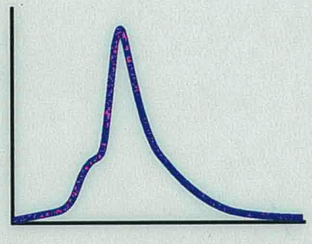
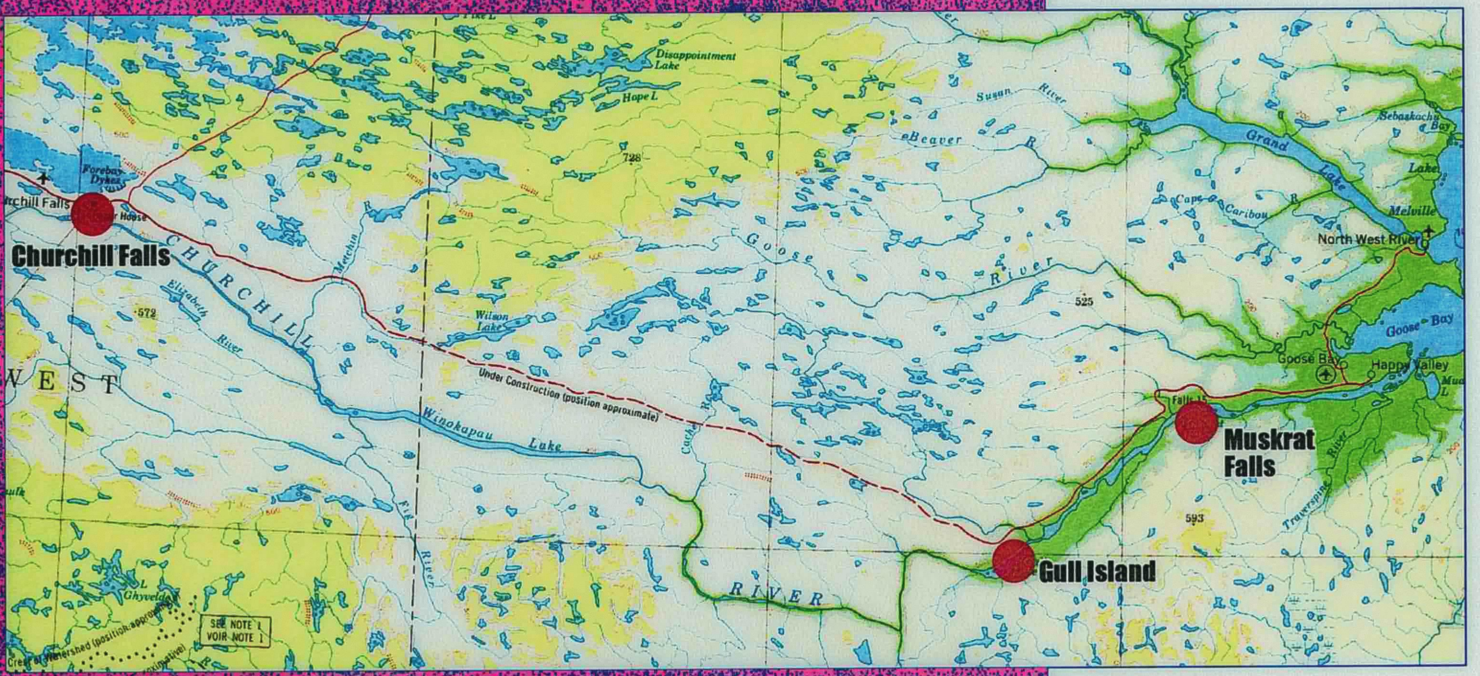
HYDRO
NEWFOUNDLAND AND LABRADOR HYDRO

Churchill River Complex

PMF Review and Development Study





Volume 1 - Main Report

January 1999

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February 3, 1999
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Newfoundland and Labrador Hydro
Hydro Place, Columbus Drive
P.O. Box 12400
St. John's, Newfoundland A1B 4K7

Attention: Mr. G. Piercy, P.Eng.

Dear Sir:

Churchill River Complex: PMF Review and Development Study

Please find enclosed twenty-four (24) copies of Volume 1, Churchill River Complex PMF Review and Development Study Main Report and twelve (12) copies of Volume 2, which contains the appendices.

The final Probable Maximum Flood (PMF) estimates for Gull Island and Muskrat Falls are 19 200 m^3/s and 21 900 m^3/s respectively, if an Upper Churchill Basin discharge of 2500 m^3/s is added to the local flows. The estimates increase to 21 700 m^3/s and 24 400 m^3/s if an upper basin discharge of 5000 m^3/s is added. The uncertainty in the upper basin contribution is primarily a question of flood operation, rather than hydrology. We expect that following the development of the new projects, the discharge from Churchill Falls during floods will be no higher than the new power flow, approximately 2500 m^3/s. Additional studies, however, are required to confirm this assessment.

The preliminary PMF estimates that were used in the feasibility studies were between the final lower and upper estimates presented herein, and therefore are appropriately conservative.

Thank you for the opportunity to carry out this study. We enjoyed working with you and appreciated your assistance throughout. We look forward to continued involvement as the development process continues.

Yours very truly,

S. H. Richter, P.Eng.
Project Manager

JB:sjc

Enclosure

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Volume 1 - Main Report

Volume 2 - Appendices

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Glossary of Abbreviations

AEB	Atmospheric Environment Branch, Environment Canada, formerly AES, Atmospheric Environment Services
CDA	Canadian Dam Association, formerly the Canadian Dam Safety Association
CEA	Canadian Electricity Association
CF1	Existing Powerhouse at Churchill Falls
CF2	Proposed Additional Powerhouse at Churchill Falls
CF(L)Co.	Churchill Falls (Labrador) Corporation Limited
GS	Generating Station
NLH	Newfoundland and Labrador Hydro
PMP	Probable Maximum Precipitation
PMF	Probable Maximum Flood
PMSA	Probable Maximum Snowpack Accumulation
SSARR	Streamflow Simulation and Reservoir Regulation (US Army Corps of Engineers - Computer Model)
WMO	World Meteorological Organization

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Executive Summary

Executive Summary

Studies are currently under way to determine the feasibility of developing the remaining hydroelectric potential of the Churchill River System in Labrador. Plans include diversions of the St-Jean and Romaine Rivers, addition of capacity at the existing Churchill Falls S and two new generating stations, ull Island and Muskrat Falls, in the Lower Churchill Basin.

Concurrent to these feasibility studies, Acres International Limited has carried out a Probable Maximum Flood (PMF) Review and Development study. The objective of this study was to review and update the PMFs for ull Island and Muskrat Falls. The scope included a review of previous studies on the Upper and Lower Churchill Basins, a meteorology study to estimate the contributors to the PMF, and detailed hydrologic modelling to estimate the Lower Basin PMF.

The PMF is defined by the Canadian Dam Association as “an estimate of hypothetical flood (peak flow, volume and hydrograph shape) that is considered to be the most severe ‘reasonably possible’ at a particular location and time of year, based on relatively comprehensive hydrometeorological analysis of critical runoff-producing precipitation (snowmelt if pertinent) and hydrologic factors favourable for maximum flood runoff”.

The following meteorological parameters were determined based on analyses by Environment Canada’s Atmospheric Environment Branch

- a Lower Churchill Basin Probable Maximum Precipitation (PMP) of 189 mm in three days;
- a 100-year basin average precipitation of 53 mm in three days;
- a temperature sequence combining a cool early May to preserve the extreme snowpack into the spring, a warm front to prime and melt the snowpack, and a cool front bringing the PMP rainfall;
- a 100-year snowpack of 577 mm of water equivalent; and
- a Probable Maximum Snowpack Accumulation (PMSA) of 725 mm of water equivalent.

A watershed model of the Lower Churchill Basin was calibrated using meteorological data from Goose Bay and Churchill Falls airports and hydrometric data from Churchill River flow records at Muskrat Falls and Churchill Falls. The model was then used to test various combinations of extreme rain, temperature and snow to determine the governing PMF case.

Several Lower Churchill Basin PMF scenarios were evaluated and the governing case is a combination of

- a spring PMP;
- a severe temperature sequence, and
- the 100-year snowpack.

During a Lower Churchill Basin PMF it is likely that the Upper Churchill Basin would experience severe weather and therefore spill from the Churchill Falls GS could contribute to the flood in the lower basin. Flood routing scenarios from the 1989 Churchill Falls Flood Handling Study were used to estimate a maximum contribution from the upper basin of 5000 m^3/s during a lower basin PMF. Conceptual studies of the upper basin suggest that following development of the new projects, flood operation during a lower basin PMF is unlikely to result in flows greater than approximately 2500 m^3/s (a conservative estimate of the combined maximum power flows of CF1 and CF2).

The conceptual watershed and operations modelling done for the Upper Churchill Basin suggests that the volume of the upper basin PMF is likely to be less than previously estimated and the lag between peak rainfall and peak runoff is likely to be shorter. Preliminary flood routing shows that the revised upper basin PMF would lead to lower maximum water levels in Smallwood Reservoir and lower maximum spill releases.

The total PMFs estimated for the Churchill River at Gull Island and Muskrat Falls are 19 200 m^3/s and 21 900 m^3/s, respectively, assuming an upper basin contribution of 2500 m^3/s. The total PMFs would be 21 700 m^3/s at Gull Island and 24 400 m^3/s at Muskrat Falls is if the upper basin contribution were as high as 5000 m^3/s. The Gull Island and Muskrat Falls feasibility studies were undertaken using preliminary PMF estimates of 19 700 m^3/s and 22 100 m^3/s respectively. The maximum difference between the PMF estimates used in the Gull Island and Muskrat Falls feasibility studies and the current estimates is about 10 percent, which is less than the inherent degree of uncertainty in PMF derivations. The more likely values, assuming an upper basin contribution of 2500 m^3/s, are slightly less than the values used in the feasibility studies. The PMF estimates used in the feasibility studies for Gull Island and Muskrat Falls are sufficiently conservative for design.

A flood handling study for the whole system is required to confirm the conclusions regarding the Upper Churchill Basin contribution to the Lower Churchill Basin PMF and to develop flood handling procedures for each Churchill River Complex facility.

Introduction

1 Introduction

1.1 Background

The Churchill Falls Hydroelectric System is located in Labrador, Newfoundland. The existing generation complex regulates two-thirds of the Churchill River basin and has a capacity of 5428.5 MW. Feasibility studies are currently underway to investigate the addition of capacity at Churchill Falls (CF2) and adding new generation at two sites on the Lower Churchill River, Gull Island and Muskrat Falls. Figures 1.1 to 1.3 show the location of the existing and proposed Churchill River facilities.

Newfoundland and Labrador Hydro (NLH) engaged Acres International to review the existing design flood for the Upper Churchill Complex and to derive a Probable Maximum Flood (PMF) for the Lower Churchill Basin. Preliminary estimates of the PMFs for the two sites were provided by Acres in early October 1998, so that spillway design could be complete by the mid-November 1998 deadline.

1.2 Probable Maximum Flood Definition

The Canadian Dam Association (CDA) defines the Probable Maximum Flood as the:

"Estimate of hypothetical flood (peak flow, volume and hydrograph shape) that is considered to be the most severe 'reasonably possible' at a particular location and time of year, based on relatively comprehensive hydrometeorological analysis of critical runoff-producing precipitation (snowmelt if pertinent) and hydrologic factors favourable for maximum flood runoff".

The CDA guidelines[1] require that:

"A Probable Maximum Flood (PMF) study shall consider the most severe "reasonably possible" combination of the following phenomena on the watershed upstream of the structure under study:

- rainstorm;
- snow accumulation;
- melt rate;

- initial basin conditions (e.g. soil moisture, lake and river levels);
- prestorm."

For dams with high consequences of failure, either financial or loss of life, the PMF is the inflow design flood to use in design of hydraulic facilities, e.g. dams and spillways, and for dam safety studies.

Current dam safety practice is to define the PMF as the largest flood that can *reasonably* be expected to occur, rather than the largest flood that could *possibly* be expected to occur. This change in thinking is reflected in the severity of the individual meteorological components that are combined to generate the PMF. In the original Upper Churchill PMF the Probable Maximum Precipitation (PMP) was combined with a Probable Maximum Snowpack Accumulation (PMSA) and maximum snowmelt temperatures. More recent PMF studies undertaken by Canadian utilities have limited the maximum size of any event in combination with a Probable Maximum event to a 100-year or 1000-year return period event; for example a PMP might be combined with a 100-year snow, or a PMSA could be combined with a 100-year rain. (Statistical events can be identified with return periods, e.g., the 100-year events, or with annual exceedence probabilities, e.g., an event with an AEP of 1/100. The former has been used in this report as that has been the terminology of the previous studies).

The CDA dam safety guidelines outline the following cases to be considered during the snow melt season:

- a combination of the PMSA with a severe rainstorm and a severe temperature sequence;

- a combination of a severe snow accumulation with the spring PMP and a severe temperature sequence; and

- a combination of the PMSA with a critically severe temperature sequence.

For the Lower Churchill Basin it was expected that the PMF would occur during the snowmelt season. Higher rainfall depths could occur later in the year, but the percentage of annual runoff from the basin that is a result of snowmelt suggests that a spring PMP in combination with snowmelt will give the maximum flow in the river.

1.3 Approach

The following tasks were undertaken during this analysis.

Review of Previous Studies
The following previous flood studies were reviewed.

1. Acres Canadian Bechtel of Churchill Falls, Churchill Falls Snowmelt and Frequency Studies for Design Floods[2], September 1969 including meteorological studies by Sparrow[3] (Department of Transport Meteorological Branch, 1968).

2. Acres Consulting Services Ltd., Gull Island Hydro-electric Project, Maximum Probable Flood Study[4], October 1975 including meteorological studies by Pollock and Rahahan[5] (Atmospheric Environment Services, 1975).

3. Acres International Limited, Flood Handling Study of the Churchill Falls System[6], March 1989.

Analysis of Meteorological Data
The analysis of meteorological data to determine the components of the PMF was undertaken by the Atlantic Atmospheric Science Division of Environment Canada's Atmospheric Environment Branch (AEB). The deliverables from their study were

- description of the meteorology of the Upper and Lower Churchill Basins;
- PMP rainfall;
- 100-year rainfall;
- critical temperature sequence;
- PMSA; and
- 100-year snowpack.

Review of Design Flood Hydrographs for Upper Churchill
This task involved a review of the hydrology for the Upper Churchill Basin to confirm, or recommend revision to, the existing PMF estimate. In particular, the meteorology of the design event was compared with the Saguenay floods.

Preliminary investigations showed that an accurate estimate of Upper Churchill Basin flood releases was important to the analysis of the lower basin floods, so SSARR modelling and flood routing of the upper basin were also carried out.

Development of Hydrological Model of Churchill River

A watershed model for the Lower Churchill Basin was created using the SSARR (Streamflow Simulation and Reservoir Regulation) model. The model uses precipitation, temperature and snowpack information and relationships that describe the runoff response of the watershed to predict flows in the Churchill River. The model was calibrated with five years of data in the early 1980s and verified using three years in the later 1980s.

Flood Routing to Establish the PMF for Gull Island and Muskrat Falls

This task involved the SSARR modelling to establish PMF flows for the proposed Gull Island and Muskrat Falls generating stations. Various scenarios using different combinations and timing of extreme events were examined to determine the governing case.

The terms of reference for this study included a review of the impact of potential diversions of the upper St-Jean and Romaine Rivers on the PMF. Early in the studies, Acres were informed that during floods no water from the diversions would flow into the Churchill Basin, so this task was no longer required.

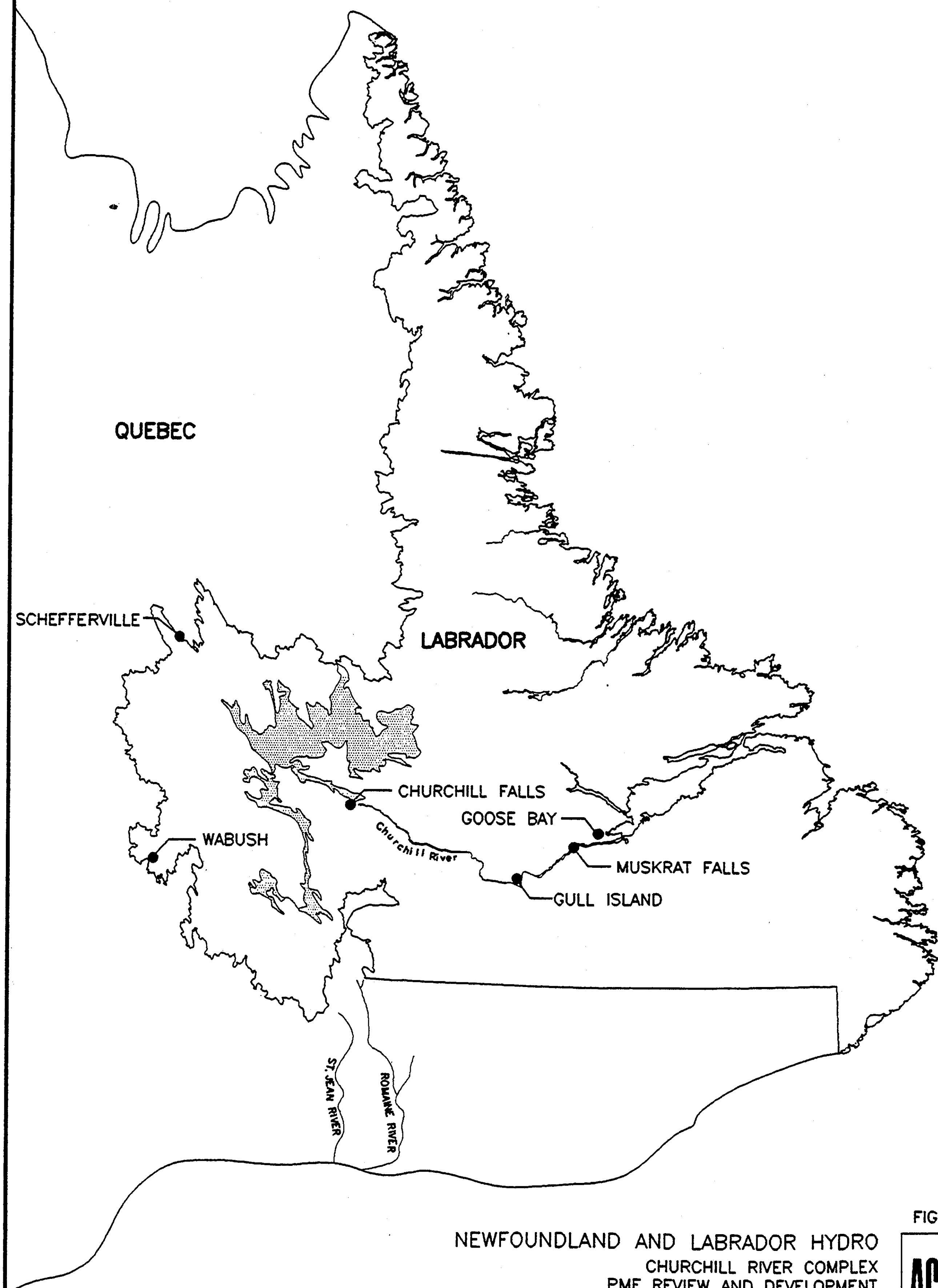

FIG. 1.1

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX
PMF REVIEW AND DEVELOPMENT
PROJECT LOCATION

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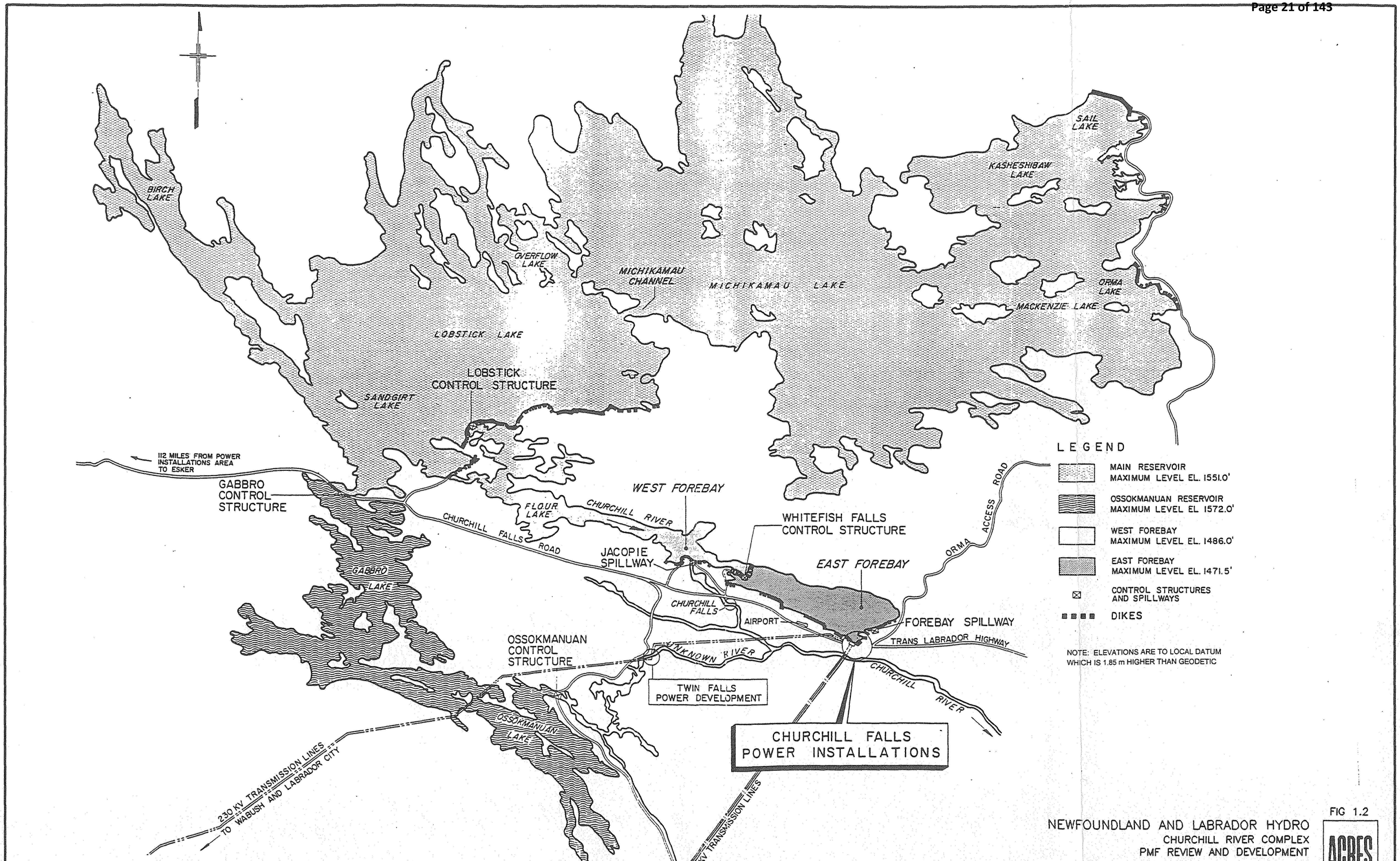
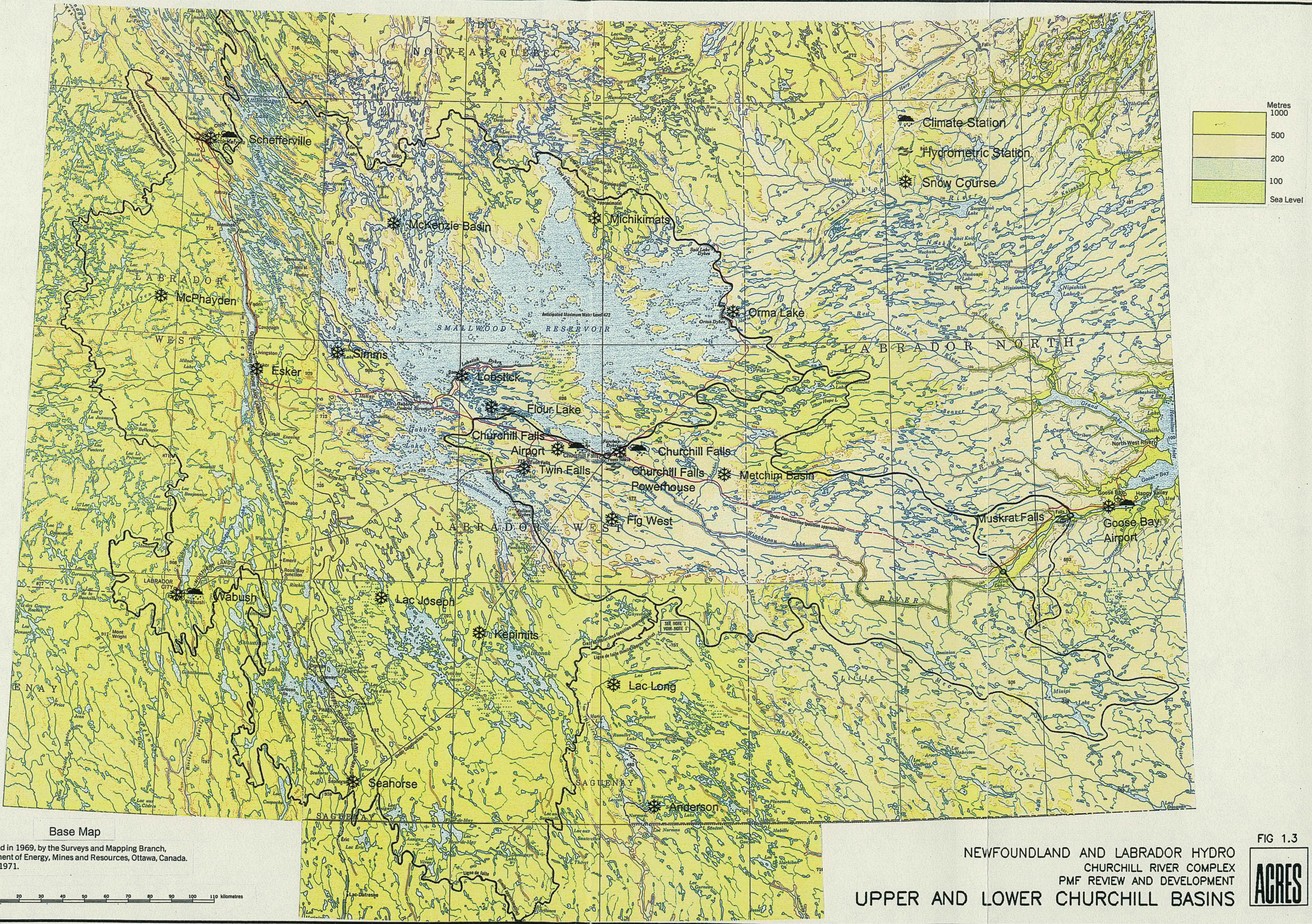


FIG 1.2

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX
PMF REVIEW AND DEVELOPMENT
UPPER CHURCHILL RIVER SYSTEM

SOURCE: FLOOD HANDLING STUDY OF THE CHURCHILL FALLS SYSTEM



Base Map

Compiled in 1969, by the Surveys and Mapping Branch, Department of Energy, Mines and Resources, Ottawa, Canada. Printed 1971.

kilometres 10 5 0 10 20 30 40 50 60 70 80 90 100 110 kilometres

FIG 1.3

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX
PMF REVIEW AND DEVELOPMENT

UPPER AND LOWER CHURCHILL BASINS

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Review of Previous Studies

2 Review of Previous Studies

Previous feasibility, design, and operation studies for both the Upper and Lower Churchill Rivers have included estimation of extreme floods. Each of these studies has been reviewed as part of this Churchill River PMF study. The 1969 and 1975 flood studies referred to the Maximum Probable Flood rather than the Probable Maximum Flood. For the purpose of this study, the two terms are synonymous.

2.1 Churchill Falls Power Project: Snowmelt and Frequency Studies for Design Floods, 1969

Design studies for the existing Churchill Falls GS were undertaken in the late 1960s, and included extreme flood estimates. Acres Canadian Bechtel of Churchill Falls derived design floods. Sparrow, of the Department of Transport's Meteorological Branch (which became the Atmospheric Environment Branch) undertook the necessary meteorological studies.

The 1969 study describes the following sequence of events resulting in the basin maximum probable flood, including

- maximum probable snow accumulation on the ground by late May.
- a relatively cool May with moderate melting that would prime the snowpack.
- a moderately strong flow of warm air causing warm temperatures over the watershed for approximately 8 days.
- a major rainstorm carrying moist Atlantic air moving slowly over the basin.
- a cold front moving through the basin after the rainfall with mean temperatures below 10°C.

The study used a probable maximum snow accumulation of 767 mm water equivalent, background temperatures and precipitation from 1966, the year which produced the then maximum historic runoff, an 8-day warm temperature sequence and a 5-day maximized spring rainstorm.

The runoff from the extreme rainfall was estimated using unit hydrographs derived using U.S. Army Corps of Engineers equations and hydrographs and hyetographs from several historic flood years to derive a unit hydrograph which represented the physical characteristics of the basin. The Smallwood Reservoir has so much storage that the inflow peak would be attenuated prior to spilling so the focus of the flood studies was on volume rather than peak.

The results are summarized in Table 2.1.

Though the maximum probable flood was estimated, the 1969 flood study recommended that the 10 000-year event be adopted as the design flood. The 10 000-year flood was estimated to have a peak of 17 000 m^3/s.

2.2 Gull Island Maximum Probable Flood Study, 1975

A Maximum Probable Flood Study was undertaken by Acres Consulting Services Limited in 1975 as part of the Gull Island Hydroelectric Project Feasibility Study. Pollock and Ranahan of Atmospheric Environment Services (AES) estimated the meteorologic conditions leading up to a maximum probable flood.

The sequence of meteorologic events leading to the maximum probable flood was similar to that postulated in the 1969 study, and the routing methodology was the same. The main differences between the two studies was in the focus of the hydrograph simulation and on the shape of the unit hydrographs. In the 1969 study for the Upper Churchill basin the focus was on accurately modelling the volume of storm runoff. The proposed Gull Island Project (and also the proposed Muskrat Falls Project) is essentially run-of-river so an accurate estimation of the flood peak is more important than the hydrograph shape and volume. The unit hydrograph derived for the lower site was much peakier than that for the Upper Churchill in 1969.

The key results of the 1975 study are summarized in Table 2.1.

2.3 Flood Handling Study of the Churchill Falls Complex, 1989

In 1989 Acres International undertook a Flood Handling Study of the Churchill Falls Complex. The primary objective of that study was to review operating procedures for use during extreme floods, and to update these procedures if necessary. In particular, the study reviewed and updated the prespill procedures, and considered the effect of unexpected restrictions to discharges resulting from failures at the water controlling structures.

A secondary objective of the 1989 study was to review the design events for the Upper Churchill Basin, including the PMF and statistical flood events with return periods up to 10 000 years in light of additional data available for the years since the original design.

The review concluded that the methodology used in 1969 was satisfactory and that nothing had occurred since the 1969 studies to change the postulated synoptic description of the maximum flood event. The review then considered each of the meteorological components in turn to see if additional data would lead to any increase in the estimates made in 1969.

A statistical evaluation of maximum snowfall using several stations in the basin area estimated a 10 000-year snowpack of 640 cm. The report concluded that the snowpack used in the 1969 study, 850 cm, was very conservative.

The peak rainstorm estimate in 1969 used storm transposition and maximization to estimate the maximum precipitation that could occur over the basin. A review of the significant events since that analysis only found one event that would be suitable, and it was considered unlikely to be more severe than the events already used.

The 1989 review of the background temperatures and critical melt temperatures used in 1969 suggested that there was some possibility that new estimates would lead to higher temperatures. However, the temperatures used in 1969 were adequate to completely melt the estimated extreme snowpack. Since the 1989 review saw no need to increase the snowpack, an increase in melt temperatures could not have a significant impact on the volume of the flood, which is the critical characteristic of the event for the Upper Churchill Project.

The study concluded that the extreme flood derived in 1969 was conservative because of the severity of each meteorological components used in combination. The examination of meteorological data for the period since the studies were done did not lead to any increase in the values used for the meteorologic parameters.

2.4 Summary

Table 2.1 summarizes values used for the key inputs and results of the various flood studies.

The 1969 study followed much the same methodology as this new evaluation of the PMF, however, as discussed in the 1989 study, the meteorological events used in combination to form the PMF were more severe than current practice dictates. For example, the draft CDA Manual of Good Practice for PMP/PMF[7] indicates that the appropriate snowpack to use in combination with a PMP event is in the order of a 100-year return period event. The 1969 study used a snowpack with a return period longer than 10 000 years, which would now be called a Probable Maximum Snowpack. Given that the original Upper Churchill and Gull Island studies are now 29 and 22 years old, each component of the meteorological input required reevaluation for the present PMF analysis.

In addition, advances in computing since the original studies have made data manipulation and watershed modelling much faster. Conceptual modelling using computer models has become the industry standard for detailed PMP and PMF studies. Though setting up the models can be time consuming, once completed the models allow simulations of many potential cases.

Table 2.1

Summary of Previous Flood Studies

Parameter	Upper Churchill Basin			Lower Churchill Basin	
	1969 MPF[1]	1989 Flood Handling Study	1998 PMF[2]	1976 Gull Island MPF[1]	1998 PMF[2]
Drainage Area	67 558 km^2	67 558 km^2	67 558 km^2	19 800 km^2	21 500 km^2
Duration of Rainstorm	5 days	5 days	3 days	3 days	3 days
Total Storm Rainfall	172 mm	172 mm	153 mm	213 mm	189 mm
Duration of Imposed Meteorologic Sequence	16 days	16 days	22 days	16 days	22 days
Snowpack Return Period	maximized snowpack	maximized snowpack	100-year	maximized snowpack	100-year
May 1 Snowpack Water Equivalent	687 mm	687 mm	550 mm	952 mm	580 mm
Peak Inflow	30 580 m^3/s	30 800 m^3/s	28 800 m^3/s	13 600 m^3/s	18 100 m^3/s
Peak Outflow	-	15 400 m^3/s	7000-9000 m^3/s	-	-
May to July Flood Volume	68 180 million m^3	68 180 million m^3	44 400 million m^3	23 200 million m^3	15 400 million m^3
Flood Peak Inflow Date	mid June	mid June	early June	early June	early June

Notes

1. Studies were done in imperial units. Results converted to metric here for comparison.
2. Results of current studies included for reference. Details on the derivations of these values are included in later sections. 1998 update of Upper Churchill Basin PMF is not as detailed as the equivalent estimate for the Lower Churchill Basin.

Lower Churchill Basin

3 Lower Churchill Basin

3.1 Basin Description

Gull Island and Muskrat Falls are located on the fast-flowing reaches of the lower Churchill River. The river varies in width between 175 m and 450 m and the velocities are estimated to range from 1.5 to 5 metres per second. On both sides of the valley, overburden extends upwards at moderate slopes of the rocky faces of the upper valley. The adjacent plateau has only moderate relief, with a maximum elevation of approximately 700 m. Dense spruce forest grows in the valley.

The project is located in the Precambrian shield. Geological investigations undertaken during previous studies show that most faults in the region are ancient and stable and bedrock is generally competent. Most of the major relief arises from erosion of the plateau by glaciers and by rivers, most prominently the Churchill River.

The U-shaped valley was created by glacial action and was filled to a thickness of 60 m by a complex succession of glacial and glaciofluvial deposits. During the final retreat of the glacier in Pleistocene time, the valley was on the margin of a marine estuary. Silt and fine sand with some coarser sand and gravel were deposited in this environment up to approximately elevation 125 m. With differential uplift of the land since the Pleistocene era, the river has cut through these fluvial and estuarine deposits and only remnants remain as terraces on either side of the river. In several places the terrace remnants have been eroded laterally by small streams.

Most of the local drainage area of the Lower Churchill River is on the Labrador Plateau. The drainage area consists of several large subbasins draining into the river along its length. Some of the larger streams which provide significant runoff to the lower river are Metchin River, Fig River, Cache River, and Minipi River. This configuration means that flood flows from each of these basins would arrive in the main channel at approximately the same time. The relatively steep slope of the river from Lake Winakapau to Lake Melville means that the routing time in the main channel is short. Runoff response can be expected to be faster than might otherwise be expected from basin of this size. In addition, bedrock throughout the plateau is close to the surface and therefore loss to groundwater is minimal and the routing time is relatively short.

3.2 Climate

The Churchill River basin has a northern continental climate, with cold winters and cool summers[8]. It is classified as cold snow-forest in the Boreal climate zone, dominated in the winter and spring by dry Arctic air. Labrador lies within the latitudinal zone of prevailing west winds which, in the North American sector, are produced between the upper air low pressure centre over the eastern Canadian Arctic archipelago and the Bermudan and north-east Pacific sub-tropical high pressure cells. The Arctic air retreats in the summer; in western Canada it is displaced by moderating air masses from the Pacific, but Labrador is too far east for this displacement to occur. As a result, deeper snowpacks persist, prolonging the occurrence of cold surface temperatures.

Sources of moisture for air masses over Labrador include the Gulf of Mexico, the Gulf of St. Lawrence and the Labrador Sea. Lake Winnipeg and the Great Lakes also provide a source of moisture, particularly in the summertime.

There are no Environment Canada climate stations directly in the Lower Churchill Basin, but stations at Churchill Falls and Goose Bay are close. Since the temperature and precipitation regime are similar at these two stations, they have been assumed to represent climate conditions in the basin.

A synoptic climate station at Churchill Falls Airport is just west of the drainage area at an elevation of 440 m. Data are available from 1968 to the present. To the east of the basin is a synoptic station at Goose Bay airport, at elevation 49 m. The Goose Bay station has been operational since 1941.

Though the two stations are approximately 240 km apart and 400 m different in elevation, the temperature and precipitation data show little difference, as summarized on Table 3.1. On average, Goose Bay is 4°C warmer than Churchill Falls and experiences 39 mm more annual precipitation, a 4 percent difference. Any given precipitation event, however, may be experienced only at one of the stations, not necessarily both. Data from both have been used to characterize the climate of the basin, with the assumption that the Churchill Falls station is representative of the westernmost two thirds of the basin and the Goose Bay station is representative of the eastern one third of the basin.

Climate normal monthly temperatures and precipitation for the two stations and the values calculated for the Lower Churchill Basin are included in Table 3.1. Average temperatures in the basin range from -20°C in January to 15°C in July. The average annual precipitation is 994 mm of which 48 percent is snow, mostly falling between November and April.

Environment Canada snow courses are located at Goose Bay Airport, Churchill Falls and Churchill Falls Airport. Two Churchill Falls (Labrador) Corporation Limited (CF(L)Co.) snow courses are located in two western subbasins of the Lower Churchill. The Churchill Falls snow course locations are at a higher elevation and generally show more snow on the ground than Goose Bay, however, the snowpack is variable from month to month and year to year. The maximum snowpack readings range from 110 mm to nearly 600 mm of water equivalent and can occur any time between early February and early May. Snow is generally melted by mid-May, or early June, according to the snow course data.

3.3 Flow Regime

There has been an Environment Canada hydrometric station on the Churchill River at Upper Muskrat Falls since 1948 with a continuous recording station since 1953 (03OE001). The drainage area is reported as 92 500 km^2. The station recorded natural flow until completion of the hydroelectric development at Churchill Falls. Releases from the Churchill Falls Powerhouse are published as station 03OD005, with a drainage area of 69 200 km^2. Table 3.2 lists all the climate and hydrometric stations in the Churchill area.

Figures 3.1 and 3.2 show examples of the annual hydrographs at Muskrat Falls prior to regulation. The shapes of the hydrographs are consistent from year to year. Flow is low (generally between 250 and 750 m^3/s) between January and April. Spring snowmelt leads to a rapid increase in flow in May and the hydrographs peak at between 3000 m^3/s and 7000 m^3/s in June or July. Flow decreases, again quite rapidly after the peak and then gradually recedes during the fall. Table 3.3 shows the monthly average flows for the unregulated period of record.

Construction of the Churchill Falls Hydroelectric Project regulated almost 75 percent of the drainage area of the Churchill River at Muskrat Falls. Figures 3.3 and 3.4 show example hydrographs at Muskrat Falls after regulation, for comparison with Figures 3.1 and 3.2. Figures 3.5 and 3.6 show the releases from Churchill Falls Powerhouse during the same years. During winter, the generation releases are between 1500 and 2000 m^3/s, in summer the releases are approximately 1000 m^3/s. There were some spill releases in the 1970s, but there have rarely been any since.

The post regulation flows at the Muskrat Falls station reflect the powerhouse flows except for the obvious snowmelt runoff period in May, June and early July. Table 3.3 shows the monthly flows for the regulated period of record at Muskrat Falls. As would be expected, post regulation flows are higher in winter and lower in summer than natural flows. The average flows since regulation have increased because of the diversions into the basin as part of the Upper Churchill project. The drainage area of the station at Muskrat Falls increased from 78 700 km^2 to 92 500 km^2 as a result of the diversions.

An estimate of the local inflows to the Lower Churchill River between the powerhouse and Muskrat Falls has been made by subtracting the Churchill Falls Powerhouse flows from the Muskrat Falls flows. The resulting synthetic flows contain many records with zero or negative flows, probably due mainly to limitations of the measurements, and, in the winter, interference from ice. In general, however, the flows during the snowmelt runoff period are not as influenced by the regulation as during low flow periods, and the local hydrographs look reasonable compared to the pre-regulation hydrographs. Figures 3.7 and 3.8 show examples of the annual Lower Churchill local hydrographs.

Table 3.1

Lower Churchill Basin Climate

Mean Monthly Values

Month	Station						Lower Churchill Basin		
	Churchill Falls Airport			Goose Bay Airport					
	Temp (°C)	Rain (mm)	Snow (mm)	Temp (°C)	Rain (mm)	Snow (mm)	Temp (°C)	Rain (mm)	Snow (mm)
Jan	-22	1	72	-17	1	81	-20	1	75
Feb	-20	2	56	-16	4	62	-19	2	58
Mar	-13	4	65	-9	4	77	-12	4	69
Apr	-5	11	58	-2	15	46	-4	12	54
May	-3	36	20	5	46	20	-1	39	20
Jun	10	88	7	11	97	3	10	91	6
Jul	14	114	0	16	119	0	15	116	0
Aug	12	93	0	14	98	0	13	95	0
Sep	6	98	12	9	87	3	7	95	9
Oct	0	38	44	3	58	22	1	44	38
Nov	-8	11	77	-4	21	66	-7	14	74
Dec	-19	3	72	-13	7	84	-17	4	76
Mean	-4	-	-	0	-	-	-3	-	-
Total	-	499	483	-	557	464	-	516	478

Note

1. Data from Canadian Climate Normals 1961-1990, Environment Canada.

Table 3.2

Climate and Hydrometric Stations

Name	Data Type	ID number	Period of Record	Latitude	Longitude
Anderson	snow course	NF001	1972-98	52° 10'	63° 34'
Churchill Falls	snow course	NF008	1972-98	53° 34'	64° 07'
Churchill Falls	climate	850A131	1993-98	53° 32'	63° 58'
Churchill Falls A	snow course	NF009	1968-93	53° 33'	64° 06'
Churchill Falls Airport	climate	8501132	1968-94	53° 33'	64° 06'
Churchill River at Flour Lake	hydrometric	03OE005	1955-71	53° 45'	64° 38'
Churchill River at Churchill Falls Powerhouse	hydrometric	03OE002	1972-96	53° 32'	63° 58'
Churchill River above Upper Muskrat Falls	hydrometric	03OE001	1948-96	53° 15'	60° 47'
Esker	snow course	NF016	1972-98	53° 51'	66° 24'
Fig West	snow course	NF019	1972-98	53° 12'	64° 01'
Flour Lake	snow course	-	1959-72	53° 45'	64° 38'
Goose Bay Airport	snow course	NF027	1962-94	53° 18'	60° 22'
Goose Bay Airport	climate	8501900	1941-98	53° 19'	60° 25'
Kepimits	snow course	NF042	1972-98	52° 42'	64° 51'
Lac Joseph	snow course	NF043	1972-98	52° 58'	65° 32'
Lac Long	snow course	NF044	1972-98	52° 36'	63° 51'
Lobstick	snow course	NF049	1972-98	53° 50'	65° 02'
McKenzie Basin	snow course	NF051	1972-98	54° 34'	65° 32'
McPhayden	snow course	NF052	1972-98	54° 12'	67° 09'
Metchim Basin	snow course	NF056	1972-98	53° 26'	63° 16'
Michikimats	snow course	NF057	1972-98	54° 34'	64° 07'
Orma Lake	snow course	NF065	1972-98	54° 08'	63° 09'
Schefferville A	snow course	-	1968-94	54° 48'	66° 49'
Schefferville	climate	7117825	1948-93	54° 48'	66° 49'
Seahorse	snow course	NF076	1972-98	52° 10'	65° 44'
Simms	snow course	NF079	1972-98	53° 46'	65° 49'
Twin Falls	snow course	NF090	1968-98	53° 36'	64° 28'
Wabush	snow course	NF095	1972-98	52° 57'	66° 42'
Wabush Lake Airport	climate	8504175	1960-98	52° 56'	66° 52'

Table 3.3

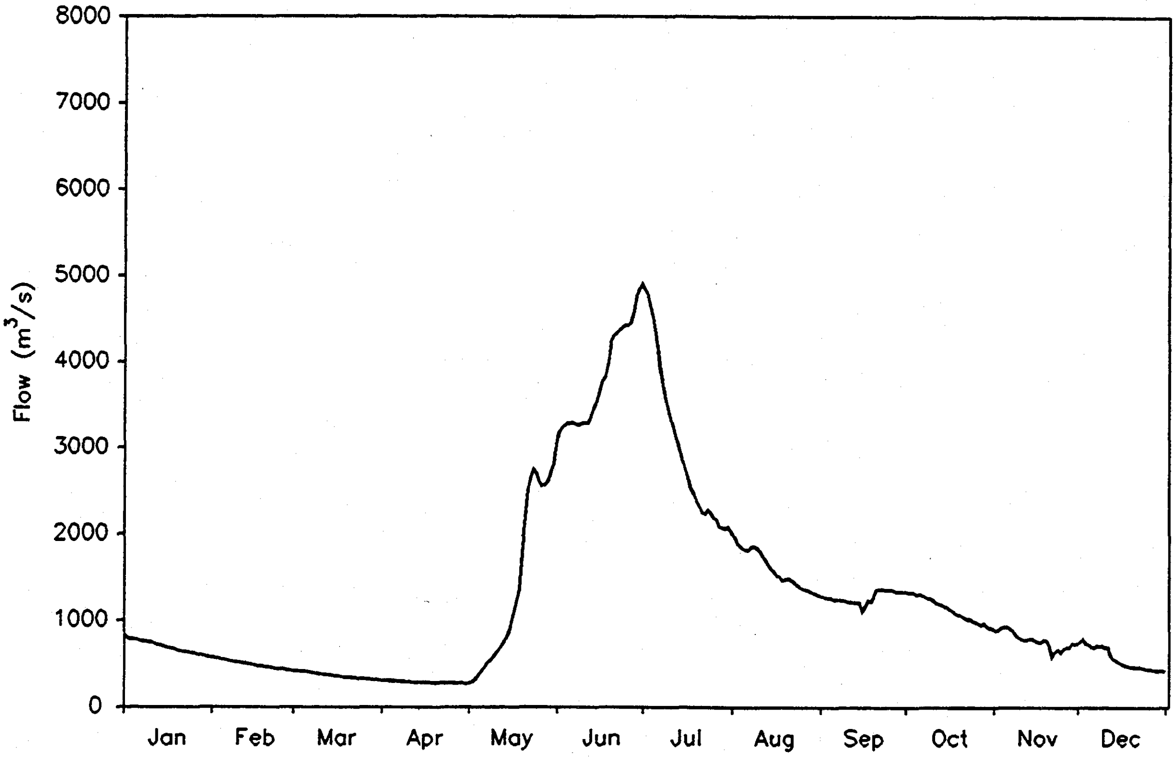
Churchill River Above Upper Muskrat Falls

Environment Canada Hydrometric Station 03OE001

Year		Monthly Mean Discharges for Period of Record (m^3/s)												Mean
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1954		726	611	568	454	2140	3090	2160	1990	2800	2050	1390	876	1580
1955		740	564	511	468	2260	3580	1700	885	681	782	831	713	1140
1956		632	562	490	433	832	4680	5140	2780	2000	2250	2010	1390	1940
1957		804	431	277	290	565	5220	4660	2410	1980	1960	1280	807	1730
1958		813	724	677	736	2570	5360	3510	2410	2600	1990	1340	905	1970
1959		622	443	361	348	2330	4910	2830	1790	1080	1200	1650	1050	1560
1960		678	575	460	405	2070	3740	2480	1880	2150	2220	1570	942	1600
1961	Unregulated	650	502	412	480	1650	2890	2410	1610	990	1600	1390	873	1290
1962		686	487	354	280	1450	3850	2970	1580	1270	1120	770	555	1280
1963		425	367	323	345	1990	3920	2830	1850	1470	1290	1060	642	1380
1964		564	521	499	563	2330	4490	2740	1680	1740	1570	1240	819	1560
1965		607	526	493	487	1880	4420	4120	2750	2710	2200	1420	842	1880
1966		616	532	483	462	816	4300	5310	3000	1910	2050	2250	1240	1920
1967		842	645	519	452	1520	3480	2480	1900	1170	1240	1630	1150	1420
1968		744	662	619	701	2790	4350	2340	1720	2270	2420	1910	1160	1810
1969		901	805	760	781	1890	5070	4300	2530	1980	2330	2070	1550	2090
1970		1020	883	805	789	1210	3910	3480	1850	1280	1110	907	593	1490
1971		533	499	483	608	2850	4130	2340	1120	983	1340	1000	909	1400
1972	Construction	741	766	776	773	995	4310	1590	1170	1060	1600	1040	1100	1320
1973		1540	1710	1020	960	2650	1820	1430	1090	1130	1280	1280	1320	1440
1974		1240	1330	1260	1790	2100	3630	1680	1280	1290	1520	1330	1410	1650
1975		1340	1340	1290	1280	2100	4070	2320	2560	1740	1620	1610	1520	1900
1976		1600	1620	1480	1650	3200	2510	1880	2310	2720	2310	1600	1580	2040
1977		1670	1530	1460	2130	2850	4220	1570	1890	2100	2530	2010	2030	2170
1978		2050	2070	1970	1810	2880	3590	2060	2490	2110	2260	1840	1990	2260
1979		2020	2070	2030	2060	3600	1980	2790	2830	1840	2080	2230	1840	2280
1980		1780	1840	1850	1810	3530	2960	2730	1950	1720	1960	1990	1980	2180
1981		2040	2050	1890	1640	2800	3240	3020	2320	1650	2070	2060	2070	2240
1982		1980	1970	1980	1820	2400	3530	1990	1700	1730	1340	1500	1580	1960
1983		1610	1590	1520	1710	3060	1920	1640	1440	1550	1850	1800	1910	1800
1984		1940	1850	1810	1630	3360	2850	1890	1620	1880	1820	1840	1840	2030
1985	Regulated	1790	1830	1700	1490	1960	2990	1680	1590	1430	1750	1670	1820	1810
1986		1800	1770	1710	1590	2600	1690	1500	1420	1570	1670	1540	1780	1720
1987		1820	1890	1730	1870	2140	1570	1390	1510	1500	1880	1990	1990	1770
1988		2150	2150	1880	1280	2530	1960	1720	1130	1230	1680	1760	1690	1760
1989							Missing Data							
1990		1840	1870	1520	997	940	1020	1210	1400	1420	1560	1440	1450	1390
1991		1700	1680	1590	1340	1750	2130	1550	1190	1130	1230	1460	1450	1510
1992		1440	1460	1290	1110	1870	2180	1340	1530	1530	1590	1550	1700	1550
1993		1780	1800	1820	1690	2670	1730	1420	1560	1350	1800	1590	1720	1740
1994		1770	1770	1200	1090	2200	2190	1550	1640	1530	1540	1820	1800	1680
1995		1850	1840	1500	1500	2650	1750	1540	1080	1090	1270	1260	1650	1580
1996		1500	1420	913	958	2240	1850	1900	1480	1370	1560	2120	1850	1597

Effect of Regulation

Mean 1954-69	691	560	488	480	1818	4209	3249	2048	1800	1767	1488	970	1634
Mean 1975-96	1784	1781	1625	1545	2540	2473	1842	1745	1628	1780	1747	1773	1856
Ratio	2.6	3.2	3.3	3.2	1.4	0.6	0.6	0.9	0.9	1.0	1.2	1.8	1.1

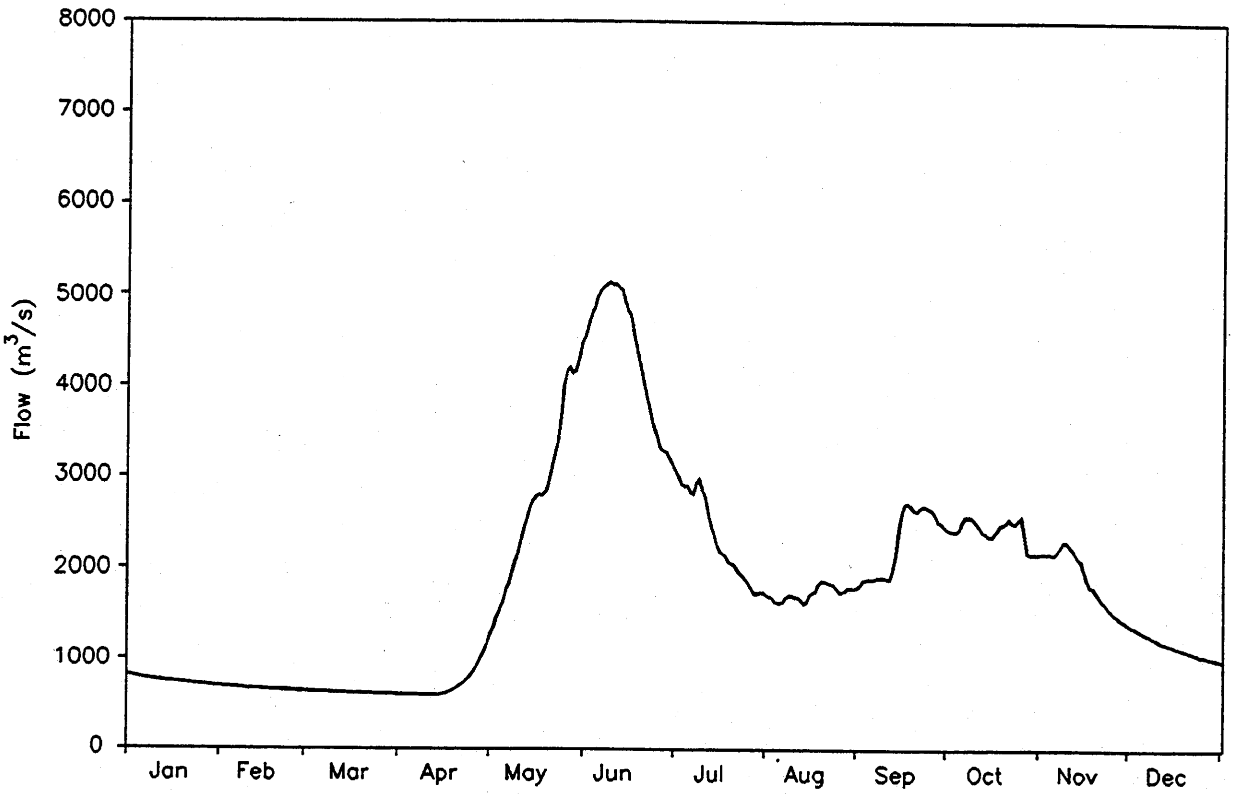


NOTES:
1. ENVIRONMENT CANADA HYDROMETRIC STATION 030E001

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
CHURCHILL RIVER ABOVE UPPER MUSKRAT FALLS, 1962 HYDROGRAPH

FIG 3.1

ACRES



NOTES:

1. ENVIRONMENT CANADA HYDROMETRIC STATION 03OE001

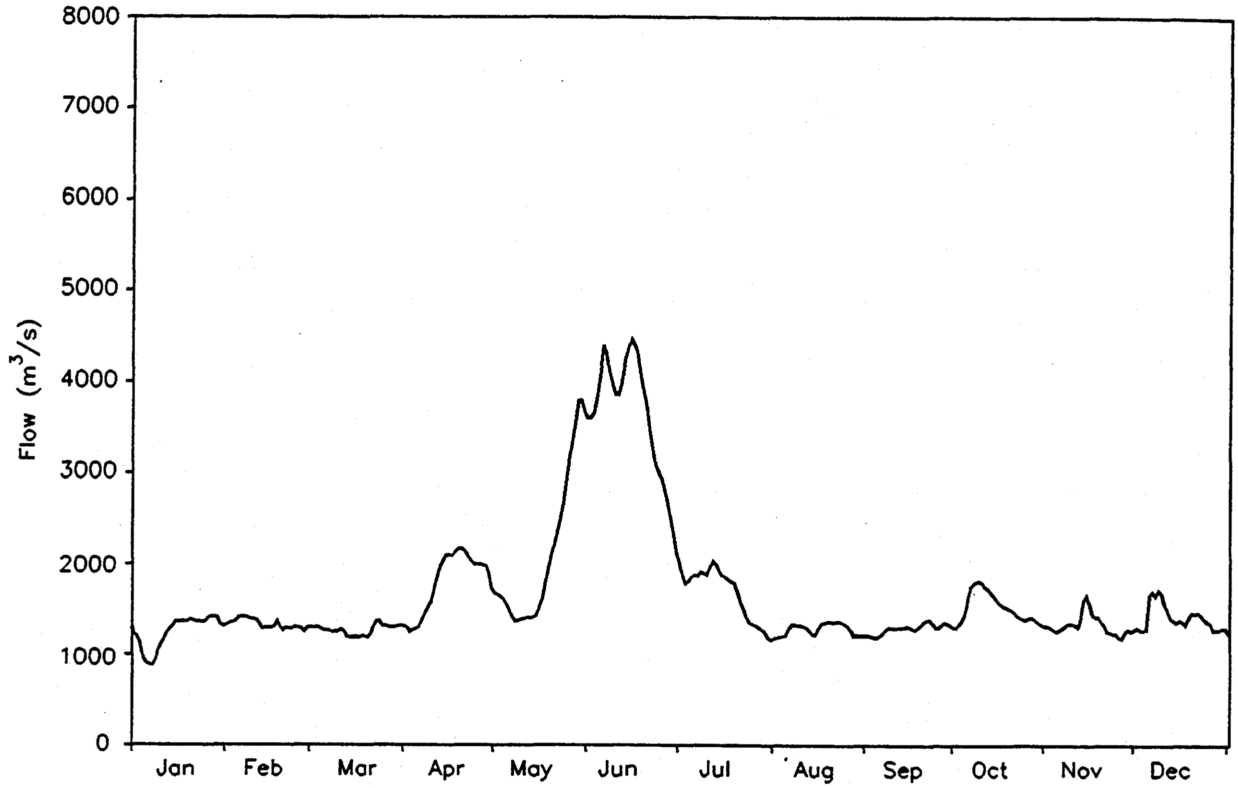
NEWFOUNDLAND AND LABRADOR HYDRO

CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

CHURCHILL RIVER ABOVE UPPER MUSKRAT FALLS, 1968 HYDROGRAPH

FIG 3.2

ACRES



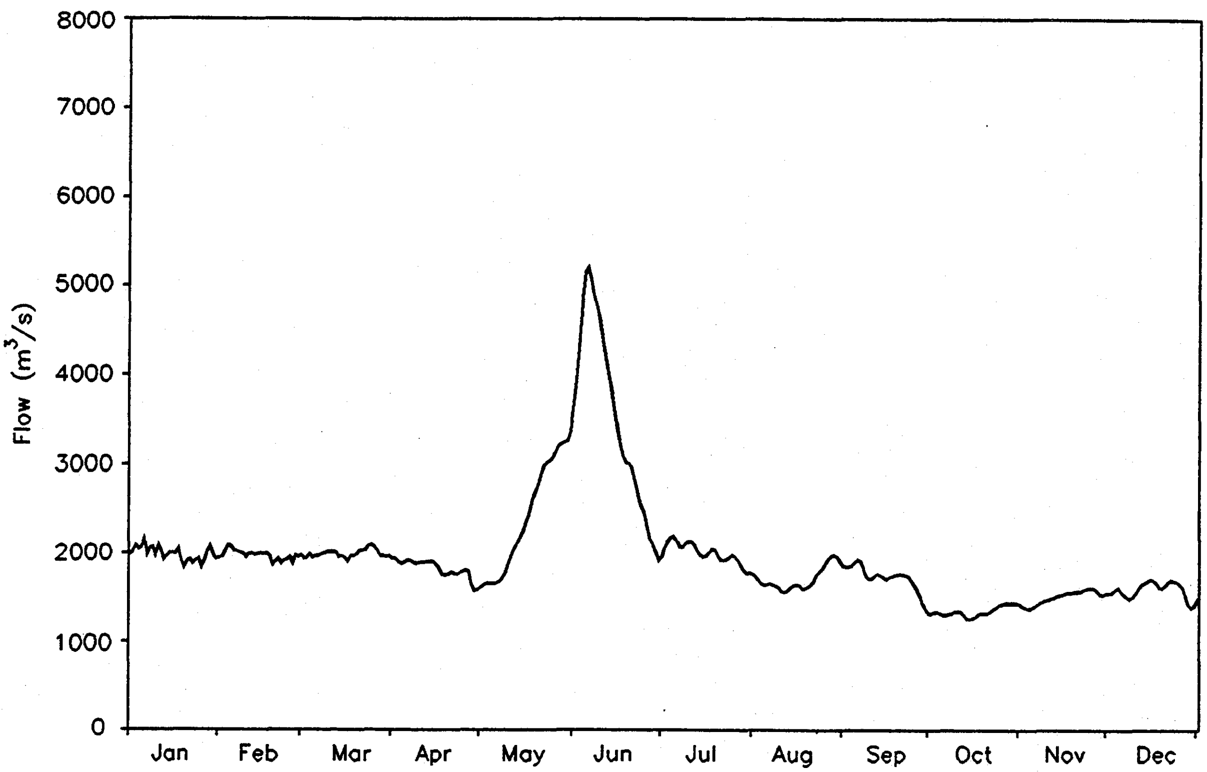
NOTES:
1. ENVIRONMENT CANADA HYDROMETRIC STATION 03OE001
2. REGULATED SINCE 1972 BY CHURCHILL FALLS PROJECT

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

FIG 3.3

CHURCHILL RIVER ABOVE UPPER MUSKRAT FALLS, 1974 HYDROGRAPH

ACRES

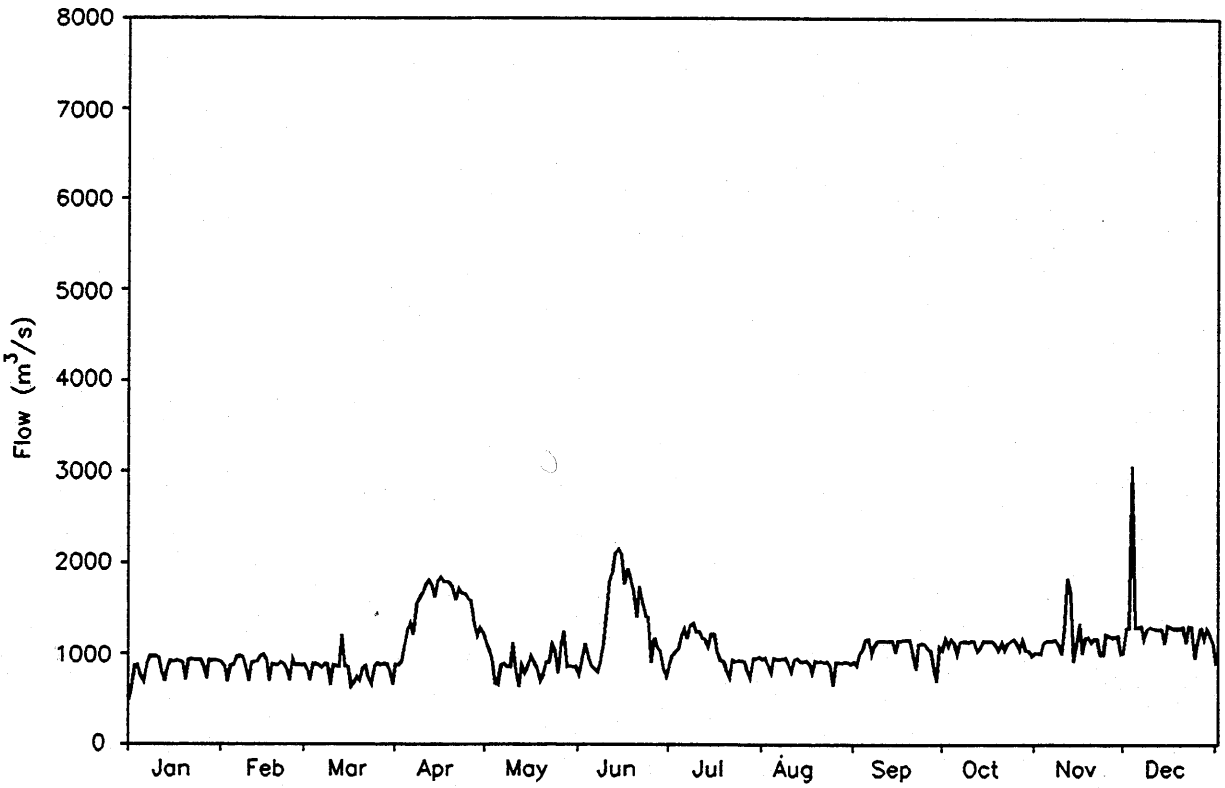


NOTES:
1. ENVIRONMENT CANADA HYDROMETRIC STATION 030E001
2. REGULATED SINCE 1972 BY CHURCHILL FALLS PROJECT

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
CHURCHILL RIVER ABOVE UPPER MUSKRAT FALLS, 1982 HYDROGRAPH

FIG 3.4

ACRES



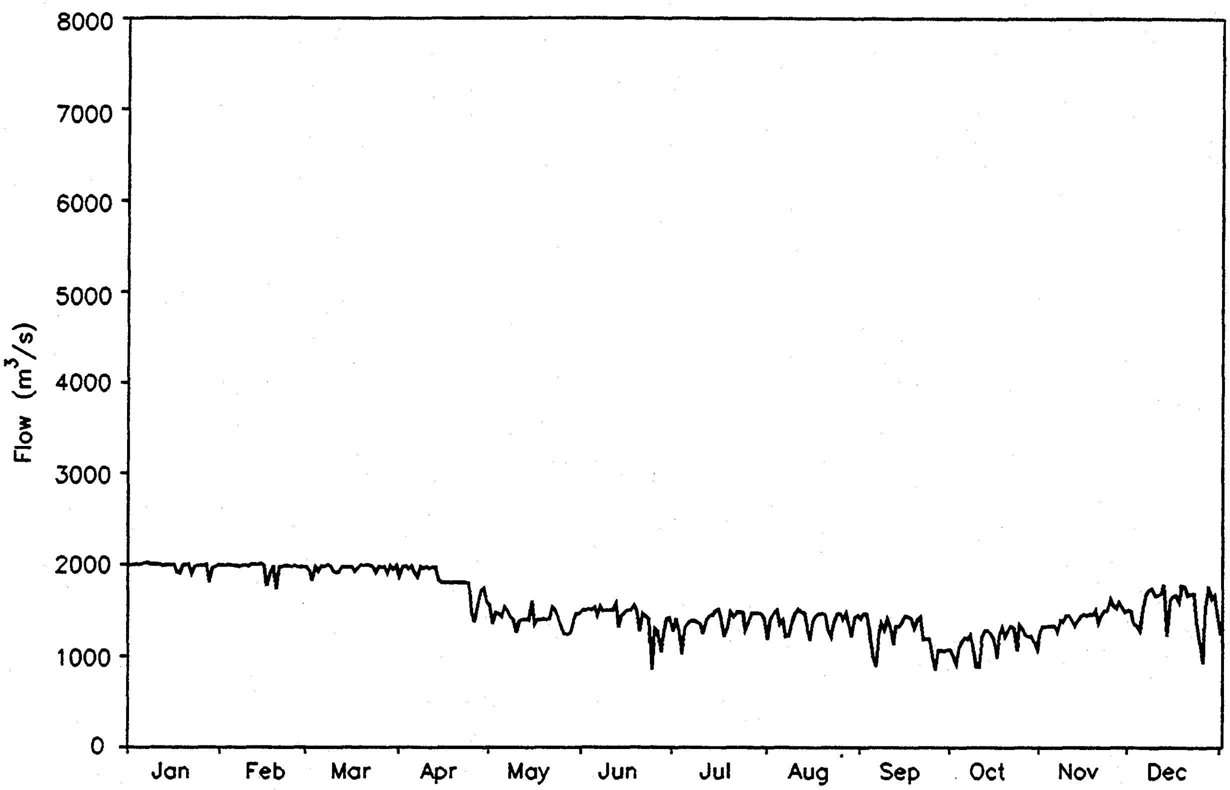
NOTES:
1. ENVIRONMENT CANADA HYDROMETRIC STATION 03OD005
2. REGULATED SINCE 1972 BY CHURCHILL FALLS PROJECT

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

CHURCHILL RIVER AT CHURCHILL FALLS POWERHOUSE, 1974 HYDROGRAPH

FIG 3.5

ACRES



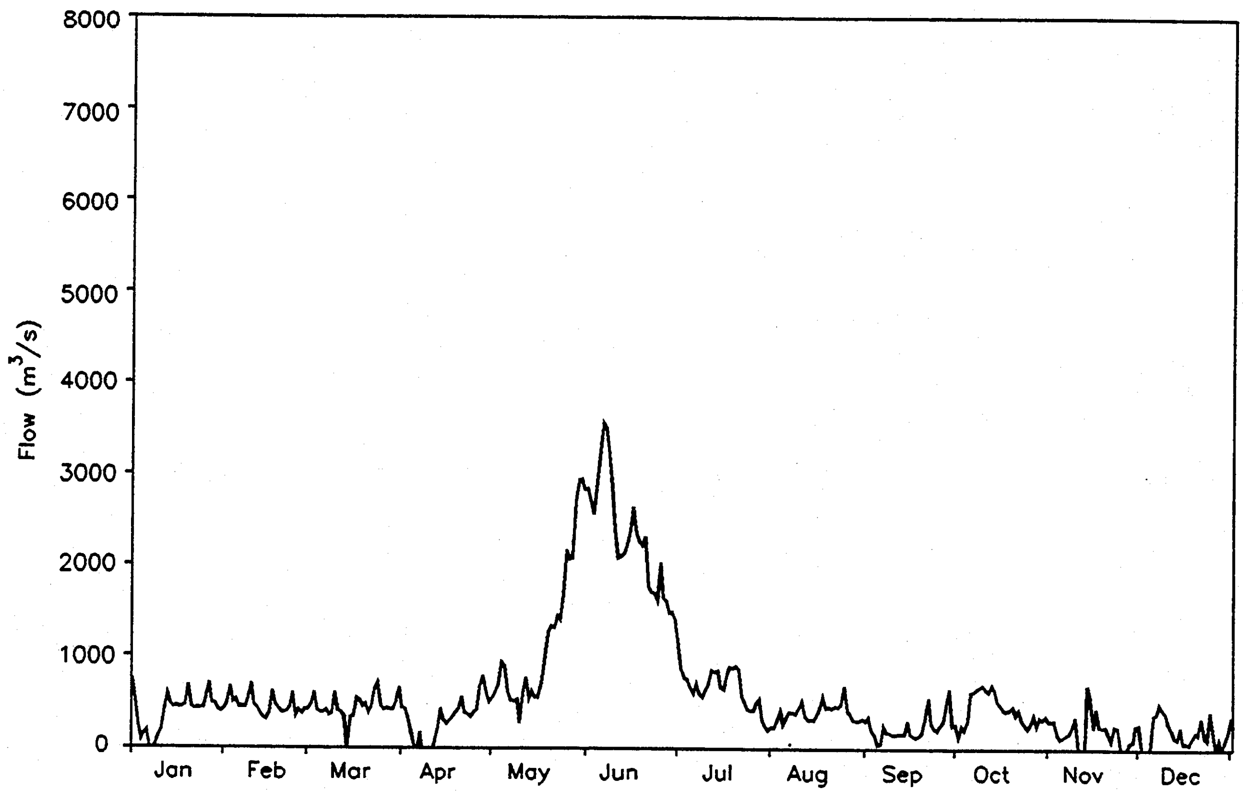
NOTES:
1. ENVIRONMENT CANADA HYDROMETRIC STATION 03OD005
2. REGULATED SINCE 1972 BY CHURCHILL FALLS PROJECT

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

CHURCHILL RIVER AT CHURCHILL FALLS POWERHOUSE, 1982 HYDROGRAPH

FIG 3.6

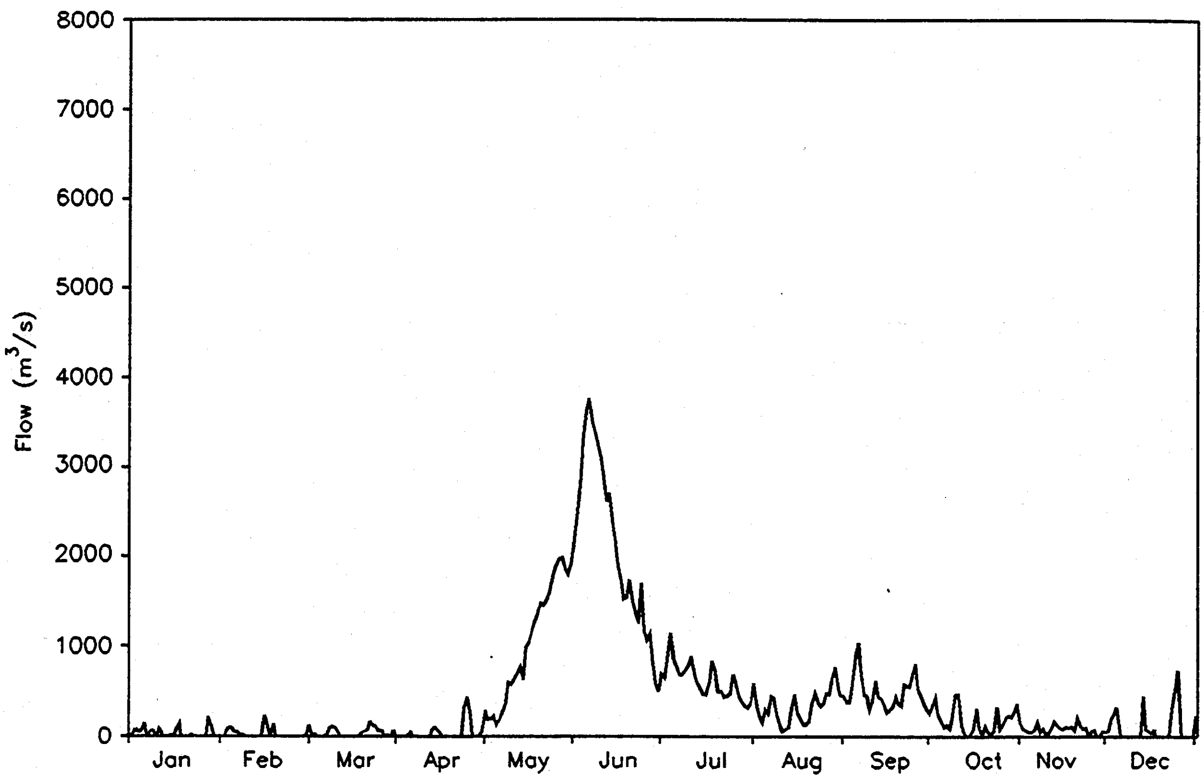
ACRES



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
LOWER CHURCHILL RIVER
LOCAL INFLOW ESTIMATE, 1974

FIG 3.7

ACRES



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
LOWER CHURCHILL RIVER
LOCAL INFLOW ESTIMATE, 1982

FIG 3.8

ACRES

Upper Churchill Basin

4 Upper Churchill Basin

4.1 Basin Description

The drainage area of the Churchill Basin above Churchill Falls is approximately 69 200 km^2, two-thirds of the drainage basin of the entire Churchill River. The upper basin drainage area is wholly contained in the Labrador Plateau and has a variation in elevation of less than 400 m. The plateau area has very shallow bedrock and is covered with small lakes and areas of muskeg. The upper basin is effectively two sub-basins. The main lakes in the southern basin are Ossokmanuan Lake (including what was Gabbro Lake), Atikonak Lake, and Lac Joseph. The combined southern portion of the basin has a drainage area of 22 400 km^2. The northern part of the basin is dominated by Smallwood Reservoir and has a drainage area of 45 200 km^2.

During normal conditions, inflow to Ossokmanuan Lake flows though a channel constriction to Gabbro Lake and then into Smallwood Reservoir through the Gabbro Control Structure. During extreme floods, the gates at Gabbro Control Structure can be closed to prevent further inflows to Smallwood Reservoir. The flow in the connecting channel between Ossokmanuan and Gabbro Lakes reverses and the Ossokmanuan Control Structure opens to release flows into Churchill River via Unknown River.

Flow from the Smallwood Reservoir is released to the West Forebay through the Lobstick Control Structure and then to the East Forebay through Whitefish Control Structure. The power intake is on the East Forebay. During floods, spill is released over the Jacopie Spillway at the West Forebay. The facilities, as constructed, included an additional spillway at the East Forebay, for use during load rejection or extreme floods. Operating history shows that the spillway is not required for load rejection and therefore it has been deactivated.

4.2 Climate

The Upper and Lower Churchill Basins experience similar meteorologic conditions. The upper basin is further inland and so is somewhat cooler and drier than the lower basin. There are two AEB climate stations in the upper basin, at Wabush Airport and at Churchill Falls Airport, both in the southern part of the basin. A station at Schefferville, just north of the Churchill Basin, is representative of the climate in the northern section of the basin. As shown in Table 4.1, Schefferville is on average cooler and drier than Wabush and Churchill Falls. Basin average monthly temperatures for the north and southern portions of the Upper Churchill Basins are given in Table 4.1.

4.3 Flow Regime

Discharges from the Churchill Falls GS are recorded as Environment Canada hydrometric station 03OD005 and are given in Table 4.2. Pre-regulation discharges for the basin prior to diversions (drainage area 33 900 km²) were recorded as Churchill River at Flour Lake (03OB002) as shown in Table 4.3. Figure 4.1 compares average flows before and after regulation. The regulated flows reflect a drainage area approximately twice the area measured at the Flour Lake station.

More recent inflows to the Upper Churchill Basin can be estimated by back-calculation using discharges and water levels. The resulting data are extremely noisy and contain seven long periods of negative inflows. Hydro-Québec is currently attempting to filter the data to improve the quality, but as yet the data are unavailable. The unfiltered data were used in this study since it is expected that though daily values may be in error, the seasonal volumes should be correct.

4.4 Previous Studies

Statistical floods and the PMF were estimated as part of the design of the Churchill Falls System in the late 1960s and were reviewed as part of an operational review in the late 1980s. A review in 1989 concluded that some of the meteorologic parameters chosen in 1969 were conservative but that the PMF hydrograph was appropriate for use in the operating study. The estimated peak inflow during the PMF was 30 800 m^3/s, occurring approximately 14 days after the peak day of the PMP rainfall. The peak outflow, assuming all spill facilities were functioning as designed, was predicted to be approximately 14 500 m^3/s, three days after the peak inflow. Peak outflows during floods have return periods of 100 to 10 000 years were 8000 m^3/s to 8600 m^3/s.

Figures 4.2 to 4.4 present the inflow and routed hydrographs for the PMF, 10 000-year and 100-year floods from the 1989 study.

4.5 Flood Operation

Table 2.1 presented a comparison of the precipitation, snowpack and temperatures used in the various flood studies of the Churchill River. Though the new values derived during the study and presented in Chapter 5 are specifically for the Lower Churchill Basin, the values would likely be similar for the Upper Churchill Basin.

Flood estimates in the Lower Churchill Basin must take into account releases from the Upper Churchill Basin. The meteorological conditions required to cause a PMF in the Lower Churchill Basin are likely to lead to severe weather conditions in the upper basin also. The snowpack and temperatures would likely be similar in the upper and lower basins and the rain storm would likely have "spillover" rain in the upper basin, or may pass over the upper basin on its way to the lower basin.

It is unreasonable to expect the upper and lower basins to experience their PMFs at the same time, but it is not unreasonable to expect that during a lower basin PMF the upper basin would experience an event in the order of a 100-year return period.

The current flood handling procedure for the Churchill Falls project is described in the Acres 1989 Flood Handling Study main report and the Manual for Spring Operating Procedure for Smallwood Reservoir [9]. Flood operation of Ossokmanuan Reservoir is simple since there is little flood storage available. The rules require that Ossokmanuan Reservoir be drawn down to its low supply level every winter in order to store the spring runoff for generation.

Prior to May 1, operators forecast spring inflows to Smallwood Reservoir based on winter precipitation and snowpack and determine whether the expected inflow volume can be stored. If not, prespill through increased generation and spillway releases is planned and undertaken when necessary. Prespill is delayed until it is absolutely necessary to hedge against poor forecasts. During normal operation, the maximum flood level of Smallwood Reservoir is Full Supply Level, El. 472.74 m. During the PMF, the reservoir would be allowed to rise to El. 473.66 m which is 3 ft less than the top of the core of Lobstick Dykes.

The prespill operation is planned so that on May 1, there is enough storage to contain the spring snowmelt runoff. The water management criteria is to refill the reservoir by August 1. From May 1 until June 10 or June 15, depending on the depth of the winter snowpack, Smallwood Reservoir is kept at the May 1 level, by generation or spillway releases, to maintain the required storage volume. By mid-June the snowpack should be melted and the risk of a severe rain on snow event is passed, so the reservoir is allowed to fill.

If the Upper and Lower Churchill Basins are experiencing a high snowpack year, Smallwood Reservoir would be drawn down by May 1. Assuming that the warm temperatures and rainfall in the lower basin trigger a 100-year flood in the upper basin, the inflows to the Upper Churchill Reservoirs would start increasing in late May and operators would open the Lobstick Control Structure and Jacopie Spillway so that the reservoir level was kept constant. The outflow hydrograph would then be essentially the same as the inflow hydrograph shown in Figure 4.4, and the peak outflow during the lower basin peak would be approximately 5000 m^3/s. The 1989 simulations assume a different scenario, that of a 100-year rainfall on an average snowpack without reservoir drawdown. The upper basin spill during the lower basin peak, however, is quite similar, also shown in Figure 4.4. Therefore, based on 1989 flood handling rules, it would appear that the upper basin discharge at the time of the peak on the lower basin would be at most 5000 m^3/s.

Comparison of Figure 4.4 with Figure 4.3 shows that during a 10 000-year event in the Upper Churchill Basin, spills would be very similar to those during a 100-year event. The assumption regarding the magnitude of the upper basin event that could occur during the lower basin PMF is not critical if the event has a return period between 100 and 10 000 years.

It should be noted, however, that the 1989 Flood Handling rules were derived without consideration of additional capacity at CF2 or of the downstream projects. CF2 will provide additional flow capability which will allow for more prespill through generation. Operators are likely to use this additional flow capacity in order to avoid spill through Jacopie or other spillway structures.

In addition, simulations undertake for the recent Churchill River Complex Optimization Study [10] show that spring reservoir levels will generally be much lower than those assumed in the 1989 study, meaning that portions of the flood volumes will be able to be stored rather than spilled.

Thus the discharge from the Upper Churchill Basin during most floods is likely to be the future combined station capacity of CF1 and CF2, about 2500 m^3/s. A system wide flood study is required to assess the prespill and flood handling procedures for the Churchill River Complex. This is discussed further in Chapter 8.

Table 4.1

Upper Churchill Basin Climate

Mean Monthly Values

Month	Station									Smallwood Basin			Ossokmanuan Basin		
	Churchill Falls Airport			Wabush Lake Airport			Schefferville Airport								
	Temp (°C)	Rain (mm)	Snow (mm)	Temp (°C)	Rain (mm)	Snow (mm)	Temp (°C)	Rain (mm)	Snow (mm)	Temp (°C)	Rain (mm)	Snow (mm)	Temp (°C)	Rain (mm)	Snow (mm)
Jan	-22	1	72	-22	0	68	-23	0	53	-22	0	62	-22	0	70
Feb	-20	2	56	-20	1	50	-22	0	43	-21	1	48	-20	1	53
Mar	-13	4	65	-14	3	60	-16	2	50	-15	3	56	-14	3	63
Apr	-5	11	58	-5	9	50	-7	7	47	-6	9	51	-5	10	54
May	-3	36	20	3	40	21	1	25	25	1	32	23	0	38	21
Jun	10	88	7	10	83	3	8	64	6	9	75	6	10	86	5
Jul	14	114	0	14	112	0	12	103	0	13	108	0	14	113	0
Aug	12	93	0	12	91	0	11	87	2	12	90	1	12	92	0
Sep	6	98	12	7	90	8	5	79	15	6	87	13	7	94	10
Oct	0	38	44	-1	34	46	-1	26	52	-1	31	49	-1	36	45
Nov	-8	11	77	-8	12	72	-9	8	65	-9	10	70	-8	12	75
Dec	-19	3	72	-19	3	78	-20	1	57	-20	2	66	-19	3	75
Mean	-4	-	-	-4	-	-	-5	-	-	-4	-	-	-4	-	-
Total	-	499	483	-	478	456	-	402	415	-	445	442	-	489	470

Note

1. Adopted from Canadian Climate Normals 1961-1990, Environment Canada.

Table 4.2

Churchill River at Churchill Falls Powerhouse

Environment Canada Hydrometric Station 03OD005

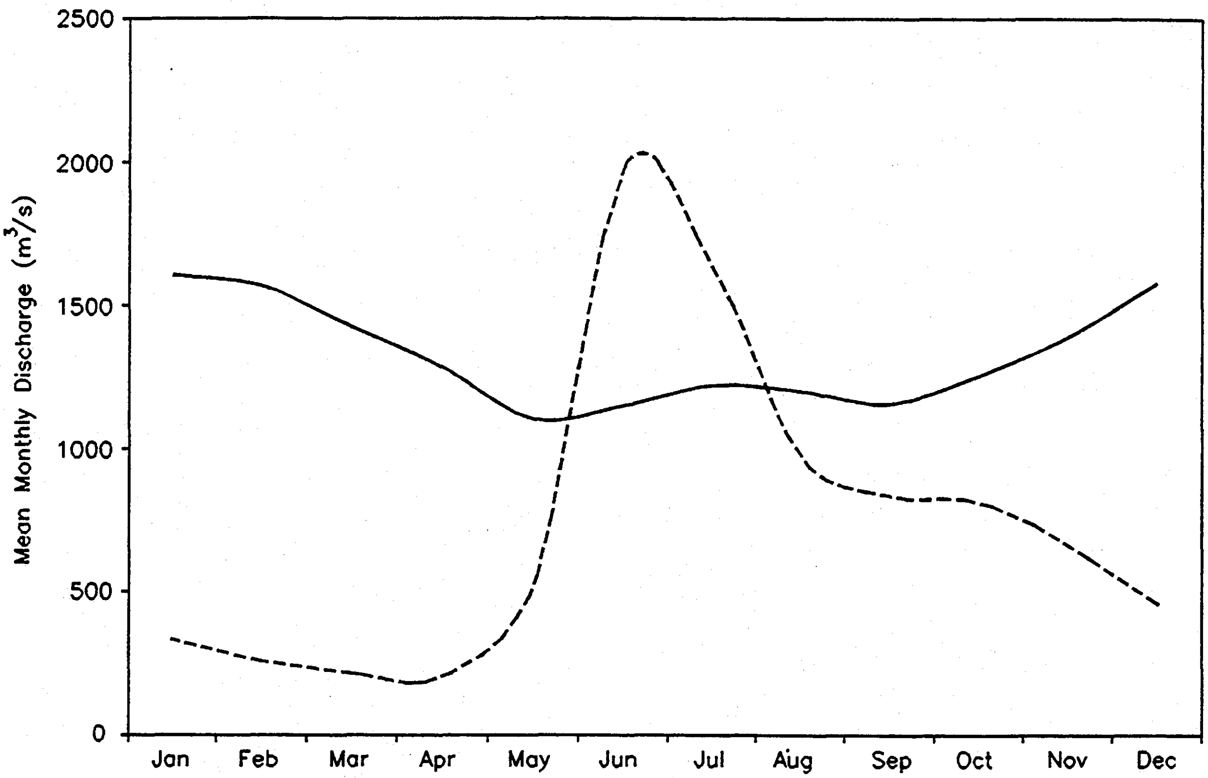
Year	Monthly Mean Discharges for Period of Record (m^3/s)												Mean
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1972	313	308	280	300	287	379	345	241	417	522	544	608	379
1973	1050	1090	634	549	394	533	506	526	660	672	680	846	676
1974	856	871	820	1490	890	1330	1030	892	1050	1100	1150	1290	1060
1975	1290	1260	1250	1220	1220	1610	1910	2080	1320	1320	1360	1410	1440
1976	1550	1380	1380	1370	1370	1530	1530	1370	1870	1840	1360	1530	1510
1977	1610	1470	1410	1560	1420	2410	1200	1300	1530	1920	1700	1900	1620
1978	1940	1900	1900	1790	1510	1270	1500	2340	1730	1600	1680	1850	1750
1979	1950	1950	1910	1760	1500	1150	2530	2170	1350	1700	1840	1680	1790
1980	1690	1760	1770	1720	1640	1450	1990	1600	1440	1570	1740	1950	1690
1981	1940	1810	1790	1420	944	1370	2530	1800	1500	1570	1920	1970	1720
1982	1980	1960	1950	1820	1410	1420	1380	1380	1240	1160	1420	1550	1550
1983	1640	1610	1490	1310	1100	1040	1080	1230	1250	1310	1610	1860	1380
1984	1880	1760	1760	1540	1370	1340	1300	1400	1370	1530	1720	1760	1560
1985	1780	1820	1650	1440	1190	1080	1070	1080	1120	1320	1460	1720	1390
1986	1760	1810	1640	1310	1120	1040	895	1020	1190	1300	1480	1750	1360
1987	1810	1770	1560	1080	1110	899	942	1130	1140	1270	1490	1680	1320
1988	1920	1900	1670	1120	917	-	1250	989	1070	1310	1390	1610	-
1989	1500	1480	1180	884	872	928	843	791	774	943	1260	1670	1090
1990	1780	1740	1260	885	820	870	982	1040	907	1100	1280	1390	1170
1991	1710	1540	1520	1290	954	904	888	842	852	866	1220	1400	1160
1992	1390	1400	1220	1100	909	842	933	914	1010	1140	1330	1700	1160
1993	1720	1750	1730	1590	1290	992	887	918	974	1070	1360	1510	1310
1994	1720	1760	1730	1590	1290	993	888	919	974	1060	1360	1510	1310
1995	1750	1720	1260	1200	1190	1140	1010	929	929	837	891	1550	1200
1996	1560	1310	804	688	808	978	1020	1040	1190	1290	1460	1690	1150
Mean	1604	1565	1423	1281	1101	1146	1218	1198	1154	1253	1388	1575	1323

Table 4.3

Churchill River at Flour Lake

Environment Canada Hydrometric Station 03OB002

Year	Monthly Mean Discharges for Period of Record (m³/s)												Mean
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1955	-	-	-	-	911	2230	1130	626	465	-	-	-	-
1956	-	-	-	-	-	-	2990	1770	1340	1390	1240	921	-
1957	542	273	176	181	342	2590	2730	1620	1270	1010	726	482	999
1958	414	377	326	332	786	2770	1660	911	999	832	598	419	869
1959	287	209	175	160	622	2470	1510	996	575	529	539	372	705
1960	274	213	172	147	420	2050	1110	1020	1140	1150	806	518	752
1961	361	301	261	263	741	1300	1240	742	446	611	641	399	610
1962	275	202	157	137	193	1570	1340	684	772	719	413	314	566
1963	237	184	148	139	308	1660	1140	772	628	554	493	305	549
1964	233	202	186	176	477	1880	1260	688	844	767	593	373	640
1965	280	235	214	208	388	1960	2100	1390	1300	1070	680	453	860
1966	343	268	219	194	402	2260	2100	1370	986	868	829	501	864
1967	335	257	214	206	427	1440	1070	858	646	616	719	476	606
1968	341	268	228	225	708	2110	1140	837	1140	1230	949	606	815
1969	418	327	280	254	380	1780	2300	1240	870	1010	758	553	850
1970	429	351	291	254	287	1660	2080	761	559	451	327	248	644
1971	197	162	137	135	854	1710	921	336	166	178	333	340	456
Mean	331	255	212	201	515	1970	1640	978	832	812	665	455	738



- - - - - CHURCHILL RIVER AT FLOUR LAKE (33 900 SQ. KM)

——— CHURCHILL RIVER AT CHURCHILL FALLS POWERHOUSE (69 200 SQ. KM)

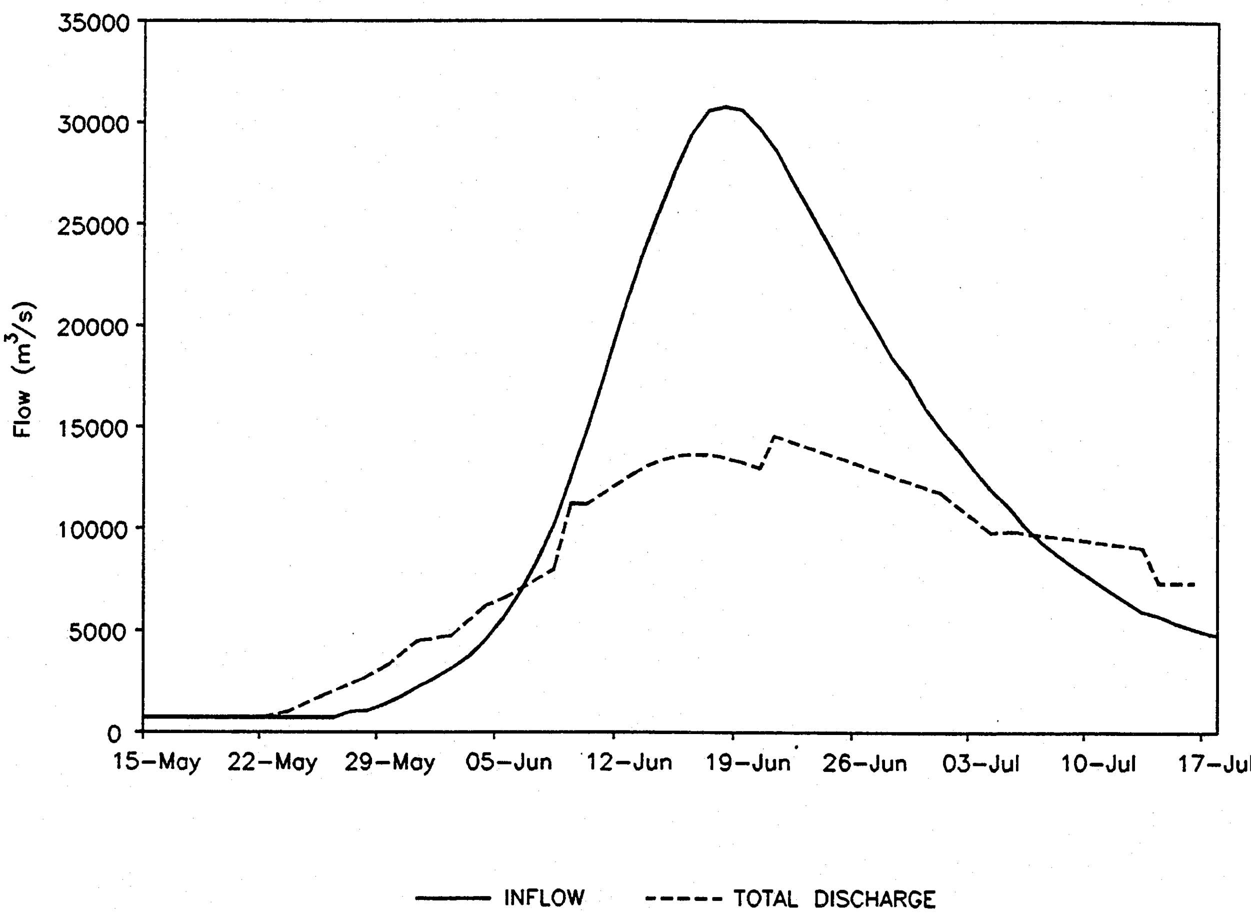
NEWFOUNDLAND AND LABRADOR HYDRO

CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

FIG 4.1

EFFECT OF REGULATION ON CHURCHILL RIVER AVERAGE MONTHLY DISCHARGES

ACRES



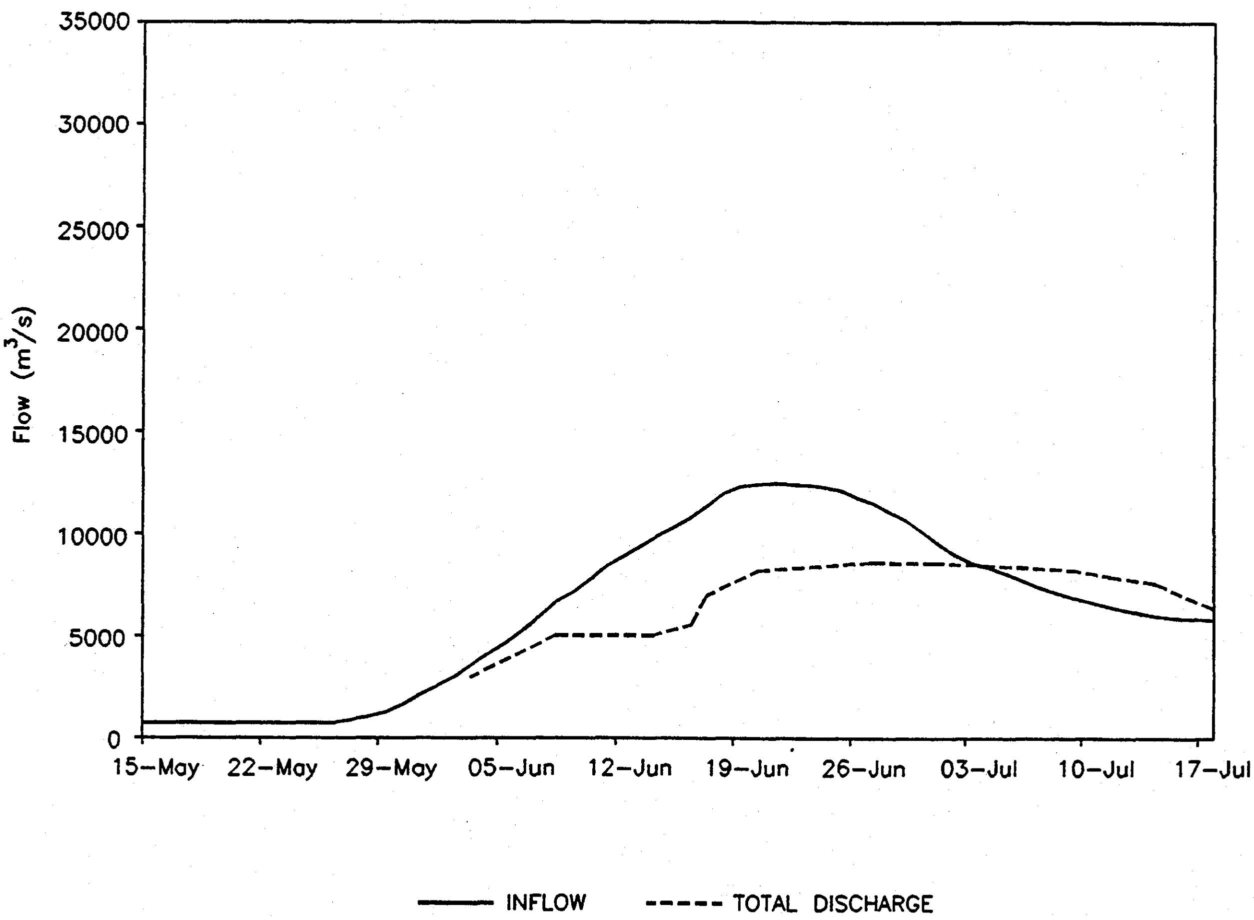
NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

UPPER CHURCHILL BASIN
PMF ROUTING

FIG 4.2

ACRES

SOURCE: FLOOD HANDLING STUDY, 1989

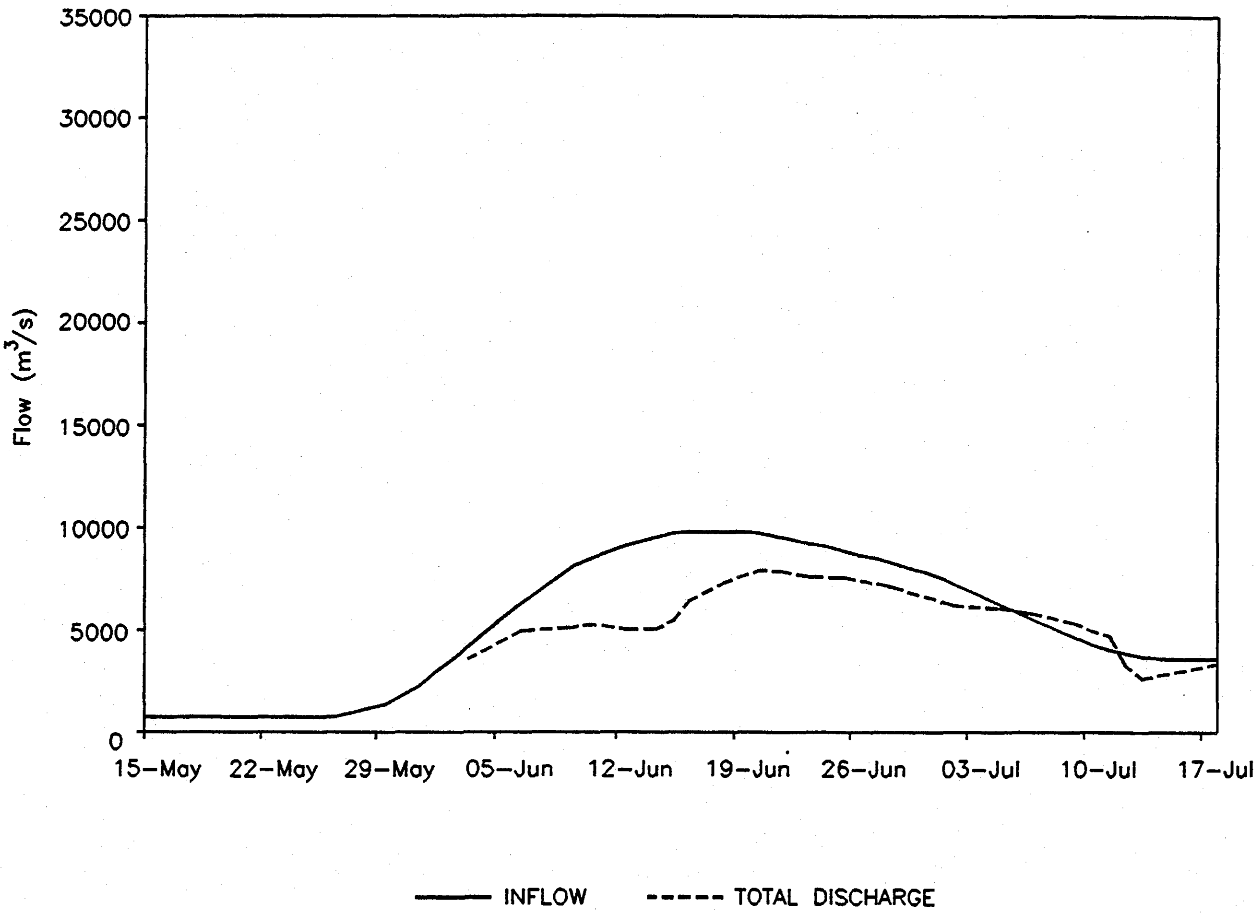


SOURCE: FLOOD HANDLING STUDY, 1989

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
UPPER CHURCHILL BASIN
10000–YEAR FLOOD ROUTING

FIG 4.3

ACRES



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
UPPER CHURCHILL BASIN
100–YEAR FLOOD ROUTING

FIG 4.4

ACRES

SOURCE: FLOOD HANDLING STUDY, 1989

Meteorology

5 Meteorology

5.1 General

The detailed report from AEB regarding the meteorological studies undertaken to derive the inputs to the SSARR model is included as Appendix A. A summary of the methods and results follows. The methodologies used by AEB to estimate the parameters were drawn from two major sources.

1. The Canadian Electrical Association's (CEA) reports on Probable Maximum Precipitation and Floods in Boreal Regions, by SNC-Shawinigan and Atria Engineering Hydraulic Inc. [11, 12] in 1994 and 1995.

2. The World Meteorological Organization's (WMO) Manual for Estimation of Probable Maximum Precipitation, second edition, published in 1986. [13]

The work was undertaken by the Atlantic Region Atmospheric Science Division, of AEB, under the guidance and review of Mr. William Hogg, of AEB in Downsview.

5.2 Precipitation

Two extreme precipitation sequences were required for the PMF analysis, the Probable Maximum Precipitation and the 100-year extreme precipitation.

The PMP study for the original Churchill Falls Project was done in 1969 by Sparrow using basically the same methodology as described in the current WMO manual. That analysis formed the basis for the Gull Island PMP done in 1975 and for the present study. The procedure examines historic storm events and then "maximizes" them to estimate the rain depth if all worst case conditions had combined.

The precipitation stations used in the selection of historic events are limited by the transposition area, the area with physiographic characteristics similar enough to the basin that it could experience the same events. AEB identified nine rain events between 1958 and 1998. Five of these events were used in the 1969 and 1975 studies.

The events were maximized using records at upper air data stations. The precipitable water available to the actual storm was compared to the 100-year precipitable water at the representative station. The ratio is used to factor up the storm precipitation.

For this study AEB derived maximization factors compared to the Sparrow work and used them to factor up the original depth-area-duration curve. Table 5.1 demonstrates the maximization process and Figure 5.1 shows the depth-area-duration curve from the 1969 study.

For the Lower Churchill Basin area, 21 500 km^2, the new PMP values are

- 24-hour = 133 mm;
- 48-hour = 174 mm; and
- 66-hour = 189 mm.

The 100-year basin average precipitation was estimated by comparing the estimated 100-year point precipitation at Churchill Falls and Goose Bay with point Hershfield (statistical) PMPs from the standard AEB station frequency analysis. The calculated ratio of 0.28 was applied to the PMP values given above to give the following values for the 100-year rain events.

- 24-hour = 37 mm;
- 48-hour = 49 mm; and
- 66-hour = 53 mm.

5.3 Temperatures

The CDA Guidelines recommend the use of two different temperature sequences in PMF analyses: a "severe" temperature sequence for combination with a severe snow accumulation and the spring PMP, and a "critically severe" temperature sequence for combination with the PMSA.

The CEA report on PMFs in Boreal Regions discusses the difficulty in generating critical temperature sequences for use in PMF studies. It recommends a procedure for including consideration of snow effects and regional effects on temperatures. There is no differentiation between a "severe" temperature sequence and a "critically" severe temperature sequence, and the temperatures are applied in combination with the extreme rainfall. Because of the difficulties in selecting temperature sequences, and to ensure that the PMF is sufficiently conservative, this study used a sequence derived using procedures similar to the CEA methodology, in both the PMP and PMSA cases.

A temperature sequence for maintaining a high snowpack and then maximizing snowmelt prior to the PMP was estimated by examination of historical temperature sequences during the snowmelt period. Maximum four, eight, and 16-day moving averages for all maximum and minimum daily temperature records in the region were calculated for the period April 1 to early June. Snow on the ground reduces air temperatures so only days when snow was present on the ground were used to calculate the highest maximum temperatures. Envelopes were drawn to encompass the maximums of each minimum and maximum sequence, as shown in Figure 5.2.

AEB constructed a 22-day temperature sequence with the following characteristics:

- minimum daily temperatures in the early part of the sequence below freezing to satisfy the recommended timing of the melt sequence to after the "last zero-crossing" day as recommended by the CEA report;

- a warm front followed by a cooler period of about 2 days prior to a major rain event. The peak melting temperatures would be associated with a warm front that would move into the region quickly;

- a maximum temperature over snow of 24°C, as recommended by the CEA report;

- a maximum temperature during a PMP of 16°C, as recommended by the WMO manual;

- a melt sequence which kept enough snow on the ground to be available for melt during the PMP;

- upper limit of the four, eight and 16-day envelopes could not be exceeded.

The critical sequence estimated by AEB is shown in Figure 5.3. Temperatures and precipitation from 1985, a moderate meteorologic year with fairly high runoff, were used as background values for this study.

5.4 Snowpack

Estimates of two extreme values of snowpack accumulation are required for PMF simulations, the 100-year snowpack and the PMSA.

The 100-year snowpack was estimated using a frequency analysis of regional snow courses. Twenty-one snow courses in Quebec and Labrador with periods of record of between 13 and 32 years were examined. Many of these snow courses are operated by CF(L)Co. and are located in the Churchill Basin, mostly in the upper basin. Two snow courses, Fig West and Metchin, are in the western side of the Lower Churchill Basin. The maximum snowpack reading, regardless of date, was noted for each year and a frequency analysis was carried out. The recorded snowpack at one of the snow courses, Esker, was extremely low in 1981. Inclusion of this data in the frequency analysis would lead to misleading results, so Esker was left out of the regional analysis.

The maximum annual snowpack water equivalent values varied between 140 mm and 660 mm water equivalent for the different years and snow courses. The 100-year snowpack estimates vary from 438 mm at Flour Lake to 708 mm at Churchill Falls Airport. Values for Fig West and Metchin Basin, the two snow courses in the lower basin, were 568 mm and 445 mm, respectively. The frequency analysis for Goose Bay Airport gave a 100-year snowpack of 543 mm. Table 5.2 lists the 100-year and 10 000-year snow water equivalent estimates for all the snow courses analysed.

An extrapolation of the frequency analysis to 10 000-year values, as an indicator of the PMSA, produced a range of values from 619 mm to 1122 mm for the various snow courses.

To more accurately assess the PMSA, a maximization analysis of snowfall during several peak years of record was undertaken. Historic snow events were maximized using the methodology described for the rainfall events in the PMP analysis. Snowfall data from six stations in the study area were assessed to determine the maximum snowfall years. These were the only stations in the area that collect the detailed data necessary for the analysis. Then each of the snowstorms within those years was maximized using upper air data to calculate maximum precipitable water available to the event. The results are shown in Table 5.3. The maximum measured snowpacks ranged from 345 mm of snow water equivalent to 592 mm. The same years with all snowstorms maximized produced snowpacks of between 404 mm and 868 mm water equivalent.

Because the snowstorm maximization technique is based on historic events rather than a pure statistical analysis, it is generally considered to provide more realistic results, and therefore the PMSA based on snowstorm maximization was used in the analysis.

5.5 Comparison with Previous Studies

Table 2.1 summarized the inputs and results from this and previous studies. The causes and relative effects of the differences in meteorologic parameters are discussed below.

The PMP used in both the 1969 and 1975 studies gave 213 mm of precipitation over three days in the Lower Churchill Basin. The present study by AEB produced a lower estimate of 189 mm. The same individual storms were used in the storm maximization process, however the use of upper air precipitable water, rather than surface dew points, to maximize those storms led to lower maximization factors. The present AEB study was carried out for the Lower Churchill Basin only. It seems likely, however, that a review of the maximization factors for the Upper Churchill Basin would also lead to a reduction in the upper basin PMP. That exercise was outside of the scope of the present AEB study.

The temperature sequence derived for this study is quite different from those used in the earlier studies. The 1975 and 1969 studies had sequences 16 days long with totals of 207 and 211 degree-days respectively. Both earlier studies included several days of warm temperatures after the PMP which would not contribute to the peak flow. The number of degree days before the PMPs are similar in all studies, ranging only from 104 for the present study to 128 for the 1969 study. Figure 5.4 shows the three temperature sequences.

Previous PMF studies have derived several different snowpacks.

1. The 1969 Upper Churchill Basin PMF study estimated a total maximum probable snowpack of 767 mm based on snowfall maximization. It was assumed that 683 mm would have fallen on or before May 1.

2. The 1975 Lower Churchill Basin PMF study estimated a maximum snow accumulation of 952 mm, again based on snowfall maximization.

3. The 1989 flood study reviewed the upper basin snowpack and estimated that the value used in 1969 was greater than a 10 000-year snowpack. The 100-year snowpack was estimated to be 536 mm using a frequency analysis of a synthetic snowpack series based on accumulated snowfall at four precipitation stations.

The current 100-year and PMSA snowpacks for the Lower Churchill Basin are similar to the values used in the upper basin studies. The PMSA value is lower than the value used in the 1975 lower basin study. The same basic methodology was used in both studies but more years were maximized in the present study. Also, the present study uses upper air precipitable water, rather than surface dewpoints, for maximization.

Table 5.1

Storm Maximization Procedure

From Atmospheric Environment Branch, Environment Canada

Storm Date	Maximum Storm Rainfall (mm)	Observation Station	Upper Air Station	Max PWC for Storm Date (mm)	100-Year PWC for Storm Date (mm)	Actual Storm PWC (mm)	Max Record / Actual	100-Year PWC / Actual	Sparrow Max Factor	DAD Modification Factor
Jun 13-15,1958	59	Knob Lake	Goose Bay	42	41	26	1.60	1.58	2.20	0.72
May 25-27,1961	81	Lake Eon	Sept Iles A	43	47	27	1.59	1.75	1.96	0.89
Jun 24-25,1962	53	Twin Falls	Goose Bay	42	41	30	1.39	1.37	1.98	0.69
May 26-29,1963	82	Nitchequon	Nitchequon	33	35	21	1.60	1.71	1.97	0.87
May 24-25,1964	87	Wabush Lake	Sept Iles A	43	47	37	1.16	1.28	1.43	0.89
Jun 1-2,1975	69	C Falls A	Sept Iles UA	43	47	37	1.15	1.27	-	-
Jun 13-14,1978	53	Wabush A	Sept Iles UA	43	47	31	1.39	1.53	-	-
Jun 27-28,1978	59	C Falls A	Sept Iles UA	43	47	32	1.36	1.50	-	-
Jun 26-28,1980	81	Goose A	Sept Iles UA	43	47	35	1.24	1.36	-	-

Key

PWC - Precipitable Water Content
UA - Upper Air
Sparrow - 1969 Meteorology Study for Upper Churchill Basin
DAD - Depth Area Duration

Table 5.2

Snowpack Water Equivalent Frequency Analysis

Adopted from Atmospheric Environment Branch, Environment Canada

Snow Course Location	Period of Record	Years	Snow Water Equivalent (mm)	
			100-Year	10 000-Year
Goose Bay	1962-94	32	543	838
Churchill Falls A	1968-93	22	708	1122
Churchill Falls	1972-98	25	544	700
Wabush	1972-98	25	533	719
Schefferville A	1968-94	24	529	870
Esker *	1972-98	24	781	2111
Fig West	1972-98	24	568	813
Metchim Basin	1972-98	23	445	619
McPhayden	1972-98	25	477	705
Orma Lake	1972-98	25	569	807
Michikimats	1972-98	25	633	845
McKenzie Basin	1972-98	21	557	843
Lobstick	1972-98	25	530	796
Simms	1972-98	25	506	714
Twin Falls	1968-98	26	600	869
Flour Lake	1959-72	13	438	665
Anderson	1972-98	25	500	745
Kepimits	1972-98	25	504	773
Lac Joseph	1972-98	25	484	667
Lac Long	1972-98	24	491	664
Seahorse	1972-98	25	523	742

* Low outliers in this data series produce unreasonably high extreme snowpacks. This snow course was not used in the analysis.

Table 5.3

Winter Storm Maximization Summary

From Atmospheric Environment Branch, Environment Canada

Station		Study Years				Maximum
		1971-72	1976-77	1980-81	1982-83	
Churchill Falls	Measured	506	474	446	527	
	Maximized	662	607	589	648	662
Schefferville	Measured	430	562	592	442	
	Maximized	551	722	784	558	784
Wabush Lake	Measured	567	516	507	535	
	Maximized	737	659	672	660	737
Goose Bay	Measured	422	441	552	528	
	Maximized	568	591	736	647	736
Nitchequon	Measured	251	429	374	346	
	Maximized	336	580	489	404	580
Sept Isles	Measured	590	396	476	327	
	Maximized	868	542	667	424	868
Maximum	Measured	590	562	592	535	
	Maximized	868	722	784	660	868

MAXIMIZED SPRING RAINSTORM DEPTH-AREA-DURATION VALUES CHURCHILL RIVER DRAINAGE BASIN (MARCH THROUGH JUNE)

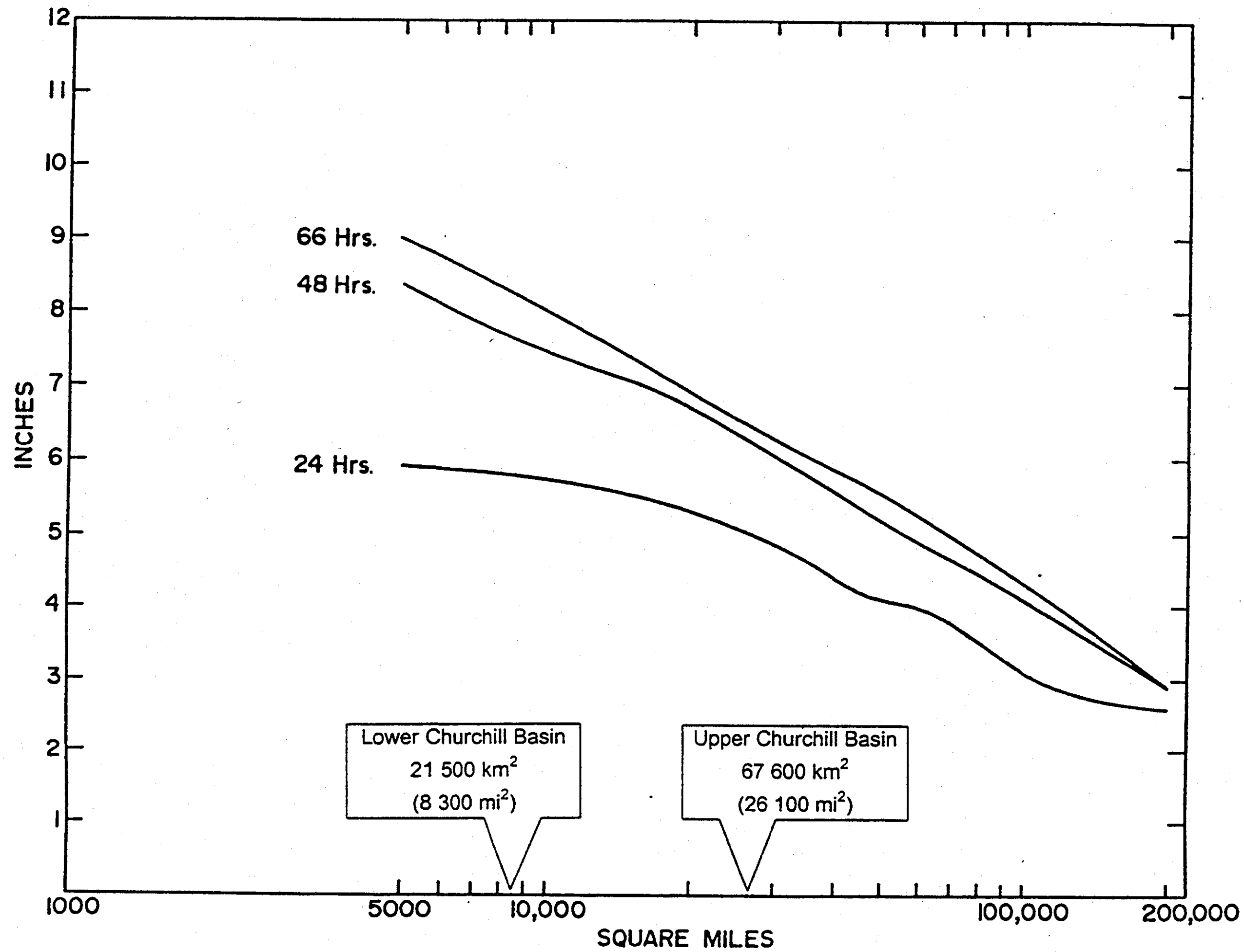
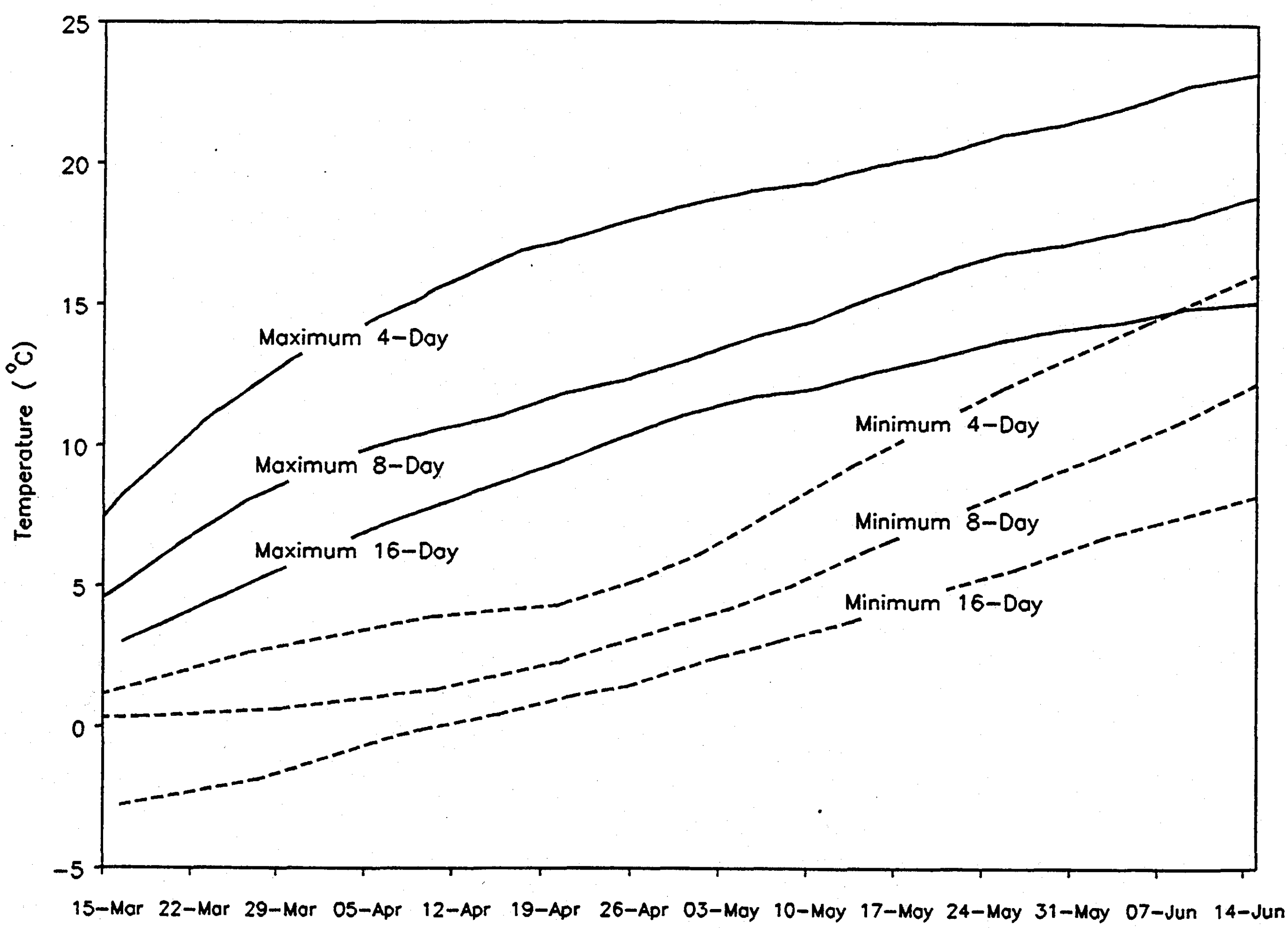


FIG 5.1

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
DEPTH–AREA–DURATION CURVES

ACRES

SOURCE: ATMOSPHERIC ENVIRONMENT BRANCH, ENVIRONMENT CANADA

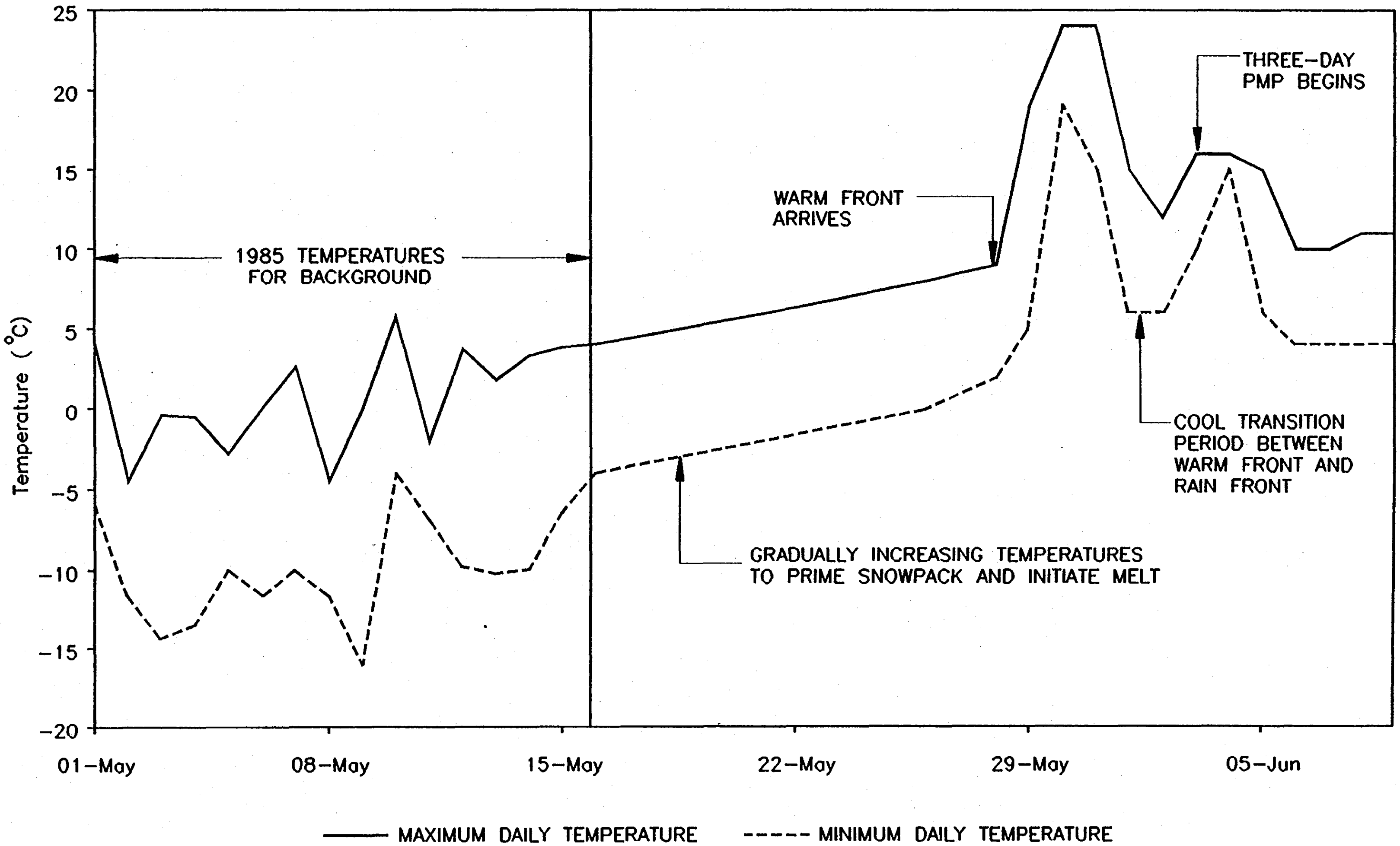


NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
MAXIMUM TEMPERATURE ENVELOPES

FIG 5.2

ACRES

SOURCE: ATMOSPHERIC ENVIRONMENT BRANCH, ENVIRONMENT CANADA



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

FIG 5.3

TEMPERATURE SEQUENCE FOR LOWER CHURCHILL BASIN PMF

ACRES

SOURCE: ATMOSPHERIC ENVIRONMENT BRANCH, ENVIRONMENT CANADA

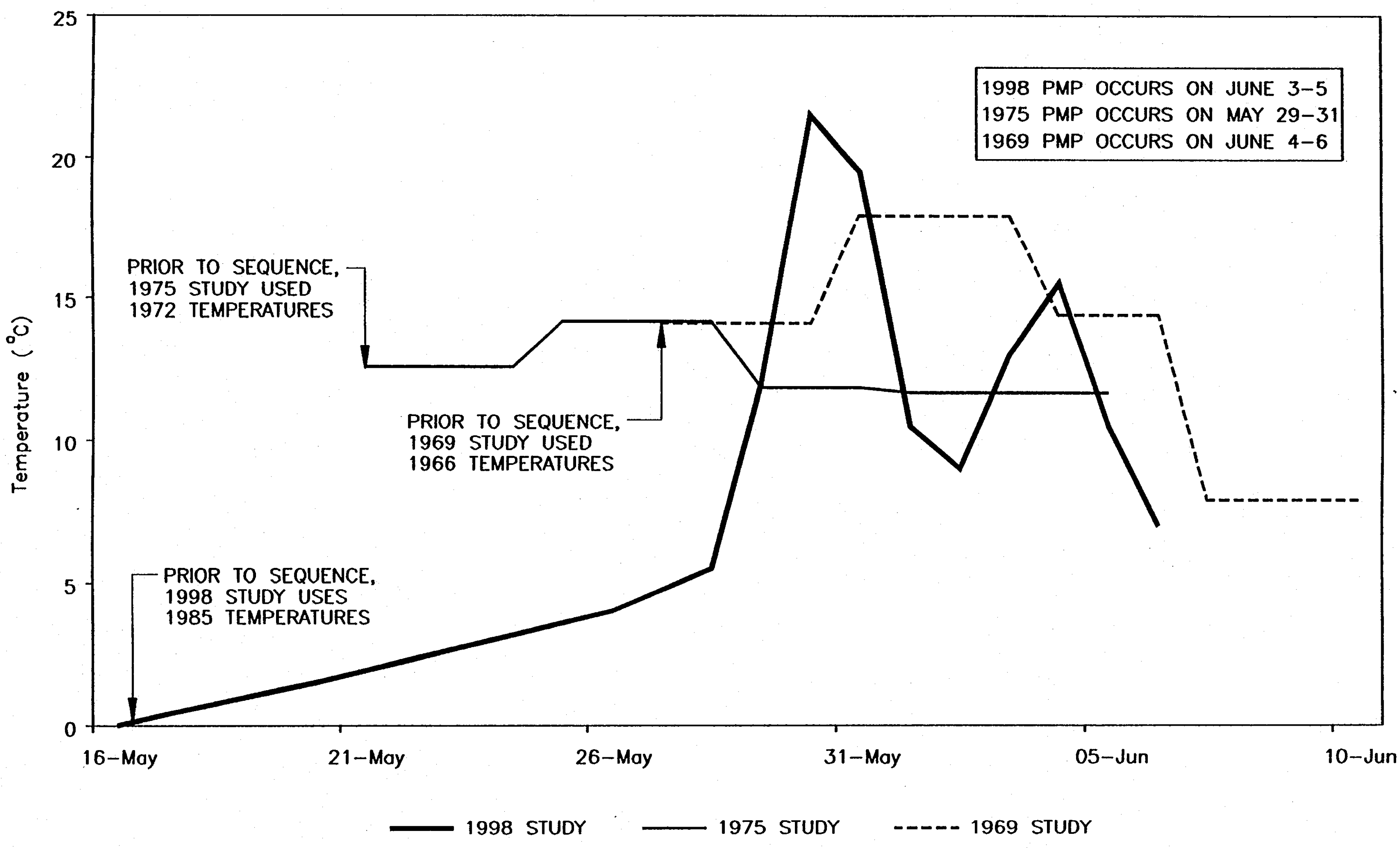


FIG 5.4

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

TEMPERATURE SEQUENCE COMPARSION

ACRES

Lower Churchill Basin Watershed Model

6 Lower Churchill Basin Watershed Model

6.1 SSARR Model

A watershed model of the Lower Churchill Basin was created using the SSARR Model.

SSARR was originally created in 1956 by the North Pacific Division of the U.S. Army Corps of Engineers "to provide mathematical hydrologic simulation for systems analysis as required for the planning, design, and operation of water control works"[14]. Continuous modifications since that time have added operational river forecasting and river management tools. SSARR has been used worldwide for operational forecasting and flood studies and is used by many Canadian utilities. The current release is SSARR-8, dated January 1991.

The current study used the watershed model portion of SSARR to simulate rainfall and snowmelt runoff. The model takes into account snowpack cold content, liquid water content and seasonal conditioning when calculating snowmelt. Interception, evapotranspiration, soil moisture, baseflow infiltration, and routing of runoff into the stream system are accounted for. Since snowmelt was expected to be a significant portion of the PMF flow, the integrated snowband option of SSARR was used. The integrated snowband model allows calculation of precipitation, snow accumulation or melt, and runoff from a series of elevation bands to more accurately account for changes in snowpack response with elevation.

Some of the key inputs to SSARR are:

- meteorological data, particularly temperature and precipitation at one or more locations in the basin;
- relationships or constants to describe losses such as evapotranspiration, and interception;
- initial conditions for each elevation band, including snowpack water equivalent and soil moisture;
- relationships to describe the rate of snowmelt as a function of accumulated and daily temperature and precipitation;

- hydrologic parameters to describe the allocation of generated runoff to surface, subsurface, lower zone and baseflow pathways; and,

- the routing characteristics to describe the various runoff pathways.

A flow chart of the model, reprinted from the SSARR manual, is included as Figure 6.1.

6.2 Lower Churchill Model

The SSARR model contains many variables and relationships input by the user to describe the watershed. The significance of the values selected for each of the parameters depends on the basin and the application of the model.

The user first sets up the SSARR model using typical values of the parameters or values based on judgement of the modeler and knowledge of the watershed characteristics. During the calibration process, the user compares flows calculated by the model, using historic temperature and precipitation information, to measured flows from the same period. The values of the watershed parameters are adjusted until the modelled output matches the recorded flows, within accepted tolerances.

Initial values for the various parameters in the Lower Churchill Basin model were chosen from the following sources

- defaults listed in the SSARR manual;

- values suggested in additional material provided by the SSARR developer;

- values used in the example SSARR models listed in the CEA Boreal Regions PMF report;

- values used in other applications.

Since the proposed developments at Gull Island and Muskrat Falls are so close to one another, and are both essentially run-of-river, the SSARR model was set up using only one basin. The modelled basin has an area of 21 500 km^2 and represents an area from the Churchill Falls Powerhouse, at the upstream end, to an arbitrary location on the Churchill River about half way between Gull Island and Muskrat Falls. The local area from Churchill Falls to Gull Island is 19 800 km^2 and to Muskrat Falls is

23 100 km^2. The SSARR results are factored by 0.922 to obtain the flows at Gull Island and by 1.074 to obtain the flows at Muskrat Falls.

The snowmelt season was modelled from April 1 to September 30 using a 6-hour compute period. Six snowbands were used to model the basin. Table 6.1 lists the areas and elevations of each band.

6.3 Calibration

Calibration of the Lower Churchill SSARR model used meteorologic and flow data for the years 1980 to 1984, inclusive. Figures 6.2 to 6.6 show the estimated basin average temperature and precipitation and the calculated local Lower Churchill hydrographs for those years.

Initial calibration was done using a 24-hour compute period and the fine tuning was done with a 6-hourly compute period. It is important to calibrate with the compute period to be used in the final simulations, since some variables are time dependent.

Since only daily, rather than hourly, meteorologic parameters are available from AEB, hourly temperature values were calculated using a sinusoidal pattern to convert reported maximum and minimum values to hourly sequences giving minimum temperatures at 6:00 a.m. and maximum temperatures at 4:00 p.m.. Values for the 6-hourly compute periods were then taken from the hourly sequence. Daily values of precipitation were divided evenly over the four 6-hour intervals so as not to artificially place the precipitation consistently in one temperature period.

Temperature and precipitation data from both the Churchill Falls and Goose Bay stations were input to the model. The data were weighted to represent the fact that most of the basin is at an elevation similar to Churchill Falls. Since the temperature and precipitation are similar at the two stations, the results are not sensitive to the chosen weighting.

The snowpack initial conditions on April 1 were estimated by examination of the snowpack data at Goose Bay, Fig West, Metchin Basin, and Churchill Falls snow courses. If no snowpack measurement was taken within three days of April 1, an estimate was made by linearly interpolating between the nearest earlier and later measurements. Snowpack initial conditions for each of the six snowbands were estimated from the four stations as shown in Table 6.2.

Initial conditions for other parameters such as soil moisture and snow cold content were estimated by first running the model for one of the calibration years with zero values and then using the end of April values as initial conditions at the beginning of April in subsequent runs. Starting the calibration simulations in April rather than May allows the conditions to self-adjust prior to the key snowmelt sequence. Sensitivity checks were done on the most important initial conditions. These are reported in Chapter 7.

Initial simulations of the calibration years with the default or typical values of the watershed characteristics gave hydrographs which were

- too flashy - each spring had four to five peaks rather than the one peak observed; and

- too late - peak runoff did not occur until September rather than in May as observed.

To improve the simulation, the following changes were made to the model parameters.

1. The melt rates and cold rates were altered. The observed local runoff starts to increase as soon as the temperature in the basin rises above zero and melt continues rapidly, seemingly almost independent of temperature, after the initial warming. Three changes were made to model this phenomenon. First, the die-away coefficient on the antecedent temperature index was increased so that prior temperature has more effect on the selected melt rate. Second, the melt rates were increased. Third, the cold rates, which is a measure of the snowpacks heat deficiency, was decreased. Of these three factors, the melt rates have the most effect on the runoff. A maximum value of 0.46 cm/°C-day was used.

2. The number of routing phases and the storage times were increased for each zone. An increase in the number of phases and the times of storage of each phase reduced the flashiness to give smoother single-peaked hydrographs more similar to those observed.

Figures 6.7 through 6.11 show the final calibration plots annotated with summaries of the modelled volumes and peaks. Copies of the SSARR input and output files for one calibration year and a record of the calibration process are included in

Appendices B and C. The final calibrated model gives peaks 95 percent to 123 percent of the actual values and volumes 88 percent to 121 percent of the actual values.

Given the lack of data for the basin, and the fact that even the "actual" flows are calculated from two series of hydrometric records, this is considered a good calibration.

Comments on each of the calibration years follow.

1980 - One of the best years of calibration. The rising limb of the hydrograph is early, but overall the peak and volume are well matched with less than 5 percent discrepancy.

1981 - The timing of the hydrograph is good, but the first peak is underestimated and the second is overestimated. The volume is within 2 percent of the actual, but the peak is 20 percent above actual. This is probably caused by a delay in modelled snowmelt.

1982 - The actual hydrograph shows a gradual increase in runoff but the model predicts two peaks separated by a period of constant flow. The second peak is of similar flow to the actual, but is delayed. The volume of the predicted runoff is 7 percent below actual but the peak is within 1 percent of actual.

1983 - Worst year of the calibration period. The actual hydrograph suggests that snowmelt happened earlier than usual. The latest snowpack reading at most snow courses was in mid-April, at which time the snowpack was at its maximum and was the highest of all the years used in the calibration and verification process. The lack of a later measurement makes it hard to verify when the snowmelt actually occurred. SSARR models the early peak quite well but then models a second peak later in May with a similar peak and more volume. The modelled peak is 12 percent below actual but the seasonal volume is 23 percent above the actual. It appears that the model is melting snow in late May that in actuality was not available for melting. It is unusual that the year of highest snowpack has a lower than average peak and volume of spring runoff.

1984 - SSARR models an early May peak which is not seen in the actual flows, but the remainder of the hydrograph is well matched. A review of the climate data shows that there was a period of warm temperatures in early May but the snowpack must have not been sufficiently primed to melt at that time. Both peak and volume estimates are within 5 percent of the actual values.

6.4 Verification

Adjustments to the various SSARR parameters during calibration led to a single set of values that produced the results shown for years 1980 - 1984. Three years, 1985, 1986 and 1987 were simulated with no additional alterations to the SSARR model to verify the calibration. The initial snowpacks were calculated using the same method as used for the calibration. The verification simulations showed good agreement with the observed hydrographs, as shown in Figures 6.12 to 6.14. Maximum discrepancies were 6 percent in peak and 12 percent in volume.

Table 6.1

SSARR Model Snowbands

Lower Churchill Basin

Snowband	Elevation Range	Average Elevation	Percentage of Basin Area	
			Band	Cumulative
1	30 to 150 m	90 m	3%	3%
2	150 to 300 m	225 m	3%	6%
3	300 to 370 m	335 m	10%	16%
4	370 to 460 m	415 m	48%	64%
5	460 to 610 m	535 m	34%	98%
6	610 to 760 m	685 m	2%	100%

Table 6.2

Lower Churchill Basin Initial Snowpack Conditions

Presented as Snow Water Equivalents (mm)

Year	Snow Courses				Elevation Bands						Weighted Average
	Goose Bay El. 38 m	Metchin El. 357 m	Churchill Falls El. 457 m	Fig West El. 480 m	1 3% El. 90 m	2 3% El. 225 m	3 10% El. 335 m	4 48% El. 415 m	5 34% El. 535 m	6 2% El. 685 m	
1980	203	264	390	402	203	233	264	396	396	396	372
1981	245	277	384	376	245	261	277	380	380	380	362
1982	198	272	338	331	198	235	272	335	335	335	321
1983	213	326	497	487	213	270	326	492	492	492	460
1984	364	392	467	444	364	378	392	456	456	456	444
1985	239	275	342	318	239	257	275	330	330	330	320
1986	54	279	286	296	54	167	279	291	291	291	279
1987	190	225	233	228	190	208	225	231	231	231	228
100-Year	543	445	626	568	543	494	445	597	597	597	577
10 000-Year	838	619	911	813	838	729	619	862	862	862	833
PMSA	736	737	662	784	736	737	737	723	723	723	725

Notes

1. Missing years were estimated by comparison with other snowcourses.
2. Not all snowcourses were read on April 1, the closest value or interpolation was used as an estimate.
3. Snowpacks estimated as follows:
   - Band 1 = Goose Bay
   - Band 2 = Average of Goose Bay and Metchin
   - Band 3 = Metchin
   - Band 4 = Average of Fig West and Churchill Falls
   - Band 5 = Average of Fig West and Churchill Falls
   - Band 6 = Average of Fig West and Churchill Falls
4. Churchill Falls Frequency analysis presented is the average of two snow courses.
5. Schefferville and Wabush substituted for Fig West and Metchin in PMSA estimates.
6. Calibration simulations require April 1 snowpacks, whereas extreme value simulations require May 1 snowpacks.
7. Percentages for each snowband indicate portion of total basin area.

*SSARR

Moisture Input Calculation
One Snowband for One Compute Period:

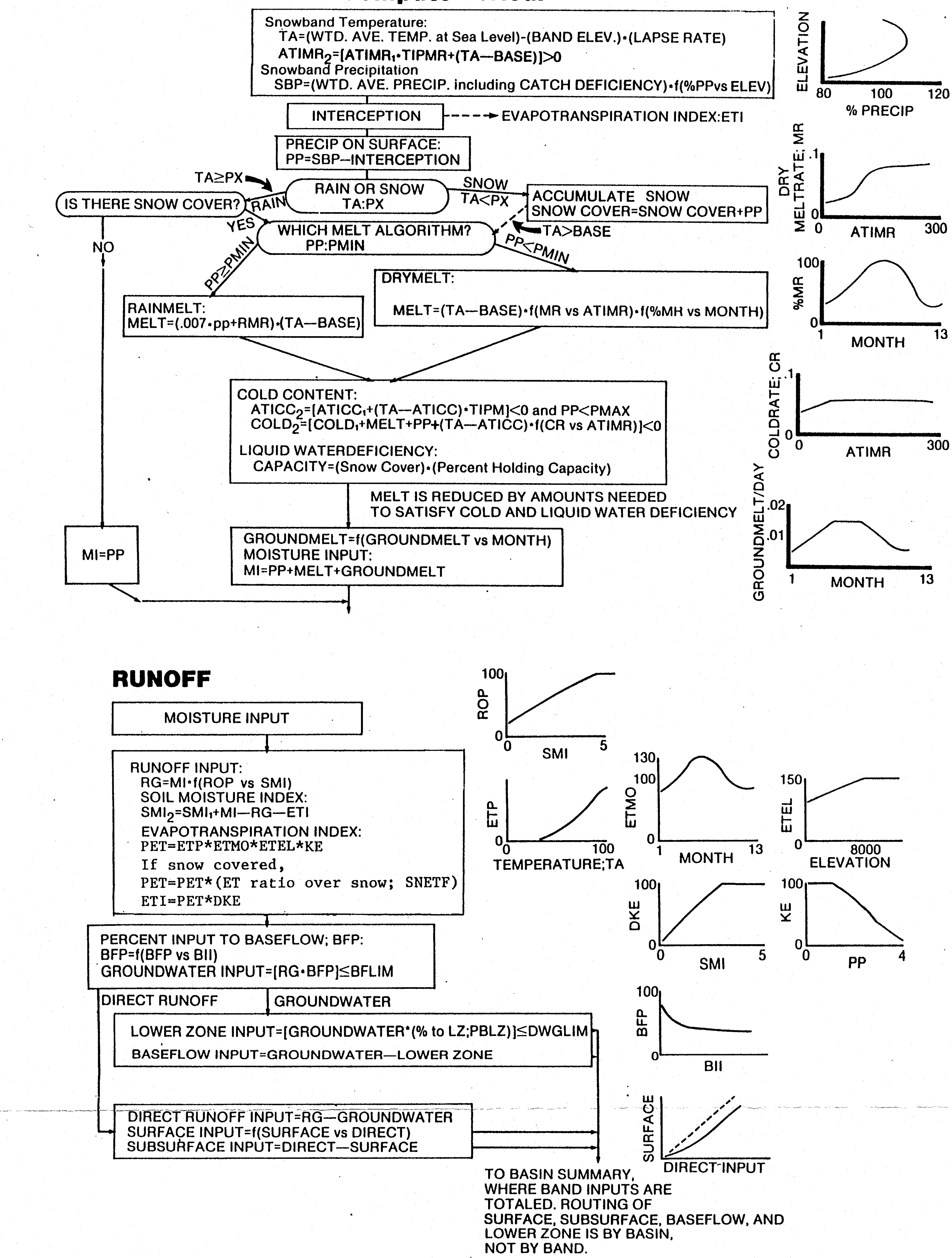


FIG 6.1

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX
PMF REVIEW AND DEVELOPMENT
SSARR METHODOLOGY SCHEMATIC

ACRES

SOURCE: SSARR USERS MANUAL, 1991

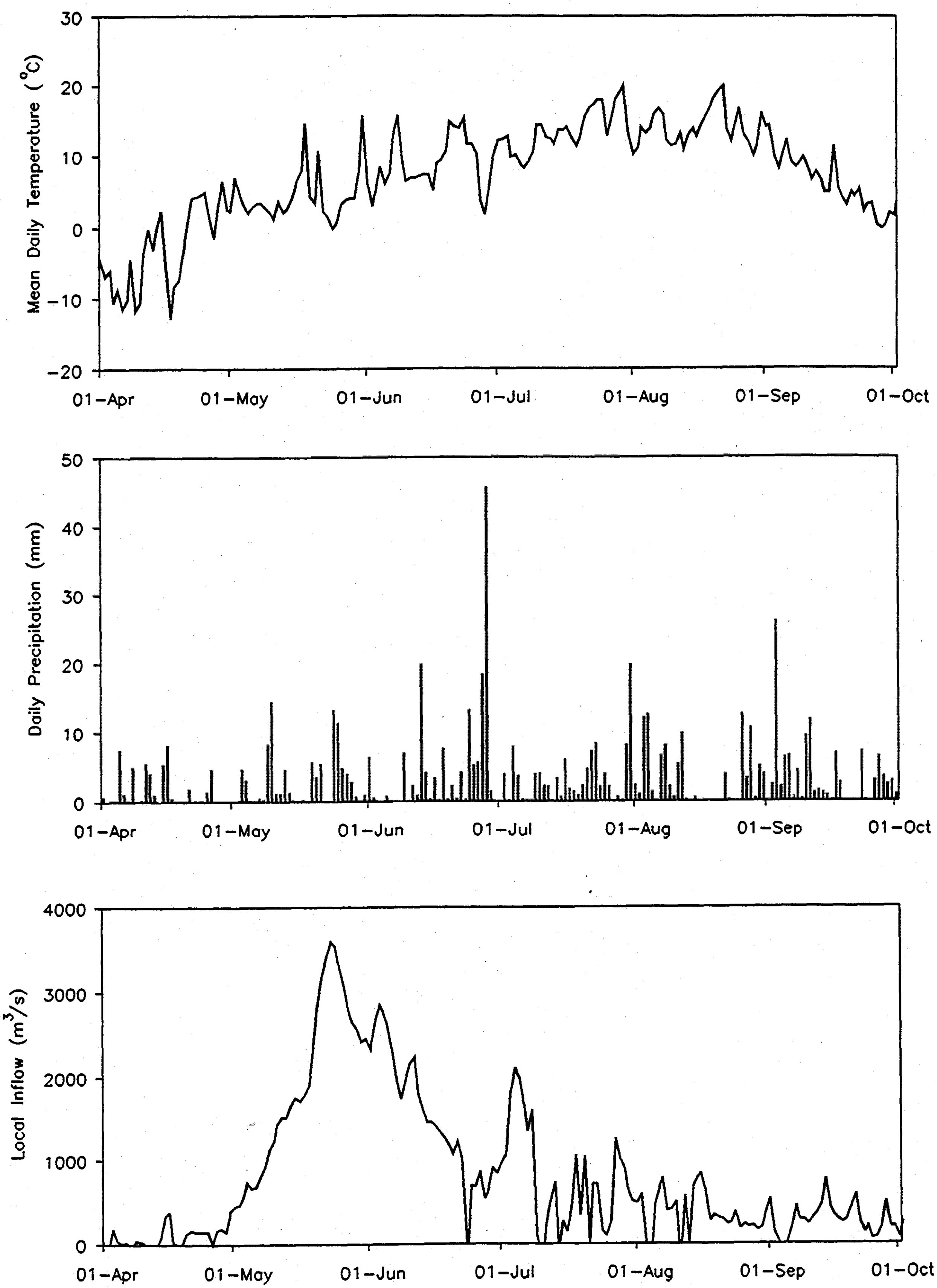


FIG 6.2

NEWFOUNDLAND AND LABRADOR HYDRO

CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

ESTIMATED 1980 LOWER BASIN HYDROLOGY

ACRES

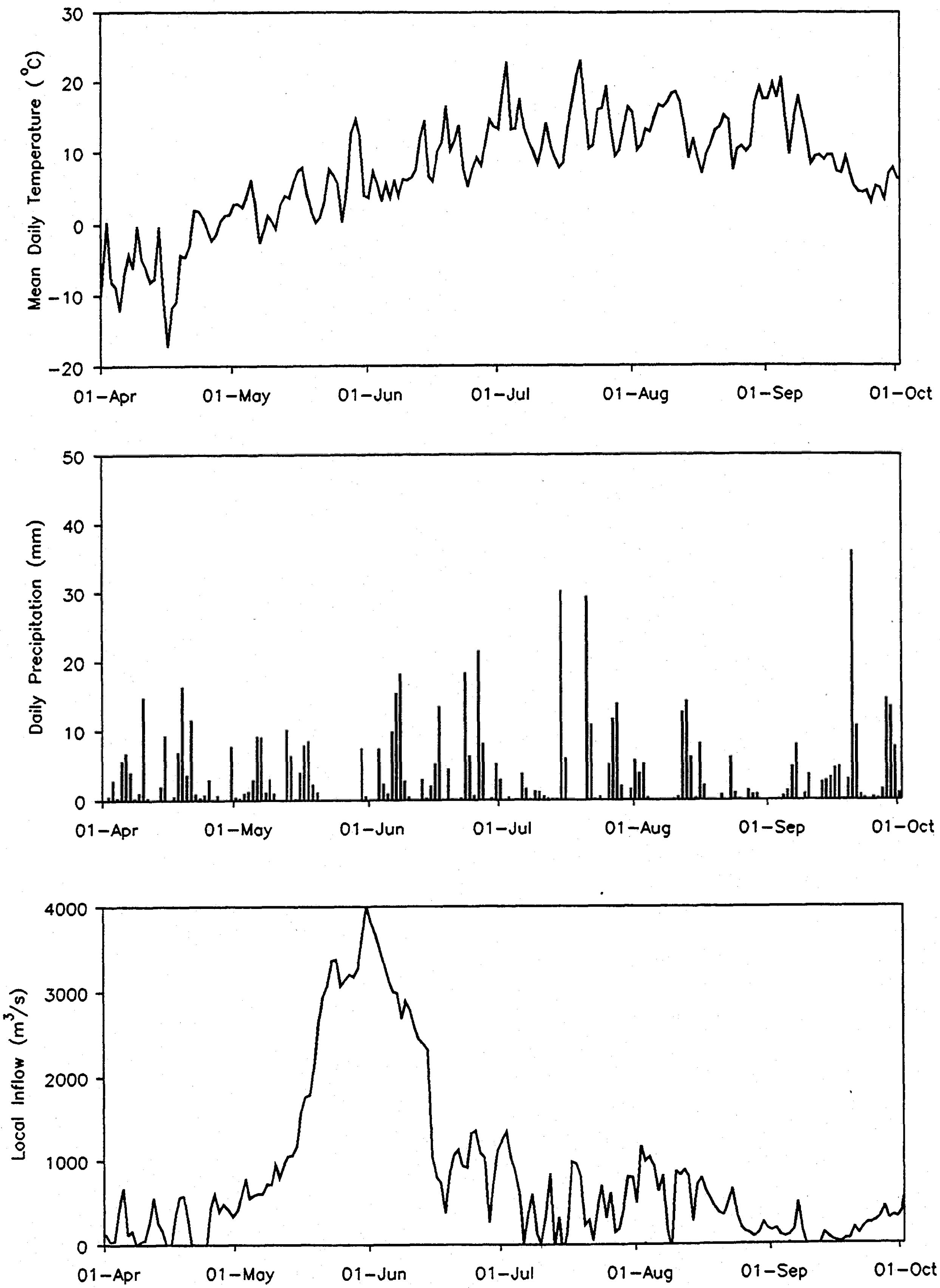


FIG 6.3

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX − PMF REVIEW AND DEVELOPMENT
ESTIMATED 1981 LOWER BASIN HYDROLOGY

ACRES

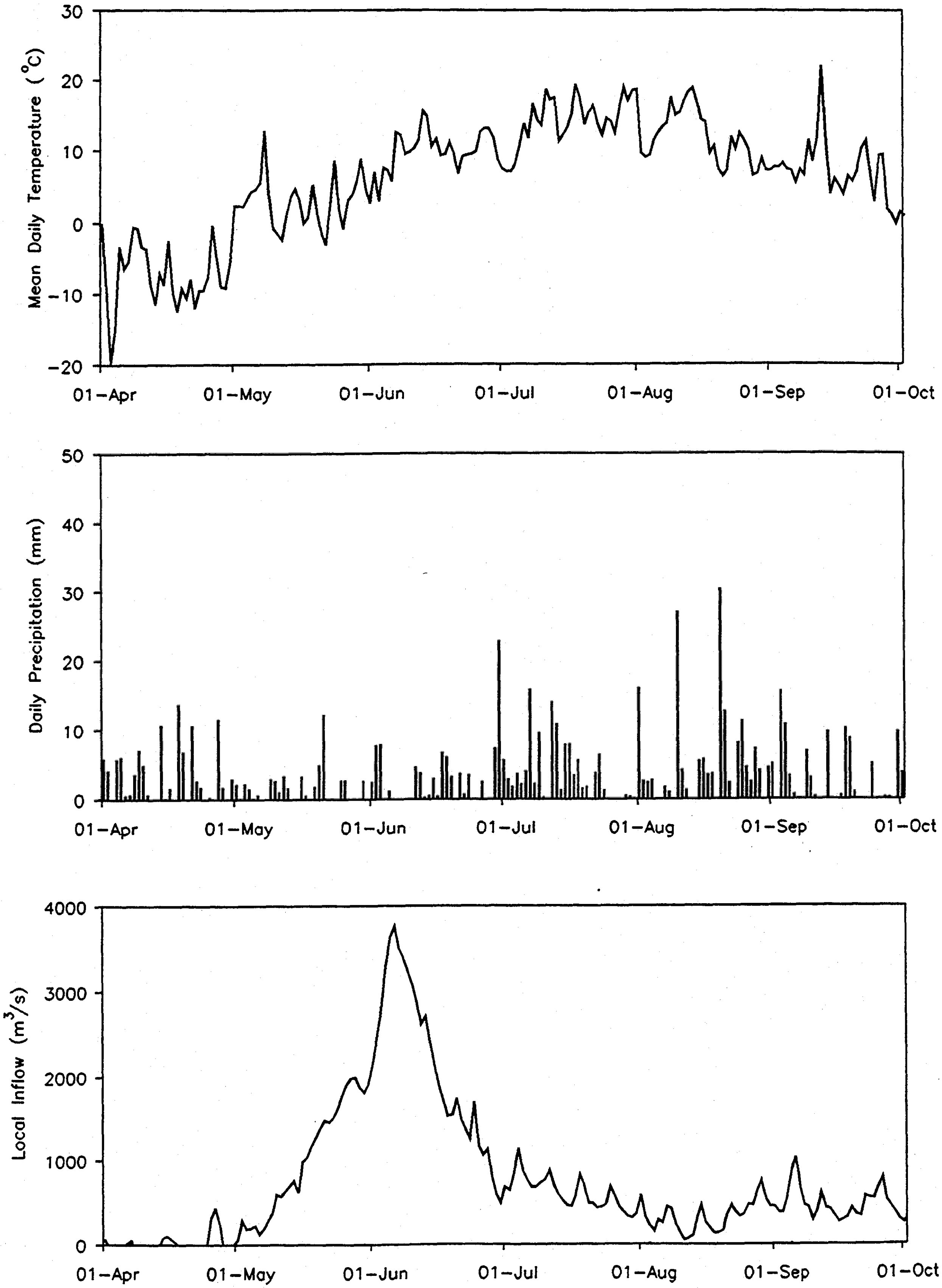


FIG 6.4

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
ESTIMATED 1982 LOWER BASIN HYDROLOGY

ACRES

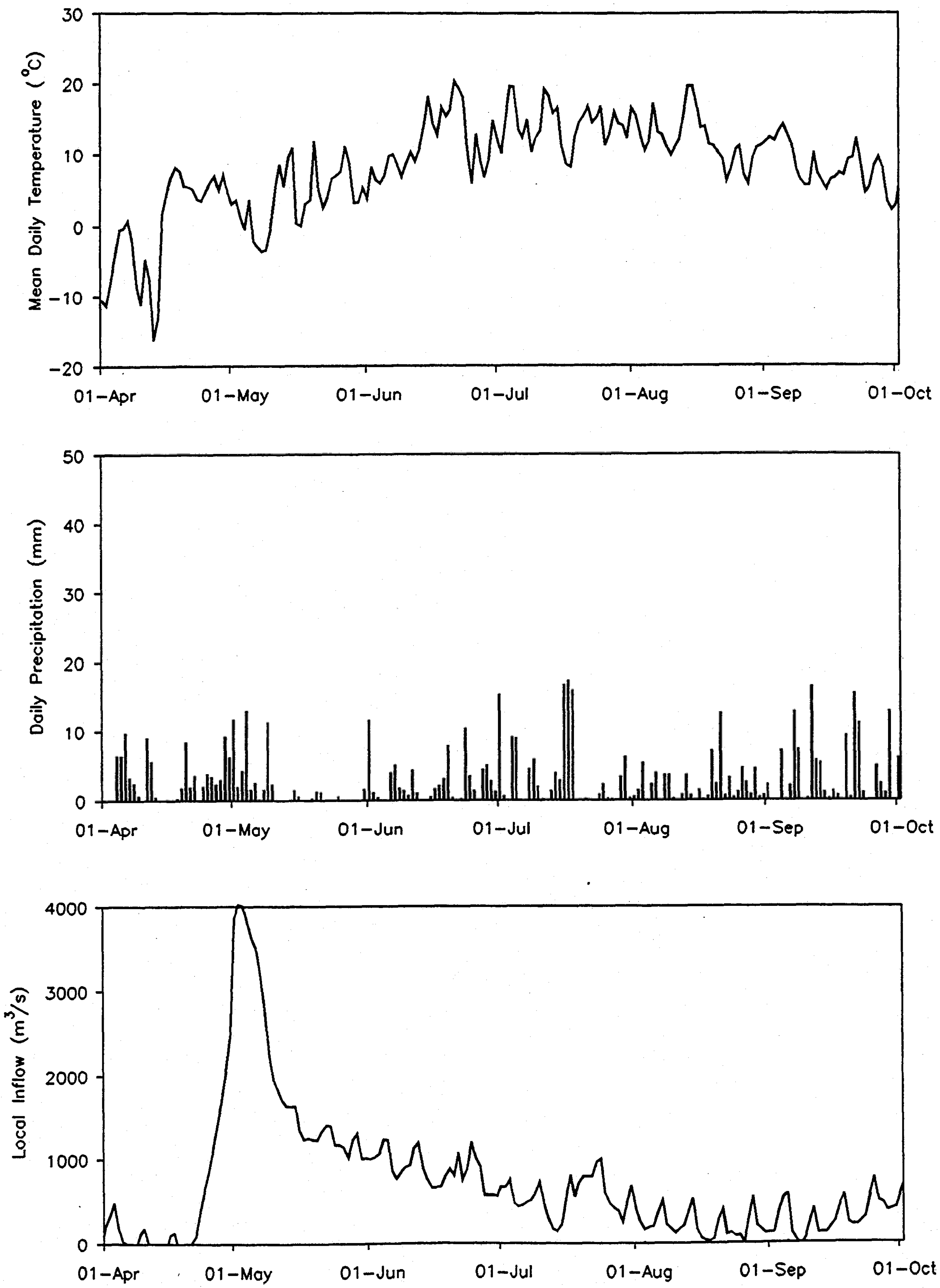


FIG 6.5

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
ESTIMATED 1983 LOWER BASIN HYDROLOGY

ACRES

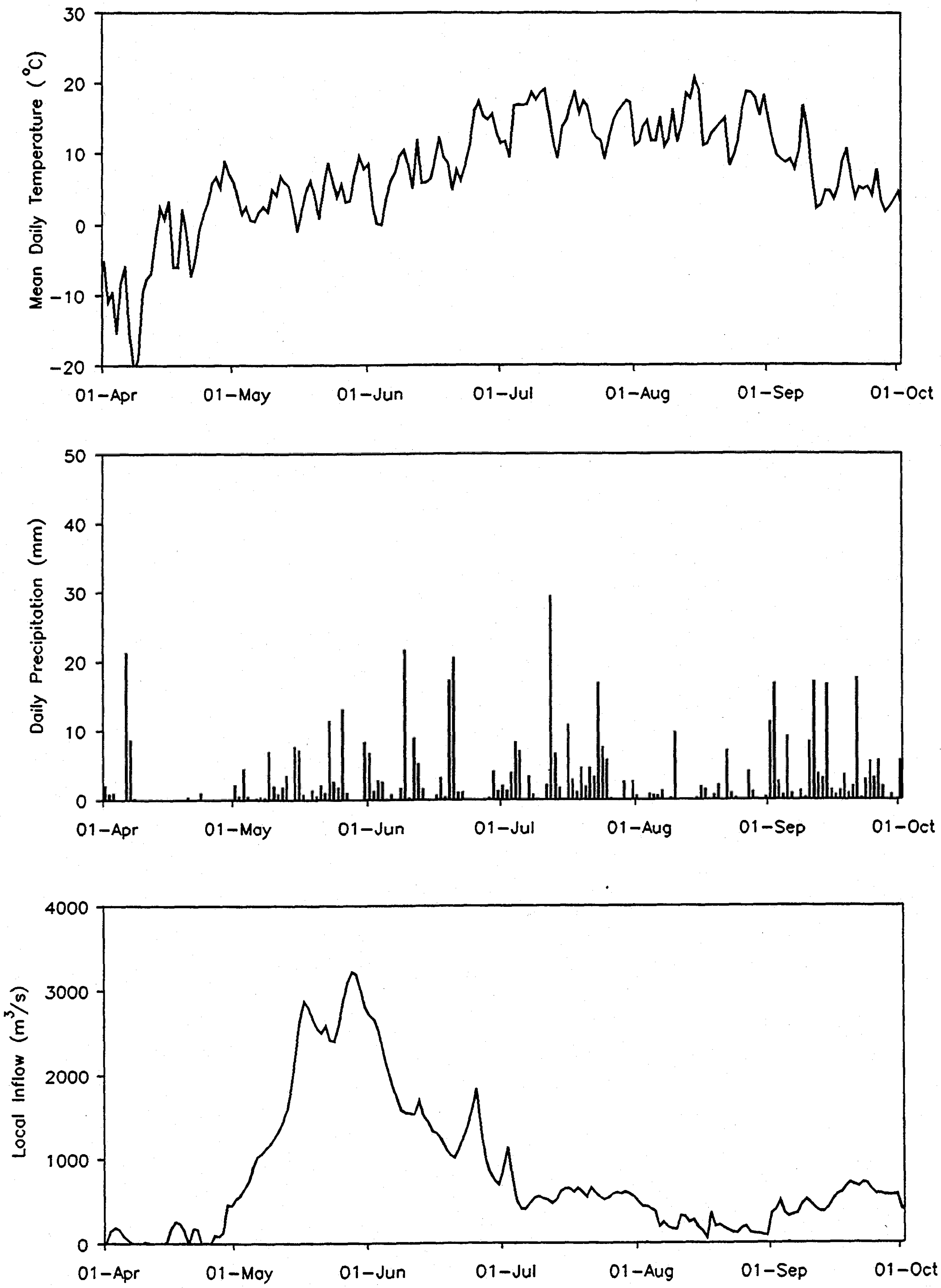


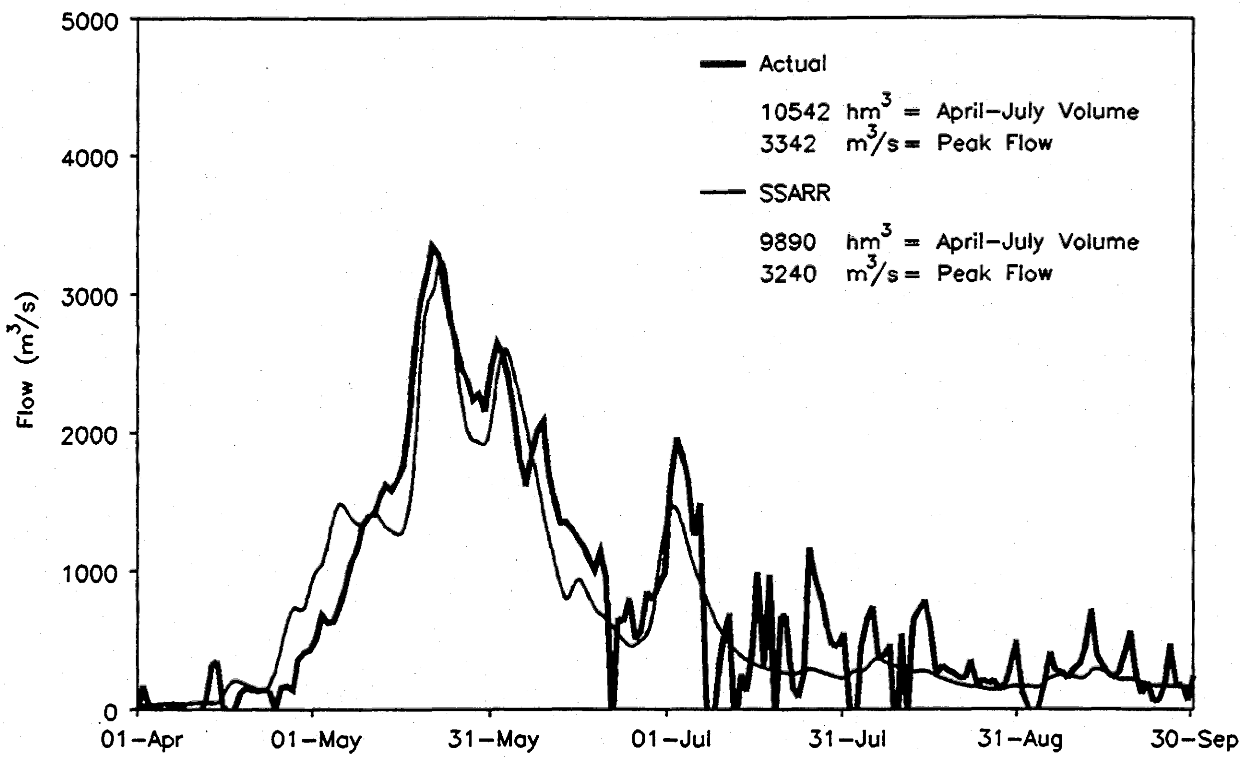
FIG 6.6

NEWFOUNDLAND AND LABRADOR HYDRO

CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

ESTIMATED 1984 LOWER BASIN HYDROLOGY

ACRES

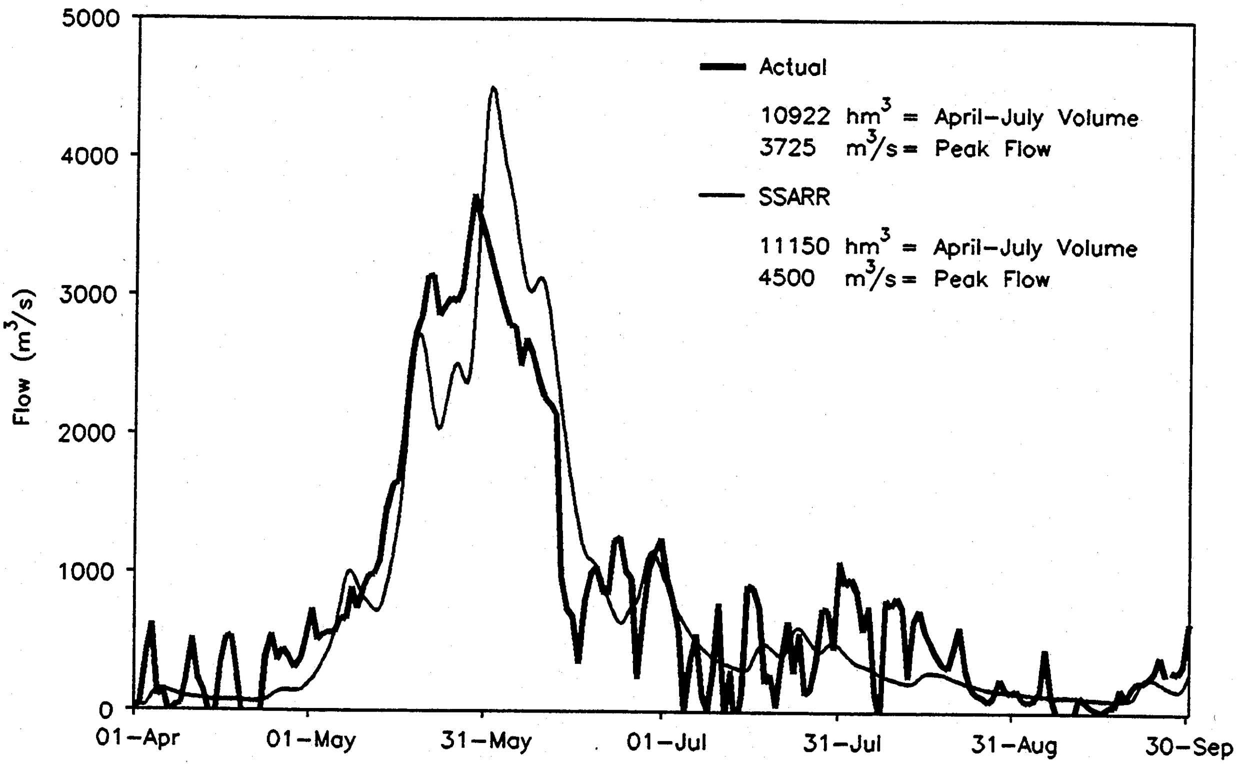


NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

SSARR MODEL CALIBRATION
1980 LOWER CHURCHILL BASIN INFLOWS

FIG 6.7

ACRES

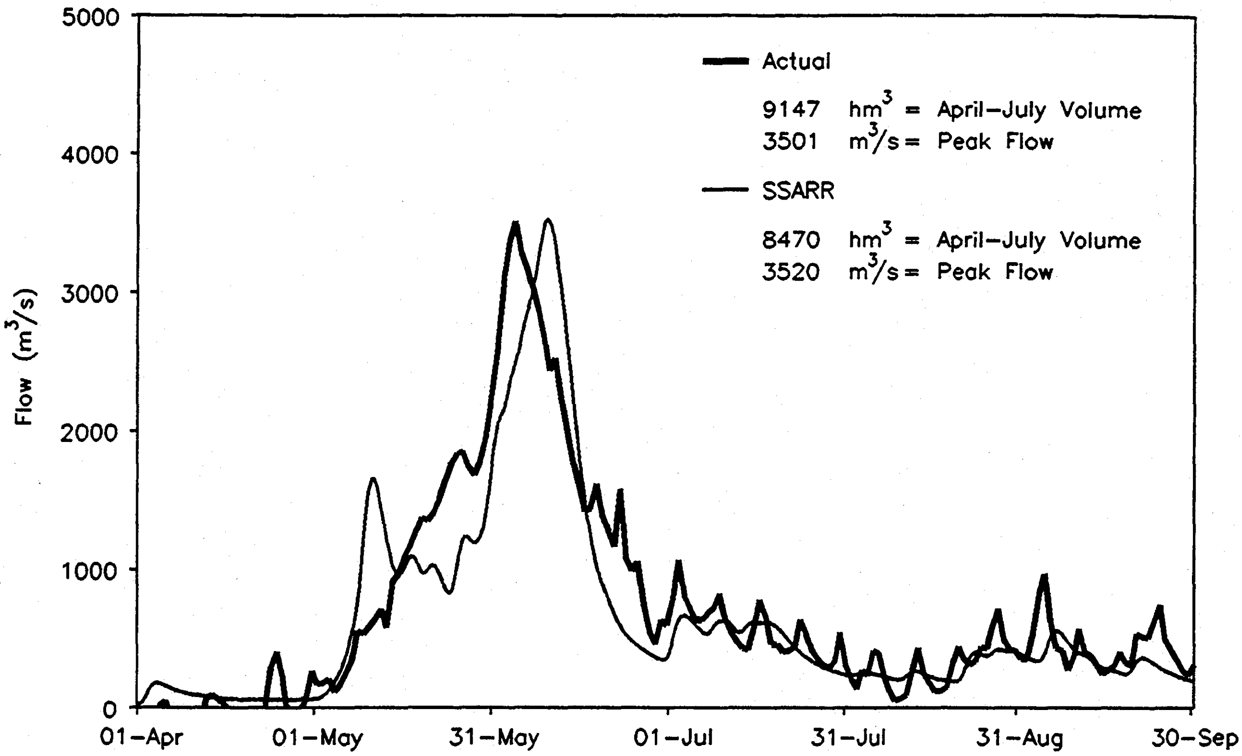


NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

SSARR MODEL CALIBRATION
1981 LOWER CHURCHILL BASIN INFLOWS

FIG 6.8

ACRES

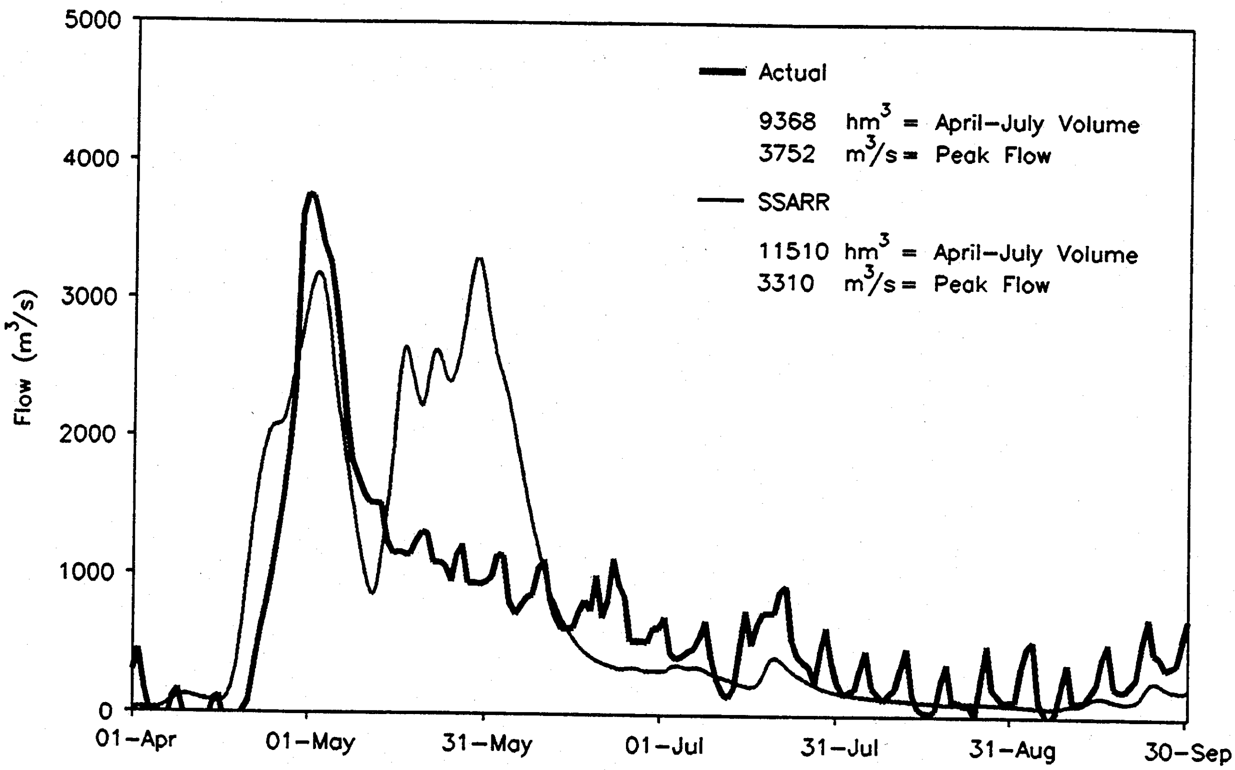


NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

FIG 6.9

SSARR MODEL CALIBRATION
1982 LOWER CHURCHILL BASIN INFLOWS

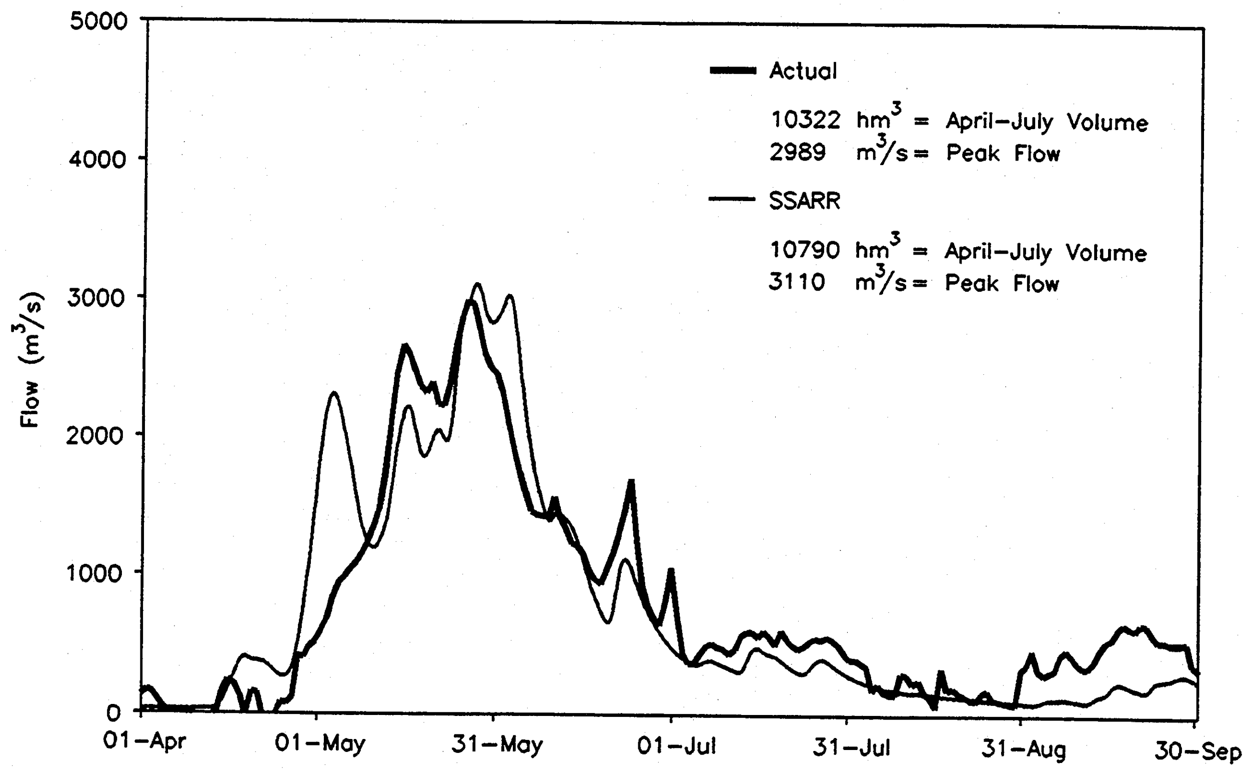
ACRES



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

FIG 6.10

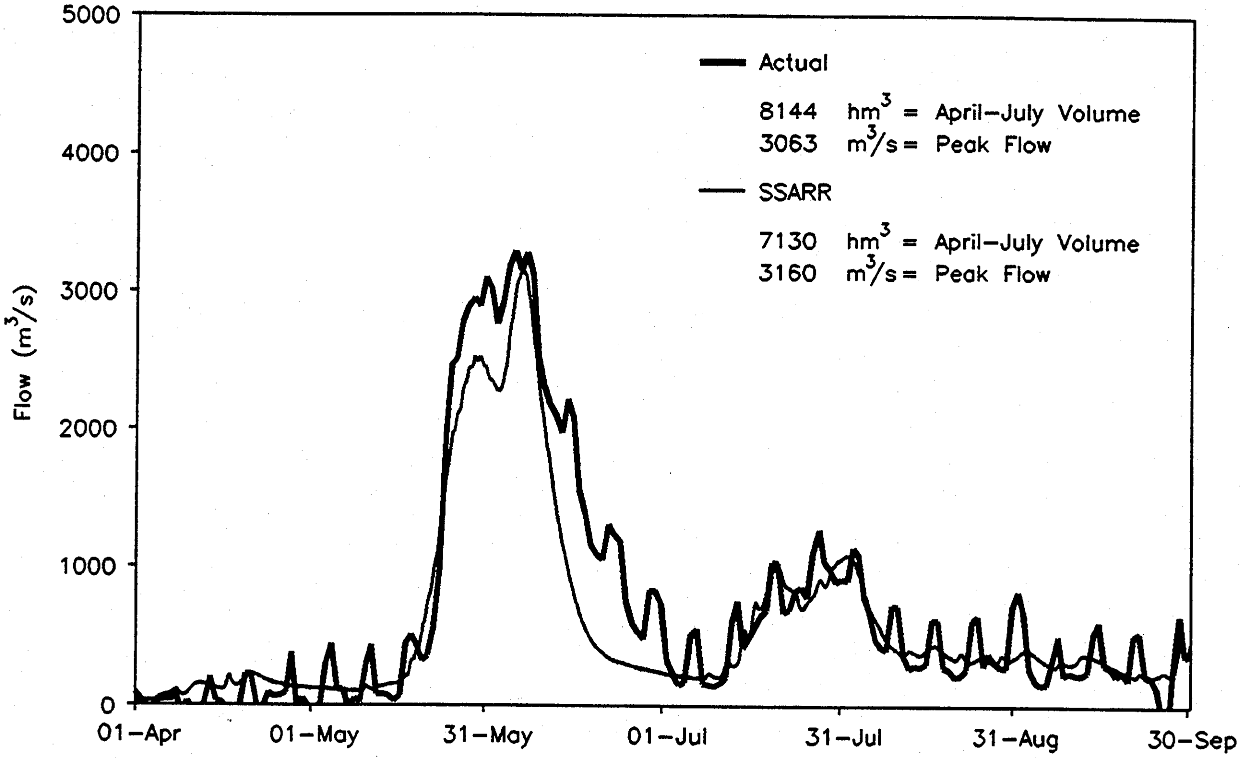
SSARR MODEL CALIBRATION
1983 LOWER CHURCHILL BASIN INFLOWS



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
SSARR MODEL CALIBRATION
1984 LOWER CHURCHILL BASIN INFLOWS

FIG 6.11

ACRES

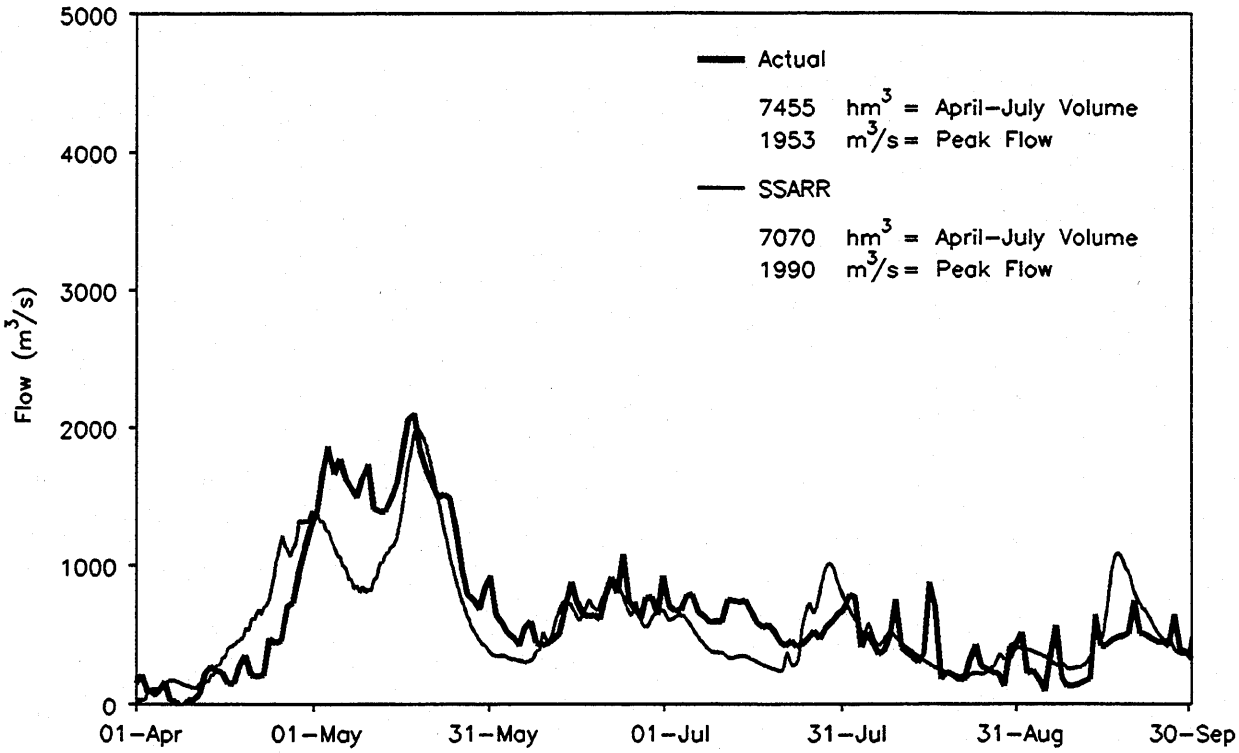


NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX - PMF REVIEW AND DEVELOPMENT

SSARR MODEL VERIFICATION
1985 LOWER CHURCHILL BASIN INFLOWS

FIG 6.12

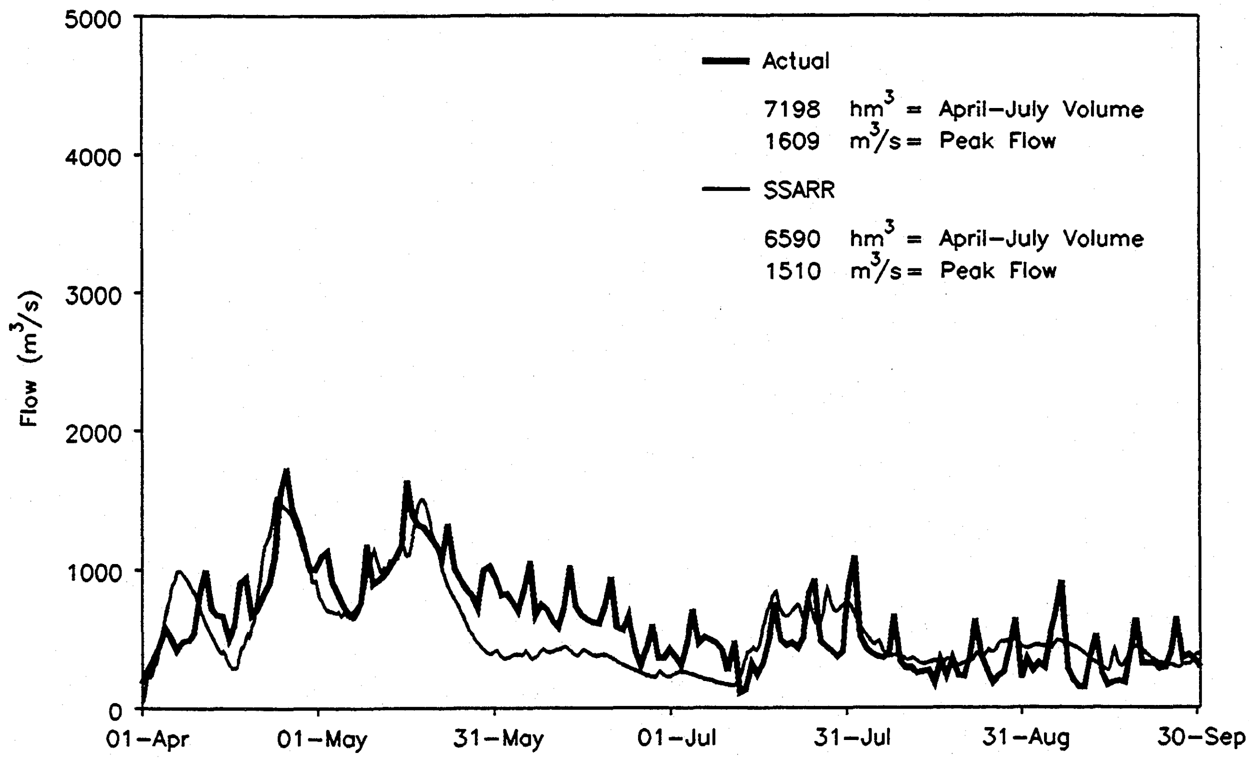
ACRES



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
SSARR MODEL VERIFICATION
1986 LOWER CHURCHILL BASIN INFLOWS

FIG 6.13

ACRES



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX - PMF REVIEW AND DEVELOPMENT

SSARR MODEL VERIFICATION
1987 LOWER CHURCHILL BASIN INFLOWS

FIG 6.14

ACRES

PMF Simulations

7 PMF Simulations

7.1 General

The calibrated SSARR model was run with various values of the extreme meteorological inputs and the watershed parameters. These simulations have two main purposes

- to test various meteorological alternatives to determine which gives the highest flow and is therefore the PMF; and

- to estimate the confidence limits of the PMF by determining how sensitive the results are to the assumptions in the parameters.

The first of these sets of simulations is discussed in Chapter 7.3. Once the governing scenario had been determined, the second set of simulations was run by varying the values in the governing case to test the sensitivity. These simulations are discussed in Chapter 7.4.

7.2 Meteorologic Input

The basic meteorologic information was provided by AEB and is described in Chapter 5 and Appendix A. The remainder of this Chapter explains how the information was interpreted for use in the PMF SSARR simulations.

Rainfall
The basic SSARR precipitation data files were set up with historic 1985 values. Six-hourly precipitation estimates were made by dividing the daily precipitation into four even values. While this assumption is not strictly representative, it does not affect the results of the study.

During the 22-day critical meteorological sequence, the only rain that occurs is the PMP. The PMP values provided by AEB were for 24, 48 and 66-hour durations. These values were transformed to 6-hourly rainfall depths using the depth-duration curve provided in the WMO Probable Maximum Precipitation Manual, as shown in Figure 7.1. Figure 7.2 shows the base case distribution of the 6-hourly rainfall increments. Other distributions which moved the peak period of rain to the second and third days of the sequence were considered during the simulations. Table 7.1

shows the PMP calculations. Table 7.2 shows the precipitation values used for each 6-hour period in the 22-day simulation.

Temperatures

The SSARR temperature data files were set up with historic 1985 values. AEB only reports maximum, minimum and mean daily temperatures so 6-hourly temperatures were estimated from the maximum and minimums.

In PMF simulations, the historic temperatures for the duration of the critical meteorologic sequence were replaced by the temperatures provided by AEB. For most of the sequence, 6-hourly values were estimated from provided maximums and minimums. AEB provided 6-hourly temperatures for the warm front and rain period since the full duration of the temperature variance during that time would not follow the normal diurnal pattern. The 6-hourly temperatures for the critical period are shown in Table 7.3

Figure 7.3 shows the temperature and precipitation values used for the full duration of the PMF base case simulation.

Snowpack

May 1 100-year snow water equivalent estimates and for each snowband were derived from the snow course frequency analysis in the same way as the historic April 1 values were estimated during the calibration process. The estimates are shown in Table 6.2. This leads to a 100-year lower basin average snowpack of 577 mm and a 10 000-year snowpack of 833 mm.

The PMSA for each snow band was estimated from the snowfall maximization results. The location of the stations used for the PMSA estimates were different than those used for the annual and 100-yr estimates, since climate, rather than snow course, information is used in the PMSA technique. The estimated PMSA for the Lower Churchill Basin is 725 mm. This estimated value is less than the extrapolated 830 mm 10 000-year snowpack. Since the snowstorm maximization technique considers real events and the limits on potential snowfall within those events, it is generally considered to give a more realistic result than the statistical extrapolation.

7.3 PMF Cases

Each PMF case is made up of selected values for the following parameters

- the total extreme precipitation and the arrangement of the values of 6-hour precipitation values within the three day period;
- the depth of the snowpack on the simulation start date;
- the temperature sequence of given duration and pattern, used to replace the values in the "background" historic temperature sequence;
- the contribution from the Upper Churchill Basin, i.e. the power flow and spill.

Table 7.4 lists the various cases examined and the peak flows resulting from each simulation. The SSARR model gives the local Lower Churchill Basin PMF. The upper basin contribution is added independently.

Figure 7.3 shows the full sequence of meteorology used in Case 1, the base case. The background temperature and precipitation are historic values from 1985. The PMF sequence is substituted for the historic values between May 16 and June 6. The base case PMF hydrograph is shown in Figure 7.4.

Cases 1 to 3 show that the PMF is not particularly sensitive to the arrangement of the rainfall within the three day precipitation period. The highest flow occurs when the peak rainfall is on the second of the three days, and is approximately 2 percent higher than the base case.

Case 4 is the second meteorological scenario which combines the maximized snowpack with a 100-year rain event. The resulting hydrograph is shown in Figure 7.5. As expected, the peak is lower than the base case simulation, by about 45 percent.

Cases 1, 5 and 6 show that the temperature sequence provided by AEB does in fact give the maximum melt at the appropriate time to lead to the peak combined snowmelt plus rainfall peak.

Case 7 tests whether a later summer PMP/PMF could be the governing PMF case. Summer events would occur without snow on the ground but upper air moisture conditions would be such that the PMP would be higher. A Hershfield statistical estimate of the July PMP gave approximately 250 mm. The peak flow of the simulation was 14 700 m^3/s, lower than the base case.

Cases 8 through 10 consider the total lower basin flow, including both the local Lower Churchill Basin flow and the Upper Churchill Basin contribution.

Cases 8 and 9 show the effect of the upper and lower bound estimates of the upper basin contribution on the base case. The total flows differ by 2500 m^3/s. Chapters 4 and 8 describe the upper basin flow estimates. Chapter 8 suggests further work to confirm the lower bound estimate as the most appropriate value.

Case 10 combines the Upper Churchill Basin PMF with a 100-year event in the Lower Basin. The resulting Lower Churchill peak is 19 100 m^3/s, as shown in Figure 7.6.

7.4 Results

The local Lower Churchill Basin PMF peak is 18 100 m^3/s, the maximum value of all the cases examined, and is shown in Figure 7.4.

Cases 7 and 10, which both represent floods with quite different meteorologic scenarios than the base case, give peaks about 20 percent of the governing case.

The local PMF at Gull Island, with a drainage area of 19 800 km^2, or 92 percent of the modelled basin, is 16 700 m^3/s. The total Gull Island PMF, including the upstream contribution of 5000 m^3/s, is 21 700 m^3/s. Figure 7.7 shows both the local and estimated total hydrographs.

The local PMF at Muskrat Falls, with a drainage area of 23 100 km^2, or 107 percent of the modelled basin is 19 400 m^3/s. The total Muskrat Falls PMF, including the upstream contribution of 5000 m^3/s, is 24 400 m^3/s. Figure 7.8 shows both the local and estimated total hydrographs.

If further study confirms that expected releases from the Upper Churchill Basin during floods is 2500 m^3/s rather than the 5000 m^3/s assumed here, the PMF estimates would reduce by 2500 m^3/s.

7.5 Sensitivity Checks and Analysis

Watershed modelling for PMF analysis implicitly makes the assumption that a calibrated model using "average" meteorology to predict "average" flood events can be applied with extreme meteorology to predict extreme floods. It is therefore important to compare the PMF simulations to the calibration simulations to see how the values of the parameters are being extrapolated.

The comparisons and sensitivity analysis were done using the base case PMF rather than Case 2, which gave the highest PMF. The differences in Cases 1 and 2 was simply the order of the rainfall increments and therefore the conclusions drawn from one case would apply to both.

Appendix E contains a selection of graphs showing the values of parameters selected or input or calculated during the PMF simulations and the 1981 calibration year for comparison. 1981 was chosen because it had the highest peak of the years modelled. Table 7.5 summarizes the maximum and minimum values for Snowband 4 (the elevation band with the highest proportion of the basin area) and for the basin averages. Several points should be noted.

1. The PMF simulation has much higher values of precipitation and therefore much higher rain intensities than the calibration years. This is the reason for many of the differences between the maximum values of parameters in the PMF and the calibration cases.

2. The maximum temperatures in the two runs are not significantly different, however the antecedent temperature indices are much higher for the PMF than for 1981. This results from the sustained warm temperatures in the warm front just before the PMP.

3. The PMF simulation has a much higher maximum melt rate. Melt rate is a function of the antecedent temperature index discussed above. This models the phenomenon that a degree day of temperature will melt more snow when it comes after a period of warm temperatures than if it occurred following days of cool temperatures.

4. The snow melts much more quickly in the PMF simulation than in 1981, but starts much later due to the assumption of maximum snowpack at May 1 and relatively cool early May.

5. The higher intensity rain in the PMF simulation leads to higher values of Soil Moisture Index and, therefore, Runoff Percent than in 1981. The PMF simulation comes close to a Percent Runoff of 100. This should not be confused with a 100 percent runoff coefficient since losses have already been subtracted from the runoff. A Runoff Percent of 100 means that the soil is too saturated to store any more water, but flow may still pass through the soil and contribute to groundwater flow.

6. Both simulations reach the minimum and maximum set values of Baseflow Percent which specifies the runoff to the baseflow and lower zones. At high rates of runoff, the lower zones cannot accept runoff fast enough so the remainder of the flow goes to the faster surface and subsurface zones. During dry periods most of the runoff goes to the slower baseflow and lower zones.

7. Only the PMF simulation reaches the limit of subsurface runoff. Again, it is the high intensity rainfall during the PMF that generates more runoff than can be absorbed by the subsurface zone and so most of the runoff goes into the surface zone. The surface zone does not have an upper limit.

A systematic sensitivity analysis assigns confidence limits to the PMF estimate by examining the effect of increases or decreases to some of the assumed parameters. This was done in two phases: first the meteorological input was varied, then the detailed SSARR parameters were varied.

Some sensitivity analysis was accomplished as part of the selection and simulation of the various potential PMF scenarios, for instance the simulations have already established that the PMF is not particularly sensitive to the distribution of rainfall within the three day period.

The sensitivity was examined by noting the changes in peak flow and in the volume of the peak month runoff resulting from changes to the input and SSARR parameters. Where appropriate, the changes were noted in both a typical calibration year and in the PMF to detect if there were parameters to which the PMF was sensitive but the calibration was not. The selection of the range of parameter variation was based on judgement and the values suggested in the SSARR users manual.

Table 7.6 shows the sensitivity to the external parameters, i.e., the meteorological input. Some comments follow.

1. The peak of the PMF is not particularly sensitive (<4 percent) to a change in snowpack.

2. The peak of the PMF is not particularly sensitive to the maximum temperatures used on individual days of the sequence.

3. The PMF is sensitive to the PMP, as is to be expected.

Table 7.7 presents the results of the sensitivity analysis to internal parameters, i.e., the value of the SSARR parameters. This table includes the sensitivity of one of the calibration years to the same changes. Some comments follow.

1. The melt rates were increased significantly during the calibration process. The PMF is quite sensitive to the melt rate, but the calibration is equally sensitive, which confirms the values selected.

2. The PMF is sensitive to an increase in the limit placed on the subsurface runoff intensity, but the calibration is not. This is because during calibration the runoff intensity remains below the limit, whereas during the PMF the intensity is high enough that the subsurface runoff is at its maximum for two full days. When the subsurface runoff is limited, more runoff goes into the surface zone and therefore basin runoff is faster. The value used for the subsurface limit in the Lower Churchill model is from the SSARR manual and has been used in other PMF studies. There is little justification for using either a higher or a lower value.

3. The PMF peak is also sensitive to the number of surface routing phases and the routing time assigned to each phase. From the statistics tabulated, the calibration simulation appears to be less sensitive to these values, but comparison of the calibration plots supports the selection used in the analysis. Increasing or decreasing the surface phases and times shifts the timing of the calibration hydrographs.

The sensitivity analysis results suggest an uncertainty of +/- 15 percent in the PMF estimates.

7.6 Comparison with Previous Studies

The 1976 Maximum Probable Flood study for Gull Island estimated a PMF peak of 16 400 m^3/s, approximately 30 percent lower than the present estimate, as shown in Figure 7.8. The difference between the two results has been reviewed, with the conclusion that it is due to the routing method used and to the contribution assumed from the upper basin.

The 1976 study used a unit hydrograph method with constant base flow added and constant infiltration losses removed. A unit hydrograph methodology treats the rainfall/runoff process as essentially linear. SSARR uses four instantaneous unit hydrographs, or zones, such that during high intensity runoff, the weighting between the zones changes to give faster runoff. The SSARR methodology is now generally accepted as the appropriate method for modelling basin response in a PMF.

The 1976 study used a PMF outflow hydrograph from the Upper Churchill Basin that increased gradually through the period of peak flows in the lower basin, to a maximum of approximately 2900 m^3/s. The flood handling procedures derived in 1989 lead to more potential spill from the upper basin during the peak flows on the lower basin. The current estimate of outflow from the existing Churchill Falls station during the Lower Churchill Basin PMF is 5000 m^3/s, however with additional generation in place, the flow will more likely be in the order of 2500 m^3/s.

7.7 Comparison with Historic Events

To put the Lower Churchill PMF estimate in context, the value was compared to maximum observed floods in basins of similar size and to results of regional flood frequency analysis.

An envelope curve of world-wide maximum observed floods (known as the Creager curve), with Canadian events added, shows a range of maximum observed floods for a 20 000 km^2 basin of between 4000 m^3/s and 25 000 m^3/s. The estimated local Lower Churchill PMF of approximately 18 000 m^3/s is within the range of these values.

The historic maximum inflow to the lower basin based on the calculated 39 year period of record is approximately 5 100 m^3/s. The PMF is approximately 3 to 3.5 times the historic peak and is approximately 14 to 16 standard deviations greater than the mean annual peak.

A regional flood frequency analysis using Environment Canada hydrometric data predicted extreme floods of

- 100-year = 6 500 m^3/s
- 10 000-year = 10 000 m^3/s
-

Ratios of 2.8 between the PMF and the 100-year event and 1.8 between the PMF and the 10 000-year event are reasonable.

Table 7.1

PMP Calculations

Duration (hr)	% of 24-Hour Value (%)	Depths	
		Calculated (mm)	Increment (mm)
0	0	0	-
6	51	68	68
12	75	100	32
18	90	119	19
24	100	133*	14
30	110	146	13
36	118	157	11
42	125	166	9
48	131	174*	8
54	135	179	5
60	139	184	5
66	142	189*	5
72	143	190	1

* values provided by Atmospheric Environment Branch, Environment Canada

Table 7.2

Critical Sequence Precipitation

6-Hour Depths (mm)

Day	6-Hour Period			
	6:00	12:00	18:00	24:00
16-May	0	0	0	0
17-May	0	0	0	0
18-May	0	0	0	0
19-May	0	0	0	0
20-May	0	0	0	0
21-May	0	0	0	0
22-May	0	0	0	0
23-May	0	0	0	0
24-May	0	0	0	0
25-May	0	0	0	0
26-May	0	0	0	0
27-May	0	0	0	0
28-May	0	0	0	0
29-May	0	0	0	0
30-May	0	0	0	0
31-May	0	0	0	0
1-Jun	0	0	0	0
2-Jun	0	0	0	0
3-Jun	5	14	68	32
4-Jun	19	13	11	9
5-Jun	8	5	5	1
6-Jun	0	0	0	0

Note

6-hour periods are denoted by time at end of period.
(eg. 12:00 indicates precipitation between 6:00 and 12:00)

Table 7.3

Critical Sequence Temperatures

6-Hour Instantaneous Values (°C)

Day	6-Hour Period			
	6:00	12:00	18:00	24:00
16-May	-4.0	1.3	3.4	-0.8
17-May	-3.6	1.8	3.9	-0.4
18-May	-3.2	2.3	4.4	0.0
19-May	-2.8	2.7	4.9	0.4
20-May	-2.5	3.2	5.4	0.9
21-May	-2.0	3.5	5.7	1.2
22-May	-1.6	3.8	5.9	1.6
23-May	-1.2	4.3	6.4	2.0
24-May	-0.8	4.7	6.9	2.5
25-May	-0.4	5.0	7.1	2.8
26-May	0.0	5.3	7.4	3.2
27-May	1.0	6.0	8.0	4.0
28-May	2.0	6.7	8.5	4.8
29-May	5.0	7.0	16.0	19.0
30-May	19.0	22.0	21.0	19.0
31-May	20.0	22.0	20.0	15.0
1-Jun	12.0	10.0	8.0	6.0
2-Jun	6.0	9.0	12.0	10.0
3-Jun	10.0	12.0	14.0	16.0
4-Jun	16.0	16.0	15.0	15.0
5-Jun	15.0	10.0	8.0	6.0
6-Jun	4.0	6.0	8.0	6.0

Notes

1. Adopted from Atmospheric Environment Branch, Environment Canada.
2. The final version of this table (see Appendix A) included revised temperatures for June 2-3. These revised temperatures were tested in the SSARR model and found to have a negligible (<1%) effect on the PMF peak.

Table 7.4

PMF Cases - Local Lower Churchill Inflow

Case	Description	Local Inflow[3]
1 Base Case	PMP on June 3-5 with peak rain on day 1 background Apr-Sep temperatures from 1985 severe temperature sequence May 16 to June 6 100-year snowpack of 577 mm	17 800 m^3/s
2	PMP on June 3-5 with peak rain on day 2	18 100 m^3/s
3	PMP on June 3-5 with peak rain on day 3	17 500 m^3/s
4	100-year rainfall on June 3-5 PMSA of 725 mm	9800 m^3/s
5	Rearranged sequence to have PMP prior to warmest three days of temperature sequence[1]	15 000 m^3/s
6	Rearranged sequence to have warmest days of the temperature sequence earlier in May[1]	16 800 m^3/s
7	100-year rain on June 3-5 100-year snow to saturate basin July PMP estimated to be 250 mm	9700 m^3/s

PMF Cases - Total Lower Churchill Flow

Case	Description	Local Inflow[3]	Upper Basin	Total Flow
8	Base Case Upper limit Upper Churchill Basin release	17 800 m^3/s	5000 m^3/s	22 800 m^3/s
9	Upper Churchill Basin release limited to power flow including CF2	17 800 m^3/s	2500 m^3/s	20 300 m^3/s
10	100-year rain on June 3-5 PMF releases from Upper Churchill Basin[2]	11 200 m^3/s	7900 m^3/s	19 100 m^3/s

Notes

1. These cases are for sensitivity analysis only.
2. Component flows not necessarily peak values, timed to produce maximum total flow.
3. Local inflow for average Lower Churchill Basin (21 500 km^2).

Table 7.5

Comparison of Calibration and PMF Parameters

SSARR Snowband 4

Parameter	Maximum		Minimum		Total	
	1981	PMF	1981	PMF	1981	PMF
Precipitation, cm	0.91	6.76	0	0	55	60
Interception, cm	***0.51***	***0.51***	0	0	16	17
Snow Water Equivalent, cm	45	60	0	0		
Antecedent Temperature Index (for cold content), degree days	1	1	-20	-9		
Cold Content, cm	0	0	-0.4	-0.2		
Liquid Water Deficiency, cm	0.1	0.0	-1.2	0.0		
Air Temperature, °C	28.3	29.9	-23.1	-13.6		
Antecedent Temperature Index (for melt rate), degree-days	52	77	0	0		
Melt Rate, cm/degree-day	0.36	0.68	0	0		
Snowmelt, cm	1.66	2.19	0	0	44	58
Moisture Input, cm	1.70	8.96	0	0	82	103
Potential Evapotranspiration, cm/day	0.67	0.77	0.00	0.01		
Evapotranspiration, cm/day	0.67	0.77	0.00	0.01		
Soil Moisture Index, cm	10.85	11.71	0.57	1.95		
Runoff Percent, %	94	99	***10***	15		
Runoff Generated, cm	1.56	8.33	0	0	60	81
Baseflow Infiltration Index, cm/day	***2.50***	***2.50***	0	0		
Baseflow Percent, %	***70***	***70***	***10***	***10***		
Surface Runoff, cm	0.70	6.78	0.00	0.00	21	40
Subsurface Runoff, cm	0.70	***0.72***	0.00	0.00	21	25
Baseflow Runoff, cm	0.36	0.66	0.00	0.00	14	12
Lower Zone Runoff, cm	0.09	0.17	0.00	0.00	3	3

Notes

1. Values from 6-hourly simulation
(eg. maximum precipitation in 1981 was 0.91 cm in 6 hours).
2. Bold, italicized values governed by a user defined limit.

Table 7.6

Comparison of Calibration and PMF Parameters

SSARR Summary

Parameter	Maximum		Minimum		Total	
	1981	PMF	1981	PMF	1981	PMF
Precipitation, cm	0.91	6.75	0	0	66	60
Interception, cm	***0.51***	***0.51***	0	0	17	17
Snowline, m	685	685	90	90		
Snow Water Equivalent, cm	43	58	0	0		
Air Temperature, °C	31	32	-21	-11		
Melt Rate, cm/degree-day	0.36	0.68	0	0		
Runoff Generated, cm	1.31	8.29	0	0	62	79
Evapotranspiration, cm/day	0.67	0.77	0	0.01		
Soil Moisture Index, cm	10.7	11.7	0.6	2.1		
Runoff Percent, %	93	98	***10***	16		
Baseflow Percent, %	***70***	***70***	14	***10***		
Discharge from Surface Zone, m^3/s (total in million m^3)	2598	14350	0	0	21	39
Discharge from Subsurface Zone, m^3/s (total in million m^3)	1863	4111	0	1	21	25
Discharge from Baseflow Zone, m^3/s (total in million m^3)	422	437	13	13	14	11
Discharge from Lower Zone, m^3/s (total in million m^3)	25	20	0	0	1	1
Total Discharge, m^3/s (total in million m^3)	4359	17800	27	27	56	75

Notes

1. Values from 6-hourly simulation
(eg. maximum precipitation in 1981 was 0.91 cm in 6 hours).
2. Bold, italicized values governed by a user defined limit.

Table 7.7

External Parameter Sensitivity Analysis Results

Parameter	Condition	Probable Maximum Flood[2]			
		Peak (m^3/s)	Change	Volume[1] (million m^3)	Change
Base Case		17800		7710	
Snowpack (58 cm)[3]	50 cm	17300	-3%	7410	-4%
	70 cm	18100	2%	7890	2%
Temperatures					
Maximum Value (24°C)	23°C	17700	-1%	7660	-1%
	25°C	17900	1%	7750	1%
Value During PMP (16°C)	14°C	16800	-6%	7330	-5%
	18°C	18800	6%	8060	5%
Length of Sequence (22 days)	17 days	17700	-1%	7680	0%
	27 days	17700	-1%	7670	-1%
Initial Soil Moisture (7 cm)	4 cm	17500	-2%	7540	-2%
	9 cm	18000	1%	7780	1%
PMP					
72-Hour Value (190 mm)	152 mm	15500	-13%	6920	-10%
	230 mm	20200	13%	8520	11%
6-Hour Distribution (typical pattern)	uniform	16400	-8%	7460	-3%

Notes

1. Volumes are maximum 28-day volumes.
2. PMF results are for base case scenario, local lower basin, Area = 21 500 km^2
3. Values in parentheses are base case values.

Table 7.8

Internal Parameter Sensitivity Analysis Results

Parameter	Condition	1980 Calibration				Probable Maximum Flood[2]			
		Peak (m^3/s)	Change	Volume[1] (million m^3)	Change	Peak (m^3/s)	Change	Volume[1] (million m^3)	Change
Base Case		3240		1750		17800		7710	
Melt Rates (increased)[3]	typical	2680	-17%	1540	-12%	14300	-20%	5910	-23%
Cold Rates (decreased)	typical	3190	-2%	1710	-2%	17800	0%	7710	0%
Baseflow									
Percent Curve	+ 10%	2970	-8%	1610	-8%	15900	-11%	6980	-9%
	- 5%	3370	4%	1820	4%	18900	6%	8100	5%
Input Limit (0.2 cm/hr)	0.18	3240	0%	1750	0%	17800	0%	7710	0%
	0.22	3240	0%	1750	0%	17800	0%	7710	0%
Runoff % vs Soil Moisture	higher runoff %	3270	1%	1770	1%	17500	-2%	7630	-1%
(typical)	lower runoff %	3130	-3%	1690	-3%	17500	-2%	7560	-2%
Surface/Sub-Surface Split	0.08 cm/hr	3280	1%	1760	1%	18600	4%	7810	1%
(SS limit = 0.12 cm/hr)	0.3 cm/hr	3240	0%	1750	0%	15400	-13%	7280	-6%
Hydrologic Routing									
Surface Phases (4)	3	3190	-2%	1710	-2%	19200	8%	7630	-1%
	5	3300	2%	1780	2%	16900	-5%	7740	0%
Surface Time (20 hrs)	15 hrs	3220	-1%	1730	-1%	20500	15%	7660	-1%
	25 hrs	3250	0%	1750	0%	16100	-10%	7640	-1%
Sub-Surface Phases (5)	4	3460	7%	1840	5%	18500	4%	7940	3%
	6	3000	-7%	1650	-6%	17100	-4%	7390	-4%
Sub-Surface Time (36 hrs)	30 hrs	3450	6%	1840	5%	18400	3%	7950	3%
	42 hrs	3060	-6%	1670	-5%	17200	-3%	7430	-4%

Refer to Table 7.7 for Notes

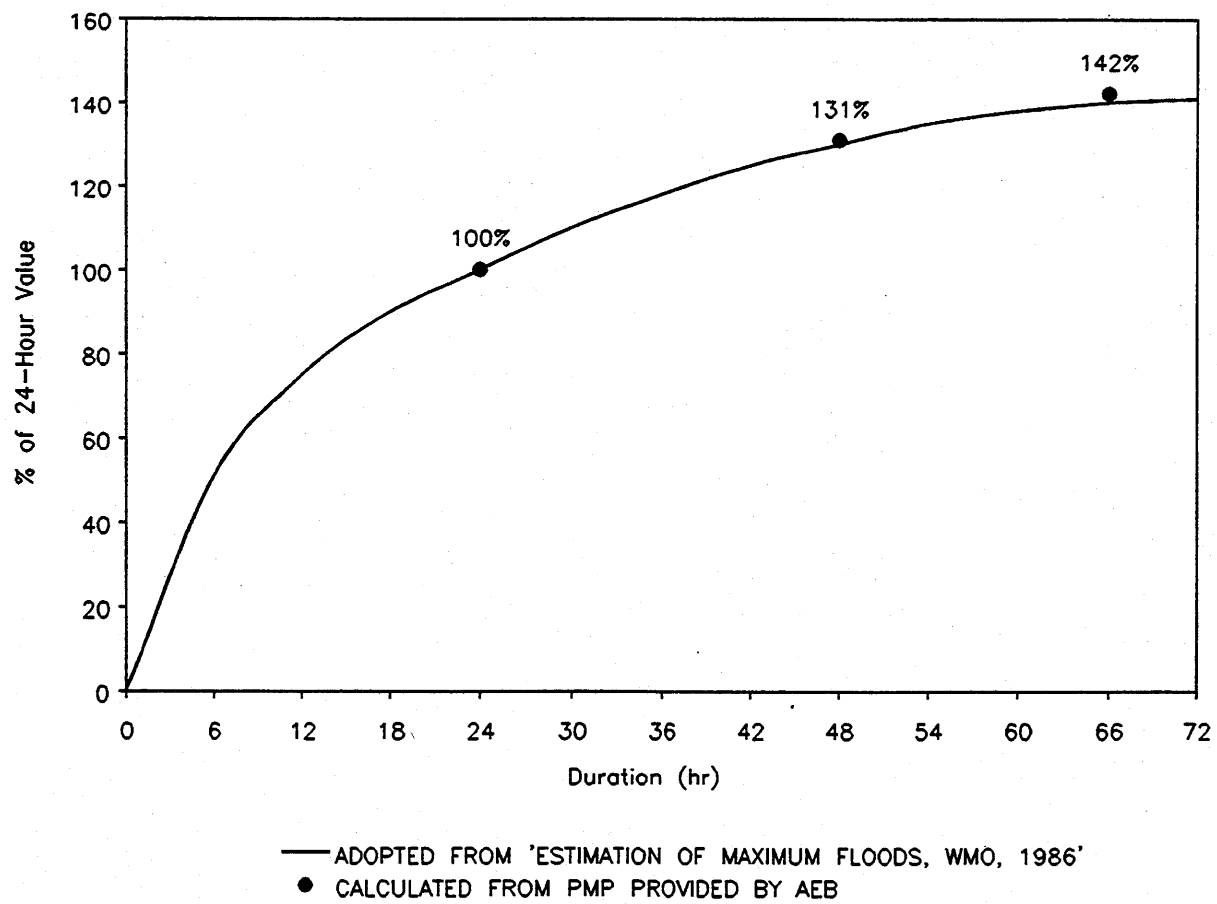
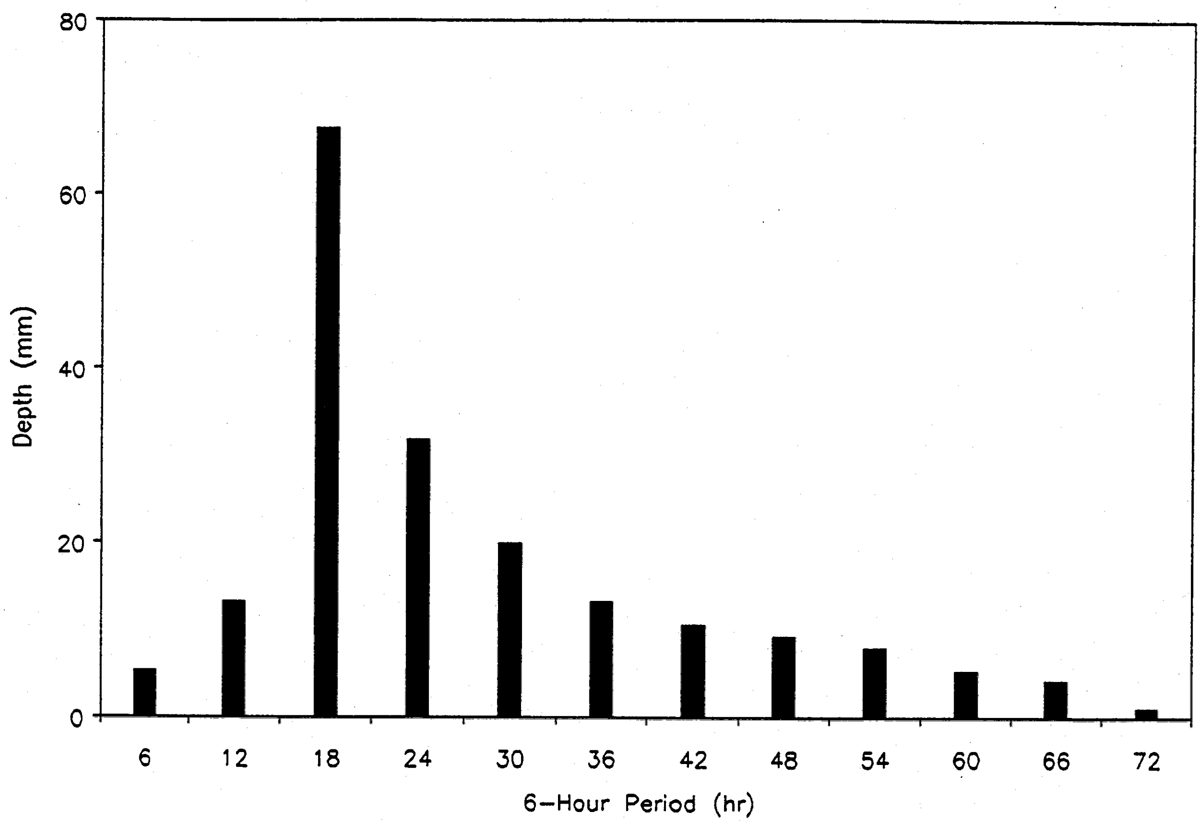


FIG 7.1

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
DEPTH DURATION RELATIONSHIP

ACRES



NOTES:
1. 6 HOUR PERIODS DENOTED BY PERIOD END TIME.
2. BASE CASE DISTRIBUTION SHOWN (PEAK RAIN ON FIRST OF THREE DAYS).

FIG 7.2

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
PMP TEMPORAL DISTRIBUTION

ACRES

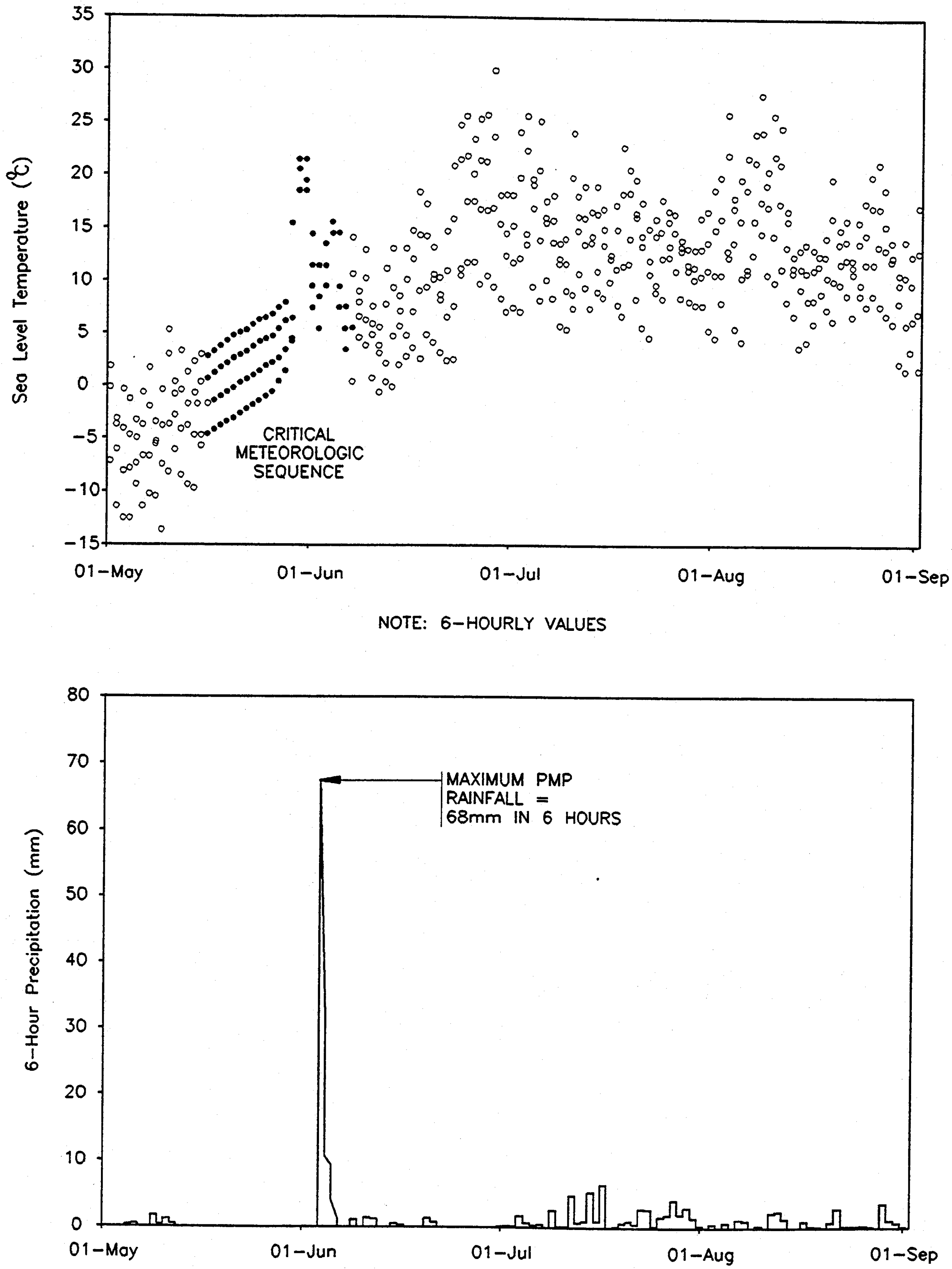
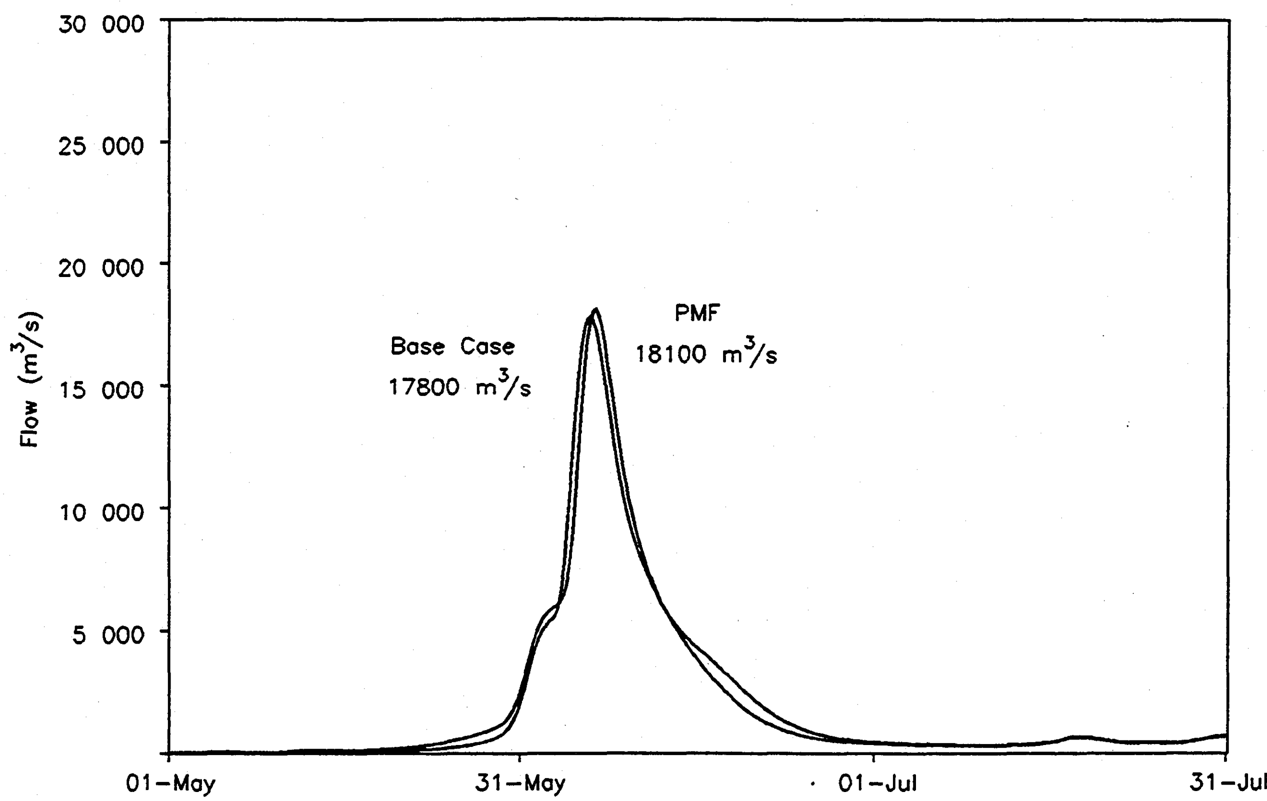


FIG 7.3

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
PMF METEOROLOGY

ACRES

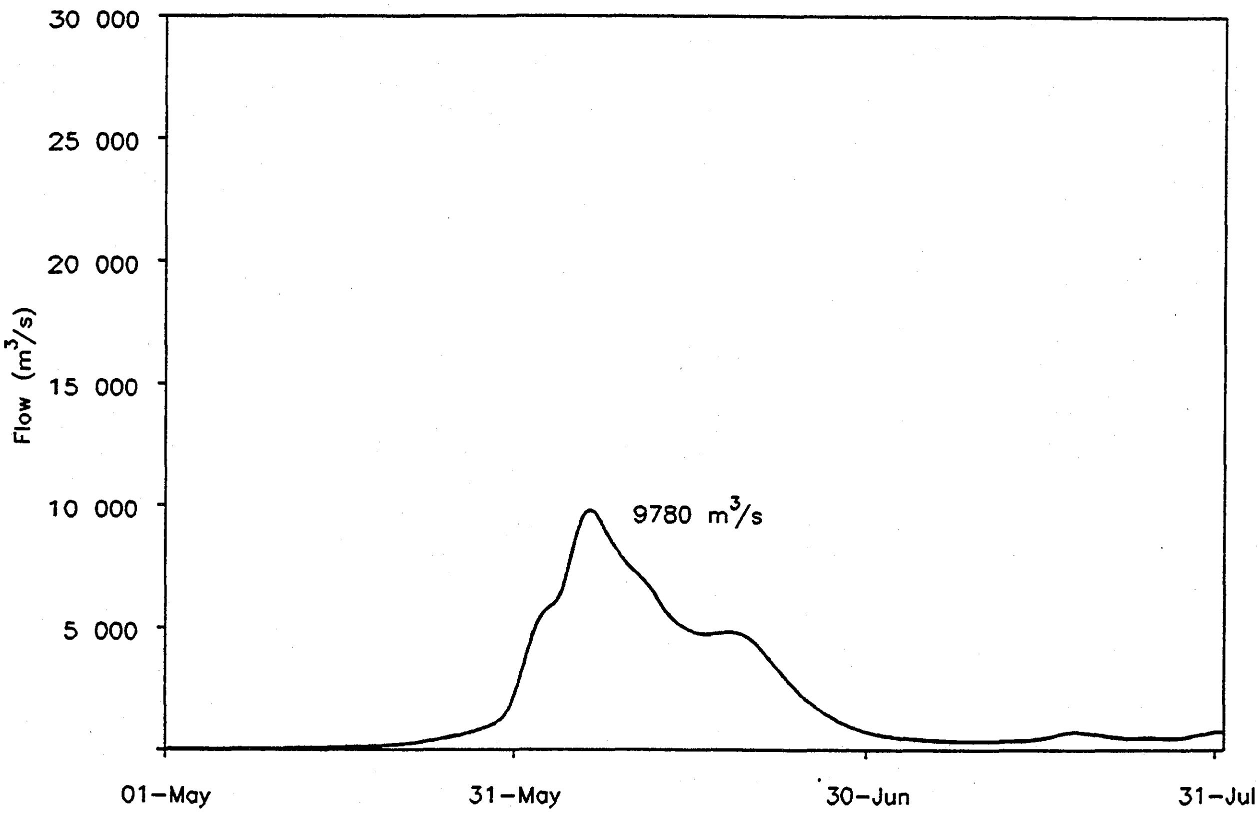


NOTES:
1. FOR AVERAGE OF GULL ISLAND AND MUSKRAT FALLS DRAINAGE AREAS (21500 SQ. km)

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
LOCAL LOWER CHURCHILL BASIN
PMF HYDROGRAPHS

FIG 7.4

ACRES

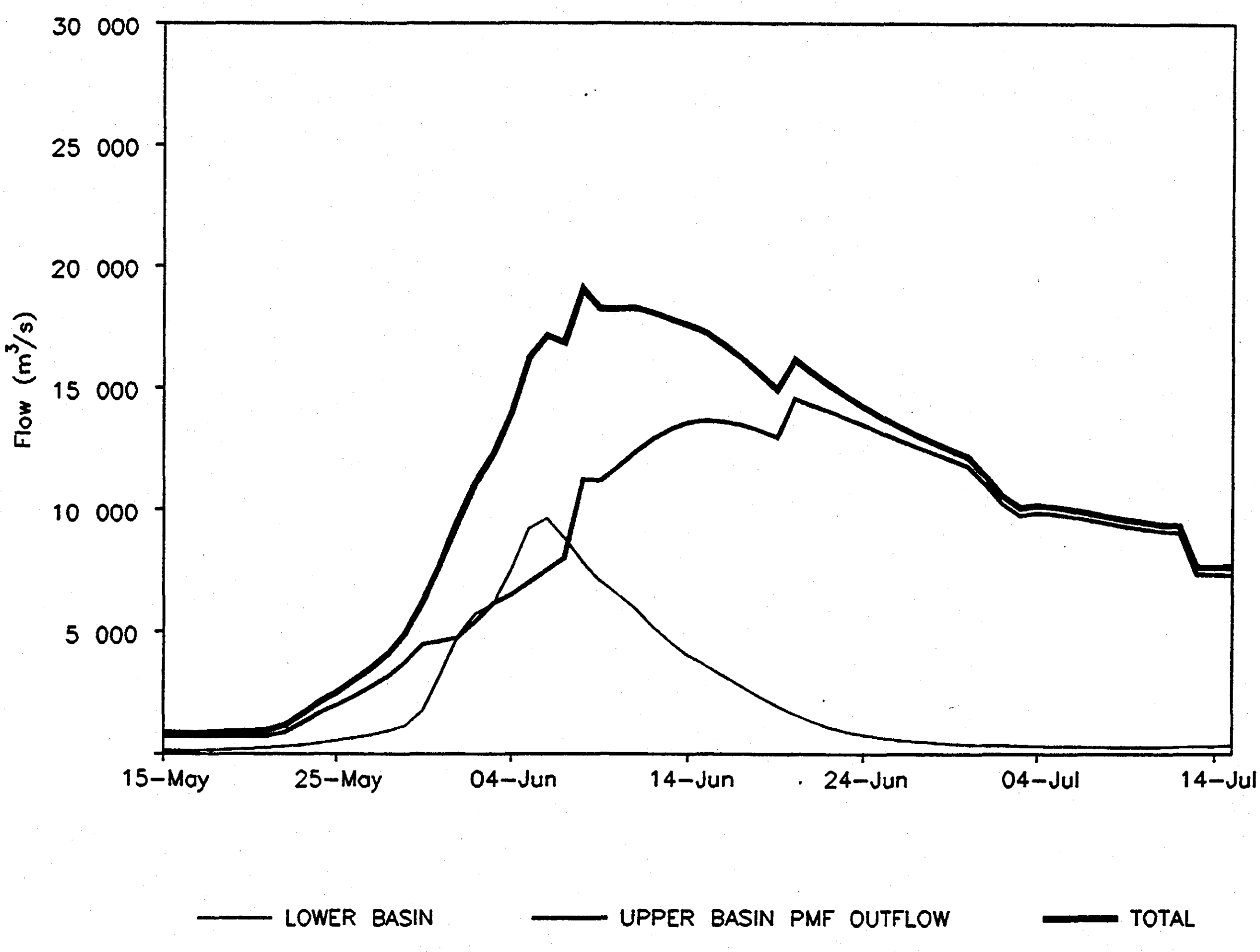


NOTES:
1. FOR AVERAGE OF GULL ISLAND AND MUSKRAT FALLS DRAINAGE AREAS (21500 SQ. km)

NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
LOCAL LOWER CHURCHILL BASIN
PMSA AND 100–YEAR RAIN HYDROGRAPH

FIG 7.5

ACRES

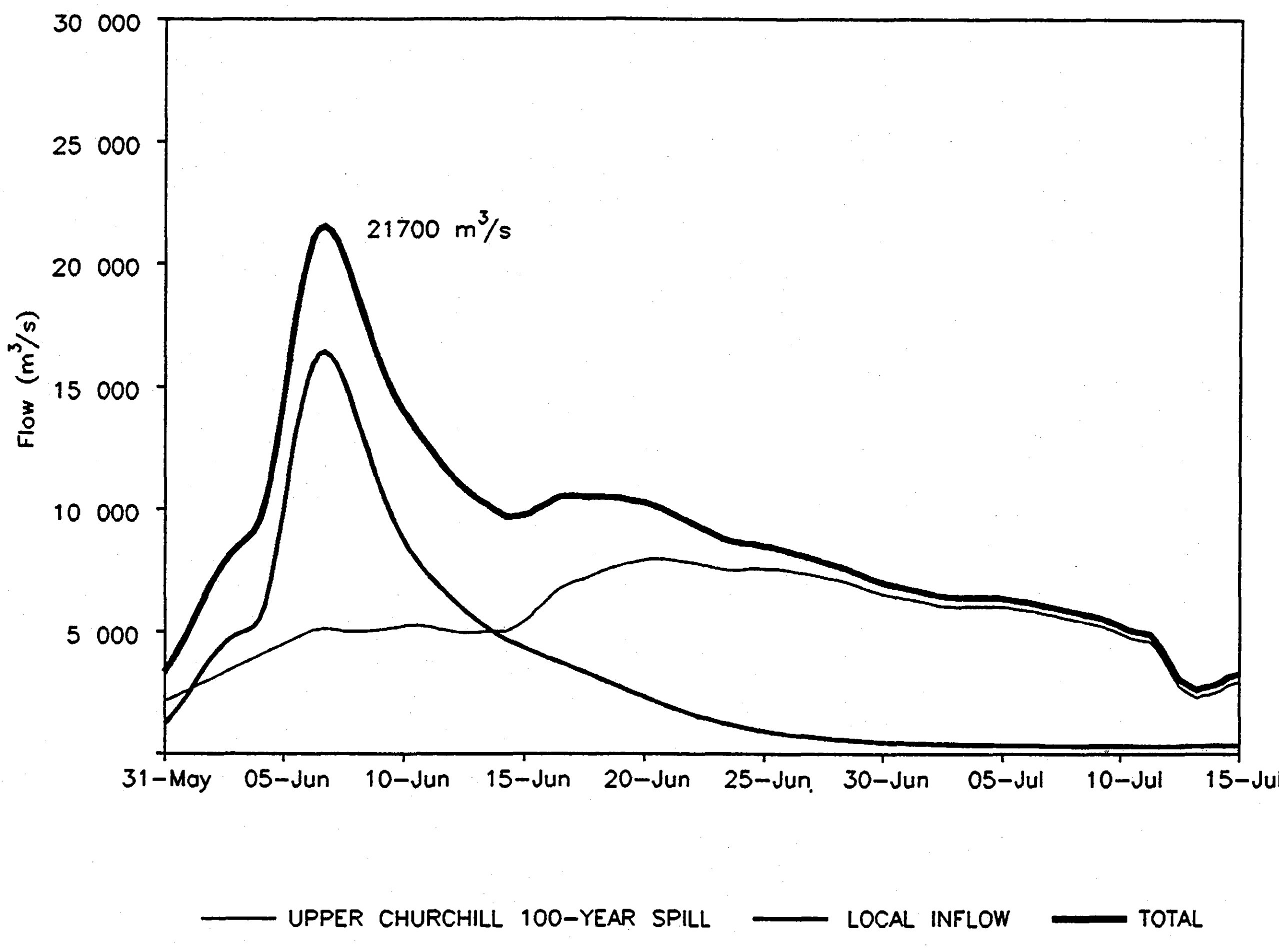


NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

FIG 7.6

UPPER BASIN PMF WITH
LESSER LOWER BASIN INFLOW

ACRES

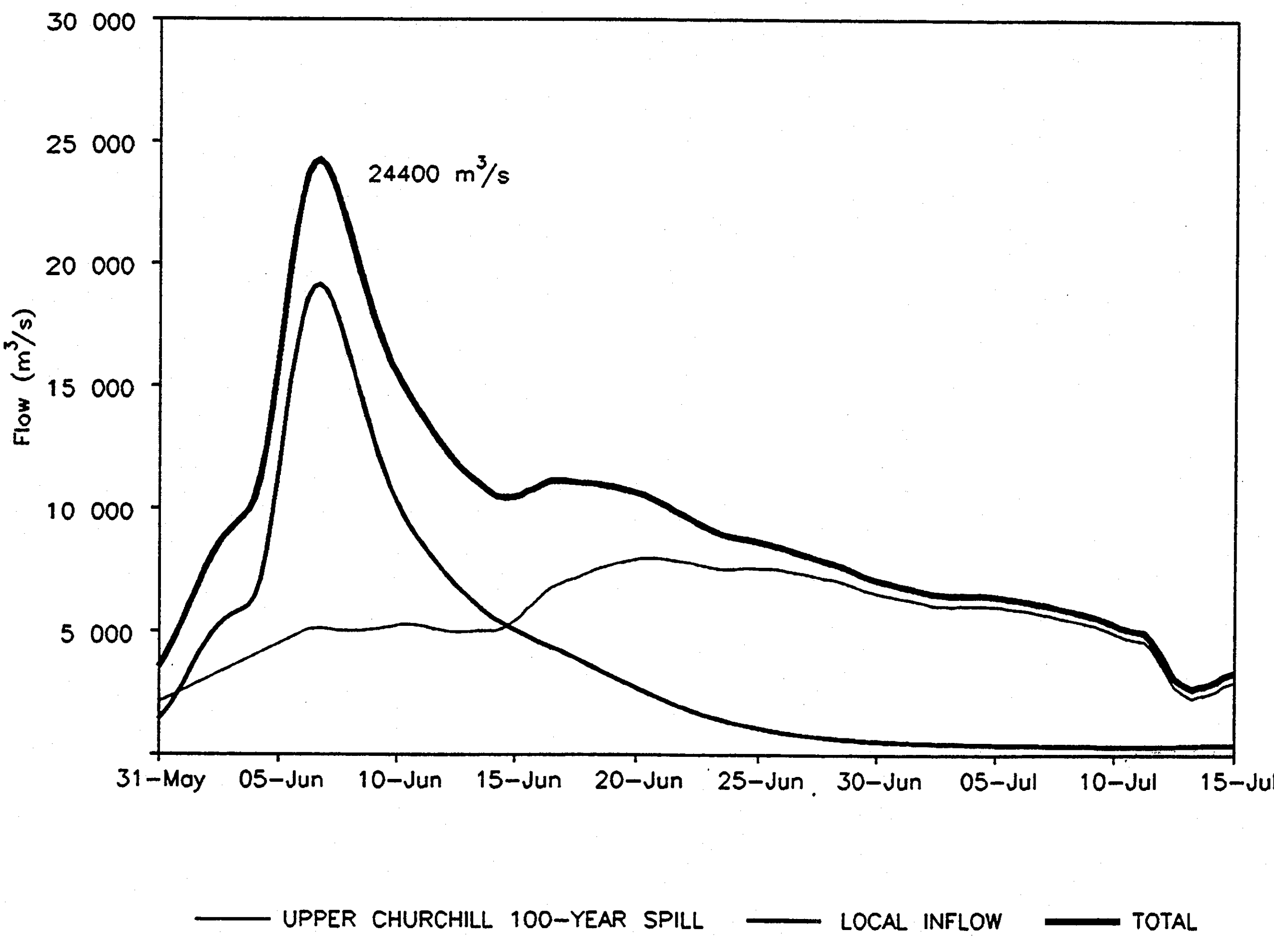


NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

FIG 7.7

TOTAL GULL ISLAND
PMF HYDROGRAPH

ACRES

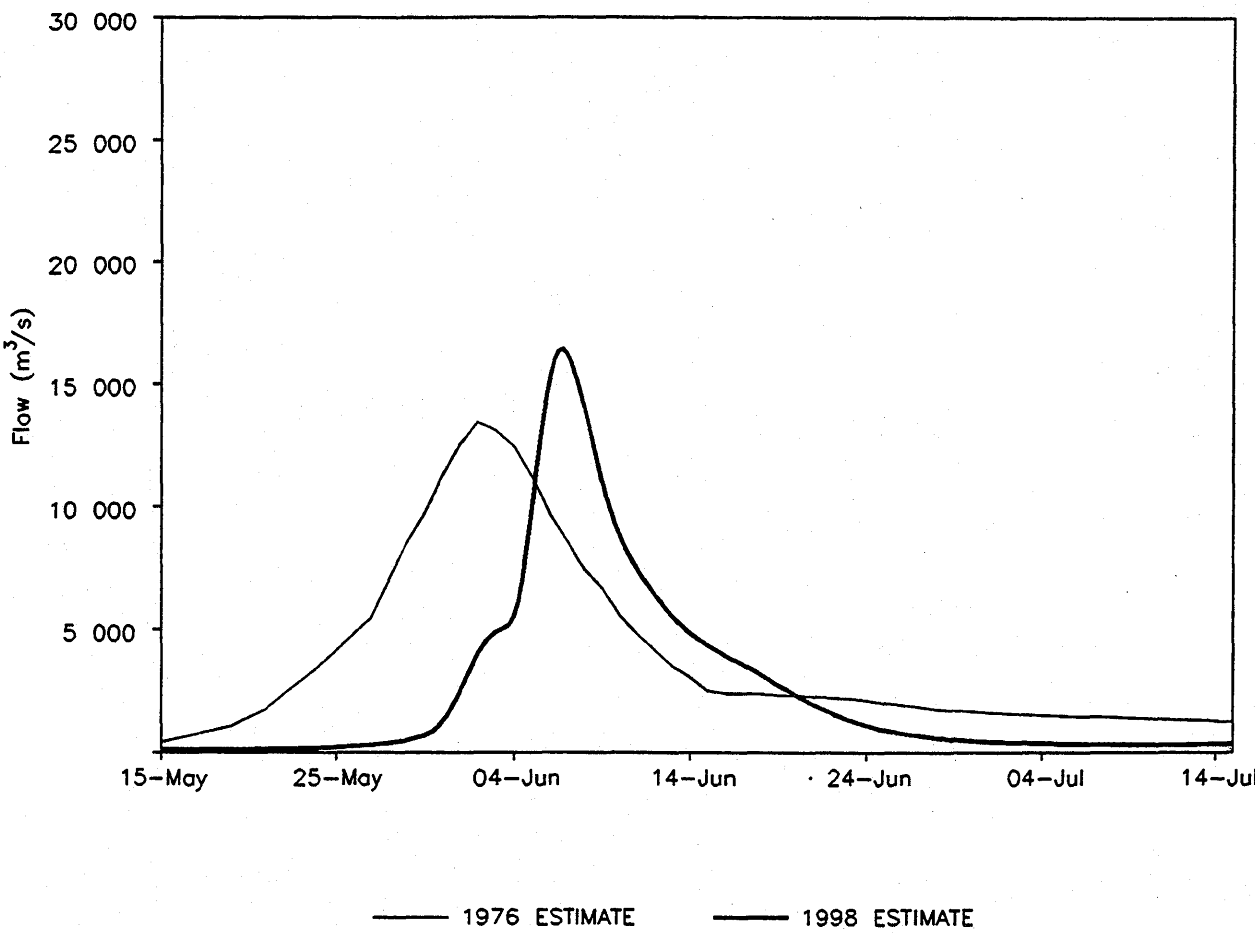


NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

TOTAL MUSKRAT FALLS PMF HYDROGRAPH

FIG 7.8

ACRES



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

LOCAL LOWER CHURCHILL BASIN
1976 AND 1998 PMF HYDROGRAPHS (GULL ISLAND)

FIG 7.9

ACRES

Upper Churchill Basin Modelling

8 Upper Churchill Basin Modelling

8.1 Introduction

Preliminary results of the Lower Churchill Basin PMF study indicated that in order to complete the study, a more detailed review of the Upper Churchill Basin flood hydrology and handling was required.

1. The local Lower Churchill PMF derived in this study is approximately 30 percent higher than derived in the 1976 Gull Island PMF study. Since the 1976 Gull Island study used essentially the same methodology as the 1969 upper basin study, further review was required to see if the Upper Churchill Basin PMF may also be underestimated. If the upper basin PMF were higher, PMF spills from the upper basin could become the governing case for the lower basin PMF.

2. With the flood handling practices described in the 1989 report and discussed in Chapter 4 of this report, the contribution of the Upper Churchill Basin discharge to the Lower Churchill Basin could be higher than estimated in 1976. Additional flood simulations were required to support the assumptions regarding the upper basin contribution.

3. Coordinated operation of the upper and lower projects taking into account the additional hydraulic capacity of CF2 would likely lead to different May 1 reservoir levels and flood handling procedures than used in earlier studies. More hydraulic capacity will mean that releases via Jacopie Spillway would be reduced and that excess water would be released earlier in the spring through additional generation. Operation simulations done by Acres for the Churchill River Complex optimization study indicate that maximum spring reservoir levels in Smallwood Reservoir will normally be at least 2.5 m below full supply level.

Additional modelling of the Upper Churchill Basin was carried out to address these issues. SSARR watershed modelling was done to estimate the PMF and an operation model was developed to estimate basin discharge. Several simplifying assumptions were made to limit the scope of this exercise. A detailed system flood handling study is required to confirm the findings of this conceptual study.

8.2 Meteorology/Hydrology

No additional meteorology was done specifically for the Upper Churchill Basin as part of this modelling. However, given that data used to derive precipitation, temperature and snowpack for the Lower Churchill Basin was often in or near the upper basin, it was considered that the lower basin meteorology study could be used to estimate the meteorology of the upper basin.

The re-maximization of the storm events used in the 1969 and 1976 PMF studies led to an 11 percent reduction in the Lower Churchill PMP. Assuming that a review of the upper basin would result in a similar reduction leads to a revised PMP for the upper basin of 153 mm over three days.

AEB data at stations in both the Upper and Lower Churchill Basins were used to derive the severe temperature sequence for the lower basin PMF. The same temperature sequence was used for this study.

The AEB snowpack analysis provided extreme snowpack estimates for snow courses in the upper and lower basins. Tables 8.1 and 8.2 show the data used and the results of the snowpack estimates for the upper basin. Because the upper basin is relatively flat, average snowpack conditions were used throughout.

Daily inflows to the upper basin reservoir based on back calculation from water level and discharge information were used in the SSARR calibration. Although the resulting input sequence is noisy, unless there is some systemic error in the flow or water level measurements, while the peaks may not be accurate, over time the volumes should be. Given the large amount of storage available in the upper basin, volumes are more important than peaks.

8.3 SSARR Watershed Modelling

Two SSARR models were set up, one for the southern (Ossokmanuan) sub-basin and one for the northern (Smallwood) sub-basin. The models were set up using the calibration parameters from the calibrated Lower Churchill Basin model as a starting point. Only two elevation bands were used in each of the upper basin models since the variation in elevation over the basin is less than 100 m.

Figures 8.1 through 8.4 show examples of the calibration and verification runs. The simulated flows do not match the actual (back-calculated) flows for the upper basins as well as they did for the lower basin. At least part of the explanation for this is the noise in the back calculated inflow sequence, rather than inaccuracies of the SSARR model. Because of the degree of storage in the upper basin, calibration focused on volumes rather than the peaks. Table 8.3 shows the accuracy of the calibrated volumes.

SSARR simulations of both the PMP plus the 100-year snowpack and PMSA plus 100-year rain cases were done. The first case gave the highest peak inflow and highest volume in both sub-basins. The total upper basin inflow is the sum of the inflows to the two sub-basins. The combined hydrograph has a peak of 28 800 m^3/s. The total May to July volume is 44 000 million m^3. Appendix F contains a printout of the SSARR input files for the north and south sub-basin PMF runs.

Figure 8.5 plots the revised upper basin PMF hydrograph together with the 1969 PMF hydrograph. It is apparent that though the peaks are similar, the revised hydrograph has significantly lower volume. The 1969 hydrograph had a May to July volume of 69 000 million m^3. The reduction is primarily because of the lower snowpack depth used, 590 mm compared to 767 mm. The PMP was also lower, 153 mm rather than 172 mm.

The timing of the revised hydrograph is quite different than the 1969 hydrograph. The 1969 simulation showed a 14-day lag between the peak rainfall and the peak flow. The SSARR model suggests a lag of only five days, similar to that observed in the lower basin. This means that the flooding in the upper basin will occur much more quickly than previously estimated, requiring decisions regarding flood operation to be made more rapidly. In addition, the reduction in anticipated lag time in the upper basin could mean that peak discharges will also occur early enough to coincide with peak local Lower Churchill inflows. Additional simulations were therefore carried out to assess the effect of a revised upper basin PMF on the lower basin.

8.4 Operation Simulations and Results

A Microsoft Excel 97® flood routing model was created for the Upper Churchill Basin. The operation of the control structures were based on rule curves, trigger elevations, and simple forecasting based on rate of water level change. For simplicity, potential additional spill capacity using dyke breaches was not modelled.

The operations model was created assuming the forebay spillway on the East Forebay was still operational. The only simulation that triggered use of that spillway was the duplication of the 1989 Upper Churchill Basin PMF routing. Similar results were obtained with the spillway turned off. Results of the modelling described below are included in Appendix G.

Upper Basin PMF

To verify the model, the base case PMF routing provided in the 1989 Flood Handling Study was duplicated. The peak discharge to the Churchill River from the Excel model was 14 000 m^3/s, which is very similar to the 14 500 m^3/s predicted by the 1989 ARSP simulation. The control structures operate with similar timing and releases except that Julian dyke breaching was not included in the Excel model. However, the total release through the Ossokmanuan spillway was similar to the total release from that reservoir in the 1989 study with dyke breaching.

The revised PMF hydrograph was routed using the 1989 Flood Handling rules to estimate the revised PMF outflow. Some adjustments to the operation strictly dictated by the rules were made to model what the operators would likely do, given the characteristics of the revised event. According to the 1989 prespill rules, Smallwood Reservoir would be at or below El. 470.7 m on May 1, based on the snowpack associated with the revised PMF. As discussed earlier, normal operation will result in the reservoir level usually being below this value.

The maximum release to the Churchill River during the revised PMF was 9800 m^3/s. This is 30 percent lower than the peak outflow from the 1969 PMF hydrograph. This simulation confirms that a revised upper basin PMF combined with a 100-year event on the Lower Churchill Basin does not become the governing PMF case for the lower Churchill basin.

100-year Upper Basin Releases

The Excel model was used to route the 100-year event on the upper basin to confirm the appropriate contribution to add to the PMF flows in the local Lower Churchill Basin. As discussed in Chapter 4.5, the current estimate is 5000 m^3/s.

A total power flow of 2500 m^3/s was assumed throughout the simulation to include CF2.

The 100-year hydrograph from the 1989 Flood Handling study was used in the routing and initially the same conservative assumption of a near full reservoir on

May 1 was made. The results show a peak discharge from the upper basin of 7400 m^3/s. At the time of the peak local Lower Churchill Basin PMF, the upper basin discharge is approximately 5000 m^3/s, half of which is power flow. The maximum Jacopie spill required to prevent the Smallwood reservoir from exceeding full supply level during peak inflow was approximately 2500 m^3/s.

If the May 1 reservoir level was lower than assumed here, as optimization simulations have shown to always be the case, no spill from Jacopie would be required, and the upper basin release would be limited to power flow only.

Protection of Lower Churchill Basin Structures

The above simulations indicated that extreme floods in the Upper Churchill Basin can be readily handled without infringing on the flood handling rule curves. An additional simulation was undertaken to investigate whether in a worst case situation, flood releases from the upper basin could be timed to reduce the total Lower Churchill PMF peak.

The 100-year simulation with the near full May 1 reservoir level was repeated assuming that the maximum allowable release from the upper basin during the peak local Lower Basin PMF was 2500 m^3/s, the power flow. The volume of water required to be stored to facilitate this delay is relatively small compared to the capacity of the Smallwood reservoir. Maximum water levels were only slightly higher than the previous simulation and the peak discharge after the delay increased by only approximately 10 percent to 8100 m^3/s.

Conclusion

Conceptual watershed and operation models suggest that following construction of CF2, operation of the system will be such that the maximum release from the Upper Churchill Basin during a PMF on the Lower Churchill Basin would be no more than the combined station power flow of 2500 m^3/s. In most years this protection would be a result of normal operation for generation keeping the reservoir level well below full supply level. However, the operating rules should be modified to ensure that in the unlikely combination of a spring flood occurring during a period of high reservoir level, decisions relating to flood releases would take into account the flows at the Lower Churchill facilities. This can be done without affecting dam safety or generation at the Churchill Falls facilities.

These results are the result of a conceptual modelling exercise on the Upper Churchill Basin. Further meteorology studies, watershed modelling and operations modelling are required to confirm this conclusion and develop flood handling procedures for the system.

Table 8.1

Initial Snowpack Conditions
Upper Churchill South (Ossokmanuan/Gabbro) Sub-Basin
Presented as Snow Water Equivalents

Year	Snowcourses							Calculated		
	Twin Falls El. 448 m	Simms El. 500 m	Anderson El. 503 m	Kepimits El. 530 m	Lac Joseph El. 549 m	Lac Long El. 549 m	Seahorse El. 610 m	Minimum	Average	Maximum
1980	422	***406***	365	***402***	330	390	389	330	386	422
1981	402	***423***	338	***349***	***414***	***368***	407	338	386	423
1982	301	283	298	270	284	289	265	265	284	301
1983	424	***419***	352	415	372	373	310	310	381	424
1984	391	***379***	394	422	379	452	396	379	402	452
1985	376	262	270	299	269	321	348	262	306	376
1986	358	324	270	271	311	275	288	270	300	358
1987	172	219	149	192	195	187	200	149	188	219
100-Year	600	506	-	-	-	-	-	-	553	-
10 000-Year	869	714	-	-	-	-	-	-	792	-

Notes
1. Missing records filled in by comparisons to other stations (bold, italicized).
2. Not all snowcourses were read on April 1, closest value or interpolation was used as estimate.
3. Average values were used as basin average sowpack on both elevation bands.
4. Calibration simulations require April 1 snowpacks, whereas extreme value simulations require May 1 snowpacks.

Table 8.2

Initial Snowpack Conditions
Upper Churchill North (Smallwood) Sub-Basin
Presented as Snow Water Equivalents

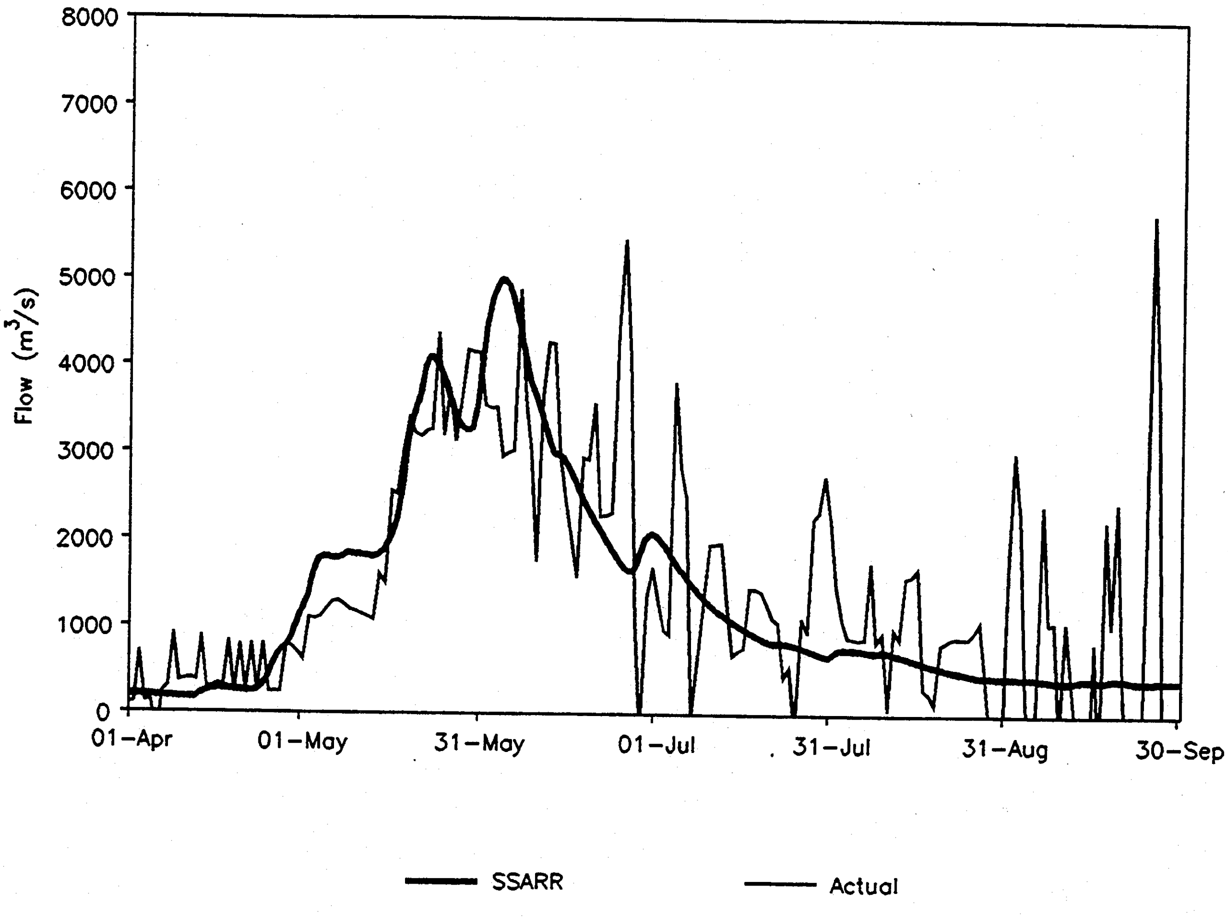
Year	Snowcourses								Calculated		
	Lobstick El. 482 m	Orma Lake El. 482 m	Esker El. 488 m	Michikimat El. 536 m	Wabush El. 579 m	McPhayden El. 597 m	Seahorse El. 610 m	McKenzie	Minimum	Average	Maximum
1980	346	451	***282***	503	369	***307***	389	***357***	282	375	503
1981	391	403	36	401	334	316	407	***403***	36	336	407
1982	285	321	254	386	268	273	265	***294***	254	293	386
1983	462	477	400	518	410	347	310	445	310	421	518
1984	344	440	335	411	395	347	310	382	310	371	440
1985	260	352	259	306	295	236	348	289	236	293	352
1986	251	296	296	326	257	229	288	258	229	275	326
1987	188	201	200	216	174	185	200	177	174	193	216
100-Year	530	569	-	633	533	477	-	557	-	550	-
10 000-Year	796	807	-	845	719	705	-	843	-	786	-

Notes
1. Missing records filled in by comparisons to other stations (bold, italicized).
2. Not all snowcourses were read on April 1, closest value or interpolation was used as estimate.
3. Average values were used as basin average sowpack on both elevation bands.
4. Calibration simulations require April 1 snowpacks, whereas extreme value simulations require May 1 snowpacks.

Table 8.3

SSARR Calibration and Verification Results
Upper Churchill Basin

Run	Peak Flow (m^3/s)		May-July Volume (million m^3)	
	Actual	SSARR	Actual	SSARR
North Sub-Basin				
Calibration				
1980	5776	4990	17 492	17 799
1981	5142	6390	18 554	20 210
1982	5849	6550	17 954	17 058
1983	8198	6070	16 793	19 684
1984	6517	5000	14 819	16 972
Verification				
1985	4084	5640	10 903	13 451
1986	6297	6380	16 589	16 292
1987	4600	2830	12 391	9 912
South Sub-Basin				
Calibration				
1980	2142	2680	10 129	9 625
1981	3010	3420	10 513	11 370
1982	2212	2700	8 549	8 177
1983	2123	2570	10 594	9 030
1984	2097	2600	9 189	9 676
Verification				
1985	1907	3370	5 916	8 216
1986	1737	2830	6 908	7 385
1987	1147	1410	5 556	4 831



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
NORTH (SMALLWOOD) SUB–BASIN
CALIBRATION, 1980

FIG 8.1

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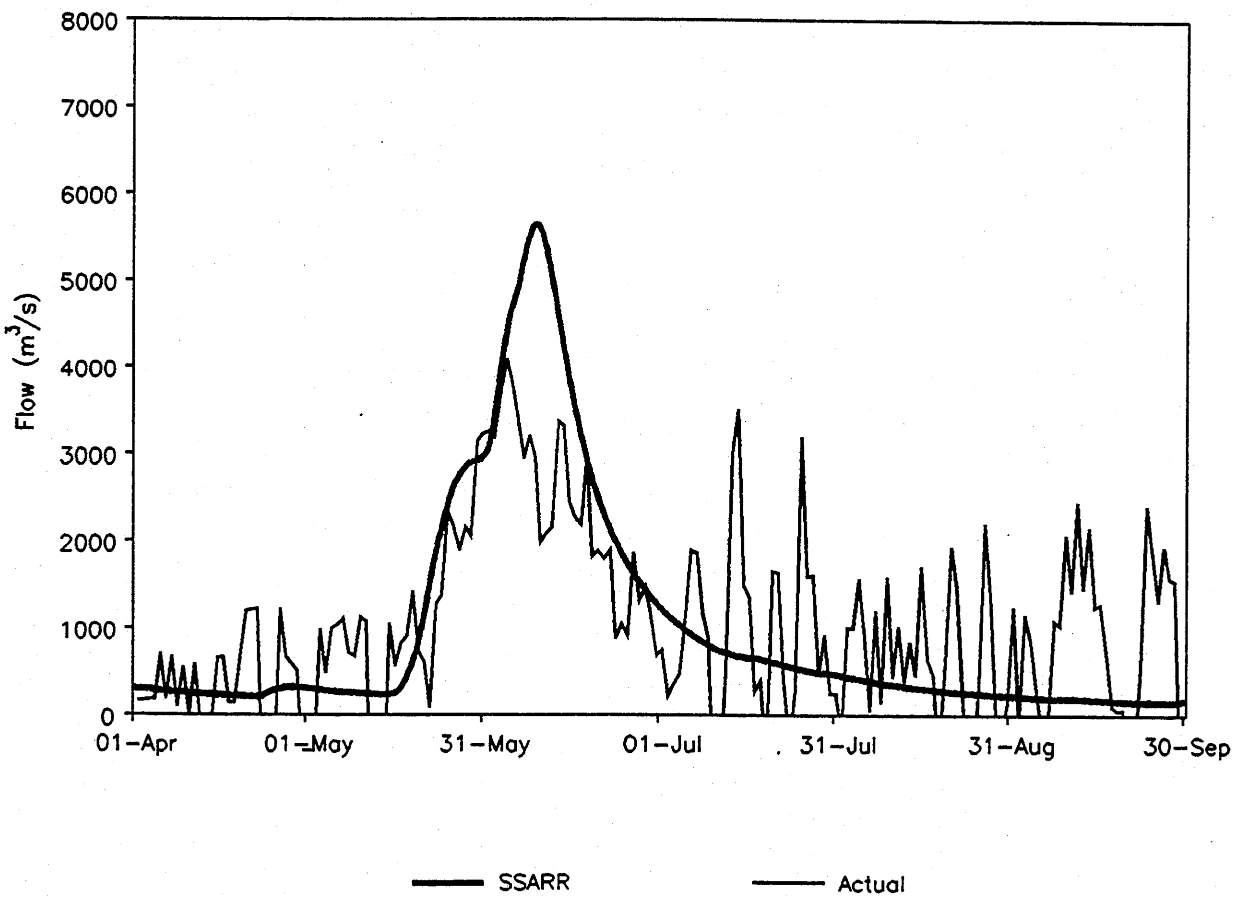

NEWFOUNDLAND AND LABRADOR HYDRO

CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

NORTH (SMALLWOOD) SUB-BASIN VERIFICATION, 1985

FIG 8.2

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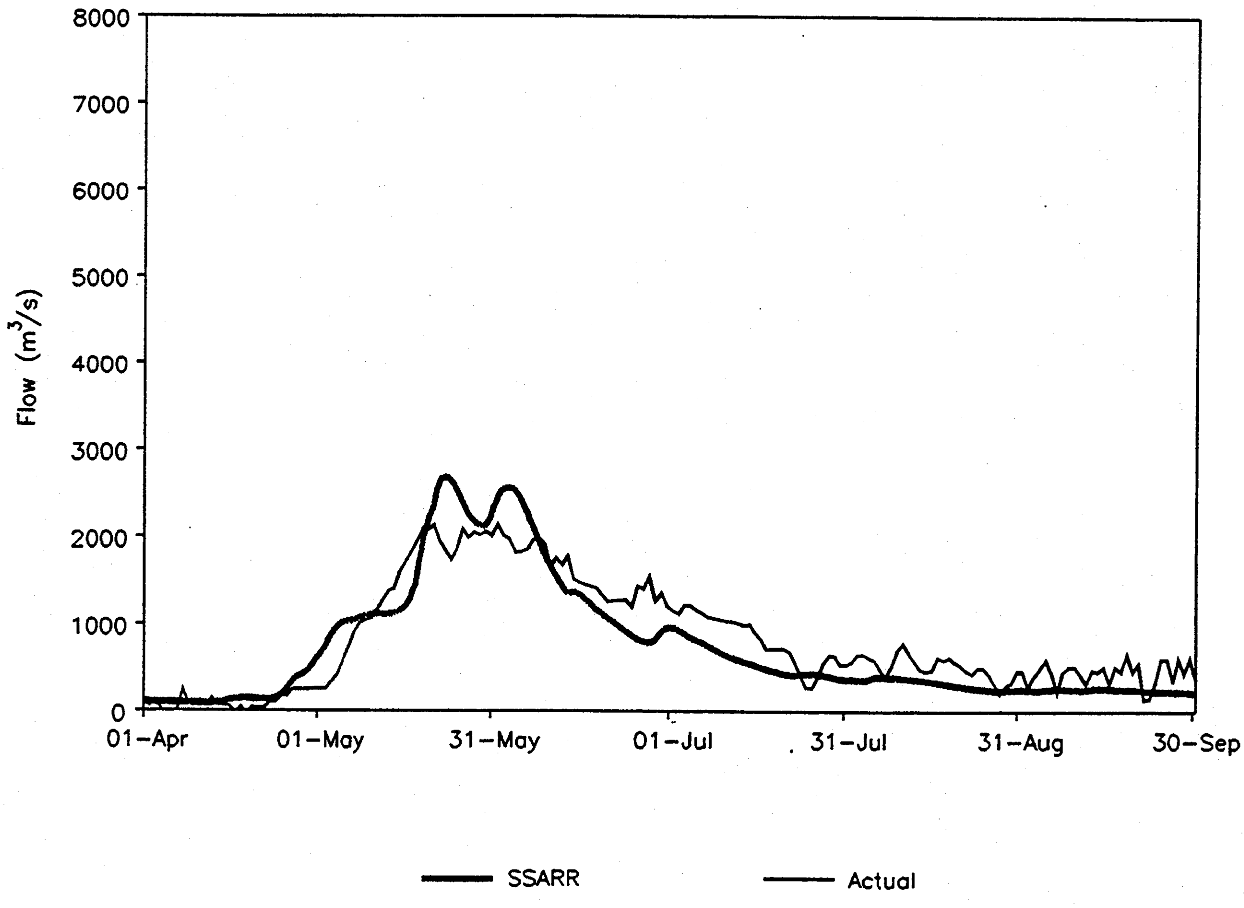
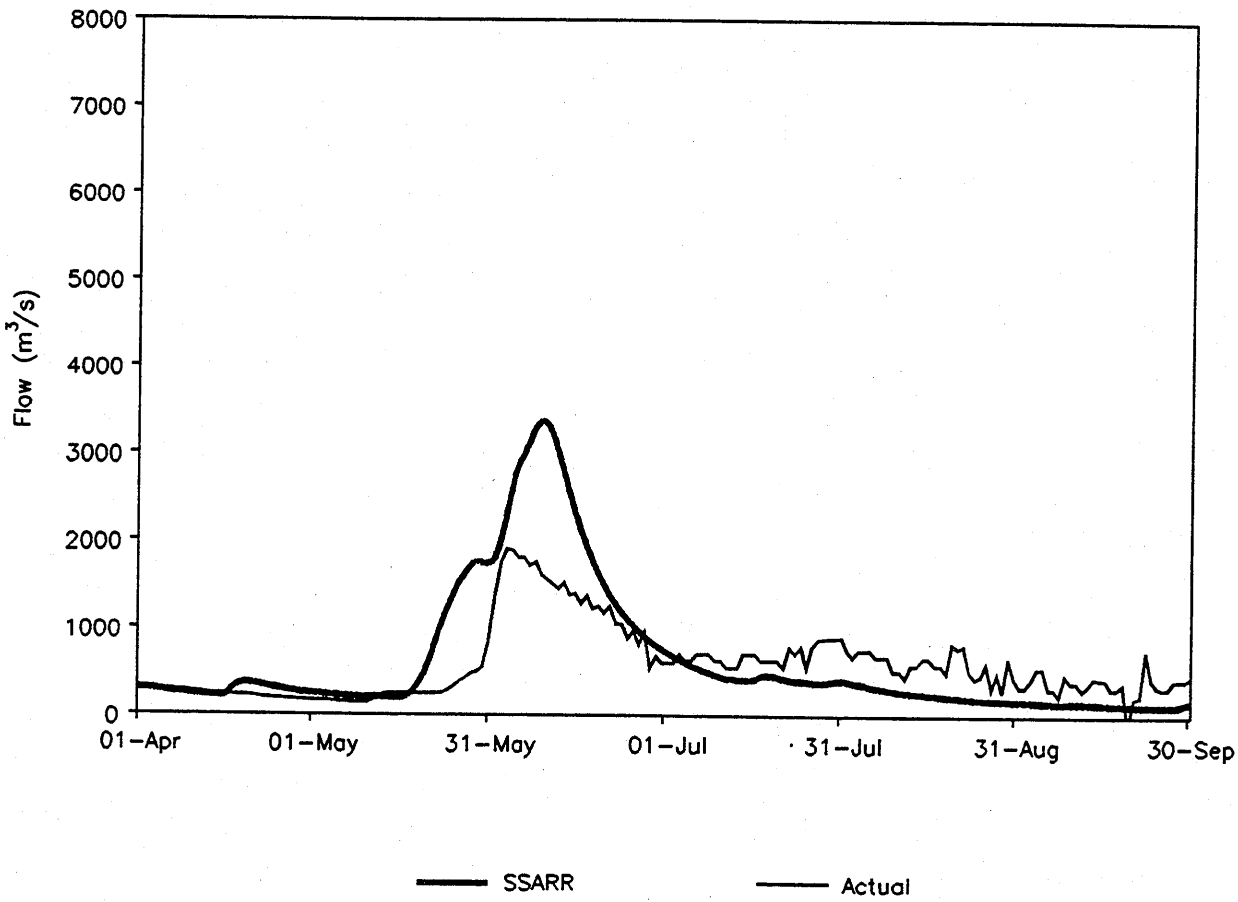


NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX - PMF REVIEW AND DEVELOPMENT
SOUTH (OSSOKMANUAN) SUB-BASIN
CALIBRATION, 1980

FIG 8.3

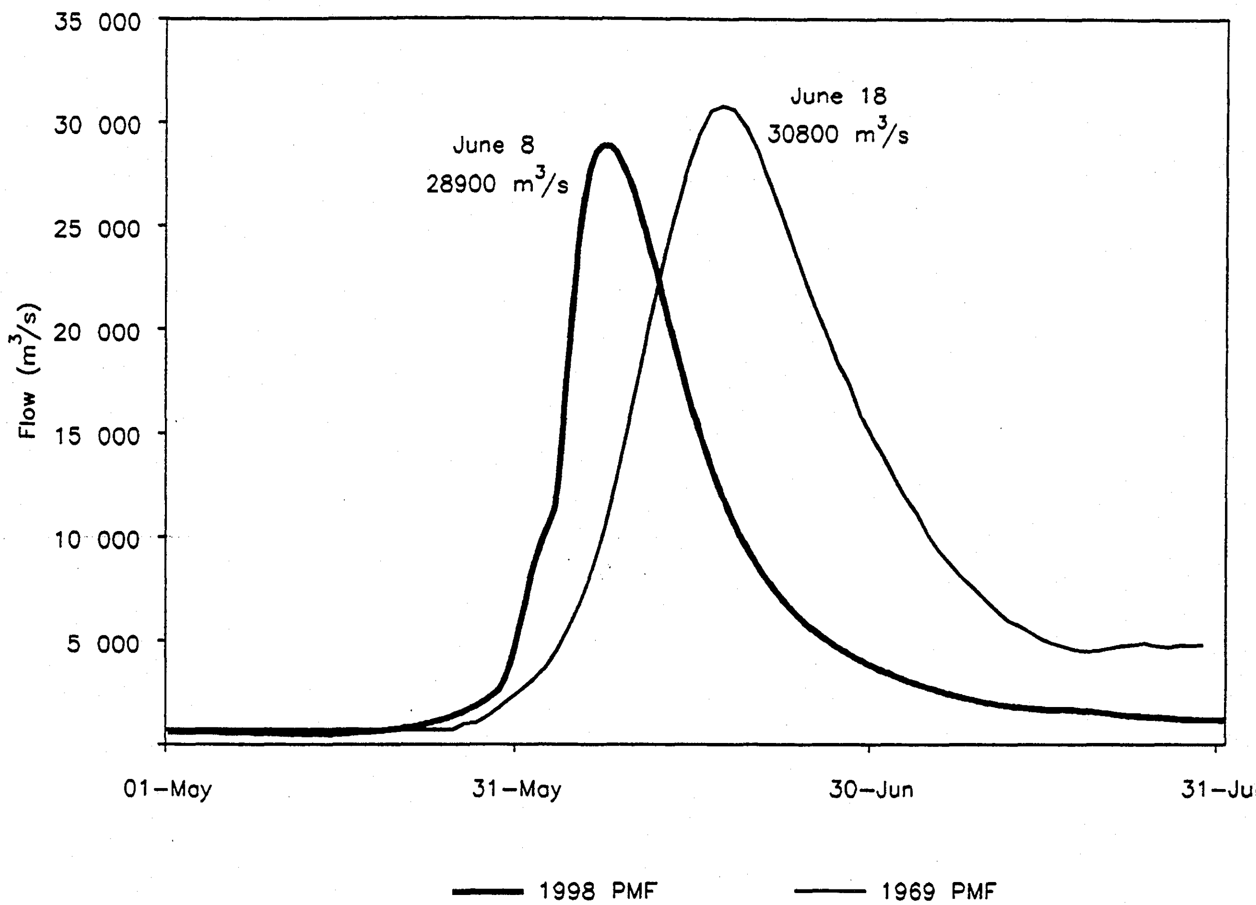
ACRES



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT
SOUTH (OSSOKMANUAN) SUB-BASIN
VERIFICATION, 1985

FIG 8.4

ACRES



NEWFOUNDLAND AND LABRADOR HYDRO
CHURCHILL RIVER COMPLEX – PMF REVIEW AND DEVELOPMENT

1969 and 1998
UPPER BASIN PMF HYDROGRAPHS

FIG 8.5

ACRES

Conclusions and Recommendations

9 Conclusions and Recommendations

9.1 Conclusions

The Churchill River Complex: Probable Maximum Flood Review and Development study has been completed with the following conclusions.

1. The Lower Churchill Basin Probable Maximum Flood occurs as a result of a warm front melting a 100-year snowpack, followed by a spring Probable Maximum Precipitation.

2. The PMP for the lower basin is 189 mm over three days.

3. The 100-year basin average snowpack on the Lower Churchill is 577 mm of water equivalent. The Probable Maximum Snowpack Accumulation is estimated to be 725 mm. The Upper Churchill Basin 100-year snowpack was estimated to be approximately 550 mm, and the PMSA is approximately 790 mm.

4. The local Lower Churchill PMF inflow for an area of 21 500 km^2 is estimated to be 18 100 m^3/s. This corresponds to a local PMF at Gull Island of 16 700 m^3/s and a local PMF at Muskrat Falls of 19 400 m^3/s. The estimated accuracy of the local PMF estimate is +/-15 percent.

5. During a Lower Churchill Basin PMF the upper basin would probably experience a large flood, but not a PMF. A conceptual review of the system suggests that following construction of CF2, operation during such a flood is unlikely to result in flows greater than approximately 2500 m^3/s (a conservatively high estimate of the combined maximum power flows of CF1 and CF2). The upper limit of upstream releases contributing to the Lower Churchill PMF is 5000 m^3/s.

6. The Upper Basin PMF derived in earlier studies may overestimate the volume of the PMF and overestimate the routing time. An overview assessment showed that revising flood handling rules to take this into account would result in lower peak discharges than currently predicted.

7. The estimate of the total PMF for the Gull Island and Muskrat Falls sites including both the current best estimate and a conservative upper bound of the Upper Churchill Basin contribution are shown in the table below.

	Local Flow	Assumed Upper Basin Flow	Total PMF	Estimate used in Feasibility Studies
Gull Island	16 700 m^3/s	2500 m^3/s	19 200 m^3/s	19 700 m^3/s
		5000 m^3/s	21 700 m^3/s	
Muskrat Falls	19 400 m^3/s	2500 m^3/s	21 900 m^3/s	22 100 m^3/s
		5000 m^3/s	24 400 m^3/s	

8. The maximum difference between the PMF estimates used in the Gull Island and Muskrat Falls feasibility studies and the current estimates is about 10 percent, which is less than the inherent degree of uncertainty in PMF derivations. The more likely values, assuming a maximum upper basin contribution of 2500 m^3/s, are slightly less than the values used in the feasibility studies. Therefore the values used in these studies are appropriate.

9.2 Recommendations

The results of the conceptual Upper Churchill Basin studies should be confirmed with additional analyses and modelling to verify the upper basin contribution to the lower basin PMF. This would best be done as part of a flood handling study for the Churchill River Complex as a whole, including both the Upper and Lower Churchill Projects and the St-Jean and Romaine Diversions. This study should

- further consider possible combinations of meteorological events on the various sub-basins to determine the worst case scenario for each development;
- revise the prespill procedure, rule curves and operating rules at the Churchill Falls GS to take into account CF2, Gull Island and Muskrat Falls developments.

An additional benefit of this work is that computer models set up for such a study could be used as the basis of a model for real time forecasting and operation.

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List of References

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