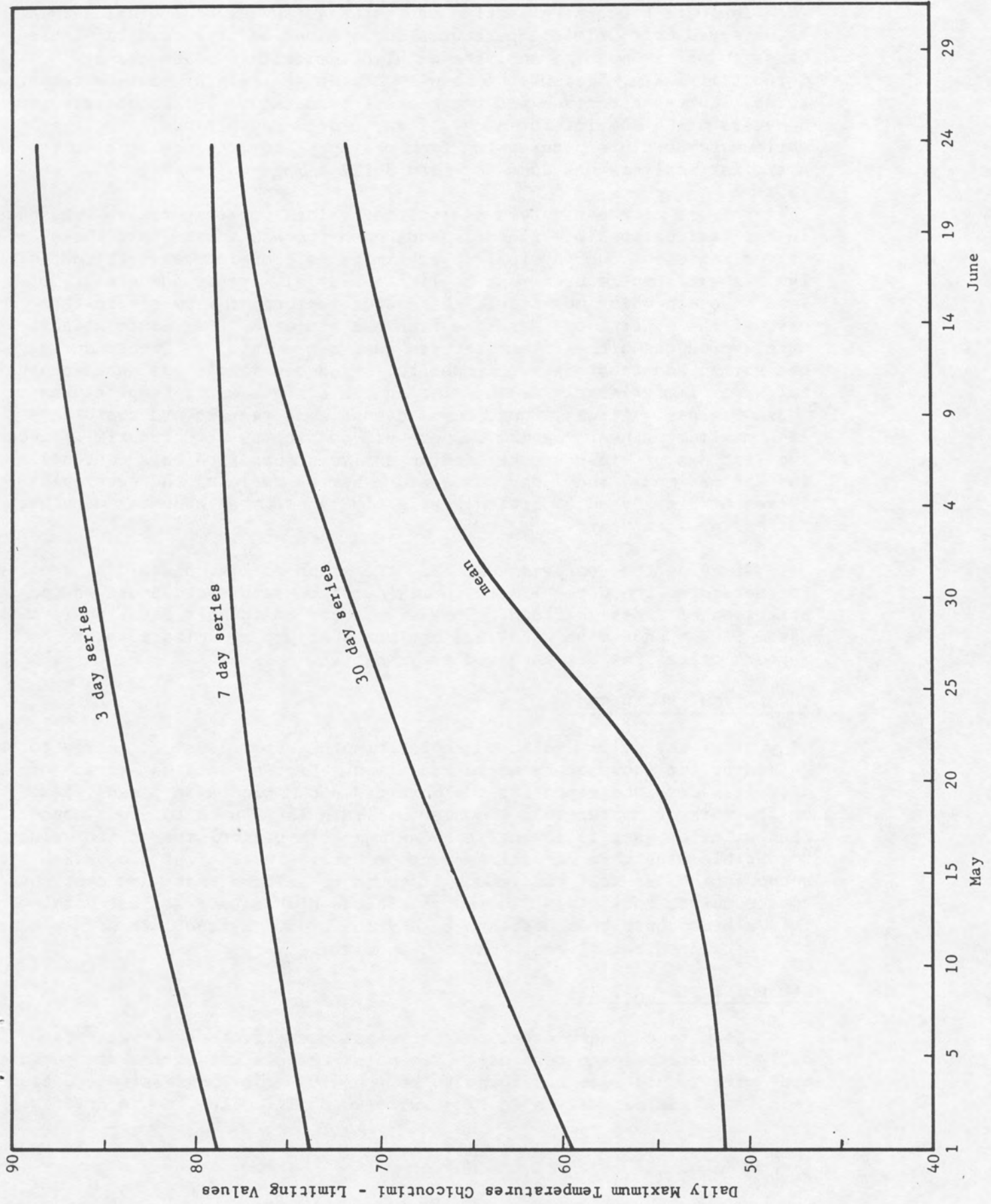


Fig. 5 Upper Limits of Maximum Temperatures for Consecutive Days

The Data Processing Section of the Canadian Meteorological Service transferred Chicoutimi temperatures for the period of record to punched cards to permit machine analyses of high temperature sequences at Chicoutimi. Fig. 5 shows the results of the analysis of maximum temperatures. Curves are given for the highest temperature series observed in 34 years at Chicoutimi for 3 day, 7 day and 30 day periods. The average maximum temperature progression from mid-April to mid-June is also shown. A similar analysis was done for mean daily temperatures (Fig. 6).

The use of these curves as limiting values for temperature sequences in the maximum possible flood depends upon the assumption that these curves represent the physical upper limits to temperature at Chicoutimi. The highest temperatures must be limited largely by the temperature of land or ocean which constitute the source regions of warm air in this part of the continent. Maritime tropical air of Gulf or South Atlantic origin produces highest temperatures (and dew points) in Quebec during the spring and thus maximum temperatures and dew points must have a physical upper limit largely dependent upon the surface water temperatures of those regions. It was, thus, assumed that a 34 year record would have seen maximum or near maximum temperature conditions at Chicoutimi. Indeed the listings provided by the machine analysis supported this contention, and the maximum 3 and 7 day temperature series defining the enveloping curves of Fig. 5 and 6 were only slightly higher than a number of other series in other years.

If using the degree-day method, the graph of Fig. 5 could be applied for determining the upper limits to maximum temperature sequences in constitution of a design flood. However, if the basin melt equation is to be used, Fig. 6 should be used, and estimates of upper limits to other meteorological factors involved are required.

#### INSOLATION AND ALBEDO:

Clear sky solar radiation represents the upper limit to energy to be gained by the snowpack by solar radiation. Fig. 6 contains a graph of cloudless day insolation for the Outardes and Manicouagan basins, based on the work of Mateer (6). However, if rain is assumed to occur concurrent with, or just following, the maximum melt period, insolation values compatible with rain conditions must be used. In critical snowpack accumulation and melt conditions it could be assumed that snow continues to accumulate until April 30 and thus has a high albedo at that data. This albedo could then decrease to a value of 40% by the 18th of May under the postulated conditions of no new snowfall.

#### DEW POINT TEMPERATURE

Using Lake Manuan data, the correlation coefficient between mean daily temperature and mean daily dew point temperature during the period mid-April to mid-June was found to be  $r = 0.90$ . The regression equation relating these parameters is  $T_d = -0.2 + 0.85 T_a$ . Thus once a critical

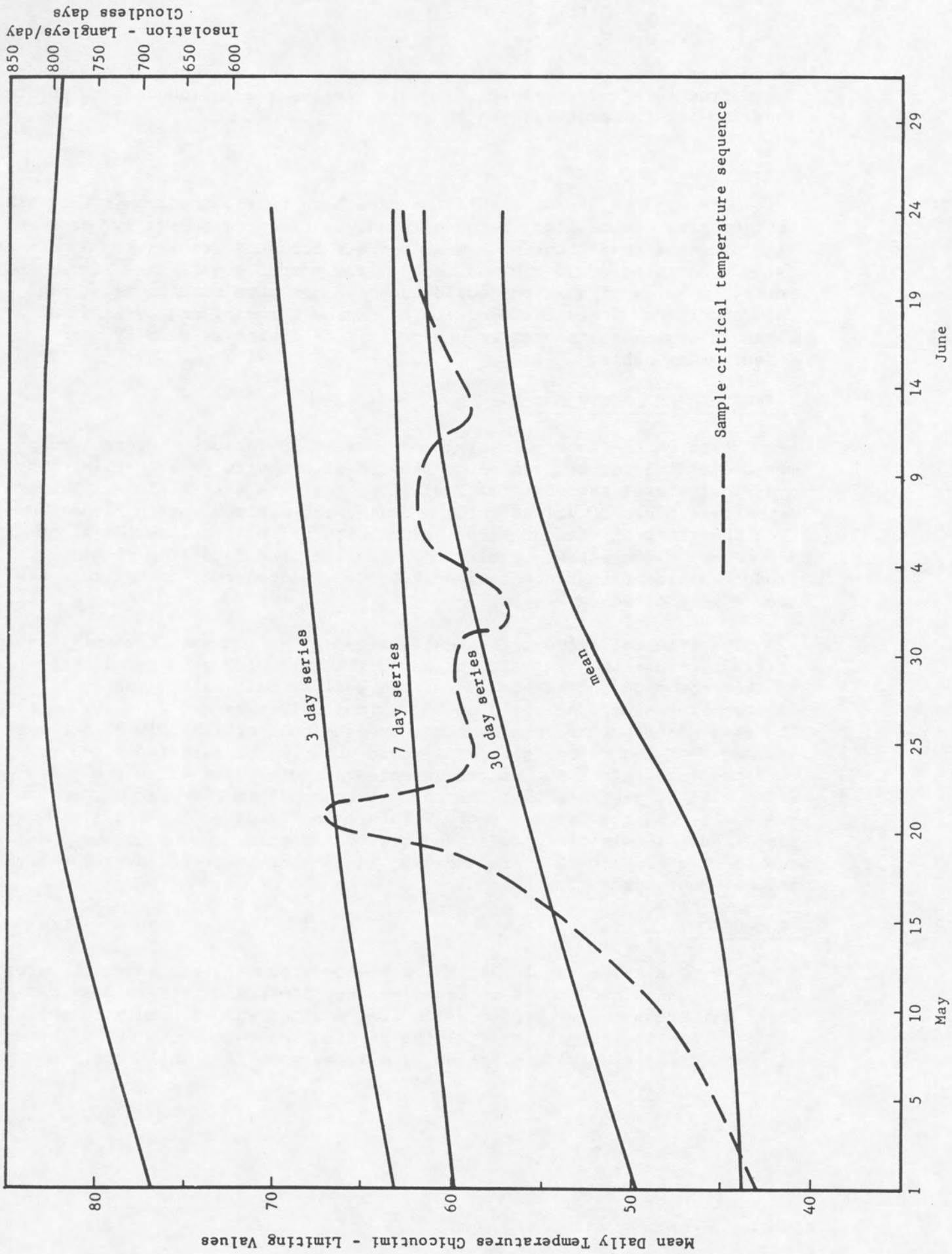


Fig. 6 Upper Limits Mean Daily Temperatures and Insolation

temperature sequence is fixed the critical dew point sequence can be deduced from this relationship. If rain periods are introduced dew points equal to air temperatures can be assumed.

#### WIND

Once high values of insolation have been taken, it becomes inconsistent to also assume high values of wind, as clear days usually occur under high pressure conditions with weak surface pressure gradients. A mean daily wind speed of 10 mph was found, from inspection of Lake Manuan reports, to be as high as one could assume under such conditions. Under rain conditions different wind limits can be assumed, and by study of winds in spring rainstorms an upper limit of 17 mph as a daily mean appears reasonable.

#### SAMPLE DESIGN CONDITIONS:

Based on the above limiting considerations various sequences of meteorological factors can be considered with a view to ascertaining by hydrologic trial the most critical in producing a design flood. Table 1 summarizes a set of values which produced the maximum spring flood flow from the point of view of large volume within a critical period of 60 days. A somewhat different sequence within the limiting condition might well produce a higher instantaneous peak flow. The proposed temperature sequence is plotted on Fig. 6.

The critical sequence suggested assumes maximum snow accumulation to April 30, moderate snow melt for the first half of May to permit ripening of the snow pack and saturation of the soil by melt water, then melt factors are assumed to build up to maximum values by May 20 - 30. After the area contributing to snowmelt decreased to approximately 50% it was assumed that two major rainstorms would occur. The magnitudes and recurrence interval of the storms selected are discussed elsewhere (3). Suffice it to say here that the storm transposed to the area of concern was Q - 17, in the series "Storm Rainfall in Canada" (5). The storm was maximized for moisture content and assumed to occur on June 1 and June 12 and to give 5.6" in 24 hours and 5.9" in 48 hours averaged over the 17,600 sq. mi. Manicouagan basin.

#### CONCLUSION:

The physical upper limits to both snow accumulations and melt rates have been calculated for a region with very limited meteorological data. Three different approaches to estimating maximum snow accumulations yielded similar results, suggesting that the physical approaches to the problem of maximum water supply to basins by melting snow is a valid one.



TABLE 1 MAXIMUM POTENTIAL SNOW MELT SEQUENCE

DATE	Solar Radiation Langleys/Day Incoming Absorbed	Mean Daily Temperature (°F)	Potential Snow Melt + Rain Inches	DATE	Solar Radiation Langleys/Day Incoming Absorbed	Mean Daily Temperature (°F)	Potential Snow- Melt + Rain Inches
		CHI				CHI	
		BASIN				BASIN	
May 1	430	44	.22	June 1	200	57	1.58 + 5.6 Rain
2	430	44	.26	2	320	57	1.31 + 0.3 Rain
3	430	45	.32	3	810	58	1.58
4	450	45	.45	4	810	60	1.66
5	450	45	.49	5	810	61	1.66
6	450	46	.53	6	810	62	1.71
7	480	46	.60	7	810	62	1.71
8	480	47	.63	8	810	52	1.71
9	480	48	.67	9	810	62	1.71
10	500	49	.73	10	810	62	1.71
11	500	50	.86	11	750	61	1.57
12	520	50	.90	12	200	60	1.91 + 5.6 Rain
13	520	51	.90	13	320	59	1.45 + 0.3 Rain
14	540	53	.94	14	810	59	1.62
15	570	54	1.03	15	810	60	1.66
16	630	55	1.17	16	810	60	1.66
17	690	57	1.35	17	810	61	1.66
18	750	59	1.53	18	810	61	1.66
19	770	61	1.59	19	810	62	1.71
20	780	65	1.78	20	810	62	1.71
21	780	67	1.86	21	800	63	1.72
22	780	65	1.78	22	800	63	1.72
23	790	60	1.62	23	800	63	1.72
24	790	59	1.57	24	800	63	1.72
25	800	59	1.60	25	800	63	1.72
26	800	59	1.60	26	800	63	1.72
27	800	60	1.64	27	800	63	1.72
28	810	60	1.66	28	800	63	1.72
29	810	60	1.66	29	800	63	1.72
30	810	60	1.66	30	800	63	1.72
31	810	60	1.57	30	800	63	1.72

In the study of maximum melting rates an interesting result was that the degree-day method appears to under-estimate high melt rates and over-estimate on low melting rate days. Possible implications of this finding in river forecasting and design flood studies warrant more extensive investigation of the matter.

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