PRELIMINARY RESULTS OF SNOWMELT - STREAMFLOW STUDIES IN THE TOBIQUE BASIN

by K. S. Davar and D. I. Bray*

1. INTRODUCTION

The endless expanses of snow that accumulate in winter in the northern regions of this continent have a potential for wealth as well as disaster. Knowledge concerning the forecasting of snowmelt and its sequential streamflow is the key to conservation, control, and utilization of this white wealth; ignorance can lead to catastrophic damages as the waters derived from the melted snowpack rage uncontrolled down our rivers in the spring.

Despite the importance of this phase of the hydrologic cycle, it is only in the last decade that concentrated research has led to an understanding of the thermodynamic and hydrologic processes producing snowmelt-streamflow. Several methods have been evolved for idealistic conditions, but the complexity of factors involved in this problem and the usual paucity of basic data, challenge the formulation of reliable solutions for a specific problem.

This paper presents the preliminary results of applying these methods to the Tobique River Basin, New Brunswick, which has been selected as a 'pilot basin' for conducting such investigations.

II. HYDROLOGICAL FEATURES OF THE TOBIQUE RIVER BASIN

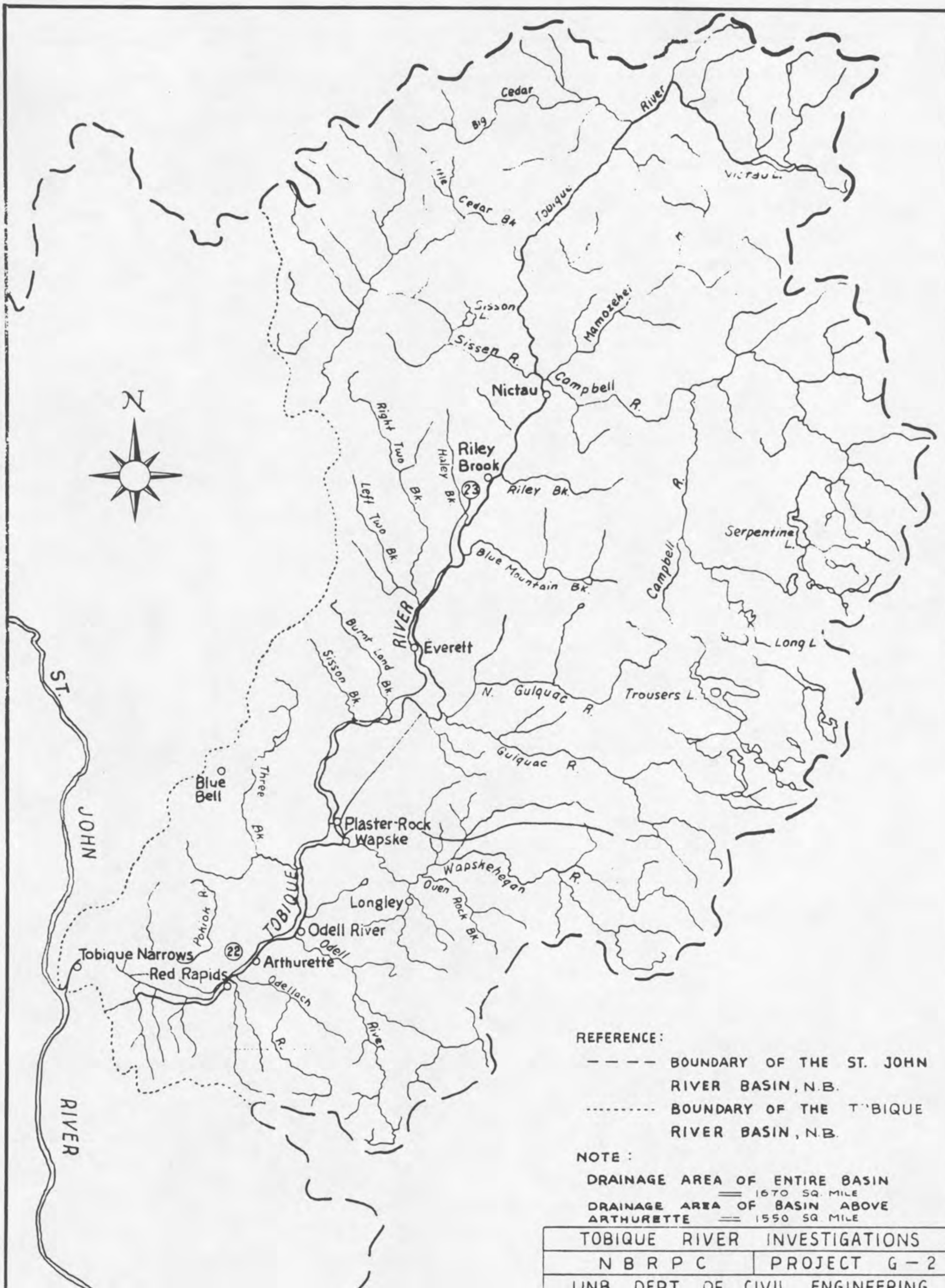
The Tobique River basin is located in the north-western section of the Province of New Brunswick. The Tobique River has a length of about 88 miles and drains an area of 1,670 sq. miles (Fig. 1). It originates at Nictau Lake at an elevation of 850 feet about mean sea level (M.S.L.) and joins the St. John River at an elevation 400 feet above M.S.L. This drainage basin has some of the most rugged terrain in the Province; the Area-Elevation Curve for the basin is shown in Fig. 2. The mean elevation for the basin is 1,050 feet above M.S.L.

It has been estimated from field observations that about 95% of the basin is covered with thickly forested coniferous vegetation, the canopy ranging in height from 20 to 30 feet. The ground surface is covered with a thick mat of decaying humus of varying depth.

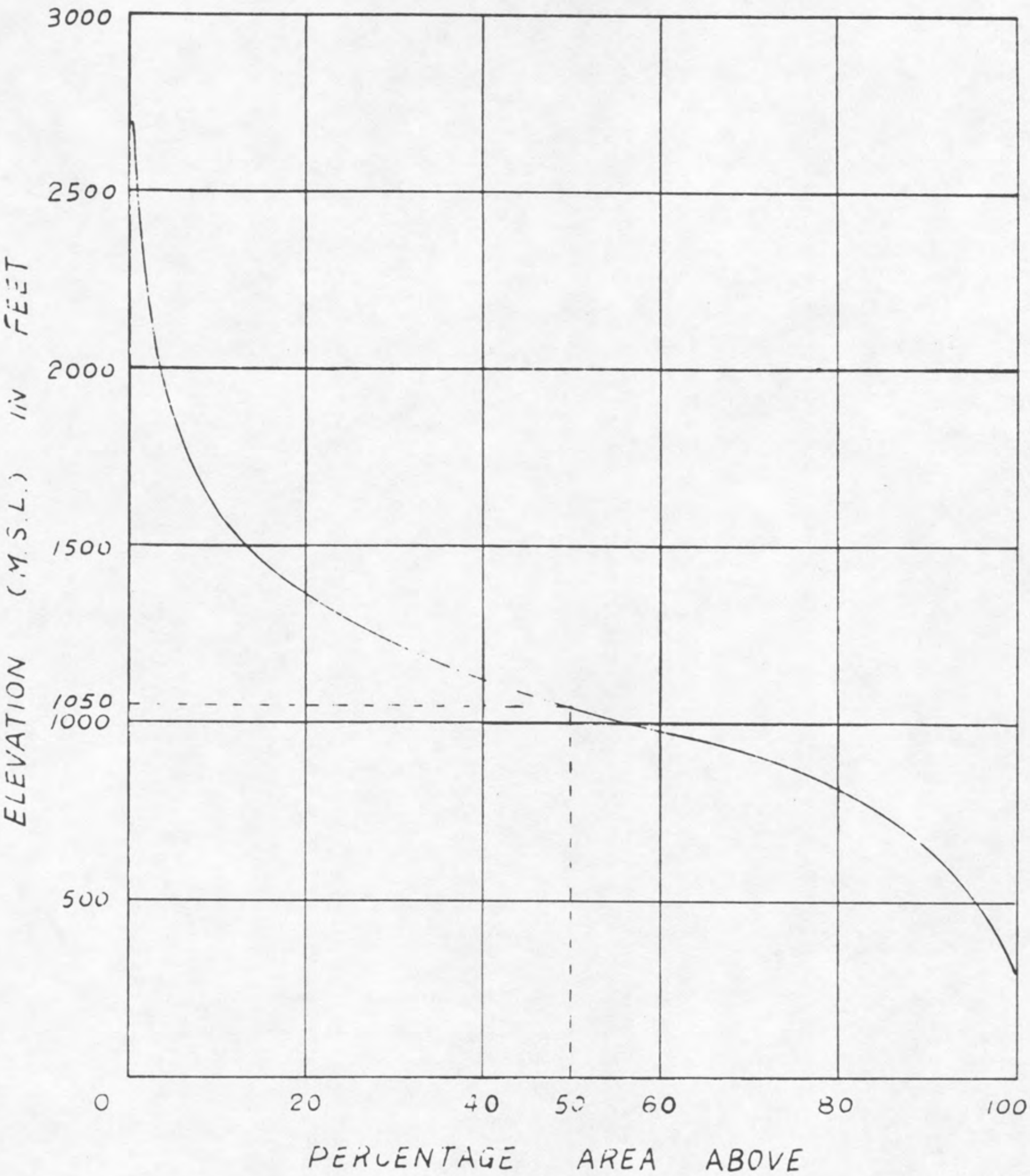
The normal mean temperature for January is estimated to be 9° F., the normal mean for July 64° F., and the annual normal 39° F. The average annual precipitation for the basin is estimated to be 41 inches of which about 10 inches (water equivalent) is in the form of snow. The streamflow regime for the Tobique River is greatly dependent on the seasonal variations in the climate. The snowmelt-streamflow is generated within a period of 100 days, from April to July.

The Tobique Basin has available records of temperature, precipitation, and streamflow, for the period 1922-31, when the natural flow regime for the river had not been interfered with by the construction of dam structures; after that time, four storage dams were constructed by the N. B. Electric Power Commission. The preliminary results presented in this report are restricted to the unregulated period from 1922 to 1931, as this greatly simplifies the analysis.

* U.N.B. Department of Civil Engineering, Fredericton, N. B., Canada



N
Big Cedar
Little Cedar Bk
Tobique River
Sisson L.
Sissen R.
Mamozekel
Nictau
Campbell R.
Right Two Bk.
Haley Bk.
Riley Brook
23
Riley Bk.
Left Two Bk.
Serpentine L.
Blue Mountain Bk.
Campbell R.
RIVER
Everett
Burnt Land Bk.
Sisson Bk.
Long L.
N. Gulquac R.
Trousers L.
Gulquac R.
ST. JOHN RIVER
Blue Bell
Three Bk.
Plaster Rock
Wapske
Wapskehegan R.
Owen Rock Bk.
Longley
Pokiok R.
TOBIQUE
Odell River
22
Tobique Narrows
Arthurette
Red Rapids
Odell
Odellach R.
River
REFERENCE:
BOUNDARY OF THE ST. JOHN RIVER BASIN, N.B.
BOUNDARY OF THE TOBIQUE RIVER BASIN, N.B.
NOTE:
DRAINAGE AREA OF ENTIRE BASIN = 1670 SQ. MILE
DRAINAGE AREA OF BASIN ABOVE ARTHURETTE = 1550 SQ MILE
TOBIQUE RIVER INVESTIGATIONS
N B R P C
PROJECT G - 2
UNB DEPT OF CIVIL ENGINEERING
THE TOBIQUE RIVER BASIN
SCALE: 1 IN = 5.08 MILES
DATE NOV 14 '63
NO 1



NOTE:

AVERAGE ELEVATION : 1050 FEET (M.S.L.)

GREATEST ELEVATION : 2690 FEET (M.S.L.)

TOBIQUE RIVER INVESTIGATIONS

N B R P C — PROJECT G – 2

UNB DEPT OF CIVIL ENGINEERING

AREA ELEVATION CURVE
TOBIQUE BASIN
(AREA = 1670 SQ.MI.)

J.C. Yan / ALB / KSD — DATE: NOV 13 '63 — NO 2

The temperature and precipitation records were obtained at the town of Plaster Rock; the station reported daily maximum and minimum temperatures, and the precipitation which fell in the form of snow was assumed to have a specific gravity of 0.1. The streamflow records for the period of study were obtained at Arthurette, where the drainage area is 1,550 sq. miles. The published mean daily flow at this station was estimated from the mean of the two flows measured for that day; this factor is a distinct disadvantage when the stage of the river was rising or falling rapidly.

For correlating heat input to the snow covered basin and the resulting snowmelt-streamflow, a '<u>snowmelt season</u>' was defined to commence 20 days before the day the flow equalled or exceeded 2,000 c.f.s. Examination of past records showed that this period was required for the ripening of the pack, when it absorbed heat but did not yield any runoff. Also, at no time did the flow exceed 2,000 c.f.s. and then recede below this value until after the seasonal maximum peak had been reached. The snowmelt season normally occurred in the first week of April and lasted for about 100 days.

If the total '<u>potential flow</u>' is defined as the accumulated precipitation in the form of snow from Nov. 1 up to the 20th day of the snowmelt season plus the rainfall from Jan. 1. to the 20th day of the snowmelt season, then the following interesting facts emerge:

$$\frac{\text{Av. Accumul. Vol. of Streamflow (First 40 days)}}{\text{'Potential Flow'}} = 0.30$$

$$\frac{\text{Av. Accumul. Vol. of Streamflow (First 60 days)}}{\text{'Potential Flow'}} = 0.95$$

$$\frac{\text{Av. Accumul. Vol. of Streamflow up to peak}}{\text{'Potential Flow'}} = 0.70$$

Although these statistics are not useful for day-to-day operational forecasts, they provide valuable knowledge in assessing overall hydrological characteristics for the basin as a representative unit for the region.

III. SNOWMELT - STREAMFLOW FORECASTING

Contemporary methods for estimating snowmelt and streamflow vary with the basin hydrological characteristics, availability of basic data, computational aids at hand, the purpose of the forecast, its timeliness and acceptable degree of accuracy. The methods of analyses being currently used are listed below in order of increasing complexity and refinement:

1. Temperature Index Methods (Ref: 7, 15)
2. U.S.B.R. Recession Analysis Method (Ref: 4)
3. U.S.C.E. Generalized Snowmelt Eqs. (Ref: 5, 15, 16)

The first three of these have been tried for the Tobique basin, and will be briefly reported on.

1. Temperature Index Method

The investigations of previous researchers (8, 12) showed that in some hydrological basins with limited hydrometeorological data, simple correlations could be obtained between snowmelt or streamflow and the degree-day-factor (D.D.F.), the most frequently used temperature index. The use of air temperature alone as a snowmelt index leads to inherent limitations in this method, as it neglects direct evaluation of the effects of important factors, such as solar radiation, albedo, wind, precipitation, humidity, and many other factors. On the other hand, a hydrologist is often faced with the task of predicting snowmelt-streamflow with air temperature as the only available index. For such conditions streamflow forecasting based on the use of D.D.F. may prove adequate; this method also offers the advantage of simplicity and speed.

In applying this method to the Tobique bssin, it was observed that the daily temperatures fluctuated greatly for successive days during the snowmelt season without a corresponding variation being reflected in the daily streamflow. A few trials suggested that the degree-day-factor be defined as follows:

$$(D.D.F.)_{\bar{5}} = \frac{Q5}{(dd_1 + dd_2 + dd_3 + dd_4 + dd_5)/5}$$

$$= \frac{Q_5}{1/5(\Sigma_{i=1}^{5} dd_i)}$$

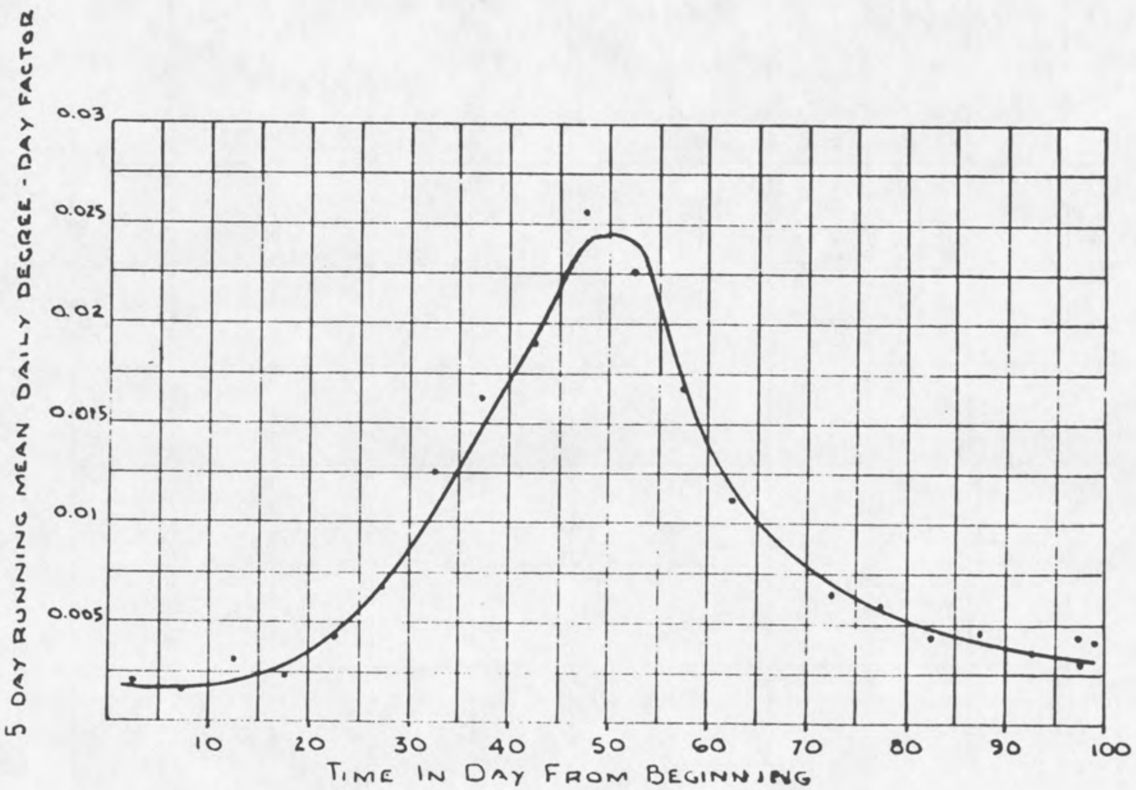
here: $(D.D.F.)_{\bar{5}}$ = Five day running mean degree-day-factor (ins/d.d.)

Q_5 = Streamflow on the fifth day (expressed in inches)

$\Sigma_{i=1}^{5}$ ddi = Sum of the degree-days for the antecedent five days

Note: The maximum temperature above a base of 32° F. was used for the temperature index. Preliminary studies in the Tobique basin and the evidence provided by Garstka (4) showed greater consistency than using mean temperatures.

Curves were constructed for the D.D.F. during the snowmelt seasons for the years 1924, 1926, 1929, 1930, and 1931. A normal D.D.F. curve for the snowmelt season was derived as shown in Fig. 3. This normal D.D.F. curve was used for predicting streamflows for 1925 (Fig. 4) and 1928 (Fig. 5). Both these years had not been used in deriving the 'normal curve'. Major deviations became evident if the entire seasonal streamflow hydrograph was predicted from the corresponding temperature distribution only. The deviations for the 1928 hydrograph (Fig. 4) can be attributed to a significant peak occurring early in the season. The apparently large deviations for the 1925 hydrograph (Fig. 5) were mainly due to an out-of-phase time distribution not compatible with the normal curve. Firstly, the seasonal hydrograph had two peaks instead of one, as for normal years; secondly, the larger peak occurred much later than in normal years.

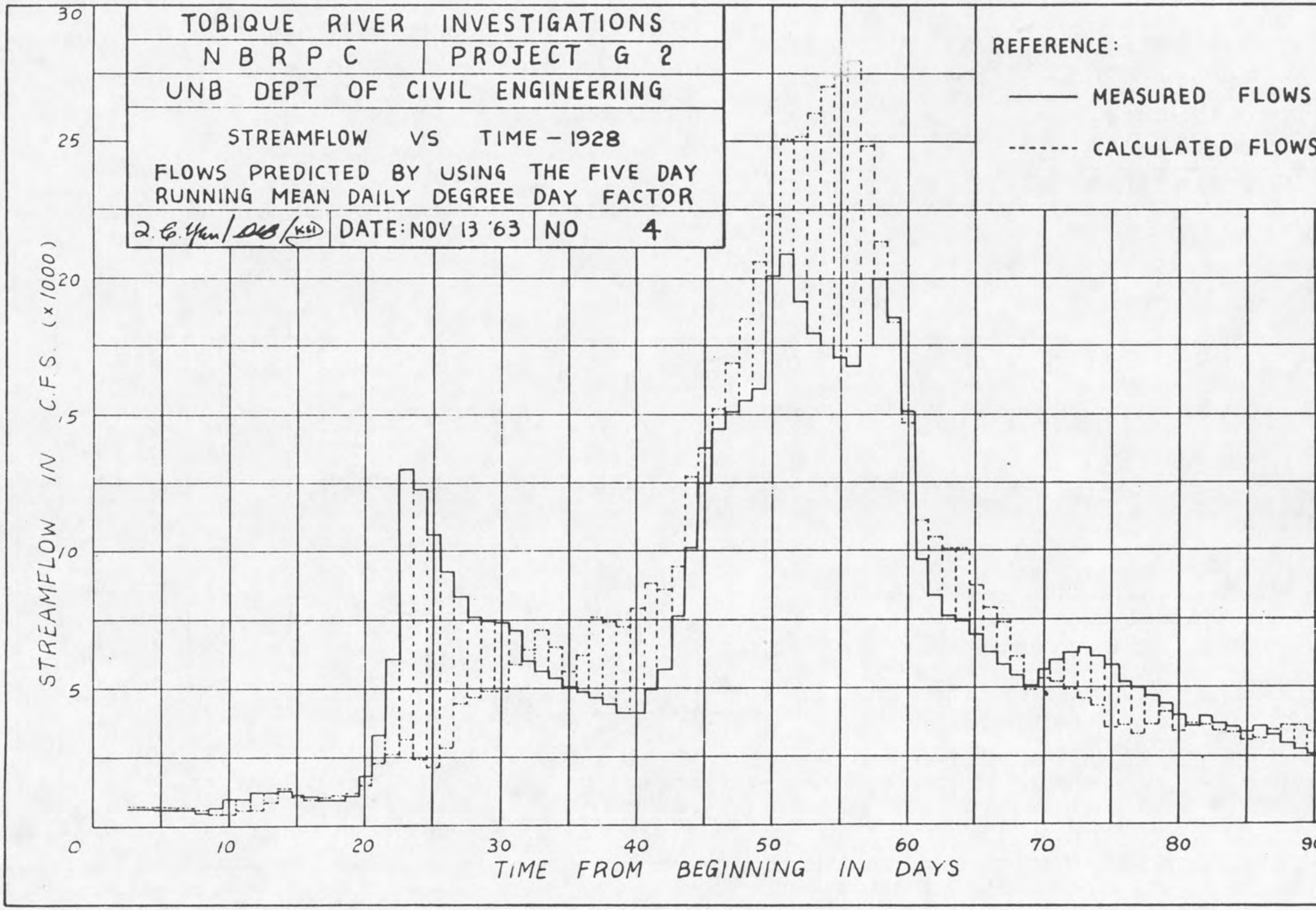


NOTE: 1. CORRECTIONS FROM THE CORRECTION CHART ARE TO BE ADDED TO THE NORMAL CURVE TO OBTAIN THE ESTIMATED FACTOR

2. THE NORMAL CURVE IS DEVELOPED FROM DATA FOR THE YEARS 1926, 1929, & 1930.

3. DEGREE-DAY FACTOR = $\frac{\text{INCHES MELT}}{\text{DEGREE-DAY}}$

TOBIQUE RIVER INVESTIGATIONS	
NBRPC	PROJECT G-2
UNB DEPT OF CIVIL ENGINEERING	
THE NORMAL FIVE DAY RUNNING MEAN DAILY DEGREE-DAY FACTOR	
VAN / AWB / KSI DATE: NOV: 15, 63	NO 3



TOBIQUE RIVER INVESTIGATIONS
N B R P C
PROJECT G 2
UNB DEPT OF CIVIL ENGINEERING
STREAMFLOW VS TIME - 1928
FLOWS PREDICTED BY USING THE FIVE DAY RUNNING MEAN DAILY DEGREE DAY FACTOR
DATE: NOV 13 '63
NO 4
REFERENCE:
MEASURED FLOWS
CALCULATED FLOWS
STREAMFLOW IN C.F.S. (x 1000)
TIME FROM BEGINNING IN DAYS
0
5
10
15
20
25
30
10
20
30
40
50
60
70
80
90

TOBIQUE RIVER INVESTIGATIONS

N B R P C	PROJECT G – 2

UNB DEPT OF CIVIL ENGINEERING

STREAMFLOW VS TIME – 1925

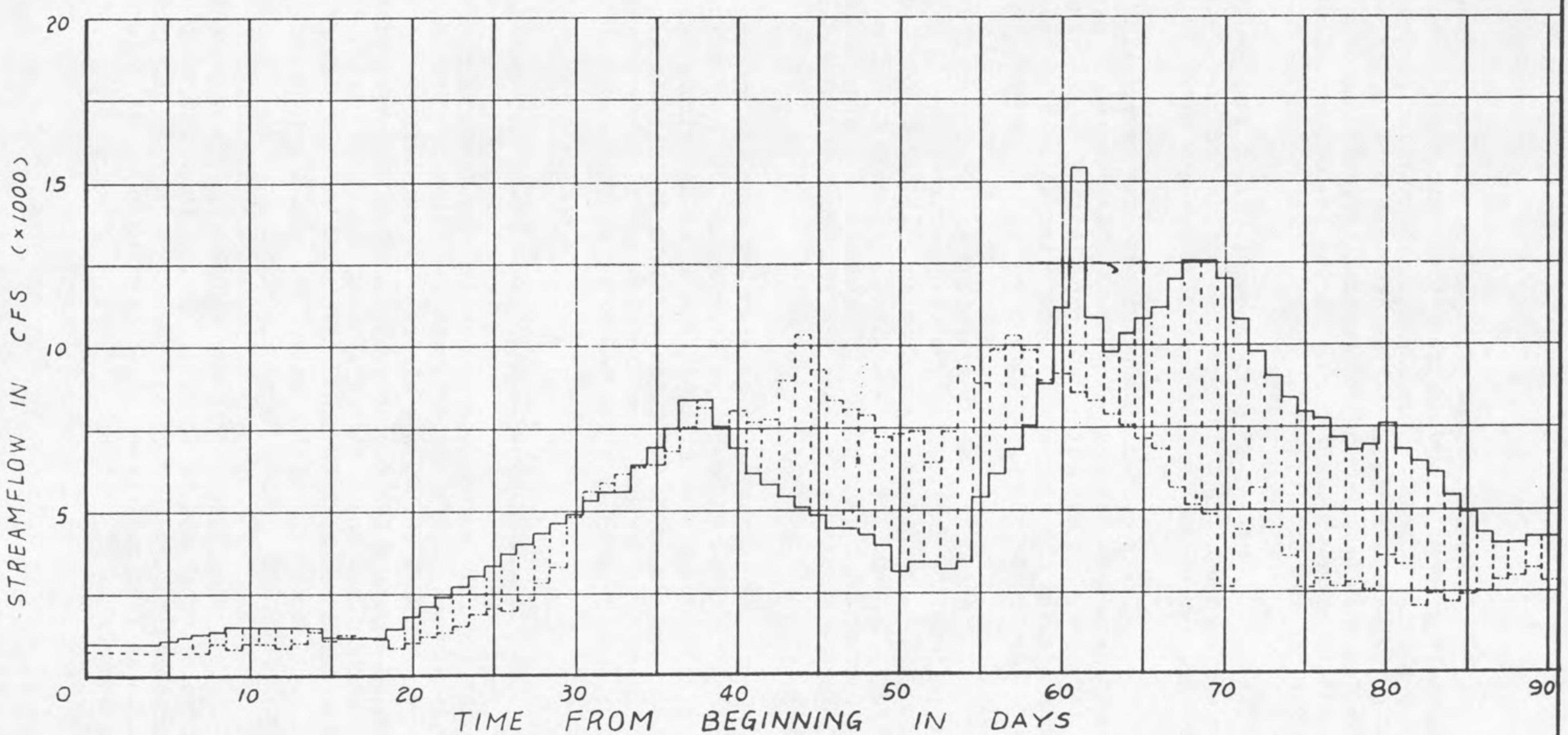
FLOWS PREDICTED BY USING THE FIVE DAY RUNNING MEAN DAILY DEGREE DAY FACTOR

2.6 cfs/deg/ksf	DATE: NOV 13 '63	NO 5

REFERENCE:

——— MEASURED FLOWS

------- CALCULATED FLOWS



The effect of rainfall did not become noticeable until late in the snowmelt season; it would appear from this that the accumulating snowpack absorbed the occasional rainfall in the earlier part of the season. Examination of an extensive rainfall period near the peak of the seasonal hydrograph indicated that only 20% of the rainfall appeared immediately as streamflow; this condition changes considerably in the latter part of the season as the snowpack thins and recedes.

The effect of fresh snowfall was not apparent until about 5 to 10 days later, when a noticeable decrease in flow occurred. This effect may be due to the greater albedo (reflectivity) of the new snow.

These comparisons point out some severe limitations inherent in using normal seasonal relations. Such methods have been favorably reported on in literature, but evidently the compatibility of the technique depends on how consistently the hydrological characteristics of a basin conform to a 'normal' behavior of its key parameters.

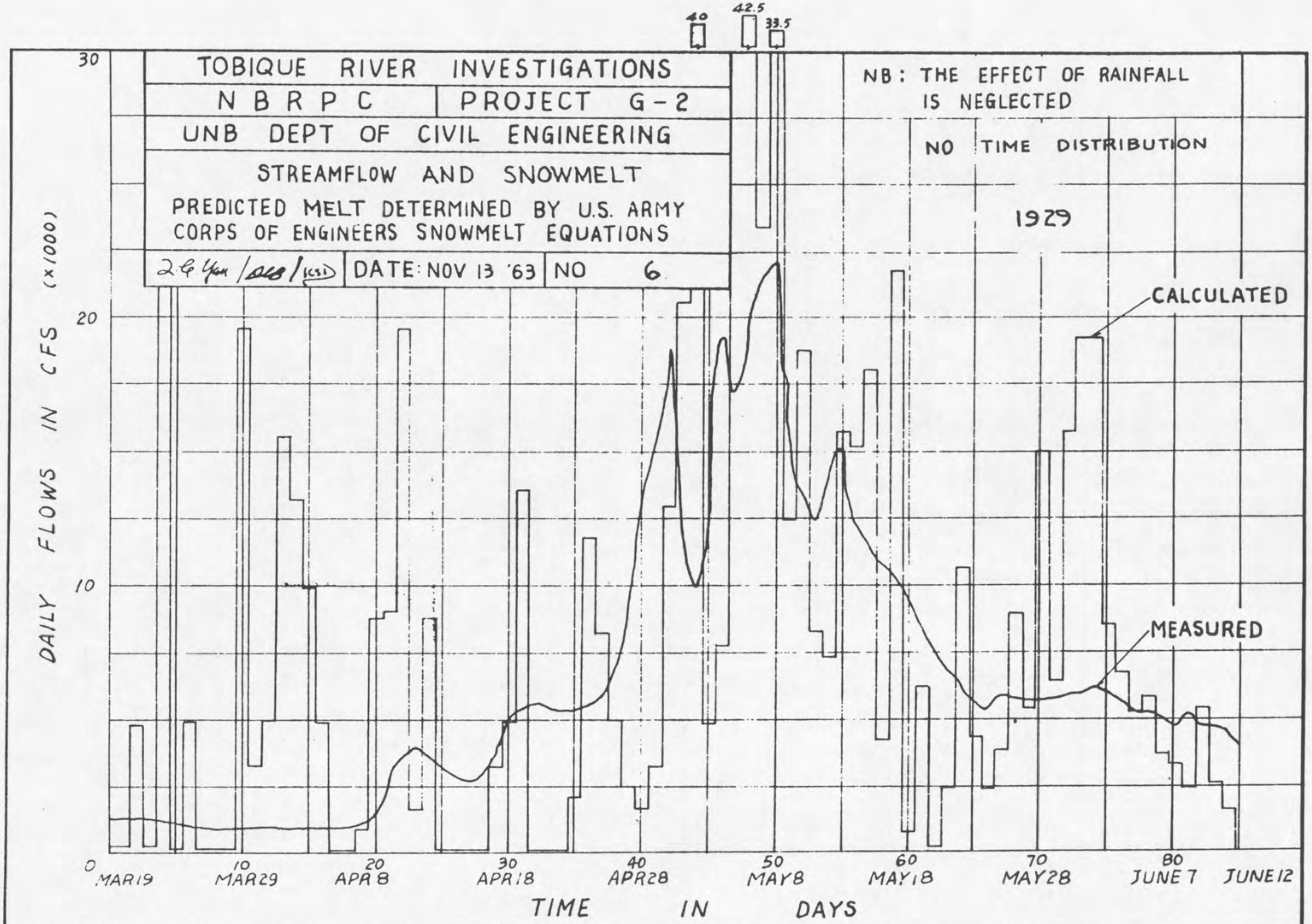
Although these limitations are severe it should be realized that for operational or day-to-day type of snowmelt-streamflow forecasts the limitations need not be considered very drastic. If any major deviations of observed flows were indicated, the normal degree-day factor could be shifted on the time scale to correspond to the phase difference in the observed trends of streamflow. Also, the whole streamflow forecasting procedure is related to the temperature forecast, which is presently limited to less than 3 days.

It must also be pointed out that the entire investigation was based on one temperature recording station and one streamflow gaging station for the entire drainage area of 1,550 sq. miles at Arthurette. Besides, the correlations were based on one representative daily value of each parameter. For a drainage area of this size, more gages and preferably of the continuous recording type, would probably yield better correlations.

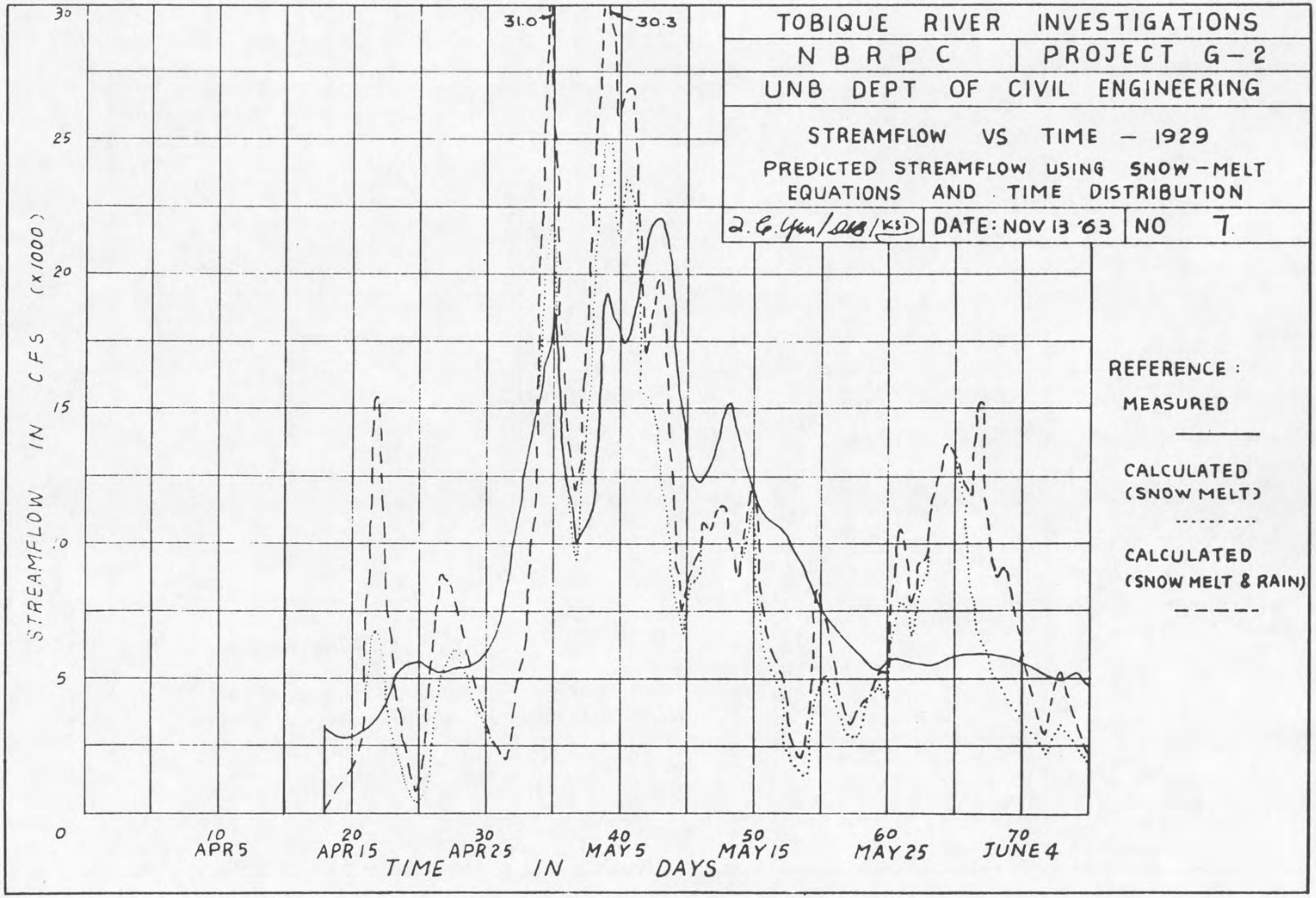
2. U.S.B.R. Temperature Index Plus Recession Analysis Method

This method was evolved in the Fraser Experimental Forest, Colorado, and was reported by the originators (4) to perform satisfactorily for areas varying from 1 to 500 sq. miles. The foundation of this method lay in developing an equation for the recession limb of the very similar diurnal hydrographs of streamflow, and then correlating the first day's volume of streamflow from that day's snowmelt to the Recession Volume of streamflow from that day's snowmelt. The details of the method and applications are described in detail in Reference 4.

When this method was applied in the Tobique basin, no satisfactory correlations could be derived. This result would appear to indicate that the recession regime for the Tobique basin is very different from that in the Fraser basin, a fact indicated in the derivation of the 5-Days Running Mean D.D.F. in Section 1.



TOBIQUE RIVER INVESTIGATIONS
N B R P C
PROJECT G - 2
UNB DEPT OF CIVIL ENGINEERING
STREAMFLOW AND SNOWMELT
PREDICTED MELT DETERMINED BY U.S. ARMY CORPS OF ENGINEERS SNOWMELT EQUATIONS
DATE: NOV 13 '63
NO 6
NB: THE EFFECT OF RAINFALL IS NEGLECTED
NO TIME DISTRIBUTION
1929
CALCULATED
MEASURED
40
42.5
33.5
DAILY FLOWS IN CFS (x1000)
0
10
20
30
MAR19
MAR29
APR 8
APR18
APR28
MAY8
MAY18
MAY28
JUNE 7
JUNE12
40
50
60
70
80
TIME IN DAYS


TOBIQUE RIVER INVESTIGATIONS
N B R P C
PROJECT G-2
UNB DEPT OF CIVIL ENGINEERING
STREAMFLOW VS TIME - 1929
PREDICTED STREAMFLOW USING SNOW-MELT EQUATIONS AND TIME DISTRIBUTION
DATE: NOV 13 '63
NO 7
REFERENCE:
MEASURED
CALCULATED (SNOW MELT)
CALCULATED (SNOW MELT & RAIN)
31.0
30.3
STREAMFLOW IN CFS (x1000)
0
5
10
15
20
25
30
10 APR5
20 APR15
30 APR25
40 MAY5
50 MAY15
60 MAY25
70 JUNE4
TIME IN DAYS

3. U.S.C.E. Simplified Snowmelt Eqs.

The U.S.C.E. Generalized Snowmelt Eqs. (5, 15, 16) have been widely accepted for predicting snowmelt. Since snowmelt is never determined directly in the field, indirect confirmation of the validity of these coefficients is generally obtained from a comparison of predicted and actual hydrograph simulations, if other assumptions and analyses techniques can be accepted as proven reliable.

The U.S.C.E. Generalized Snowmelt Eqs. are used in conjunction with the Unit Hydrograph or Storage Routing methods (see special section of references) for time distribution of the snowmelt excess. Initial applications of these equations are shown in Figs. 6 and 7. In Fig. 6 a simplified form of these equations (see Appendix 1) was used for the Tobique basin, and the predicted snowmelt compared with the contemporaneous streamflow. The comparison immediately demonstrates the importance of time distribution. In Fig. 7, a trial unit hydrograph was used and the comparison immediately demonstrates a substantial improvement. In the future, these studies will be extended; until then, a proper evaluation of these methods needs to be postponed.

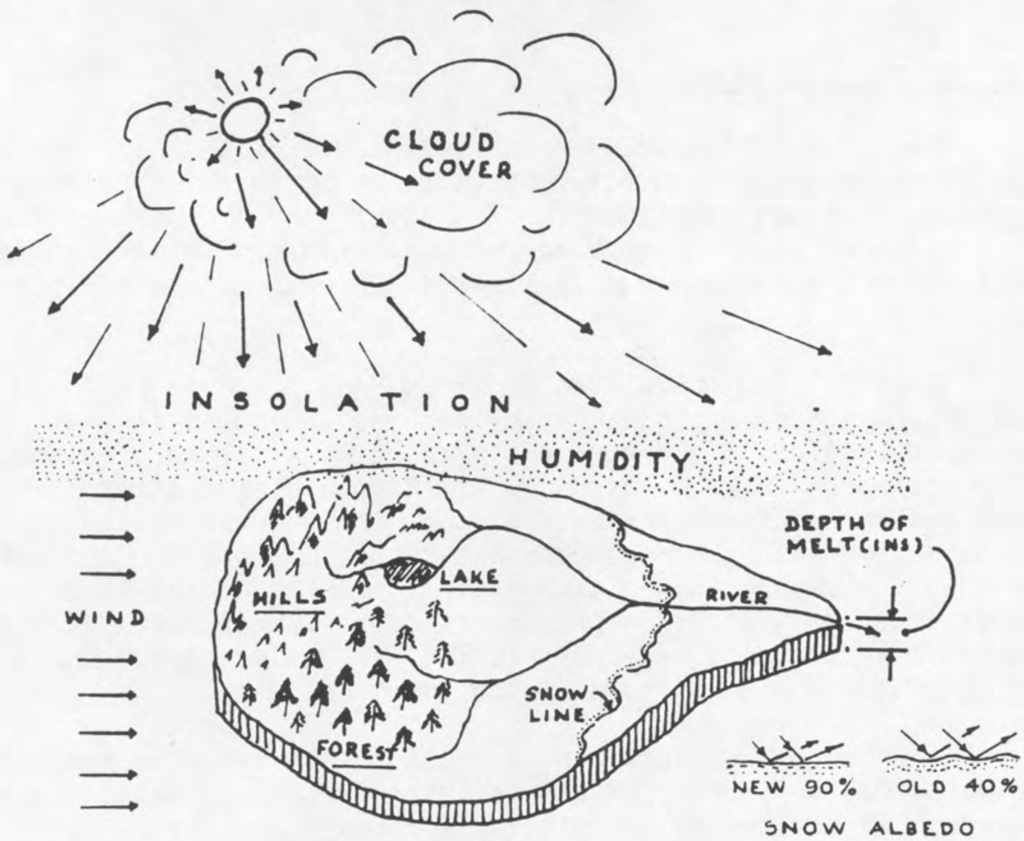
These complex procedures necessitate the use of electronic computers and are well adapted for design office use, such as estimating spillway floods. Their success in day-to-day operational forecasts has yet to be conclusively demonstrated.

IV. CONCLUDING REMARKS

The frontiers of knowledge in snowmelt-streamflow forecasting have been greatly advanced in the last decade, and our understanding of its scientific basis vastly improved. But, as applications in the Tobique River basin show, many of its outstanding problems remain to be attacked in depth before its prediction techniques can be applied with confidence and consistency to important programs for design and operation of river regulation projects.

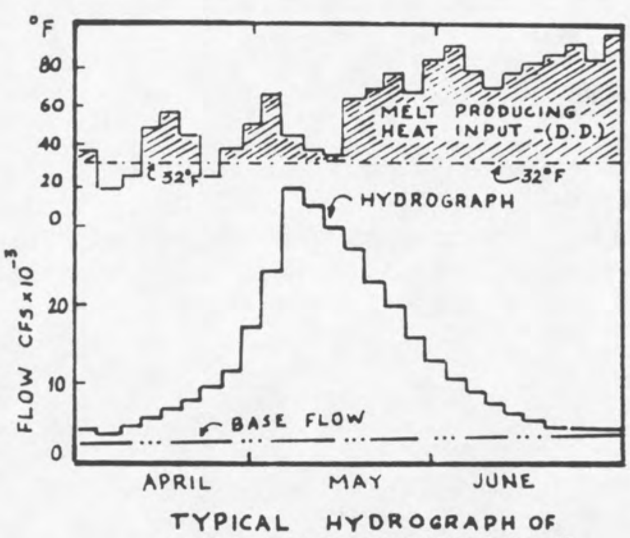
ACKNOWLEDGEMENT

The research reported in this paper was made possible by sponsorship of the New Brunswick Research and Productivity Council. Mr. W. B. Cuthbertson (N.B.E.P.C.) and Mr. R. B. Dickison (DOT - Met. Branch) have both made valuable contributions to the development of the research program through their constant interest and co-operation.

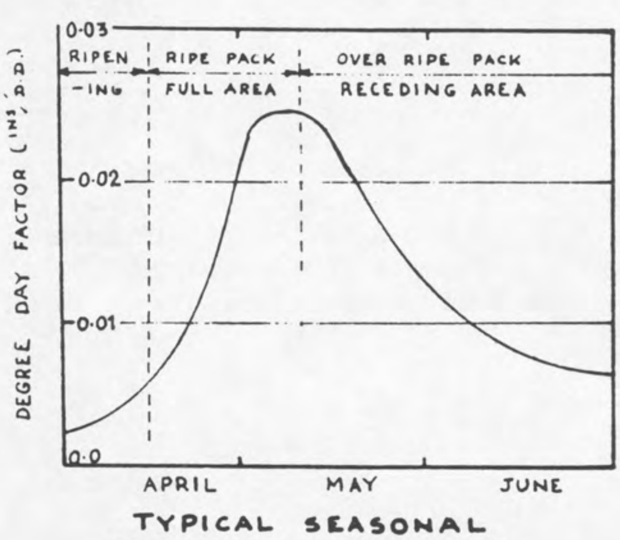


DRAINAGE BASIN (SQ. MILES)

$$\text{SNOWMELT} = \text{D.D.F.} \times \text{D.D.} \quad \text{ins}$$
$$= \text{D.D.F.} \times \text{D.D.} \times A \quad \text{in - sq.mi}$$
$$= \text{D.D.F.} \times \text{D.D.} \times A \times 26.9 \quad \text{sfd.}$$



TYPICAL HYDROGRAPH OF SNOWMELT OR STREAMFLOW



TYPICAL SEASONAL DEGREE DAY FACTOR

K.S.D./1964

FIG- 8 THE DEGREE-DAY-FACTOR METHOD

APPENDIX I

SOME REMARKS ON USE OF U.S.C.E. GENERALIZED SNOWMELT EQUATIONS AND STREAMFLOW SIMULATION BY ELECTRONIC COMPUTERS

The generalized snowmelt equations (References 5, 15, 16) have been widely used but it must be pointed out that the various coefficients have been determined by statistical averaging of data obtained in the western U.S.A. As the U.S.C.E. references carefully point out, they may vary in other regions and the given coefficients should be used initially as trial values only. Since snowmelt is never determined directly in the field, indirect confirmation of the correctness of these coefficients is generally obtained from a comparison of predicted and actual hydrograph simulations, if other assumptions and analyses techniques can be accepted as proven reliable.

Streamflow Synthesis and Routing by Electronic Computers

The generalized equations permit an estimate of the snowmelt; there still remain the challenging problems of estimating the runoff fraction that will emerge as streamflow and its time distribution, or the problem of synthesizing the hydrographs of streamflow generated by the snowmelt. Two methods are currently used for this purpose, the choice depending on basin-hydrological characteristics and available computational aids:

a) Unit hydrograph techniques (Refs: 7, 13, 16)
b) Storage Routing techniques (Refs: 7, 14, 16)

The unit hydrograph method is well established for hydrograph analyses of runoffs resulting from rainfall, but for snowmelt runoff it presents a difficulty in clearly determining the unit duration to be used. Also, the long flat recession limb introduces problems in its application. When rainfall runoff occurs in various combinations with the snowmelt runoff, a further complication results as the characteristics of unit hydrographs for the two types of runoff are very different.

Storage routing has been found particularly advantageous for use with electronic digital computers. It offers flexibility in deriving hydrograph reconstitution parameters by trial-and-error analyses of historical floods. Further, it permits adjustment of computed streamflows to actually observed flows, which is a distinct advantage for day-to-day operational forecasts of streamflow.

This method normally requires the total snowmelt runoff to be separated into surface runoff and ground contribution, the two components then being separately routed by using different times of storage. The times of storage for each component need to be empirically determined by trial fits to historical data.

In practice, an arbitrary separation of the two components, and corresponding selection of storage times for each component to fit historical flood hydrographs of similar characteristics, may lead to successful reconstitutions of floods produced under similar surface and ground flow conditions. However, when the ground flow conditions for any season are very different from those assumed for the reconstitution, the recession limb of the prediction hydrograph may be dissimilar. The same would be true for dissimilar surface runoff conditions which would lead to deviations in the ascending limb of a prediction hydrograph.

Both these elaborate methods of analyses are well adapted for estimating project design floods, but their use for flood forecasting should be accepted with caution. The complexity of these methods tends to mask the indefinite nature of the assumptions regarding: a) separation of the surface runoff and ground water contributions, which many hydrologists would challenge in the case of snowmelt runoff; b) selection of proper storage times for the arbitrarily separated components; the storage times may vary seasonally and annually according to antecedent hydrological conditions in the basin.

An even more fundamental restriction applies in using these methods for operational forecasts of stream flows. Snowmelt being a thermodynamic process is greatly dependent on temperature conditions in the basin; any streamflow forecast mainly connected with snowmelt is therefore restricted by the present limitations in predicting temperatures, which are rarely forecast more than three days in advance.

Perhaps the best use of these elaborate methods would be in developing comprehensive forecasting nomograms or prediction graphs which could be used with observed parameters, rather than uncertain prediction of variables such as 5-day temperatures. Also, when the soundness of the fundamental assumptions is unproven, and the basic data is insufficient in scope and detail, it would appear desirable to keep the techniques of analyses simple and rapid, rather than unnecessarily complex; a proper measure of compatibility needs to be preserved between the authenticity of the assumptions and complexity of the analyses. In brief, the end results must be accepted with a thorough appreciation for the limitations of the basic assumptions and data which cannot be overcome by complexity of computational techniques.

An important factor about which very little is known is the role of the regime of ground flows during snowmelt season streamflows. Most of the research reported thus far concerns the influence of above ground variables, yet evidence is increasing that the streamflow is strongly correlated to the ground flow regime. The ground flow regime is established by antecedent hydrometeorological factors of much longer duration than the commonly accepted diurnal variations. Temperature profiles below the ground, soil mantle, the geological and hydraulic properties of the rock strata through which ground flows travel should also receive increasing attention in future research.

APPENDIX II

The snowmelt equations derived by U.S.C.E. for a heavily forested area (80%-100%) are as follows:

for rain-free periods $M = 0.074(0.53\ Ta^1 + 0.47\ Td^1)$ - (1)

for rain periods $M = (0.074 + 0.007\ Pr)(Ta^1) + 0.05$ - (2)

The modified snowmelt equations as applied to the Tobique River basin are as follows:

for rain-free periods $M = 0.055\ (0.53\ Ta' + 0.47\ Td')$ - (3)

for rain periods $M = 0.75\ [(0.074 + 0.007\ Pr)(Ta') + 0.05]$ - (4)

where M = inches of melt per day

Ta' = (mean air temperature - 32° F.) for day

Td' = (mean dew temperature - 32° F.) for day

Pr = inches of rainfall per day

The value of Td' may be evaluated by a relation developed for the St. John River basin involving air temperature (1). This relation is as follows:

$$Td = -0.2 + 0.71\ Ta$$

Then $Td' = +0.71\ Ta' - 9.5$

when Td = mean dew point temperature (° F.)

Ta = mean air temperature (° F.)

Td' and Ta' as defined previously

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