FLOOD CONTROL SIMULATION FOR FRASER RIVER BASIN

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CONTENTS

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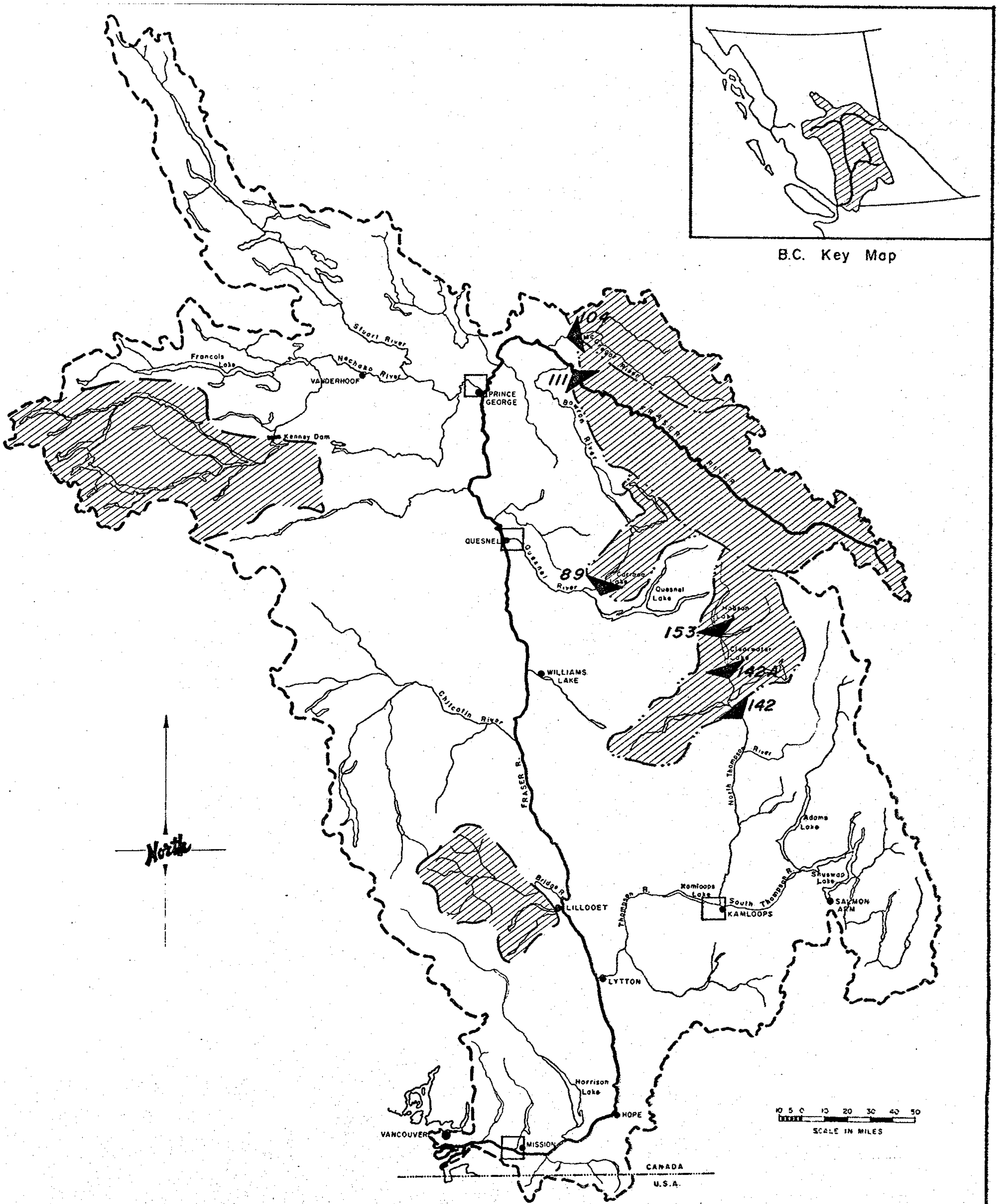
INTRODUCTION

The Fraser River is the largest and most important river in the province of British Columbia. Its basin covers an area of 90,000 square miles or about a quarter of the province (see Figure 1). The mountain and plateau areas of the basin accumulate vast amounts of snow each winter. It is this accumulated snow which constitutes the major flood threats to the centre of population, farming and industry in the Lower Fraser Valley during the snowmelt period. The lessons provided by the historical floods have hastened a joint effort by federal and provincial agencies in exploring effective flood control measures. As a result of the study carried out previously by the Fraser River Board, a system of upstream reservoirs, referred to as "System E Projects" (see Figure 1), was proposed as one alternative of flood control which would also contribute hydroelectric power with minimum environmental damage.

The nature of this study was to evaluate the flood control effectiveness and the economics of System E projects. The flood control evaluation can be measured by the reductions of flood damages, or "flood control benefits", at various magnitudes of floods. To measure the flood peak reduction, it requires a simulation study for the proposed projects which would operate for flood control under the condition comparable to that under the real-time condition. A real-time flood control operation usually involves the forecasts of freshet runoff volume, target regulated level and expected daily inflow. The operation takes into consideration the uncertainties under the forecast conditions. This approach was adopted in the studies carried out previously for the Columbia River system by the U.S. Corps of Engineers although the procedures used were different from those used in this study.

The regulated peak flows at flood damage centres were obtained through the simulation studies carried out for a number of study years and for various combinations of the proposed projects. The peak flows were used to produce flood-frequency curves representing the effects of flood regulations under the operation of the proposed developments. These flood-frequency curves were then integrated with stage-discharge curves and stage-damage curves to produce the average damage to be expected over a given period of time under each alternative development in the basin.

The purpose of this paper is to present the procedures developed for the Fraser River flood control simulations under the real-time condition. These procedures are summarized and described under the categories of long-term forecasts, short-term forecasts and flood control simulations which are introduced in the paper in that order.



LEGEND

- Power and Storage Sites
- Sub-Basin
- Developed Sub-Basin
- Fraser River Basin
- Gauging Stations located in Flood Damage Center

INDEX

SITE		SUB-BASINS
111	GRAND CANYON	UPPER FRASER BASIN
104	LOWER McGREGOR	McGREGOR RIVER
89	CARIBOO FALLS	CARIBOO RIVER
153	HOBSON LAKE	CLEARWATER RIVER
142A	CLEARWATER – AZURE	CLEARWATER RIVER
142	HEMP CREEK	CLEARWATER RIVER

FIGURE I – LOCATION OF PROPOSED SYSTEM E PROJECTS AND FLOOD DAMAGE CENTERS

LONG-TERM FORECASTS

For Fraser River flood control studies, long-term forecasts consist of two components. Firstly, a forecast of total freshet runoff volume is essential for reservoir operations. Secondly, an estimate of the critical hydrograph is needed for daily scheduling of the usage of flood control storage. The critical hydrograph is the hydrograph that would result if the "critical" melt conditions were to occur during the remainder of the freshet.

Freshet runoff volume forecast is a useful indicator for incoming flood potential, and based upon it the required flood control space is scheduled and an orderly evacuation followed prior to the freshet. Freshet runoff volume forecast referred to herein is the total runoff volume forecast from 1 April to 30 September. The residual runoff volume forecast is computed by subtracting the accumulated runoff volume after 1 April from the total runoff volume forecast. The residual runoff volume forecast provides the basis for day-to-day estimation of the critical hydrograph. The residual runoff volume forecast is also used to assure that the reservoir can be refilled by a given target date for the purposes of recreation, water supply and power production. The B.C. Water Resources Service makes the forecasts available each year prior to the freshet. The forecast is based on the accumulated snow in the basins throughout the winter and average rainfall conditions for the freshet period.

There are two purposes for estimating the critical hydrograph; assessment of the possible flood peak at the flood damage centre if a critical melt pattern persists, and the estimation of a target regulated level at the flood damage centre with the best use of available upstream reservoir storage. For these studies, the Lower Fraser Valley is considered as the major flood damage centre and the levels at the town of Mission are used as the flood control target.

A critical hydrograph was estimated at the flood control centre. It is a "conceptual" hydrograph which represents the time distribution of the freshet runoff volume. The shape parameters of the critical hydrograph were derived from a major historical flood in which warm weather persisted throughout the snowmelt period to produce a steeply rising runoff pattern. When this shape is fitted to the remaining volume forecast, an estimate of worst expectancy is obtained comparable to that which would be obtained with more detail modelling using a critical weather sequence.

The critical hydrograph is defined by a series of straight lines rising to and falling from a single peak and fitting a base flow recession curve falling to a fixed point at the end of September as shown in Figure 2. The requirements for defining a predicted hydrograph are that total runoff volume, or sum of volumes 1, 2, 3, 4 and 5, under the predicted hydrograph should equal the residual runoff volume forecast, that the slopes for all straight lines are known, that the relative magnitudes of points BI and C in terms of B are defined from the critical hydrograph shape and that point E is the average flow on September 30. With known flow at point A and beginning and ending dates, the positions of the other points can be defined by solving a group of simultaneous equations which express the geometric relationships among flows, dates, slopes and volumes. With the aid of a computer, it appears that an approximate solution obtained through an iterative process is more favourable than solving simultaneous equations.

The day-to-day prediction of the target regulated level at the

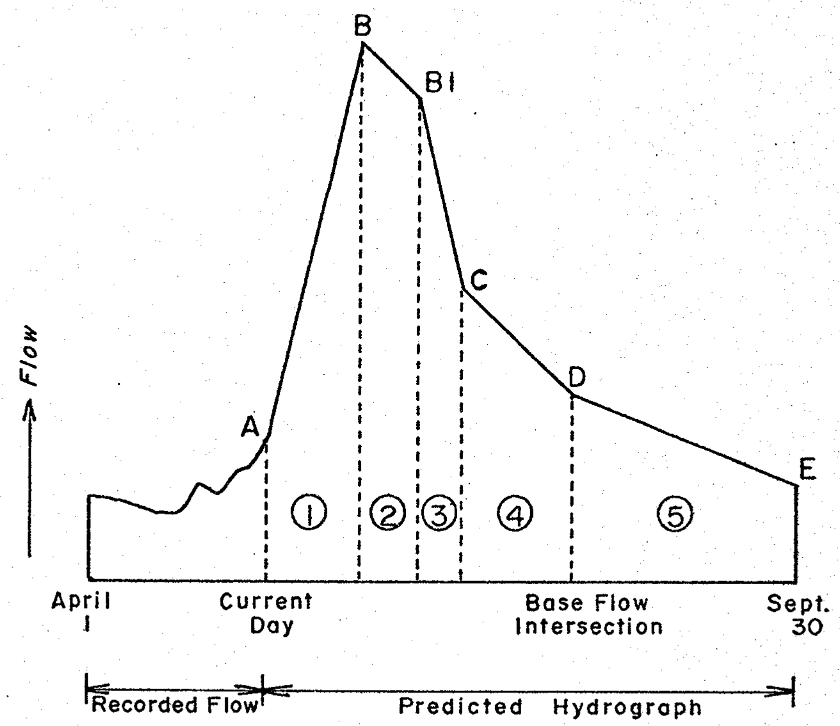


Figure 2 - Representative Critical Hydrograph for a Particular Day

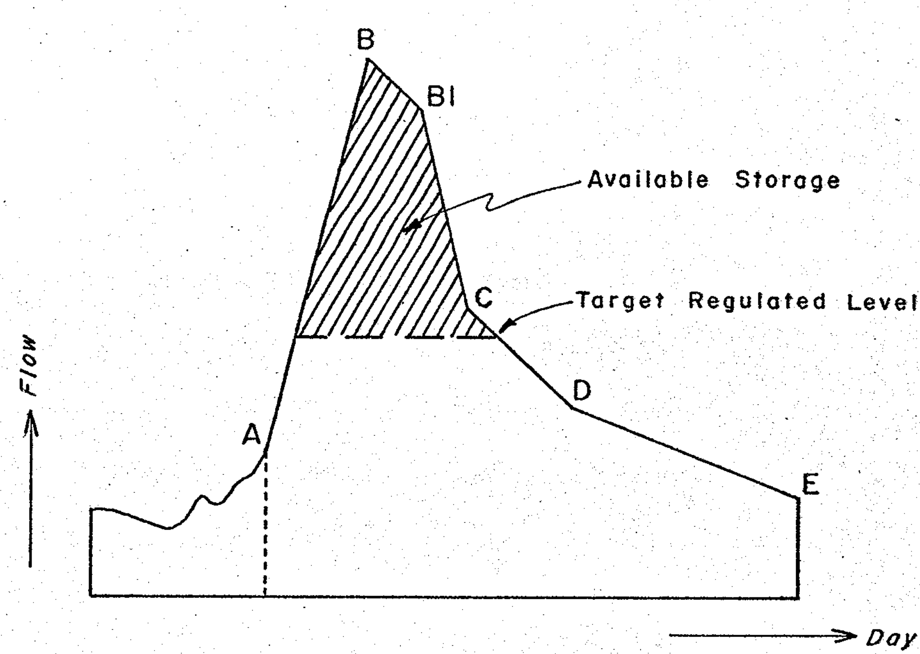


Figure 3 - Estimation of Target Regulated Level

flood damage centre is necessary in order to schedule the amount of holdout for the reservoir system. This is based on the assumption that a hypothetical reservoir having an available storage equivalent to that of the actual reservoir system is located immediately upstream of the flood damage centre so as to regulate the flood level effectively. With this effective regulation and the assumption that the predicted hydrograph would be realized, a target regulated level is computed by fitting the available storage into the upper portion of the predicted hydrograph as shown in Figure 3. Again, an iterative solution was adopted to compute target regulated level by adjusting the level upward or downward with the computed volume enclosed by the predicted hydrograph and target level approximately equalling available storage. Holdout at the reservoir commences once the forecast flow at the flood damage centre exceeds the current target regulated level.

The prediction of the critical hydrograph and target regulated level is dynamic in that it is computed each day throughout the freshet, as shown in Figure 4. As the season progresses, the residual volume forecast is revised each day to account for runoff that has already occurred during the freshet. Although the critical hydrograph shape factors remain constant in the day-to-day computations, the predicted critical hydrograph changes in magnitude according to the residual volume forecast. The target regulated level is also revised each day as the new predicted hydrograph and available storage are computed. The target regulated level adjusts itself and aims at preventing reservoirs from filling too soon as long as a flood threat exists. The actual holdouts are apportioned to upstream reservoirs according to the scheduled holdout at the hypothetic reservoir with the consideration of routing time lags.

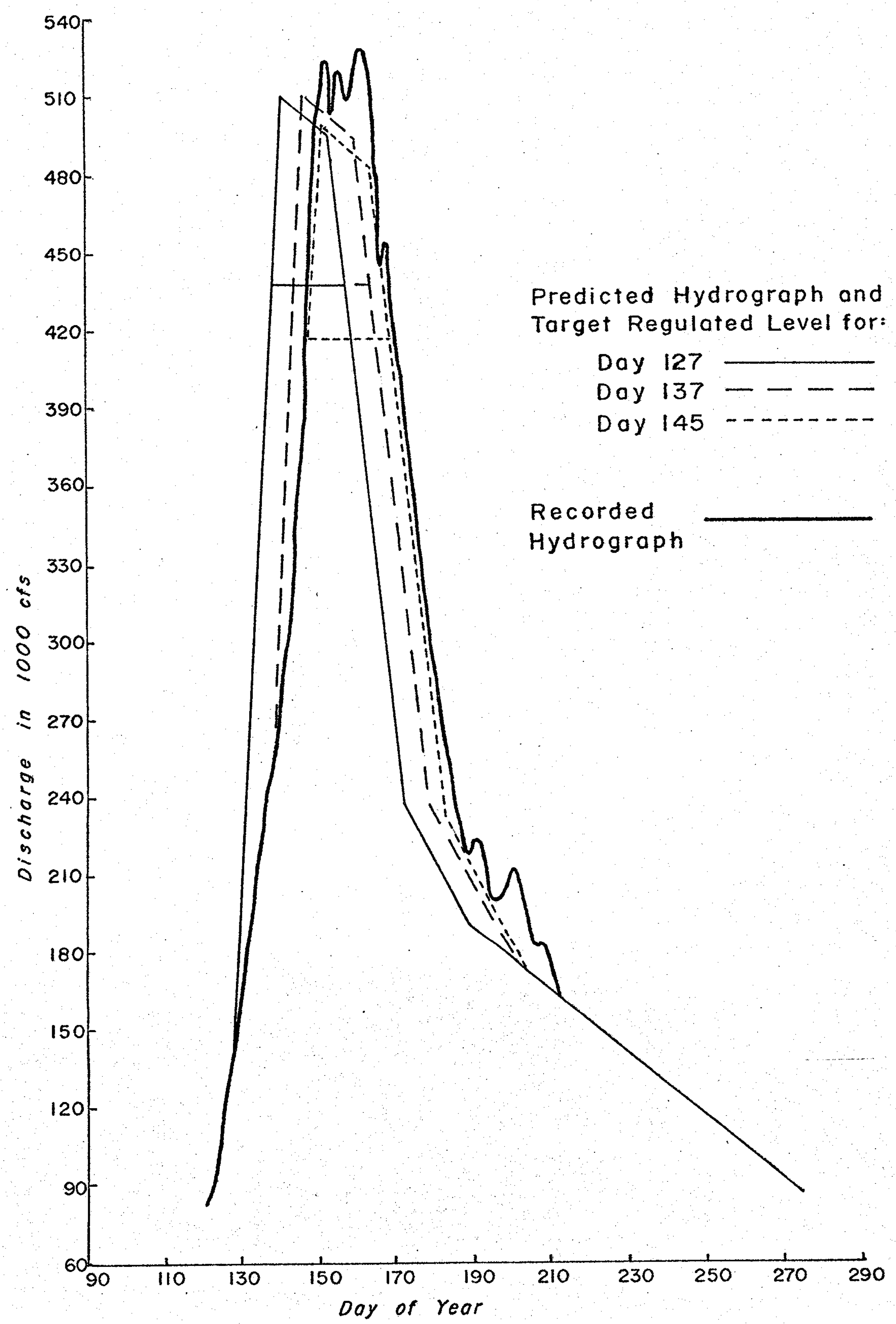


Figure 4 - Day-to-day Predictions of Critical Hydrograph and Target Regulated Level

SHORT-TERM FORECASTS

The short-term forecast referred to herein is the day-to-day forecast of streamflow at the flood damage centre. As described previously, the amount of scheduled holdout is entirely dependent on forecasted flow and target regulated level at the flood damage centre. An over-forecast at an early stage of the freshet could consume the flood control storage unnecessarily and sometimes cause the shortage of available storage for effective flood control during the peak period. In contrast, an under-forecast during the peak period could result in the unexpected flooding downstream and possibly the loss of human life and assets. Therefore the short-term forecast is the key for day-to-day reservoir operation.

The proposed reservoir sites for the Fraser system are located far upstream from the major flood damage area in the Lower Fraser Valley and the effect of changes in flows at the reservoir sites do not reach the lower valley until three to four days later. Because of this time lag between the action of storing at the reservoirs and its effect in the lower valley, any decision to store water for flood control purposes at the reservoir must be made in anticipation of flows three to four days later in the lower valley. The consideration of this time lag makes the use of short-term forecasts necessary in day-to-day scheduling of reservoir holdouts. Normally the short-term forecasts require a comprehensive approach. A comprehensive streamflow forecast technique requires meteorologic data, physiographic data and streamflow data as input. However, for these studies, there was inadequate information available to carry out a comprehensive streamflow forecasting and an empirical method of simulating real-time forecasts was derived based only on available current streamflow information.

The method used in streamflow forecasting involved the selection of a set of key stations and local inflows, producing one through four-day forecasts for each of these stations. Using past flow information, the forecasted flow at flood damage centres is calculated by routing and summing the recorded and forecasted flow from each of the upstream points. The method was tuned to gain the best possible coincidence of the forecast hydrograph with the recorded at all points while at the same time meeting certain specific requirements. These were that the forecast should not be significantly low for any length of time, that it should not be significantly high for any length of time prior to the peak, and that peaks and valleys of the hydrograph should be forecasted with as little delay as possible. The first condition is to prevent under-estimating the flood damages, within the four-day period and thus operating the reservoirs too late. The second is to prevent unnecessarily using up storage prior to the peak. The last is to be sure to store early enough when a steep rise is preceded by a fall.

Examination of plots of the hydrographs at the key stations indicated that forecasts could be made by extrapolating the hydrograph on the basis of slope and curvature. The slope is computed by subtracting previous day flow from current day flow. The curvature is the difference of slopes for the current day and the previous day. The forecasts are made by analyzing four possible combinations of slopes and curvatures:

(1) Negative curvature and positive slope,

(2) Negative curvature and negative slope,

(3) Positive curvature and positive slope,

(4) Positive curvature and negative slope.

For each of these situations, a separate method is used to extend the hydrograph forward so as to produce a forecast of flows for a four-day period. The forecast algorithm was derived empirically and may vary from station to station. The underlying principle in creating the algorithm was that forecasts should always simulate the worst flow condition that would occur during the forecast period. The forecast method described herein was developed through a number of tests in which the parameters used were calibrated to give a workable forecast for use in flood control regulations.

FLOOD CONTROL SIMULATIONS

A flood control simulation model was developed and operated for the Fraser River Basin on a day-to-day basis. The simulations have been based on reservoir operating rules that would be similar to the rules used under actual operation. The rules reserve most of the storage until the flood threat is greatest, then allocate the storages at all reservoirs to produce the largest possible reduction in the flood peak that could reasonably be expected. Some storage space is maintained as long as any appreciable flood threat remains. In real-time operation of such reservoirs the only prior knowledge of the flood peak would be forecast information and this must be the basis of operating rules. Although recorded streamflow data have been used to test the effect of reservoirs, the simulation procedures have assumed no prior knowledge of these streamflows. All decisions within the simulations are made using only recorded flows from the current day and prior days and simulated forecasts of subsequent days and expected seasonal runoff volumes.

The simulation model has been applied to freshet flows for each year in the study period. The model operates mainly for flood control purpose on a day-to-day basis. A descriptive skeleton flow chart for the simulation model is shown in Figure 5. It should be noted that although the day-to-day streamflow flow forecasts could have been included in the simulation model, it was computed separately prior to the simulation and used as if it were a real-time forecast. This setup was done in order to minimize the complication of the model and improve the efficiency of computer runs yet maintain its original objective. Some features of the model are described in the following sections.

Reservoir Linkages

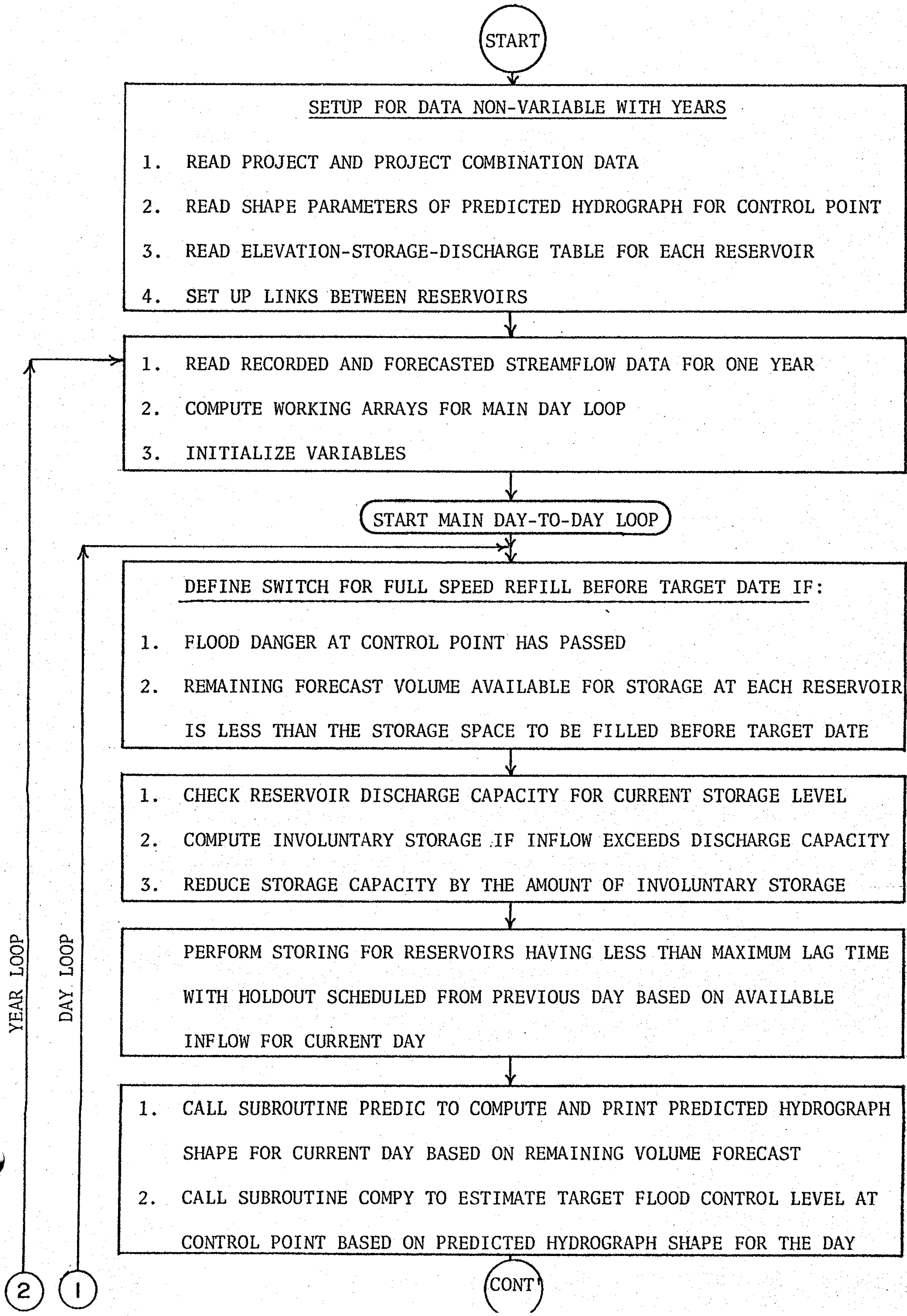
The linkages between reservoirs in a project combination were defined by the computer program based on the order the input data for each project was read. At each project any upstream and downstream reservoirs were specified by their code names. The names were converted to sequential numbers of the projects and this set of numbers were then referred to by the computer in the computations of local inflows and local volume forecasts. Local inflow was computed as the difference between the natural inflow at the project under consideration and that at the upstream project or projects. Similarly, the local inflow volume forecast was computed as the difference between volume forecast at the project under consideration and that at the upstream project or projects.

Involuntary Storage

Involuntary storage is a significant factor in the effectiveness of small flood control reservoirs. It occurs when the outflow capacity is less than the inflow rate prior to the flood period and the reservoir is forced to store water early thereby reducing the storage available for flood control. The computation of involuntary storage is included in the simulation model for the sake of completeness although it was later found that for this study only a small amount of involuntary storage occurred in a few years and had no significant effect on the flood control results.

Determination of Target Regulated Level

As described previously under "LONG-TERM FORECAST", determination of the target regulated level at a flood damage centre is necessary for scheduling day-to-day usage of upstream reservoir storage. The target regulated level is based on available upstream storage and the predicted


START
SETUP FOR DATA NON-VARIABLE WITH YEARS
1. READ PROJECT AND PROJECT COMBINATION DATA
2. READ SHAPE PARAMETERS OF PREDICTED HYDROGRAPH FOR CONTROL POINT
3. READ ELEVATION-STORAGE-DISCHARGE TABLE FOR EACH RESERVOIR
4. SET UP LINKS BETWEEN RESERVOIRS
1. READ RECORDED AND FORECASTED STREAMFLOW DATA FOR ONE YEAR
2. COMPUTE WORKING ARRAYS FOR MAIN DAY LOOP
3. INITIALIZE VARIABLES
START MAIN DAY-TO-DAY LOOP
DEFINE SWITCH FOR FULL SPEED REFILL BEFORE TARGET DATE IF:
1. FLOOD DANGER AT CONTROL POINT HAS PASSED
2. REMAINING FORECAST VOLUME AVAILABLE FOR STORAGE AT EACH RESERVOIR IS LESS THAN THE STORAGE SPACE TO BE FILLED BEFORE TARGET DATE
1. CHECK RESERVOIR DISCHARGE CAPACITY FOR CURRENT STORAGE LEVEL
2. COMPUTE INVOLUNTARY STORAGE IF INFLOW EXCEEDS DISCHARGE CAPACITY
3. REDUCE STORAGE CAPACITY BY THE AMOUNT OF INVOLUNTARY STORAGE
PERFORM STORING FOR RESERVOIRS HAVING LESS THAN MAXIMUM LAG TIME WITH HOLDOUT SCHEDULED FROM PREVIOUS DAY BASED ON AVAILABLE INFLOW FOR CURRENT DAY
1. CALL SUBROUTINE PREDIC TO COMPUTE AND PRINT PREDICTED HYDROGRAPH SHAPE FOR CURRENT DAY BASED ON REMAINING VOLUME FORECAST
2. CALL SUBROUTINE COMPY TO ESTIMATE TARGET FLOOD CONTROL LEVEL AT CONTROL POINT BASED ON PREDICTED HYDROGRAPH SHAPE FOR THE DAY
YEAR LOOP
DAY LOOP
2
1
CONT'

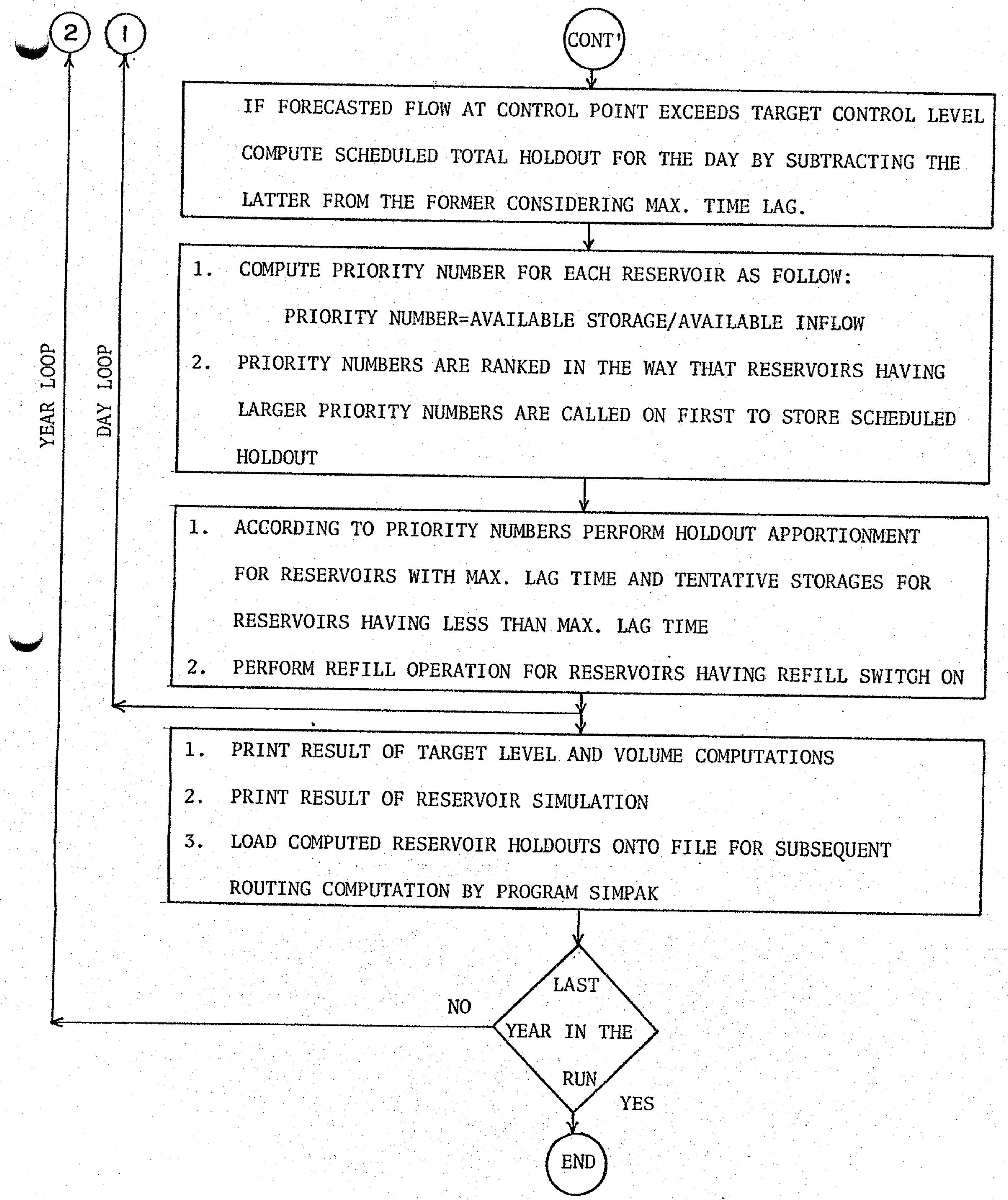


Figure 5 - Skeleton Flow Chart for Flood Control Simulation Model

hydrograph. The predicted hydrograph is in turn based on the volume forecast. Subroutine PREDIC is called to compute the predicted hydrograph for the current day based on remaining volume forecast. Subroutine COMPY is then used to estimate target regulated level based on the predicted hydrograph from output of subroutine PREDIC. This target level was constrained in the way that once the usage of flood control storage has begun it can not move downward. This is based on the belief that once a given flood level occurred there would be little use in regulating to a lower level and that it would be preferable to reserve as much storage as possible to protect against a larger subsequent peak.

Reservoir Storing Priorities

For the Fraser River studies, flood control schemes considered include reservoir storage for flood control and diversion of river flows to other basins. Both methods are effective in reducing peak flows at the flood damage centre but in slightly different ways.

A total diversion of a river provides the most effective flood control because the total flow of the river, excepting the minimum required release for local needs, can be diverted at all times. This flow is removed from the system for the whole of the freshet period, and thus reduces the flow in the main river authomatically without any need for detailed flow forecasts and holdout schedules.

Reservoirs, however, are limited in volume and usually cannot store all the inflow during the whole freshet period. In this case, it is necessary to ration the use of limited reservoir storage to the most opportune time for reducing the flood peak. It is, therefore, necessary to make decisions regarding the best times and best locations to store water.

Usually, a reservoir storage that is small relative to the inflow volume requires careful use of storage while reservoirs that have relatively larger storages are more flexible in operation. It is based on this concept that a priority number representing storage sequence for each reservoir in the system is computed as follows:

$$\text{Priority Number} = \frac{\text{Remaining Storage Volume}}{\text{Remaining Volume Forecast}}$$

The priority numbers are computed each day and ranked in such a way that reservoirs with higher priority numbers are scheduled for storage first.

<u>Holdout Scheduling and Apportionment</u>

Holdout for flood control purpose was scheduled each day at the flood control centre and apportioned to upstream reservoirs according to priority numbers. This procedure accounts for the time lag between reservoirs and the flood control centre. Holdouts are scheduled once the daily forecasted flow exceeds target regulated level and the amount of scheduled holdout is computed by subtracting the latter from the former. The actual day-to-day holdout at each reservoir is apportioned in order of decreasing priority number as given in the following steps.

1. If reservoir inflow for current day is large enough to meet holdout requirement, set the holdout at the reservoir equal to scheduled holdout for that day and reduce volume available at the reservoir.

2. If reservoir inflow for current day is not large enough to meet holdout requirement, set the holdout at reservoir for that day as inflow minus minimum release, then reduce volume available at the reservoir and the holdout requirement by the amount stored at the reservoir.

3. If the holdout requirement has not been met totally, repeat steps 1 and 2 with the reservoir having the next higher priority number.

4. For reservoirs having time lag one day less than the maximum time lag, the scheduled holdouts at the reservoirs are tentative and have to be adjusted according to the inflow for next day.

As far as flood peak reduction is concerned, a reservoir having larger storage in relation to inflow volume is normally limited by the rate of inflow past the reservoir site while a reservoir having smaller storage in relation to inflow volume is normally limited by its storage capacity. With larger floods this storage capacity becomes more critical.

<u>Holdout Routing</u>

The proposed reservoir sites for the Fraser River system are a long distance upstream from the major flood damage area in the Lower Fraser Valley and the flood routing effect will be significant in determining the flood flow reduction in the area. The flood routing effect can be considered as consisting of the lag effect and the smoothing effect. The lag between the action of storage at reservoirs and its effect in the lower valley plays an important role in flood regulations for the reason that the effect of changes in flows at the reservoir sites do not reach the lower valley until three or four days later. The smoothing effect usually reduces the peak flow somewhat and does tend to compensate for the lack of precision in forecasts.

The detailed routing procedures were not included in the simulation model because it was felt that the routing could be handled separately after completion of the simulation with almost the same degree of accuracy maintained. The intention was to reduce the complication of the model because the problem could be compounded if considering back routing of scheduled holdout from control point to reservoir sites. In the simulation procedures, a simple time lag was assumed without the consideration of the smoothing effect. For example, a scheduled holdout in the amount of 10,000 cfs at the control point for day 10 is apportioned to a reservoir considered having a 4-day time lag, the actual storage at the reservoir is performed on day 6 in the amount of 10,000 cfs if there is enough inflow. The day-to-day reservoir holdouts are loaded onto a computer file and retrieved subsequently by program SIMPAK which performs a more detailed routing of the holdouts downstream to the control point. The regulated flows at the control point are then computed by subtracting routed holdouts from preproject flows.

EXAMPLES

Two examples showing the results of flood control simulations with the application of the methods described herein are given in Figures 6 and 7. Computer runs were carried out for the period 1 May to 31 July for a typical flood year of 1948 for two different levels of development in the basin. The first one includes only one reservoir located at Grand Canyon while the second includes six flood control developments comprising the proposed "System E" developments. In these examples, the objective was to regulate the flood level at the major damage centre as measured at the Mission gauge.

Figure 6 shows regulated and unregulated hydrographs for the Grand Canyon reservoir site and for the Fraser River at Mission under the condition of single reservoir regulation. The Grand Canyon reservoir has a storage capacity of 1,960 thousand acre-feet and a required minimum release of 1,800 cfs. The storage capacity is small relative to its freshet inflow volume and the flood control effect is usually limited by its storage capacity. As can be seen from the Mission regulated hydrograph, there is a late rising on 14 June at 488,000 cfs due to the shortage of storage capacity. The best regulation could have been achieved and the peak reduced from 528,000 cfs to 477,000 cfs (on 10 June) by storing all reservoir inflow except the minimum release if there had been enough storage to subdue the late rising or if there were more accurate forecasts to avoid unnecessary early storing.

Figure 7 shows regulated and unregulated hydrographs at Mission with all System E projects in combined operation for flood regulation and the corresponding hydrograph at each project site. The Lower McGregor project is a diversion scheme in this example and diverted all the water except minimum release of 1,000 cfs as shown in the hydrograph. The reservoirs with large storage capacity relative to their freshet inflow volumes, such as Cariboo Falls and Hobson Lake, store the water in a way similar to regulation by a diversion scheme. In contrast, the reservoirs that are small relative to their inflow, such as Grand Canyon and Hemp Creek, have the crucial flood control storage. An examination of the simulation output reveals that the two highest regulated peaks at 407,000 cfs and 396,000 cfs occurred corresponding to the times when Grand Canyon and Hemp Creek run out of storage. However, optimum regulation could reduce the unregulated peak from 528,000 cfs to 392,000 cfs which can be seen as the third peak on the Mission regulated hydrograph.

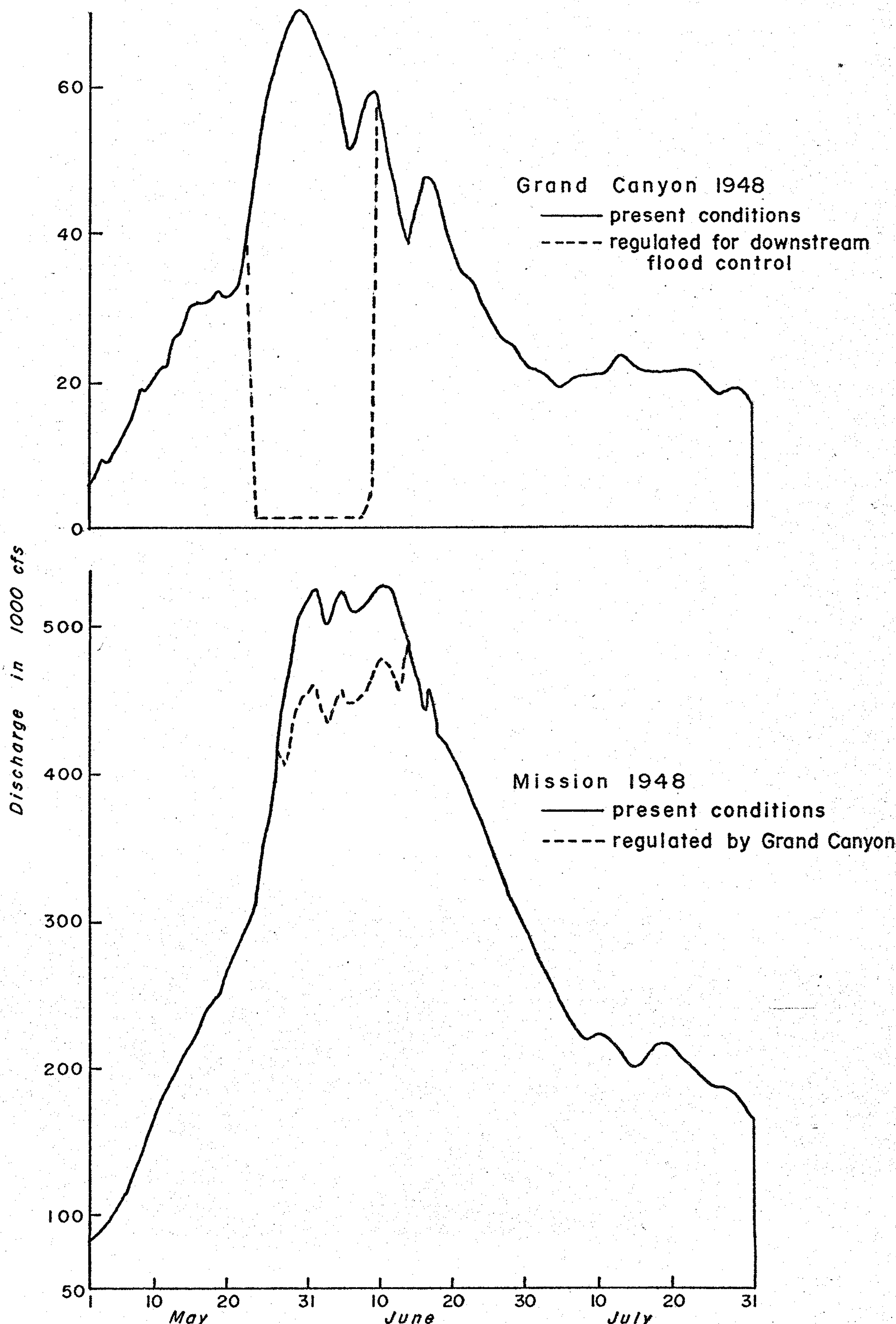


Figure 6 – 1948 Freshet Regulated by Grand Canyon Project

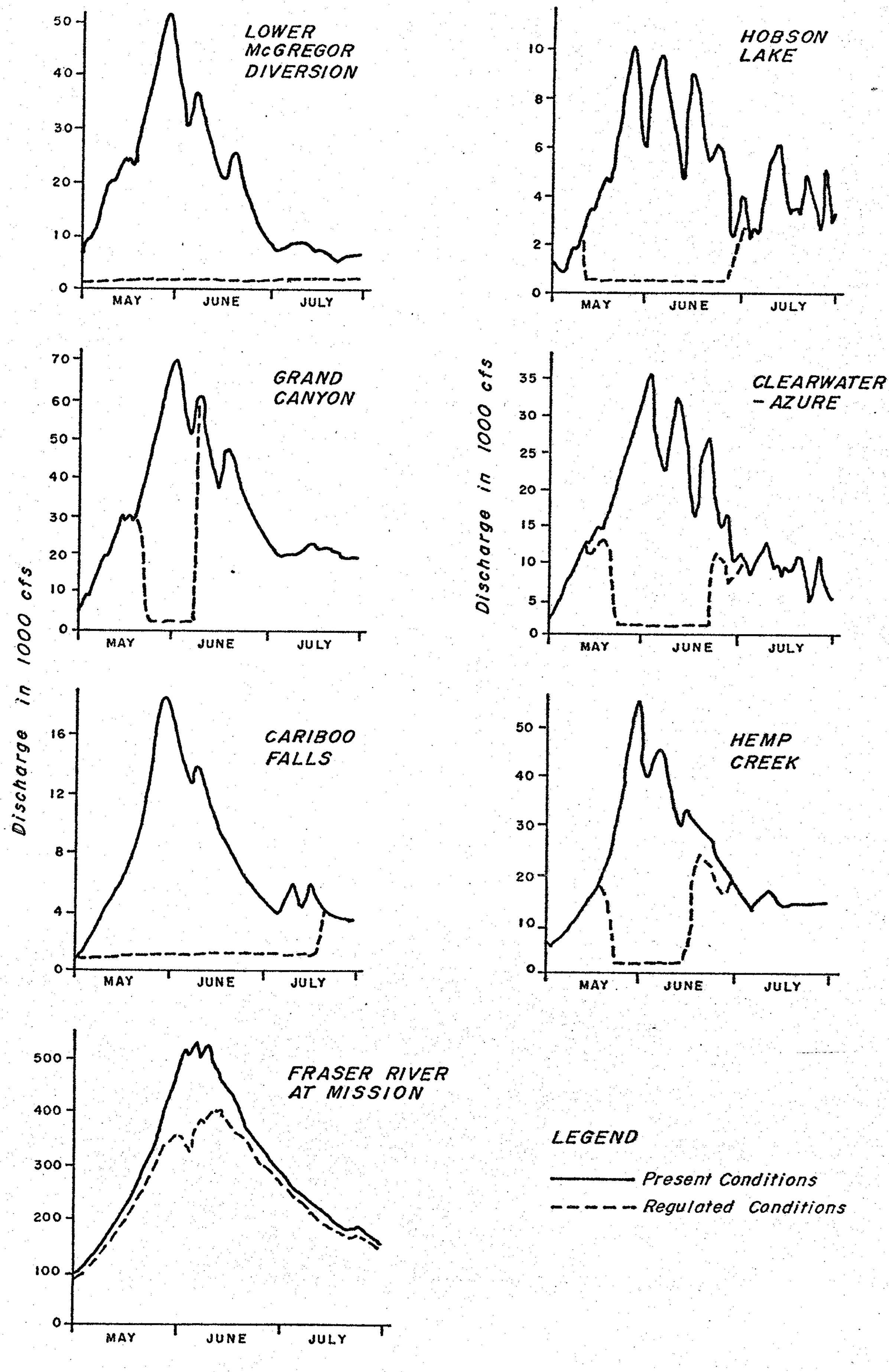


Figure 7 – 1948 Freshet Regulated by All System E Projects

SUMMARY AND CONCLUSIONS

In the studies of a proposed reservoir system for the Upper Fraser River Basin, computerized procedures were developed for the simulation of flood control operation on a real-time basis. The procedures include empirical methods for long-term forecasts, short-term forecasts, reservoir storage scheduling and flood routing. The short-term forecasts used in this study were developed specifically for day-to-day reservoir flood control operation. The technique derived for the forecasts is a simplified approach yet provides a very workable and useful tool for reservoir operation.

Because the nature of this study is for planning purposes, various assumptions were made in the development of these methods due to either the limited available information or the intention to simplify the procedures. However, the results obtained from this study have been accepted as a good basis for planning and evaluation of flood control projects. It is considered that the computer programs developed for the purpose of this study could be applied, with minor modifications, on a real-time basis to any river basin with similar flood concerns due to snowmelt.