

FLOOD FORECASTING WITH THE AID OF A
HYDROLOGICAL SIMULATION PROGRAM

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FLOOD FORECASTING WITH THE AID OF A HYDROLOGICAL SIMULATION PROGRAM

1 - INTRODUCTION

The problems associated with the flooding of large tracts of land have been of concern to mankind since he began to inhabit the fertile flood plains of the world's major rivers. Even today a large percentage of the world's population is found in areas which are subject to flooding at more or less frequent intervals.

It is not surprising, therefore, that through the years a large number of attempts have been made to devise a system of flood prediction which would make it possible to give sufficient warning of imminent floods to keep the loss of life and property to a minimum. In general, and especially for snow fed rivers, these attempts have not been very successful. One of the main reasons for this failure can be found in the large number of dependent and independent variables which effect runoff resulting from rainfall, snow-melt or snowmelt and coincident rainfall.

Recent research in snow hydrology carried out mainly by the U.S. Corps of Engineers and the U.S. Weather Bureau has lead to a better understanding of the mechanics of snowmelt and the resulting runoff. While it is generally agreed that much research remains to be done, the formulae which have been developed have proven to include the major effects of the variables which affect snowmelt and runoff. These formulae are by their nature extremely cumbersome and their application requires a large amount of basic data. It is, therefore, only by employing high-speed electronic computers that it has been possible to use these formulae effectively.

The program which is described in the following pages was used for several rivers in Canada to establish design floods and to determine safe operating procedures for storage reservoirs. More recently the same program was used for the prediction of spring flood discharges on the Saint John River in New Brunswick. The results of this last application have shown that it is possible with the aid of this type of program to predict in advance the peak flows and the date of occurrence of these peaks along an entire river with reasonable accuracy. While it is true that during the course of the work, several areas of less satisfactory agreement were found to exist, the overall results are very encouraging and indicate a great promise for future applications of this type of technique for purposes of flood prediction.

2 - DESCRIPTION OF SIMULATION

As pointed out, the application of the snowmelt formulae is very time consuming and can be carried out effectively only with the aid of an electronic computer. At the same time, it must be recognized that the results obtained from any computation are only as accurate as the basic data used for it. Since the hydrometeorological conditions are seldom the same for an entire drainage basin, it is, in most cases, necessary to divide the drainage basin in smaller sub-basins for which it can reasonably be assumed that the same conditions apply. Furthermore, the shape of the hydrograph is considerably modified by the storage and the retention characteristics of each sub-basin. By including the effect of these characteristics in the program of computations, it has essentially become a simulation or mathematical model of the drainage basins in which all hydrological processes and storage and retention characteristics are represented by mathematical functions.

The program which was used for the flood forecasting consists essentially of five subroutines, and a control program which directs the order in which each subroutine is used. A simplified computer flow sheet of a typical application is shown on Figure I, while the five subroutines are described in the following sections.

2.1 Calculation of Runoff (Inflow into End of Reach) -

This routine computes the runoff from rainfall snowmelt or from snowmelt and coincident rainfall. For snowfree conditions runoff is computed by standard methods such as the unit hydrograph or lag and route methods depending on the basic data available. In calculating runoff due to snowmelt or snowmelt with coincident rainfall the formulae developed by the U.S. Corps of Engineers are used. These formulae are described in detail in the Corps' Snow Manual and are given in the attached Table I for reference. It will be noted that the appropriate formula must be selected for rainy and non-rainy days and according to the degree of forest cover on each sub-basin. In the subroutine provision is made for dividing each sub-basin into four sections according to the amount of forest cover.

As air temperature which is one of the most important meteorological variables affecting snowmelt varies with elevation provision has been made in the subroutine for dividing the sub-basin into four elevation bands. In calculating snowmelt the potential melt as determined from the formulae is adjusted for evapotranspiration losses and is then multiplied by a coefficient obtained from an area contributing curve. This curve takes account of the percentage of snow already melted and of the effect of the initial priming (wetting) of the snowpack.

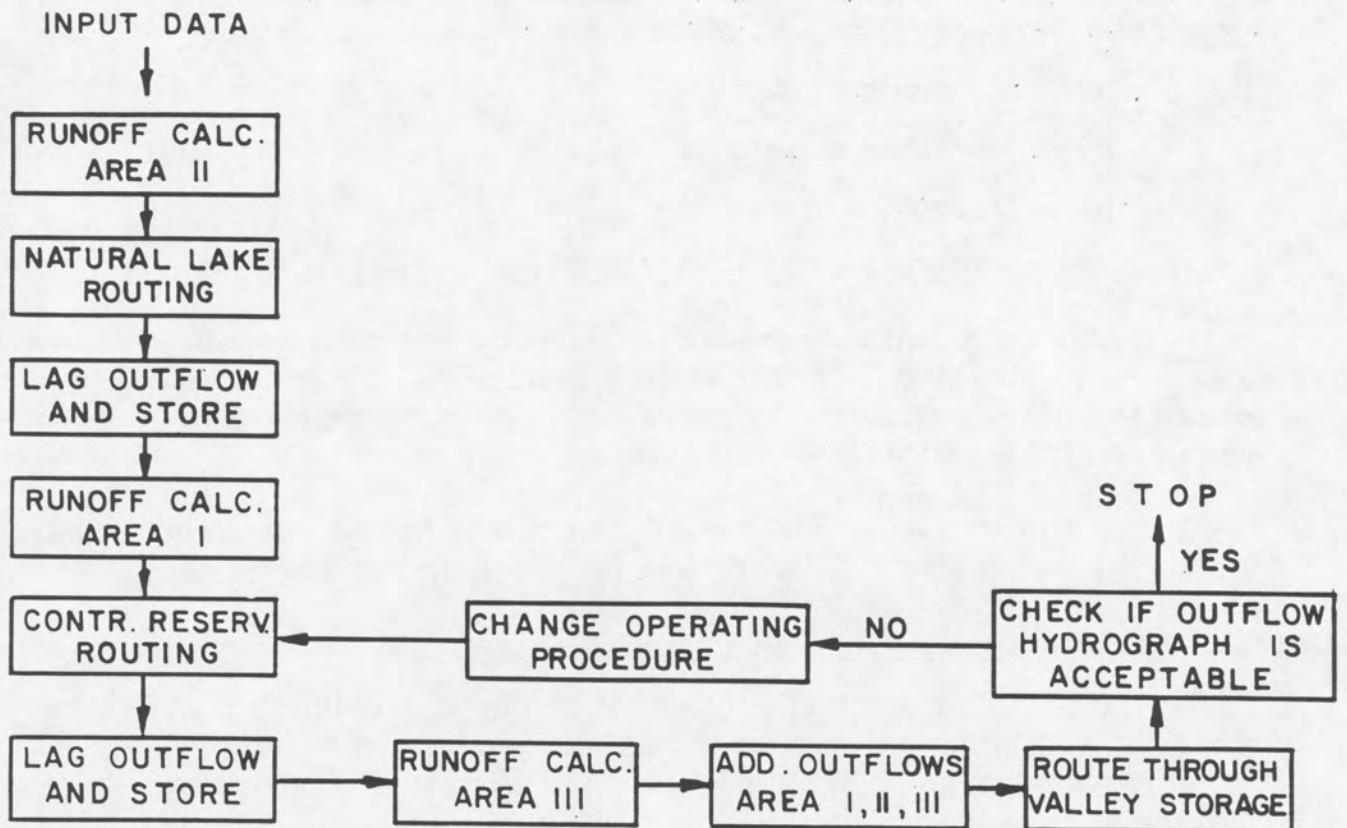
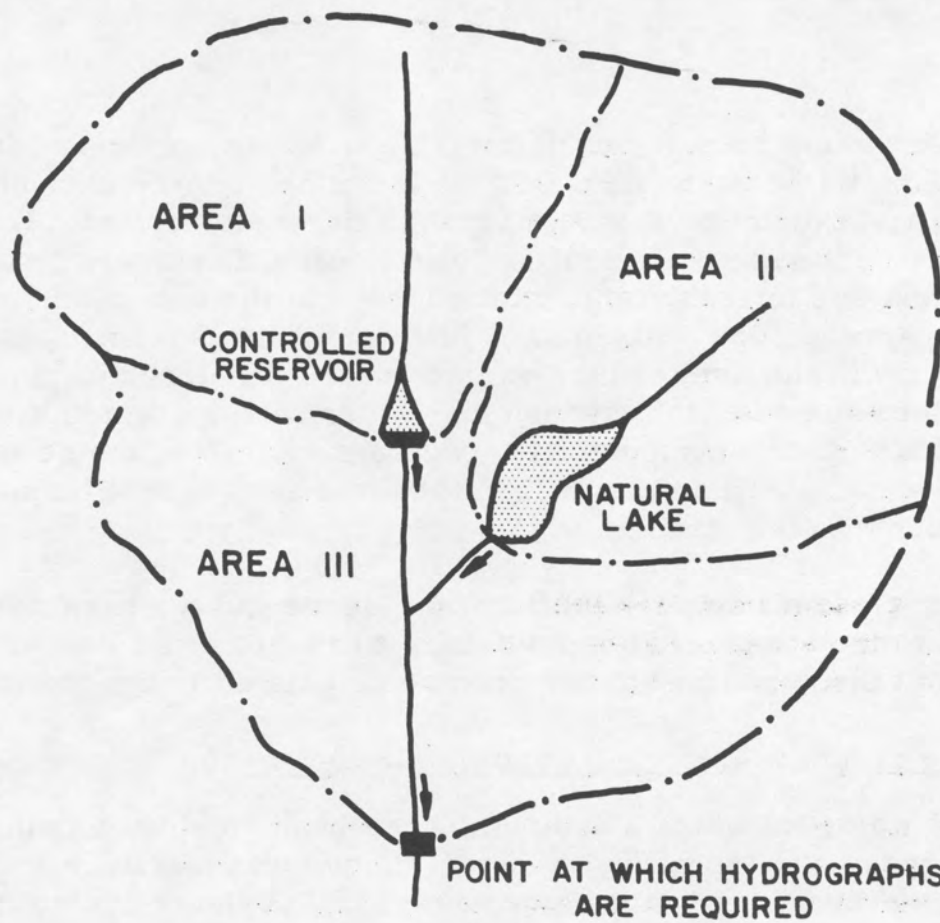


FIGURE I - SIMPLIFIED COMPUTER FLOW SHEET FOR A TYPICAL APPLICATION

After the total runoff due to rainfall, snowmelt or snowmelt and coincident rainfall, has been computed, it is divided into components of direct and indirect runoff to which varying lag times are applied. For the period under investigation, the lagged flows in each time interval are added together. From this total, the infiltration losses of the sub-basin are subtracted to give the outflow hydrograph. Addition of the outflow hydrograph to the base flow in the river at the downstream end of the sub-basin gives the 'inflow-into-end-of-reach' hydrograph. Alternatively, where hydrometric records suitable for unit hydrograph analysis are available, the outflow hydrograph from each sub-basin may be obtained by means of distribution graphs supplied as input to the simulation.

At the present time, the infiltration losses and the base river flows are supplied to the computer as input data. It is anticipated that when more is known about these phenomena they can be calculated in the program.

2.2 Routing of Inflow Through a Controlled Reservoir -

If the area for which a hydrograph has been obtained terminates in a controlled reservoir, the runoff is routed through this reservoir in a manner determined by established control procedures. Since the computer program has been set up for the most general case, the subroutine is written for a reservoir which has the following discharge works:

- (a) - Hydraulic turbines
- (b) - Low level outlets
- (c) - Controlled spillways
- (d) - Uncontrolled spillways

Since a controlled reservoir can be operated in many different ways, rules must be provided for either storing or releasing the water. This is accomplished in the subroutine by providing a rule curve which gives for each time interval the desired reservoir level.

The input data required are rating curves for the discharge works, rule curves for reservoir operation and the reservoir storage curve.

2.3 Routing of Inflow Through a Natural Lake -

The flood hydrographs in a river can be considerably modified by natural lakes which may exist in the drainage area. To simulate this effect in the computer program, the runoff above a lake is calculated and routed through the storage in the lake. If the drainage area contains a large number of small lakes, the lakes may be combined in the simulation to form one large hypothetical lake through which the combined inflow into each lake is routed.

It is assumed that the lakes have horizontal water surfaces so that routing can be performed using standard techniques. The only input data required consists of the lake storage curve and the rating curve of the lake outlet.

2.4 Routing of Inflow Through Valley Storage -

In this subroutine, the effect of valley storage is simulated using the Muskingum routing method. This method can, however, only be applied with confidence when recorded inflow and outflow hydrographs are available for the reach of river under consideration.

2.5 Routing of Inflow Through a River Reach with Backwater -

This subroutine is used to simulate pondage upstream from a proposed dam or other river control, or where the Muskingum routing method is not applicable. Rating curves for various points along the reach and channel storage curves are supplied as input data, and the routing proceeds from point to point along the river. This subroutine can be applied where water levels along the river during floods are to be computed.

3 - PROVING OF SIMULATION

Before the simulation can be used for the forecasting of floods, a number of hydrological characteristics of the river basin must be determined. Only very few of these characteristics are susceptible to direct measurement and they must, therefore, be determined by analysis of existing hydrometeorological records. The hydrometeorological variables which are supplied as input to the simulation, include the base flow, infiltration losses, lag times, area contributing curves, air temperatures, precipitation, snow cover, wind speed, and solar radiation. In the hydrological simulation for the Saint John River, the base flows and infiltration losses were estimated from an analysis of measured river flows and recorded meteorological data. The other basin characteristics could be obtained only by simulating recorded hydrographs. In general, the procedure for determining these parameters was to select a hydrograph for which the corresponding hydrometeorological records were readily available. These records, together with best estimates of the basin characteristics, were used as input data for the simulation. An outflow hydrograph was then computed and matched with that actually recorded. In most cases, it was necessary to adjust the values of the unknown parameters several times before a satisfactory match could be obtained. The combination of values with which the recorded hydrograph could best be reproduced was then retained as input and used in the simulation to reproduce another recorded hydrograph, preferably of dissimilar shape to the first. This process was repeated as often as required and only after it was found that several hydrographs could be reproduced with sufficient accuracy, were the values of the basin characteristics used as permanent input data for other computer runs.

Examples of the degree of accuracy which can be obtained with this technique are illustrated on Figures 2 and 3. These figures show computed and recorded hydrographs of the Saint John River at Grand Falls and Beechwood for the years 1958 and 1960. In this study, the unknown basin characteristics were determined by simulating the hydrographs for the year 1958. The values obtained were then used to calculate the hydrographs for the year 1960, which was selected because the records showed two pronounced flood peaks caused respectively by snowmelt, and by snowmelt and coincident rainfall. It was considered that reproduction of the 1960 flows would give a rigorous test of the validity and accuracy of the simulation.

4 - FLOOD FORECASTING FOR THE SAINT JOHN RIVER SPRING 1963

4.1 Procedures

Before the program was used for purposes of flood forecasting, a selection was made of the meteorological stations which could be used to provide day-by-day meteorological information for large sections of the drainage basin. A total of eight stations were selected, from which it was believed daily information could be most readily obtained. These stations, together with the sub-basins are shown on Figure 4.

The rainfall rates observed at these stations were assumed to represent adequately the average rainfall rate for each sub-basin. Only when general meteorological summaries indicated that this was not realistic, was data from a wider distribution of rain-gauging stations used to obtain a more accurate estimate.

For the other variables, the average values shown in Table II were used, with the exception that the wind velocity was adjusted when the observed or forecasted values exceeded the average by a significant amount.

TABLE II

| Type of Day | Radiation Langleys | Cloud Cover per Unit | Wind Velocity M.P.H. |
|------------------|--------------------|----------------------|----------------------|
| Bright and Sunny | 650-700 | Zero | 7 |
| Overcast | 500 | 0.5 | 7 |
| Rainy | N.A. | N.A. | 7 |

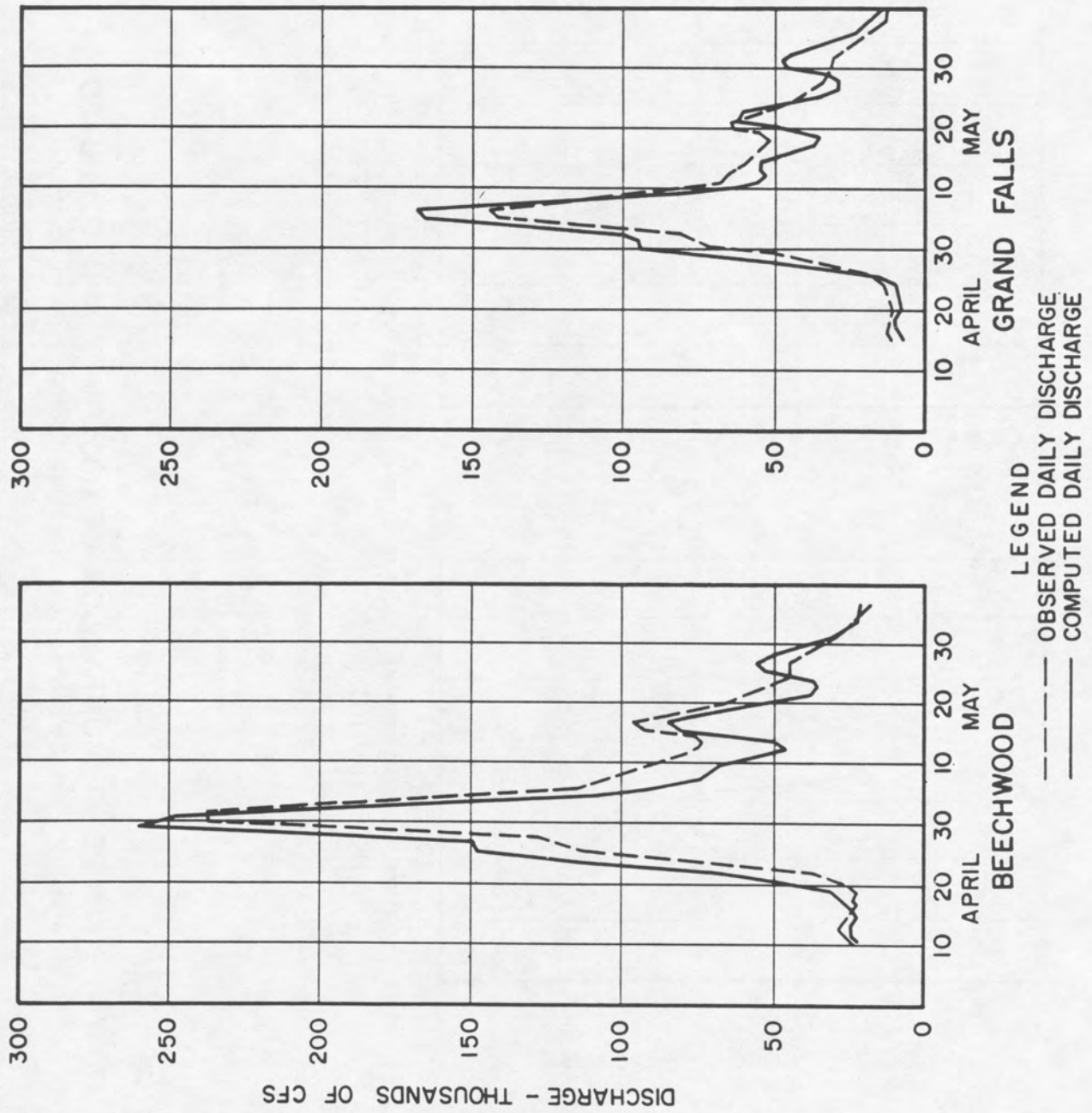
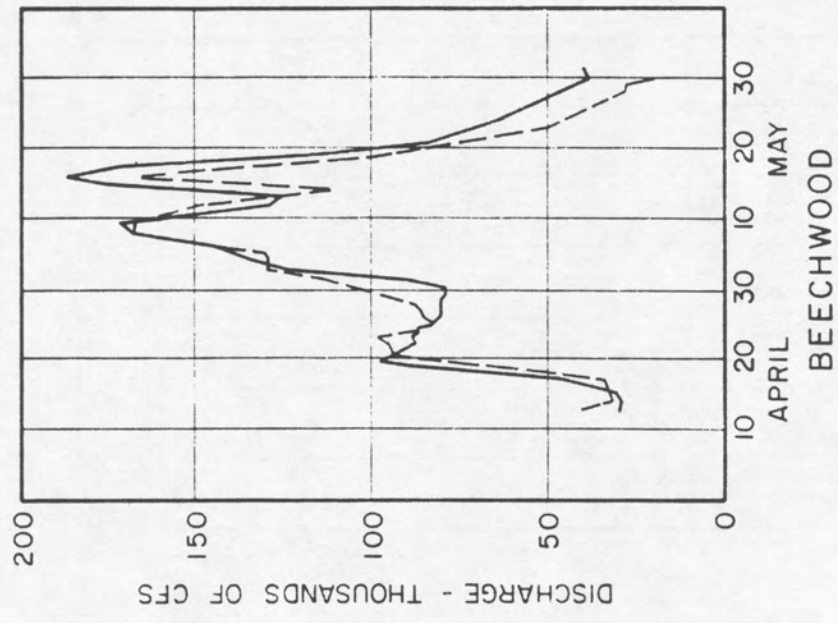
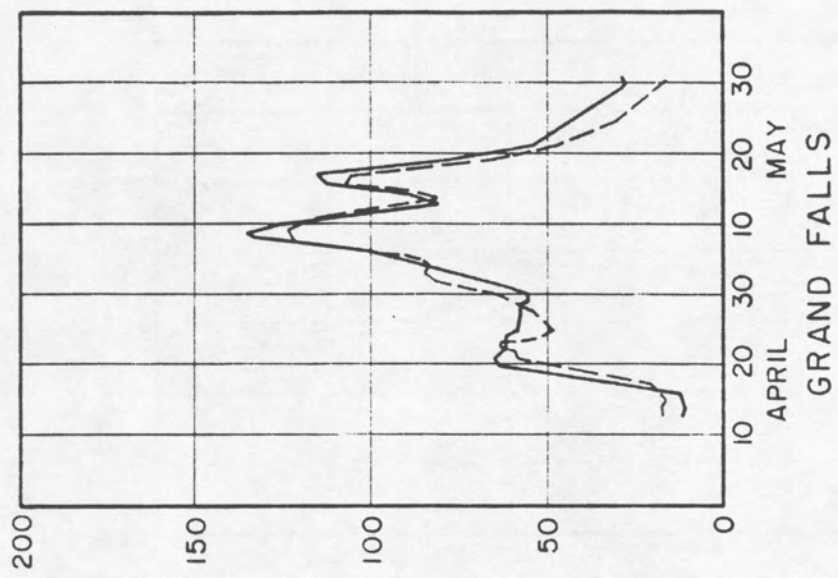


FIGURE 2 - COMPARISON OF OBSERVED AND COMPUTED SPRING FLOOD HYDROGRAPHS FOR 1958



LEGEND
 --- OBSERVED DAILY DISCHARGE
 - - - COMPUTED DAILY DISCHARGE

FIGURE 3 - COMPARISON OF OBSERVED AND COMPUTED SPRING FLOOD HYDROGRAPHS FOR 1960

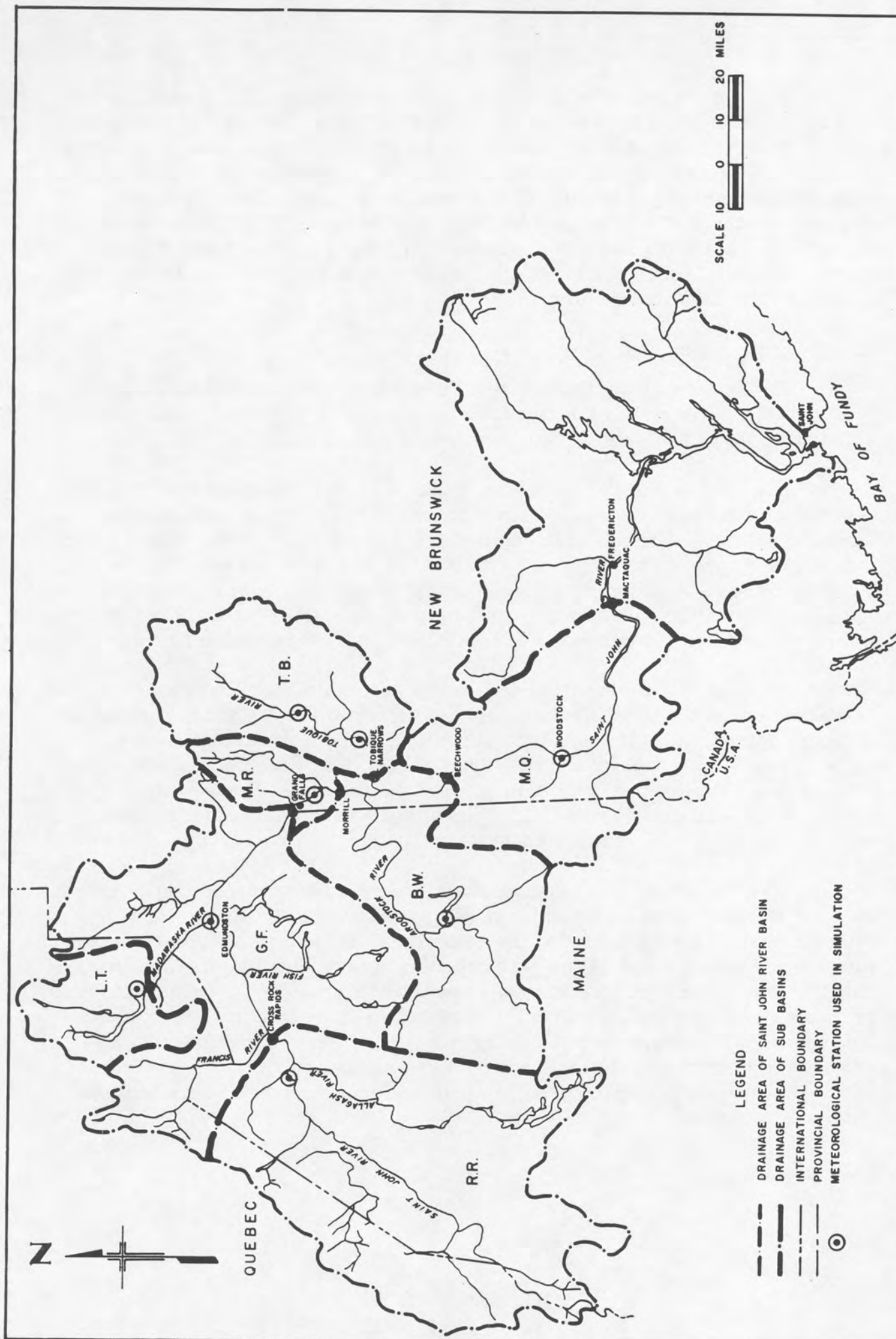


FIGURE 4 - SAINT JOHN RIVER DRAINAGE AREA SHOWING SUB-BASINS AND METEOROLOGICAL STATIONS USED IN SIMULATION OF 1963 SPRING FLOOD

In consultation with personnel of the Meteorological Branch, it was decided that the five-day weather forecast for the northern part of Maine, which is published three times per week, would be the most accurate indication of the expected weather conditions over the Saint John River basin. The computer simulation was run using this weather forecast, and the forecasted weather conditions were changed to the actual measured conditions as soon as these measurements became available. In this way it was possible to follow the river discharge prior to the forecast date and then predict the river discharge five days in advance.

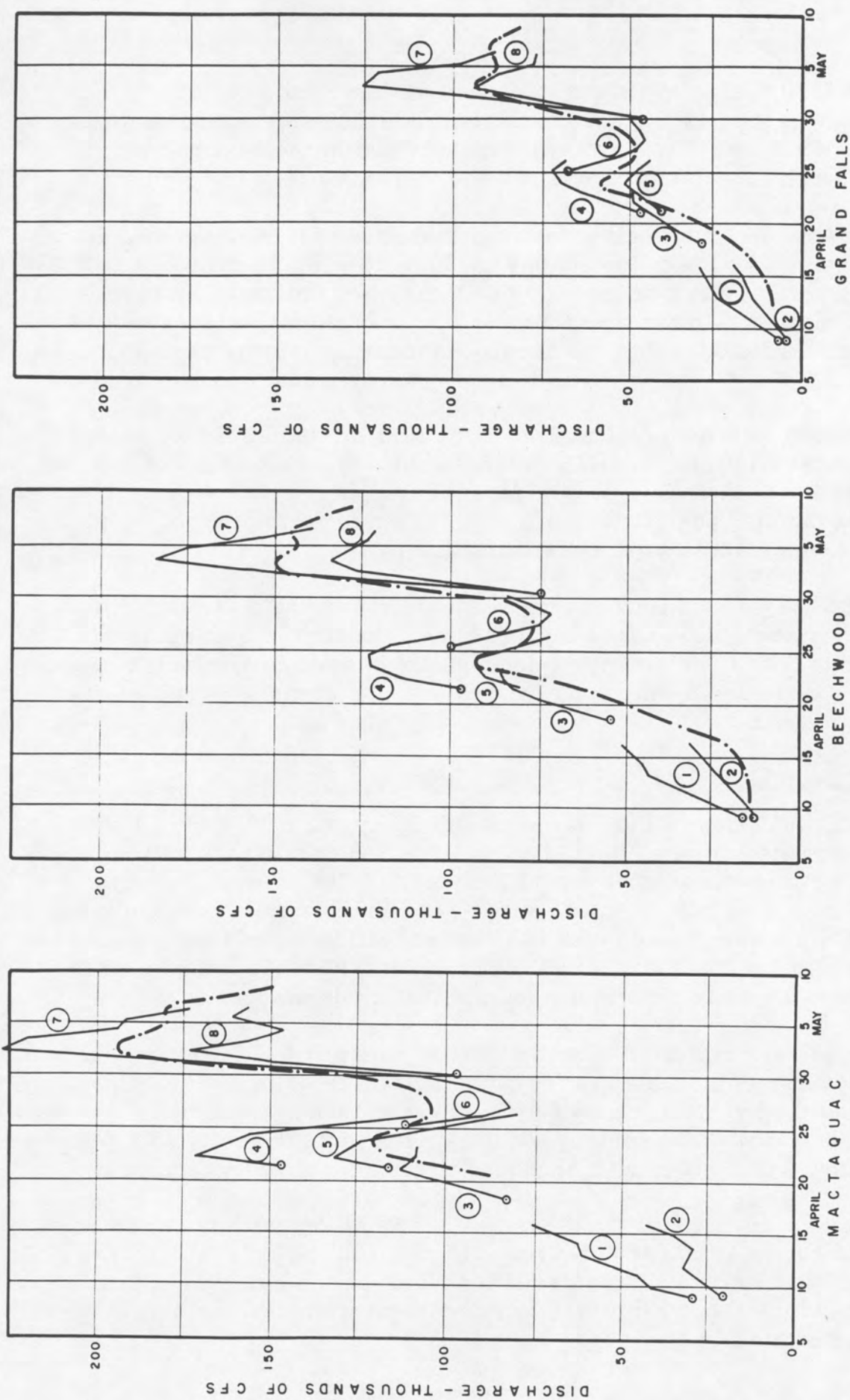
4.2 Description of Results

The results of the flood forecasting study are shown graphically on Plate 5. This plate shows the recorded hydrographs, together with the forecasted river flows at Grand Falls, Beechwood and Mactaquac.

The first forecast shown was made on April 9, when the temperatures over the Saint John River basin started to rise. The calculated river flows (1) increased sharply, whereas the recorded river flows were found to rise more gradually. This was thought to be attributable to underestimation of the infiltration losses. A new prediction (2) was therefore made at a later date, in which the infiltration losses were increased to more realistic values, resulting in a much better agreement between calculated and recorded flows.

On April 19, the weather forecast predicted rather heavy rainfall over the drainage area for the following days. The predicted (3) and recorded precipitation agreed very closely, both showing a sharp increase in river discharge. While the shape of the two hydrographs are very similar, the actual recorded flows occurred two days later than the predicted flows. This time lag during the initial melt period has been observed in all previous simulations and will be discussed in greater detail in the next paragraph.

On April 22, the weather forecast predicted more precipitation and a new river flow forecast was made. While precipitation did occur, it was not nearly as heavy as predicted; at the same time the drop in temperatures caused a substantial part of the precipitation to occur in the form of snow rather than rain. The first forecast (4) in which the predicted precipitation was assumed to occur in the form of rain, resulted in flows which were considerably higher than those recorded. Subsequently, a new prediction (5) was made in which most of the precipitation was assumed to occur in the form of snow. This new forecast resulted in a much closer agreement between predicted and recorded flows.



LEGEND
 —○— OBSERVED RIVERFLOWS
 - - -○- - - PREDICTED RIVERFLOWS
 BASED ON FIVE DAY WEATHER FORECASTS

FIGURE 5 -- COMPARISON OF OBSERVED AND PREDICTED RIVERFLOWS, SPRING 1963

On April 26, a new forecast (6) was made during a period when no precipitation was predicted. The calculated river flows were in general below the recorded flows. This, as will be explained in the next paragraph, is caused by the way in which channel storage is simulated in the program.

On April 29, the weather forecast indicated that heavy precipitation could be expected for the following days. Since it was anticipated that this would result in river flows of record proportions, two forecasts were made for two rates of rainfall. In the first forecast (7), the rainfall was assumed to be larger than predicted and in the second forecast (8), it was assumed to be smaller.

The two forecasts indicated that the flow at Mactaquac would increase to between 180,000 and 225,000 cfs with a probable value of 200,000 cfs, and that the peak discharge would be reached on May 3. As is shown on Plate I, the predicted peak flows were in close agreement with the recorded and the peak was reached on the predicted date.

After May 6, the flows continued to decrease and no further predictions were made. However, a number of additional computer runs were made after this date in an attempt to improve the overall comparison between computed and observed hydrographs, and to examine areas of less satisfactory agreement.

4.3 Discussion of Results

A careful study of the 1963 spring flood hydrograph, and of the associated hydrometeorological data, has indicated one or two anomalies in the simulation, which were to some extent also found to be evident in the reconstituted hydrographs of 1958, 1960, and 1937, which were used to prove the program. While these inaccuracies in no way invalidate the effectiveness of the basic simulation, they constitute areas within which the forecasting of daily river discharges become less accurate than is desirable.

It has been indicated that the rates of rise and fall of river discharge have been accurately simulated in the program, and there has been no problem in reproducing the hydrograph peaks. The troughs of the hydrograph, however, are less satisfactorily represented, with the simulation generally showing decreases in flow which are more pronounced than those actually recorded.

The second difficulty that has been encountered with the flood studies is the accurate simulation of runoff due to precipitation in the early part of the melt period. Although this has little effect on the hydrograph peaks, it, too, creates difficulties when trying to forecast river discharges during the initial stages of the flood.

Discharge-Storage Relationship

The rate and extent to which changes in meteorological conditions are reflected in the discharge of the river, depend to a large degree on the inflow and outflow characteristics of the storage volumes which are contained in the channels and lakes of the watershed. The hydrographs shown on Plates 2 and 3 indicate that close agreement in timing between the peaks and troughs has been achieved in the simulation, and since the slopes and location of the rising and falling limbs of the hydrograph have also been satisfactorily reproduced, there is no reason to doubt the general accuracy of the storage characteristics provided for each part of the basin in the simulation. However, it is evident that at the end of each period of flow recession the computed discharge falls appreciably below those observed in the river.

In the light of the various trial and error studies which were made to produce an accurate simulation, it is believed that this discrepancy is due to the fact that in the program used for the flood forecasting, all storages were treated as level storage reservoirs for which an unique relationship exists between storage and outflow. In actual fact, a large percentage of the storages can be classified as valley storages for which the outflow depends both on the storage and the inflow. The result of this over-simplification is that the rising limb of the hydrographs is overestimated relative to the mean discharge, while the falling limb underestimated. Examination of the reconstituted hydrographs indicates that this phenomenon has indeed taken place. Furthermore, since this effect could be experienced over any range of discharges, it is apparent that, at present, the simulation is oriented towards accurate reproduction of the hydrograph peaks, thus causing a greater discrepancy at times of lower discharge.

Unfortunately, the accurate determination of the true storage characteristic, when the type of condition described above occurs, is not easily accomplished. Basically it involves obtaining independent estimates of river discharge, during both rising and falling conditions, such that true stage-discharge relationships can be obtained. Since the recorded discharges for a river are related directly to a single rating curve, the normal flow records are not suitable for this type of determination. The alternatives are either, to undertake a series of independent gauge measurements for various stages of the river at each end of the reach in question or, to carry out trial and error investigations using average records, until sufficiently accurate reconstitution of recorded hydrographs can be achieved.

Infiltration

During dry periods the discharge from a river basin is derived from the storage of water in the ground. The longer the dry period, the greater the storage depletion and, consequently, the greater the percolation of water into the ground during subsequent periods of precipitation.

Since the major portion of the precipitation, during the winter months, occurs as snow in the Saint John River basin, substantial depletion of the ground water storage has taken place by the time the melt season arrives. The volume of the initial infiltration "losses" depends on the extent of the depletion, predetermination of which is necessary if accurate forecasting is to be achieved. A measure of the infiltration volume can be obtained by computing a water balance for the winter period, taking into account the runoff from the watershed, the losses by evapotranspiration, and the difference between total average precipitation and accumulated average snowpack water equivalent. Prediction of the time distribution of the initial infiltration loss however, is not easily achieved and requires further study.

In the forecasting procedure carried out during the spring of 1963, the total volume of runoff at each station for various intervals during the early part of the season was calculated subsequent to the event, so that the correct volumes of water excess could be used as input data. Rainfall in excess of this volume was assumed to occur as snowfall, and while this is a reasonable assumption it was realized that a certain amount of this water was contributing to the build-up of the groundwater storage.

It seems probable that a device such as this can be used as a satisfactory procedure during the early part of most flood seasons, since the filling of the depleted storage is normally complete as a result of rainfall well in advance of the period of peak melt runoff. It is possible, however, that if the early part of the melt season was unusually dry, and the temperature rise was quite sharp, a substantial portion of the initial melt would be "lost" to infiltration, with the result that the forecasts of runoff would be too high. Development of an antecedent index of groundwater depletion as described above would greatly reduce the work load of the forecaster during the initial stages of the flood season, and contribute materially to the improvement of the simulation and the better understanding of the hydrology of the river basin.

TABLE I
SNOWMELT FORMULAE

A - Snowmelt During Dry Periods

- (i) - Heavily Forested Areas (80% - 100%)

$$M = 0.074 (0.53T_a + 0.47T_d)$$
- (ii) - Medium Forested Areas (60% - 80%)

$$M = 0.0084 KV (0.22T_a + 0.78T_d) + 0.029T_a$$
- (iii) - Partly Forested Areas (25% - 60%)

$$M = 0.0040 K (1-a) I_1 (1-F) + 0.029 T_a F + 0.0084 KV (0.22T_a + 0.78T_d)$$
- (iv) - Open Areas (0 - 25%)

$$M = 0.0051 K (1-a) I_1 + 0.029N (T_a - 5) + 0.0084 KV (0.22T_a + 0.78T_d) + (1-N) (0.022T_a - 0.84)$$

B - Snowmelt During Rainfall Periods

- (i) - Forested to Heavily Forested Areas (60% - 100%)

$$M = T_a (0.007r + 0.074) + 0.05 (2-F)$$
- (ii) - Open to Lightly Forested Area (0-60%)

$$M = T_a (0.0084 KV + 0.007r + 0.029) + 0.05 (2-F)$$

Reference: "Application of Snow Hydrology to the Columbia Basin", Johnson and Boyer, J.A.S.C.E. - Hydraulics Division - Vol. 85, January 1959.

LEGEND

| <u>Symbol</u> | <u>Units</u> | <u>Designation</u> |
|----------------|-----------------|--|
| M | Inches of Water | Potential Snowmelt |
| T _a | °F | Air Temperature Minus 32 |
| T _d | °F | Dew Point Temperature Minus 32 |
| K | - | Basin Convection - Condensation Melt Factor |
| V | Mph | Wind Velocity |
| K/ | - | Shortwave Radiation Melt Factor |
| F | Per Unit | Effective Forest Cover |
| a | Per Unit | Albedo of Snow Surface |
| I _i | Langleys | Incident Shortwave Radiation |
| N | Per Unit | Cloud Cover |
| r | Inches of Water | Rainfall |