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THE Lower Churchill PROJECT

GI1140 - PMF and Construction Design Flood Study

prepared by

HATCH™

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Jan 25/08
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Glossary of Abbreviations

AEB	Atmospheric Environment Branch, Environment Canada
AEP	Annual Exceedance Probability
ARSP	Acres Reservoir Simulation Package (Computer Model)
CDA	Canadian Dam Association
CEA	Canadian Electrical Association
CF(L)Co.	Churchill Falls (Labrador) Corporation Limited
CS	Control Structure
DEM	Digital Elevation Model
GEV	General Extreme Value (distribution)
GIS	Geographical Information System
GLFRC	Great Lakes Forest Research Centre
GS	Generating Station
HEC-RAS	Hydrologic Engineering Centers River Analysis System (Computer Model)
HYDRO	Newfoundland and Labrador Hydro
PMP	Probable Maximum Precipitation
PMF	Probable Maximum Flood
PMSA	Probable Maximum Snow Accumulation
SSARR	Streamflow Simulation and Reservoir Regulation (Computer Model)
SWE	Snow Water Equivalent
WMO	World Meteorological Organization
WSC	Water Survey of Canada

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Executive Summary

Newfoundland and Labrador Hydro (Hydro) is undertaking preliminary engineering studies of the development of the hydroelectric potential of the Lower Churchill River at Gull Island and Muskrat Falls. As part of these feasibility studies, Hatch has carried out a Probable Maximum Flood (PMF) and Construction Design Flood Study.

The principal objective of this study was to determine the PMF for Gull Island and Muskrat Falls and to route the PMF hydrographs dynamically through the reservoirs formed by the dams to estimate the spillway design capacity required at each site. 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 of the entire Churchill River Basin to estimate Gull Island and Muskrat Falls PMF peaks.

The second objective of the study was to review the diversion discharge capacity requirements at each site during the periods of construction.

The PMF is defined by the Canadian Dam Association (CDA) 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".

A watershed model of the Churchill Basin was calibrated using meteorological data from Atmospheric Environment Branch, Environment Canada (AEB) climate stations at Goose Bay, Churchill Falls, Schefferville and Wabush, snow course, precipitation and lake level data from CF(L)Co. and hydrometric data from eleven Water Survey of Canada (WSC) streamflow stations. The model was then used to test the various combinations of extreme rainfall, temperature and snowpack recommended by the CDA to determine the governing PMF case.

The critical PMF scenario for the Upper and Lower Churchill Basin is a combination of:

- A 100-year snowpack;
- A severe temperature sequence; and
- A spring PMP.

The following meteorological parameters would contribute to the PMF at the project sites.

- A 100-year basin average snowpack is 535 mm, varying from 533 mm in the Lower Basin to 536 mm in the Upper Basin.
- A temperature sequence combining a cool early May to preserve the extreme snowpack into the spring, a warm front with a maximum temperature of 24° C to prime and melt the snowpack, and a cool front with a maximum temperature of 16° C bringing the Probable Maximum Precipitation (PMP) rainfall.
- A critical spring PMP would have a 66-hour rainfall depth of 286 mm over the central 10 km^2 and would be centered over the Lower Churchill River approximately 70 km west of Gull Island. This PMP would have an average depth of 121 mm, varying from 188 mm in the Lower Basin to 98 mm in the Upper Basin.

PMF hydrographs for Upper Churchill Basin from the watershed model were routed through the Churchill Falls Complex using a decision based operation model to implement the flood handling procedures for Smallwood and Ossokmanuan Reservoirs. The resulting Upper Basin outflow hydrographs and inflow hydrographs from the major tributaries in the Lower Basin were then routed through the Lower Churchill River using a dynamic hydraulic model. This hydraulic model was calibrated using survey data and historical flood data, and then run with the critical PMF hydrographs for the pre- and post-project conditions on the river.

Adding the dams, with the configurations given in the feasibility studies, results in dynamically routed PMF peaks of 20,800 m^3/s at Gull Island and 22,420 m^3/s at Muskrat Falls. Any new variants to the project configurations should be tested with the post-project dynamic hydraulic model for their ability to safely pass these floods.

The current flood handling procedures for the Churchill Falls Project were established in 1989 using a 1969 estimate of the PMF. The current PMF study suggests that these flood handling procedures could be revised to reduce the flood peaks at Gull Island and Muskrat Falls by approximately 2,000 m^3/s. It is recommended that the 1989 Flood Handling Study be updated before the next stage of the Lower Churchill Project.

A review of the construction design floods at the project sites yielded the following conclusions.

- No spill from the Upper Basin would be required during a 40-year design flood in the Lower Basin.
- Diversion discharge capacities at the project sites must be capable of passing the 40-year local inflow flood peak at each site plus the minimum acceptable powerhouse flow from Churchill Falls.
- The 40-year local inflow flood peaks have been estimated as 4,480 m^3/s at Gull Island and 4,900 m^3/s at Muskrat Falls.
- The 20-year local inflow flood peak has been estimated as 4,510 m^3/s at Muskrat Falls.

A flood forecasting procedure should be developed for the Lower Churchill River, coupled with a unit shut down procedure at Churchill Falls, to minimize the flood peaks at each site during the construction period.

1. Introduction

Newfoundland and Labrador Hydro (Hydro) is undertaking preliminary engineering studies of the development of the hydroelectric potential of the Lower Churchill River at Gull Island and Muskrat Falls. These sites are located downstream 225 km and 285 km respectively from the Upper Churchill hydroelectric facility that was developed in the early 1970's. The total potential capacity at the two sites is approximately 2800 MW (megawatts), the Gull Island site being the larger at 2000 MW. In addition to the development of these sites, the overall concept includes various potential alternative power transmission arrangements involving combinations of AC and DC lines of various capacities.

In April, 2007, Hydro contracted Hatch Ltd of St. John's to undertake a program of studies to address aspects of this development relating primarily, but not exclusively, to hydrology/hydraulics and transmission components. Approximately thirty such studies have been carried out by Hatch and its associated subconsultants- RSW of Montreal, Statnett of Oslo, and Transgrid of Winnipeg. The program has been managed from Hatch's office in St. John's using the company's project management tools and a project services team that has liaised throughout with a similar group in Hydro.

The study which is the subject of this report pertains to the Probable Maximum Flood (PMF) for the Gull Island and Muskrat Falls Projects. The purpose of the study was to determine the PMF for the two projects and to route the PMF hydrographs dynamically through the reservoirs formed by the dams to estimate the spillway design capacity required at each site.

A second objective of the study was to review the diversion discharge capacity requirements at each site during the periods of construction.

1.1 Background

The Churchill Falls Hydroelectric System is located in western Labrador, in the province of Newfoundland and Labrador. The existing generation complex regulates two-thirds of the Churchill River basin and has a capacity of 5428.5 MW. Figures 1.1 to 1.3 show the location of the existing and proposed Churchill River facilities.

Hydro engaged Hatch Ltd. to determine the PMF for the Gull Island and Muskrat Falls Projects in accordance with guidelines and recommendations of the Canadian Dam Association (CDA). The PMF study shall include the total Churchill River drainage basin areas of 89,099 km^2 upstream of the Gull Island Project site and 92,355 km^2 upstream of the Muskrat Falls Project site.

1.2 Probable Maximum Flood Definition

The 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); and
- pre-storm."

For dams with high consequences of failure, either social, environmental 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. The CDA dam safety guidelines limit the maximum size of any event in combination with a Probable Maximum event to a 100-year return period event; for example a PMP might be combined with a 100-year snowpack, or a PMSA could be combined with a 100-year rain. (Statistical events can be identified with return periods, e.g., the 100-year event, or with annual exceedance probabilities (AEP), 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 PMF scenarios to be considered:

- A combination of a 100-year snow accumulation with the spring PMP and a 100-year temperature sequence;
- A combination of the PMSA with a 100-year rainstorm and a 100-year temperature sequence; and
- A summer/autumn PMF resulting from a summer/autumn PMP, with no snow on the ground, preceded by a 100-year pre-storm.

For the total Churchill River 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.

1.3.1 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 Ranahan[5] (Atmospheric Environment Services, 1975).

3. Acres International Limited, Flood Handling Study of the Churchill Falls System[6], March 1989.
4. Acres International Limited, Churchill River Complex, PMF Review and Development Study[7], January 1999.

1.3.2 Analysis of Meteorological Data

The following analysis of meteorological data was undertaken to determine the components of the PMF:

- description of the meteorology of the Upper and Lower Churchill Basins;
- assessment of historic extreme meteorological events that could affect the determination of the PMF;
- PMP rainfall;
- 100-year rainfall;
- critical 100-year temperature sequence;
- PMSA; and
- 100-year snowpack.

1.3.3 Development of the Hydrological Model of the Churchill River

A watershed model for the entire Churchill River Basin was created using the SSARR[8] (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 SSARR model was disaggregated into twelve sub-basins in the Upper Churchill Basin and twelve[1] sub-basins in the Lower Churchill Basin to enable the centre and orientation of the design storms to be moved throughout the basin. These SSARR sub-basins are shown on Figure 1.4. This allowed the full interaction of the Upper and Lower Churchill Basins to be analysed under a range of PMF scenarios.

The model was calibrated with four years of data from 1980, 1981, 1982 and 1999 and verified using three recent operating years 2000, 2002 and 2004. Flow data from eleven Water Survey of Canada (WSC) gauges and water level data from CF(L)Co. Lobstick and Gabbro Control Structure gauges were used in the calibration and verification exercises.

PMF operating procedures and elevation-storage curves from [6] were consolidated in the model to route the Upper Basin floods through Smallwood Reservoir and Ossokmanuan/Gabbro Lake into the Lower Churchill River.

1.3.4 Review of Flood Handling Procedures for Upper Churchill

The disaggregation of the Upper Basin into twelve sub-basins, including routing through three major lake systems, as well as Smallwood Reservoir and Ossokmanuan/Gabbro Lake, demonstrates that flood travel times can vary significantly throughout the basin. Thus, depending on the location of storm centre associated with the PMF, the critical flood handling scenario for Smallwood Reservoir and Ossokmanuan/Gabbro Lake could result from different PMF combinations. The existing flood handling

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[1] The sub-basins for the Upper Minipi River and the Upper Cache River are each separated into two sub-basins for measurement purposes, giving a total of 26 sub-basins in Figure 1.4. These separated sub-basins (4 + 5) and (6 + 7) were combined in the SSARR model, giving an actual total of 24 sub-basins modeled.

procedures were reviewed with the various PMF scenarios generated in this study to verify their continued applicability.

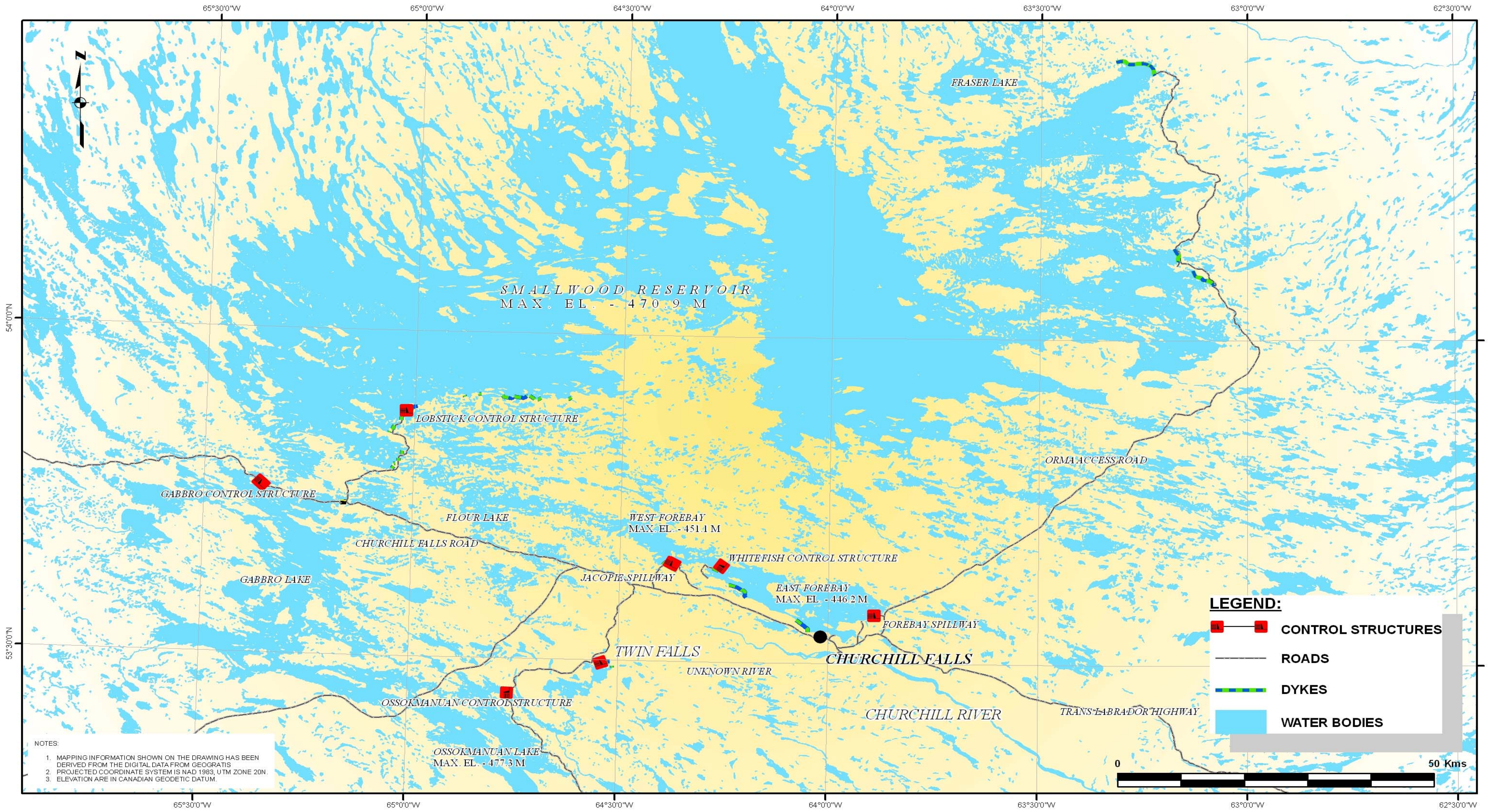
The ARSP[9] Operational Model for the Churchill Falls complex was used to confirm the applicability of the effective discharge ratings used in the SSARR model for Smallwood Reservoir and Ossokmanuan/Gabbro Lake to determine the critical PMF/PMP storm centre. When the critical PMF/PMP storm centre had been determined, the ARSP Operational Model was used once again to route the SSARR generated PMF inflows through Smallwood Reservoir and Ossokmanuan/Gabbro Lake to the Lower Churchill River for combination with the local PMF hydrographs.

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

In the SSARR model flood hydrographs enter the Lower Churchill River from eight separate locations along the length of the river. The Lower Churchill River is approximately 330 km long and flows through storage reaches such as Winokapau Lake and Gull Lake as well as steeper reaches such as Mouni Rapids and Muskrat Falls. The river routing effect of these reaches is captured in the SSARR model using a form of linear reservoir routing in which the time of storage of each routing phase decreases as flow increases. This hydrological Lower Churchill River routing was calibrated as part of the SSARR model calibration, but its accuracy is uncertain at higher flows, such as the PMF, and with the projects in place.

To overcome this uncertainty a dynamic HEC-RAS[10] hydraulic model was developed for the Lower Churchill River. The pre-project HEC-RAS model was calibrated using surveyed water level data and compared to the SSARR routing and WSC historical flood data. The calibrated HEC-RAS model was then used to route the PMF inflow hydrographs generated by the SSARR model, for the pre-project condition and then with the reservoirs created by Gull Island and Muskrat Falls generating stations, to improve the accuracy of the spillway flood estimates at each dam.

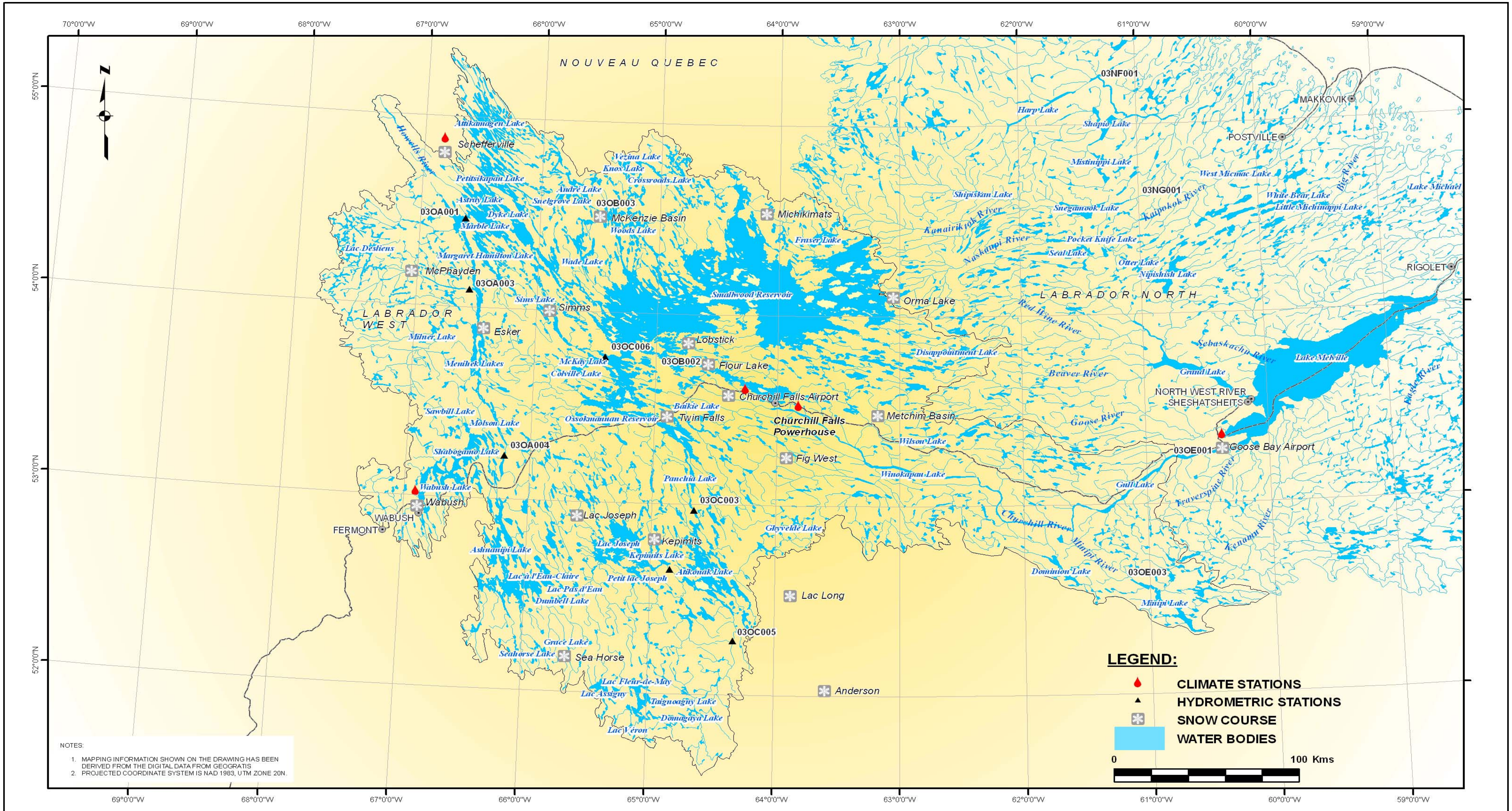
Figure 1.1
Lower Churchill Project
PMF and Construction Design Flood Study
PROJECT LOCATION



NOTES:

1. MAPPING INFORMATION SHOWN ON THE DRAWING HAS BEEN DERIVED FROM THE DIGITAL DATA FROM GEOGRATIS
2. PROJECTED COORDINATE SYSTEM IS NAD 1983, UTM ZONE 20N.
3. ELEVATION ARE IN CANADIAN GEODETIC DATUM.

Figure 1.2
Lower Churchill Project
PMF and Construction Design Flood Study
UPPER CHURCHILL RIVER SYSTEM



NOTES:
1. MAPPING INFORMATION SHOWN ON THE DRAWING HAS BEEN DERIVED FROM THE DIGITAL DATA FROM GEOGRATIS
2. PROJECTED COORDINATE SYSTEM IS NAD 1983, UTM ZONE 20N.

LEGEND:

💧	CLIMATE STATIONS
▲	HYDROMETRIC STATIONS
✱	SNOW COURSE
🟦	WATER BODIES

0 100 Kms

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Figure 1.3
Lower Churchill Project
PMF and Construction Design Flood Study
UPPER AND LOWER CHURCHILL BASINS

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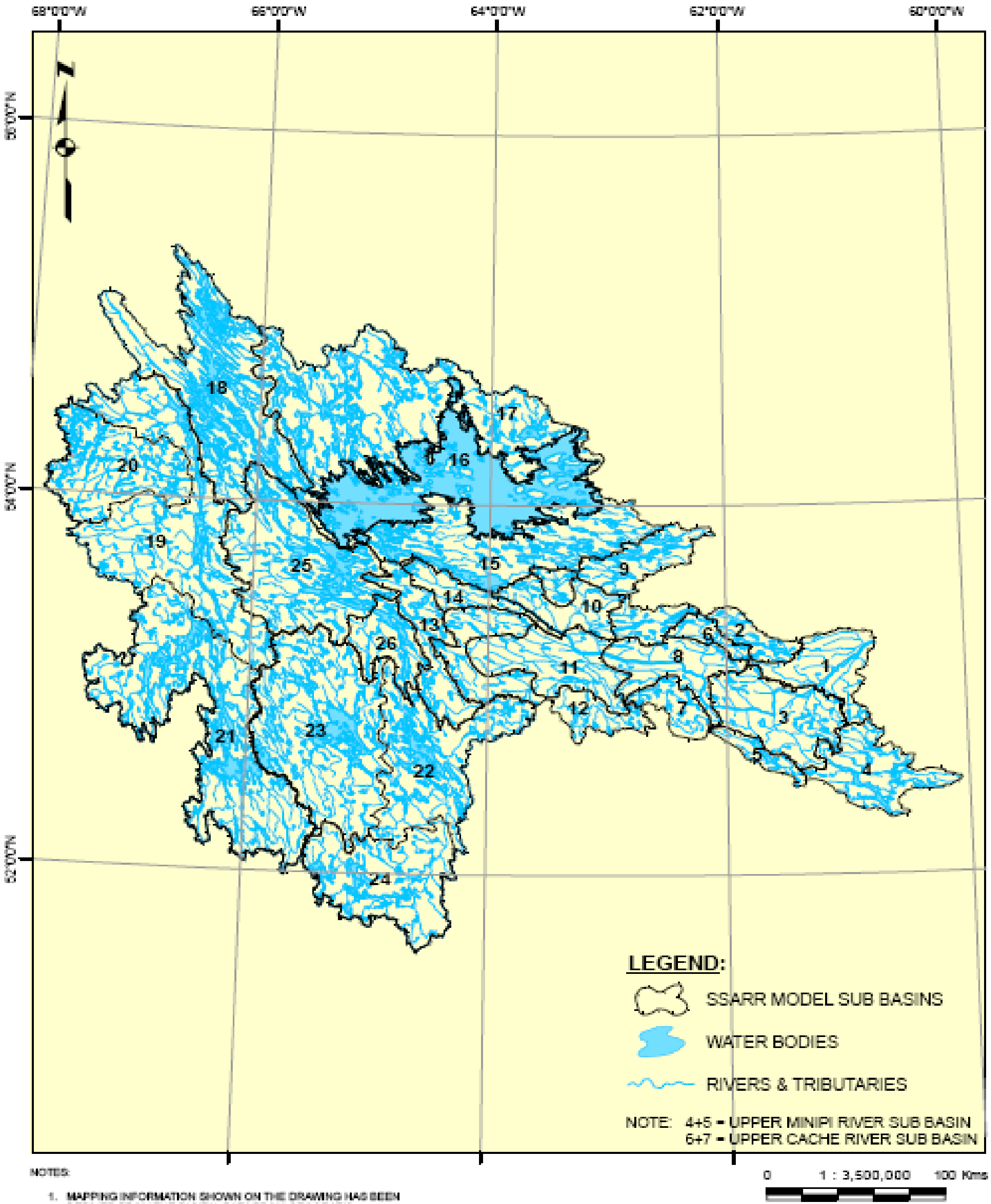

NOTES:

1. MAPPING INFORMATION SHOWN ON THE DRAWING HAS BEEN DERIVED FROM THE DIGITAL DATA FROM GEOGRATIS
2. PROJECTED COORDINATE SYSTEM IS NAD 1983, UTM ZONE 20N.

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Figure 1.4
Lower Churchill Project
PMF and Construction Design Flood Study
SSARR MODEL SUB BASINS

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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[2] derived design floods. Sparrow[3], 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; and
- 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 flood volume rather than flood peak.

The results of the 1969 study are summarized in Table 2.1.

Although 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[4] in 1975 as part of the Gull Island Hydroelectric Project Feasibility Study. Pollock and Ranahan[5] of Atmospheric Environment Services (AES) estimated the meteorological conditions leading up to a maximum probable flood.

The sequence of meteorological 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 difference 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 more "peaky" 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[6] 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 pre-spill 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, 767 mm, 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 meteorological parameters.

2.4 Churchill River Complex, PMF Review and Development Study, 1999

Acres International[7] undertook a PMF Review and Development Study for Gull Island and Muskrat Falls in 1999. The severity of the combined meteorological inputs to the PMF was reduced in the 1999 study in accordance with the then current guidelines and recommendations of the Canadian Dam Association. 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 Snow Accumulation (PMSA) of 725 mm of water equivalent.

A SSARR 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 was 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 Project 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 5,000 m^3/s during a lower basin PMF. Conceptual studies of the upper basin suggested that following development of the new projects, flood operation during a lower basin PMF is unlikely to result in flows greater than approximately 2,500 m^3/s.

The conceptual watershed and operations modelling undertaken for the Upper Churchill Basin in 1999 suggested 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 showed that the revised upper basin PMF would lead to lower maximum water levels in Smallwood Reservoir and lower maximum spill releases.

The total PMF estimated for the Churchill River at Gull Island and Muskrat Falls ranged from 19,200 to 21,700 m^3/s and 21,900 to 24,400 m^3/s, respectively, assuming an upper basin contribution of 2,500 m^3/s and 5,000 m^3/s.

A flood handling study for the whole system was recommended 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.

The results of the 1999 study were subsequently used by SNC-AGRA[20],[21] in the final feasibility studies for Gull Island and Muskrat Falls.

Key results of the 1999 study are given in Table 2.1.

2.5 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 the current 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 current draft CDA guidelines indicate that the appropriate snowpack to use in combination with a PMP event is the 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 the Probable Maximum Snow Accumulation (PMSA).

The previous Upper and Lower Churchill studies are now 38, 31 and 8 years old, so each component of the meteorological input requires re-evaluation for the present PMF analysis.

There were a number of hydrological shortcomings in the previous studies that the current study has attempted to overcome:

- The three basins contributing to Smallwood Reservoir, Ossokmanuan/Gabbro Lake and the Lower Churchill River were each modelled by a single sub-basin in which precipitation and snow cover were considered uniform across the basin. This ignores the areal variation of moisture input, routing through lakes and travel times throughout the basin. In the current study each basin has been broken down into sub-basins and the use of GIS has enabled the storm rainfall and snow to be distributed more realistically. This is particularly important for Smallwood Reservoir where runoff from the local drainage areas and direct precipitation on the reservoir surface arrive faster than inflows from the Ashuanipi River.
- The previous flood studies of the Lower Churchill River have focussed on the Lower Basin with contributions from the Upper Basin added as a fixed outflow from Churchill Falls. This approach does not consider the variable spill through Jacopie Spillway, the Ossokmanuan Control Structure and the Julian dyke breaches, which could occur during a PMF. The current SSARR model includes the entire Churchill River Basin, so that the impacts of flood handling in the Upper Basin on Lower Churchill flows is computed directly for each storm centre, without the need for indirect estimation.

Table 2.1
Summary of Previous Flood Studies

Parameter	Upper Churchill Basin				Lower Churchill Basin		
	1969 MPF[1]	1989 Flood Handling Study	1998 PMF	2007 PMF[2]	1976 Gull[1] Island MPF[3]	1998 PMF[3]	2007 PMF[4]
Drainage Area	67,558 km^2	67,558 km^2	67,558 km^2	69,200 km^2	19,800 km^2	21,500 km^2	92,500 km^2
Duration of Rainstorm	5 days	5 days	3 days	66 hours	3 days	3 days	66 hours
Total Storm Rainfall	172 mm	172 mm	153 mm	139/106 mm[5]	213 mm	189 mm	98/188 mm[6]
Duration of Imposed Meteorologic Sequence	16 days	16 days	22 days	22 days	16 days	22 days	22 days
Snowpack Return Period	maximized snowpack	maximized snowpack	100-year	100-year	maximized snowpack	100-year	100-year
May 1 Snowpack Water Equivalent	687 mm	687 mm	550 mm	536 mm	952 mm	580 mm	535 mm
Peak Inflow	30,580 m^3/s	30,800 m^3/s	28,800 m^3/s	21,240 m^3/s	13,600 m^3/s	18,100 m^3/s	20,900 m^3/s[7]
Peak Outflow	-	15,400 m^3/s	7000-9000 m^3/s	11,000 m^3/s	-	-	22,800 m^3/s[8]
May to July Flood Volume	68,180 million m^3	68,180 million m^3	44,400 million m^3	39,200 million m^3	23,200 million m^3	15,400 million m^3	49,500[8] million m^3
Flood Peak Inflow Date	mid June	mid June	early June	early June	early June	early June	early June

Notes
Results of current studies included for reference. Details on the derivations of these values are included in later sections.
1. Studies were done in imperial units. Results converted to metric here for comparison.
2. PMP storm centre 7 over Upper Basin
3. Does not include Upper basin outflow (± 5,000 m^3/s)
4. Includes entire Churchill River Basin
5. Upper Basin/Lower Basin averages
6. PMP storm centre 2 over Lower Basin
7. At Gull Island
8. At Muskrat Falls

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 the 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 projects are 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 Lower Churchill River 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 sub-basins draining into the river along its length. Some of the larger rivers which provide significant runoff to the lower river are Unknown River, Metchin River, Fig River, Cache River, Minipi River and Pinus River. In the upper reaches of these rivers the gently sloping plateau has given rise to the formation of chains of lakes through which runoff from higher areas must drain. Some of these lakes have a significant attenuating effect on downstream flood peaks. However, flood flows from most of these sub-basins would arrive in the main channel at approximately the same time.

The great depth of Lake Winokapau also provides some attenuation to flows from the Unknown River, Metchin River and Fig River, then the relatively steep slope of the river to Lake Melville accelerates floods. The travel time in the main channel from Churchill Falls to Muskrat Falls is approximately three days. Overall the shape and geomorphology of the Lower Churchill Basin means that runoff response can be expected to be faster than might otherwise be expected from a 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[11]. 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 bracket the basin to the west and east. Since the temperature and precipitation regime are similar at these two stations, they have been assumed to represent climate conditions in the basin.

There is a synoptic climate station at Churchill Falls Airport just west of the drainage area at an elevation of 440 m. Data are available from 1968 to the present, although data availability is sporadic in recent years. 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, although snow pack water equivalent data was discontinued in 1995.

Although Churchill Falls Airport and Goose Bay Airport stations are approximately 240 km apart and 400 m different in elevation, their temperature and precipitation data show little difference, as summarized in Table 3.1. On average, Goose Bay is 3° C warmer than Churchill Falls and experiences 23 mm more annual precipitation, a 2 percent difference. Any given precipitation event, however, may be experienced at one of the stations only, not necessarily both. Data from both stations 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 934 mm of which 45 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 sub-basins of the Lower Churchill River at Metchin and Fig West. 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 a WSC hydrometric station on the Churchill River at Upper Muskrat Falls since 1948 with a continuous recording station since 1953 (03OE001). The drainage area at this station 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.

The Churchill Falls Hydroelectric Project regulates almost 75 percent of the drainage area of the Churchill River at Muskrat Falls. Figures 3.1 and 3.2 show hydrographs at Muskrat Falls after regulation, and the releases from Churchill Falls Powerhouse for 1999 and 1987, the highest and lowest flood years at Muskrat Falls. During winter the generation releases are between 1,500 and 2000 m^3/s, in summer the releases are approximately 1,000 m^3/s. There were some spill releases from the Upper Basin in the 1970s, but there have not been any since the operating rules were finalized. 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 accurate estimate of the local inflow hydrographs to the Lower Churchill River between the powerhouse and Muskrat Falls cannot be determined directly from the available flow records because of the routing effect of Lake Winokapau, ice effects and the variable travel time in the river. Direct subtraction of Churchill Falls Powerhouse flows from the Muskrat Falls flows results in a synthetic flow series containing many records with zero or negative flows. Calibration of the SSARR model of the Lower Basin has included releases from Churchill Falls Powerhouse to implicitly include the effect of these flows on flood routing in the main river channel.

The flow regime of the tributary rivers draining to the Lower Churchill River comprises three stages:

- Rapid runoff from the higher reaches above the plateau;
- Slower runoff from the plateau areas and routing through chain lakes; and
- Rapid runoff from the areas below the plateau.

The effects of the chain lakes on flood flows varies with each tributary. The Minipi River below Minipi Lake (03OE003) generally peaks 7 to 10 days after the peak at Muskrat Falls (03OE001), whereas the Pinus River (03OE011) and the East Metchin River (03OD007) peak 0 to 3 days before the peak at Muskrat Falls. In the SSARR model each tributary has been represented by an upper sub-basin, a natural lake and a lower sub-basin to capture this flow regime.

Table 3.1
Lower Churchill Basin Climate
Mean Monthly Values[1]

Month	Station						Lower Churchill Basin		
	Churchill Falls Airport (8501132)			Goose Bay Airport (8501900)					
	Temp (°C)	Rain (mm)	Snow (mm)	Temp (°C)	Rain (mm)	Snow (mm)	Temp (°C)	Rain (mm)	Snow (mm)
Jan	-22	1	68	-18	2	80	-21	1	72
Feb	-21	1	53	-16	3	63	-19	2	56
Mar	-14	4	64	-10	5	76	-12	4	67
Apr	-5	10	58	-2	19	52	-4	13	56
May	3	37	20	5	47	20	4	40	20
Jun	10	85	6	11	92	3	10	87	5
Jul	14	112	0	15	114	0	14	113	0
Aug	12	96	0	15	99	0	13	97	0
Sep	7	96	11	9	92	3	7	95	8
Oct	0	41	45	2	60	22	0	47	38
Nov	-9	8	78	-5	20	62	-7	12	73
Dec	-19	3	63	-14	6	78	-18	4	68
Mean	-4	-	-	-1	-	-	-3	-	-
Total	-	494	465	-	559	459	-	513	463

Note

1. Data from Canadian Climate Normals 1971-2000, Environment Canada.

Table 3.2
Climate and Hydrometric Stations

Name	Data Type	ID number	Period of Record	Latitude	Longitude
Anderson	snow course	NF001	1972-07	52° 10'	63° 34'
Ashuanipi River at Menihek Rapids	hydrometric	03OA001	1955-05	54° 27'	66° 37'
Ashuanipi River below Wightman Lake	hydrometric	03OA004	1972-83	53° 13'	66° 12'
Atikonak River above Atikonak Lake	hydrometric	03OC005	1972-00	52° 17'	64° 20'
Atikonak River at Gabbro Lake	hydrometric	03OC006	1973-05	53° 46'	65° 24'
Atikonak River above Panchia Lake	hydrometric	03OC003	1972-05	52° 58'	64° 40'
Churchill Falls	snow course	NF008	1972-07	53° 34'	64° 07'
Churchill Falls	climate	850A131	1993-05	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 Churchill Falls Powerhouse	hydrometric	03OD005	1972-05	53° 32'	63° 58'
Churchill River above Upper Muskrat Falls	hydrometric	03OE001	1948-05	53° 15'	60° 47'
East Metchin River	hydrometric	03OD007	1998-05	53° 26'	63° 14'
Esker	snow course	NF016	1972-07	53° 51'	66° 24'
Fig West	snow course	NF019	1972-07	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	1941-05	53° 19'	60° 25'
Kepimits	snow course	NF042	1972-07	52° 42'	64° 51'
Kepimits River below Kepimits Lake	hydrometric	03OC004	1972-00	52° 39'	64° 51'
Lac Joseph	snow course	NF043	1972-07	52° 58'	65° 32'
Lac Long	snow course	NF044	1972-07	52° 36'	63° 51'
Lobstick	snow course	NF049	1972-07	53° 50'	65° 02'
McKenzie Basin	snow course	NF051	1972-07	54° 34'	65° 32'
McPhayden	snow course	NF052	1972-07	54° 12'	67° 09'
McPhayden River near the Mouth	hydrometric	03OA003	1972-82	53° 06'	66° 34'
Metchim Basin	snow course	NF056	1972-07	53° 26'	63° 16'
Michikimats	snow course	NF057	1972-07	54° 34'	64° 07'
Minipi River below Minipi Lake	hydrometric	03OE003	1979-05	52° 37'	61° 11'
Orma Lake	snow course	NF065	1972-07	54° 08'	63° 09'
Pinus River	hydrometric	03OE011	1998-05	53° 09'	61° 34'
Schefferville A	snow course	-	1968-94	54° 48'	66° 49'
Schefferville	climate	7117825	1948-05	54° 48'	66° 49'
Seahorse	snow course	NF076	1972-07	52° 10'	65° 44'
Simms	snow course	NF079	1972-07	53° 46'	65° 49'
Twin Falls	snow course	NF090	1972-07	53° 36'	64° 28'
Wabush	snow course	NF095	1972-07	52° 57'	66° 42'
Wabush Lake Airport	climate	8504175	1960-05	52° 56'	66° 52'

Table 3.3
Churchill River above Upper Muskrat Falls
Water Survey of 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	Unregulated	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		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	Construction	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		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	Regulated	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		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
1997		1862	1756	1718	1398	2464	2665	1864	1593	1683	1807	1814	1588	1851
1998		1871	1954	1924	1802	3790	2169	1324	1369	1822	2096	2034	1819	1999
1999		1855	1850	1809	1624	3584	1855	1536	1673	1465	1650	1880	1940	1896
2000		1959	1935	2028	1854	2456	2448	1651	1204	1216	1366	1615	1819	1795
2001		2069	2089	2002	1465	2965	1637	1435	1360	1356	1580	1759	1913	1803
2002		1910	1859	1865	1532	1968	2669	1382	1742	1611	1879	1873	1704	1832
2003		1821	1858	1841	1570	3009	1757	1467	1187	1291	1364	1669	1852	1724
2004		2023	1888	1747	1428	2579	2737	1232	1243	1074	1562	1807	1722	1753
2005		1816	1818	1778	1595	2311	1472	1258	1542	1532	1383	1769	2216	1708

Effect of Regulation

Mean 1954-69	691	560	488	480	1818	4209	3249	2048	1800	1767	1488	970	1634
Mean 1975-05	1822	1814	1695	1557	2615	2378	1728	1652	1575	1735	1763	1794	1844
Ratio	2.6	3.2	3.5	3.2	1.4	0.6	0.5	0.8	0.9	1.0	1.2	1.8	1.1

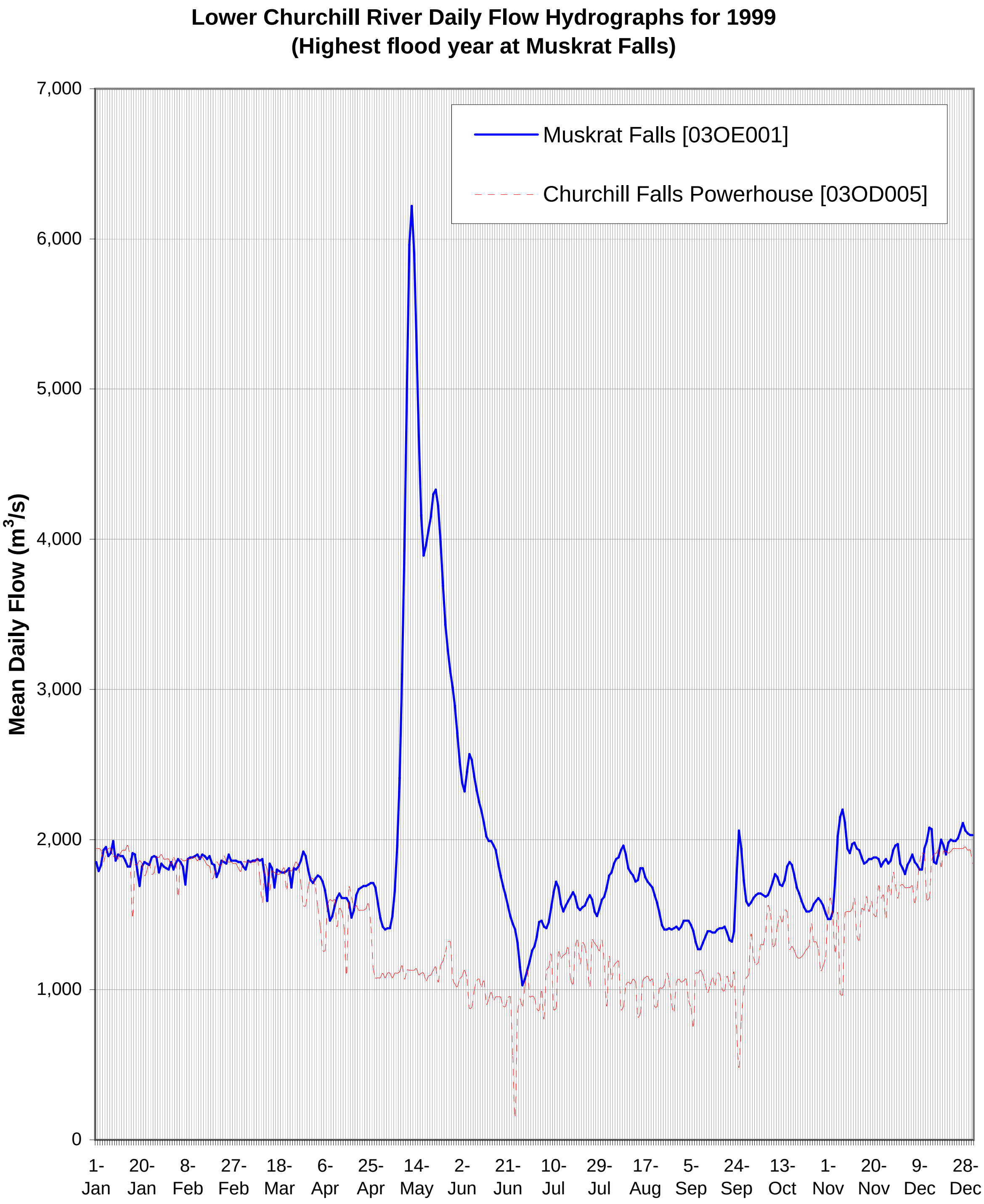

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Figure 3.1

Lower Chruchill Project

PMF and Construction Design Flood Study

LOWER CHURCHILL RIVER DAILY FLOW HYDROGRAPHS FOR 1999

C:\PMF Figs\[H325967-FIG-CA01-00004.xls]1.1

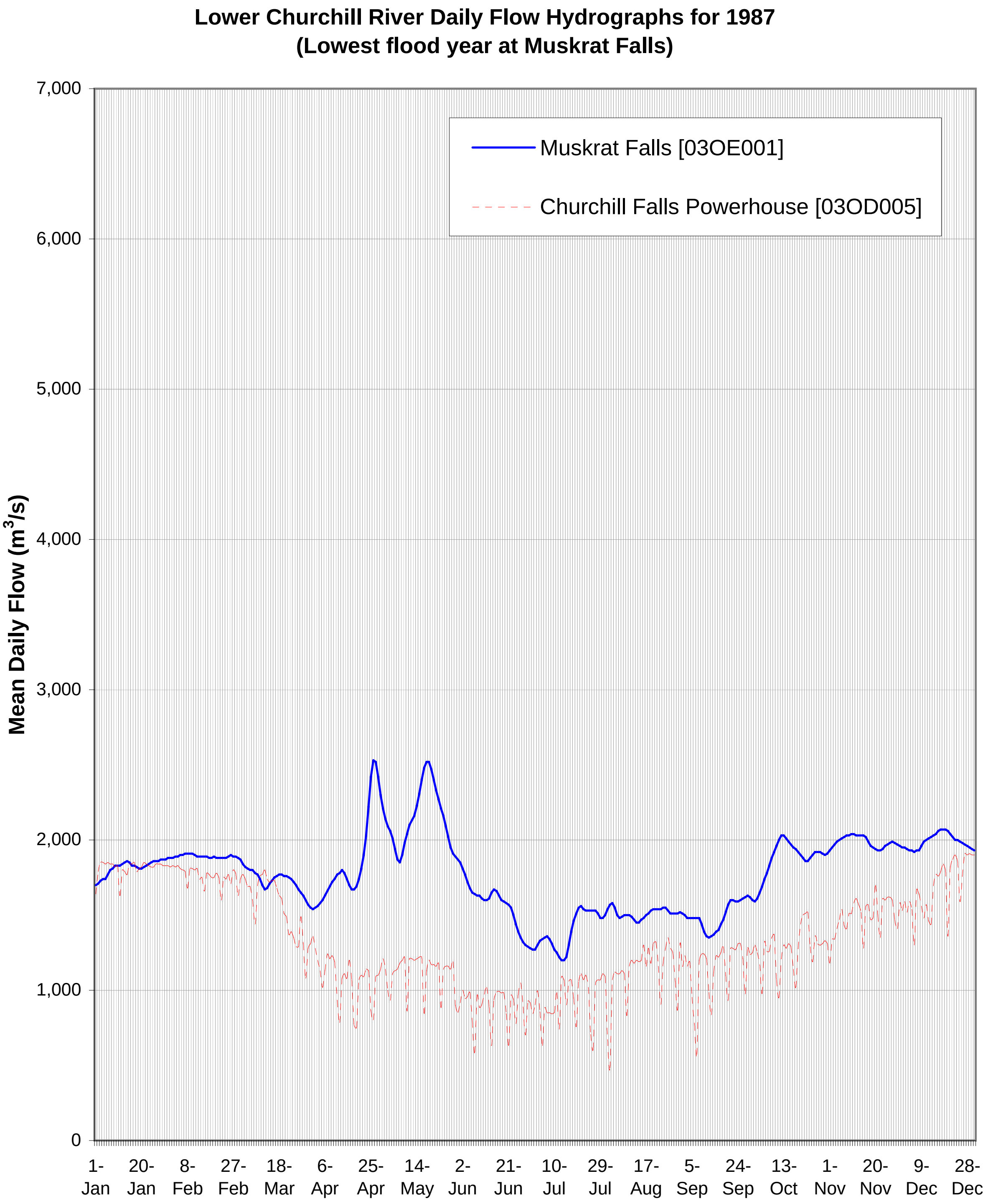

Figure 3.2
Lower Chruchill Project
PMF and Construction Design Flood Study
LOWER CHURCHILL RIVER DAILY FLOW HYDROGRAPHS FOR 1987

4. Upper Churchill Basin

4.1 Basin Description

The drainage area of the Churchill Basin above Churchill Falls has been measured as 69,200 km^2, three-quarters 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 around 400 m. The plateau area has very shallow bedrock and is covered with large and small lakes and areas of muskeg. The upper basin is effectively two sub-basins; the southern basin, which drains via the Atikonak River to Ossokmanuan/Gabbro Lake; and the northern basin, which drains via the Ashuanipi River and local drainage to Smallwood Reservoir and the West and East Forebays.

The main lakes in the southern basin are Lac Joseph, Atikonak Lake, and Ossokmanuan/Gabbro Lake. The combined southern portion of the basin has a drainage area of 22,432 km^2. The northern part of the basin contains Ashuanipi, Wabush and Shabogamo Lakes in the southwest, but is dominated by Smallwood Reservoir. The combined northern portion of the basin has a drainage area of 46,768 km^2 (including the West and East Forebays).

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 spill flows into the Churchill River via the Unknown River.

Flow from 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 on 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 and is not included in the flood routing analysis.

4.2 Climate

The Upper and Lower Churchill Basins experience similar meteorological 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 normally cooler and drier than Wabush and Churchill Falls. Basin average monthly temperatures for the northern and southern portions of the Upper Churchill Basin are given in Table 4.1.

4.3 Flow Regime

Discharges from the Churchill Falls GS, recorded as WSC hydrometric station 03OD005 are given in Table 4.2. Releases from Gabbro Control Structure to Smallwood Reservoir (03OC006) are given in Table 4.3.

The gentle slopes of the Labrador Plateau have resulted in the formation of numerous lakes, both large and small in the Upper Basin. WSC stations have monitored the outflows from the largest of these lakes on the Atikonak and Ashuanipi Rivers for varying lengths of time in the past. A list of these hydrometric stations is given in Table 3.2. Flood hydrographs from the Atikonak and Ashuanipi Rivers are significantly attenuated by the natural lake regulation en route to Ossokmanuan Lake and Smallwood Reservoir. In contrast the direct flood runoff to these storages from local, unregulated drainage areas will be swifter, as demonstrated by the Upper Atikonak River (03OC005) and the McPhayden River (03OA003). The results of this wide range of "times to peak" throughout the Upper Basin are less “peaky” inflow hydrographs to each storage, with a more gradual recession limb.

4.4 Flood Operation

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 also likely to lead to severe weather conditions in the upper basin. The snowpack and temperatures would likely be similar in the upper and lower basins. The only variable component in each of the potential PMF scenarios for either the Upper Basin or the Lower Basin would be the magnitude, location, timing and orientation of the storm rainfall contributing to the PMF.

The snowpack and temperature sequences for each PMF scenario are fixed in the SSARR model throughout the Churchill Basin and the rainfall sequence for a range of storm centres is defined for each of the 24 sub-basins by the GIS model of the system. Introduction of these storm rainfall sequences to the SSARR model will generate inflow hydrographs to Smallwood Reservoir and Ossokmanuan/Gabbro Lake. These flood hydrographs will then be routed through the Churchill Falls project according to the flood handling procedures designed to protect against extreme floods.

The current flood handling procedures for the Churchill Falls project are described in the Acres 1989 Flood Handling Study main report and the Manual for Spring Operating Procedure for Smallwood Reservoir [12]. Flood operation of Ossokmanuan/Gabbro Lake is simple since there is little flood storage available. The rules require that Ossokmanuan/Gabbro Lake 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, pre-spill through increased generation and spillway releases is planned and undertaken when necessary. Pre-spill is delayed until it is absolutely necessary to hedge against poor forecasts. During normal operation, the maximum flood level of Smallwood Reservoir is the full supply level, El. 472.74 m. During the PMF, the reservoir would be allowed to rise to El. 473.66 m, which is approximately one metre below the top of the core of Lobstick Dykes.

The pre-spill operation is planned so that on May 1st, there is enough storage to contain the spring snowmelt runoff. The water management criterion is to refill the reservoir by August 1st. From May 1st until June 10th or June 15th, depending on the depth of the winter snowpack, Smallwood Reservoir is kept at the May 1st 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 1st. The extent of this drawdown would depend on the PMF scenario, the PMSA + 100-year rainfall or the 100-year snowpack + PMP. The closure of Gabbro Control Structure, the opening of Ossokmanuan Control Structure, and the operation of Lobstick Control Structure and Jacopie Spillway will all vary according to the rising water levels in Smallwood Reservoir and Ossokmanuan/Gabbro Lake. Thus, each storm centre would produce unique outflow hydrographs to the Lower Churchill River and the Unknown River, that are reintroduced to the SSARR model to continue the PMF routing to Gull Island and Muskrat Falls.

For the critical PMF scenario the two flood hydrographs from the flood handling model and the six flood hydrographs from the Lower Churchill tributaries from the SSARR model are routed dynamically through the reservoirs created by Gull Island and Muskrat Falls using the HEC-RAS hydraulic model developed for the Lower Churchill River.

Table 4.1
Upper Churchill Basin Climate
Mean Monthly Values[1]

Month	Station									Smallwood Basin			Ossokmanuan Basin		
	Churchill Falls Airport (8501132)			Wabush Lake Airport (8504175)			Schefferville Airport (7117825)								
	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	68	-23	1	66	-24	0	57	-23	0	62	-23	1	67
Feb	-21	1	53	-21	2	49	-23	0	43	-22	1	47	-21	1	51
Mar	-14	4	64	-14	3	65	-16	2	57	-15	3	60	-14	3	64
Apr	-5	10	58	-5	12	53	-7	8	55	-6	10	55	-5	11	55
May	3	37	20	4	40	17	1	28	23	2	33	20	3	39	18
Jun	10	85	6	10	82	3	9	65	8	9	74	6	10	83	4
Jul	14	112	0	14	112	0	12	107	1	13	109	0	14	112	0
Aug	12	96	0	12	95	0	11	83	2	12	89	1	12	96	0
Sep	7	96	11	7	89	7	5	85	13	6	89	11	7	93	9
Oct	0	41	45	0	37	42	-2	24	57	-1	32	50	0	39	43
Nov	-9	8	78	-9	7	75	-10	5	71	-9	6	74	-9	8	77
Dec	-19	3	63	-19	3	70	-21	1	55	-20	2	61	-19	3	67
Mean	-4	-	-	-4	-	-	-5	-	-	-4	-	-	-4	-	-
Total	-	494	465	-	483	446	-	408	441	-	448	448	-	488	456

Note

1. Data from Canadian Climate Normals 1971-2000, Environment Canada.

Table 4.2

Churchill River at Churchill Falls Powerhouse

Water Survey of 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	1051	1092	634	549	394	533	506	526	660	672	680	846	676
1974	856	871	820	1490	890	1335	1028	892	1053	1097	1155	1290	1064
1975	1288	1259	1246	1218	1217	1611	1909	2085	1317	1325	1357	1413	1439
1976	1550	1381	1378	1367	1371	1530	1526	1369	1867	1839	1360	1527	1506
1977	1612	1468	1413	1561	1421	2414	1203	1301	1532	1923	1699	1896	1619
1978	1938	1901	1900	1793	1507	1274	1497	2341	1731	1599	1682	1854	1752
1979	1951	1946	1909	1757	1498	1155	2527	2167	1348	1698	1844	1680	1792
1980	1691	1759	1768	1723	1635	1454	1988	1601	1435	1567	1745	1948	1694
1981	1937	1813	1786	1422	944	1367	2530	1802	1500	1573	1921	1975	1715
1982	1976	1961	1953	1819	1407	1415	1383	1379	1245	1164	1425	1554	1554
1983	1639	1608	1488	1313	1097	1039	1080	1228	1251	1306	1606	1865	1376
1984	1880	1763	1759	1541	1372	1344	1302	1401	1365	1535	1718	1756	1561
1985	1779	1816	1650	1442	1187	1082	1069	1078	1118	1323	1459	1721	1392
1986	1757	1806	1639	1313	1120	1038	895	1015	1187	1295	1478	1755	1356
1987	1815	1768	1559	1083	1112	899	942	1128	1143	1274	1495	1685	1323
1988	1919	1899	1673	1123	917	1103	1248	989	1065	1311	1394	1615	1354
1989	1504	1480	1183	884	872	928	843	791	774	943	1255	1671	1092
1990	1778	1743	1263	885	820	870	982	1042	907	1103	1283	1392	1170
1991	1714	1541	1524	1294	954	904	888	842	852	866	1219	1396	1164
1992	1387	1399	1220	1101	909	842	933	914	1011	1140	1328	1701	1157
1993	1720	1755	1726	1593	1292	992	887	918	974	1074	1363	1513	1315
1994	1774	1688	1087	894	847	983	977	1124	956	1159	1506	1694	1222
1995	1754	1715	1260	1202	1188	1136	1010	929	929	837	891	1548	1197
1996	1565	1308	804	688	808	978	1020	1042	1185	1292	1464	1689	1154
1997	1792	1705	1621	1276	1110	973	986	1086	1196	1467	1653	1496	1362
1998	1815	1847	1834	1678	1536	1182	1047	1141	1342	1355	1595	1807	1513
1999	1864	1841	1771	1443	1125	937	1138	1020	1013	1315	1510	1829	1399
2000	1881	1919	1871	1555	1176	973	851	1024	1176	1275	1554	1805	1420
2001	1921	1903	1641	1292	1195	1003	819	952	1007	1080	1382	1717	1323
2002	1880	1874	1842	1447	1112	977	992	1140	1186	1272	1610	1737	1420
2003	1856	1870	1755	1490	1363	904	996	953	1113	1078	1141	1579	1339
2004	1818	1697	1576	1279	1038	910	801	831	881	1364	1701	1783	1306
2005	1805	1743	1685	1378	574	1081	1045	1258	1167	1090	1605	1745	1345
Mean	1670	1630	1486	1300	1097	1104	1153	1163	1144	1257	1430	1620	1337

Table 4.3
Atikonak River at Gabbro Lake
Water Survey of Canada Hydrometric Station 03OC006

Year	Monthly Mean Discharges for Period of Record (m^3/s)												Mean
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1973	0	0	0	0	680	858	470	317	0	13	85	0	203
1974	0	0	0	0	135	703	538	430	324	427	301	268	262
1975	172	101	529	676	286	720	699	620	455	426	716	370	482
1976	210	172	173	591	644	655	482	581	869	710	820	359	522
1977	238	488	351	117	378	1302	605	596	618	752	545	359	528
1978	319	449	614	352	562	1484	947	603	511	596	410	230	590
1979	320	707	403	286	1100	1107	1133	791	622	605	610	337	668
1980	233	766	473	286	632	1118	795	517	434	522	392	323	539
1981	220	750	500	311	425	1644	1010	570	337	453	325	285	567
1982	205	728	430	233	345	1148	652	598	509	400	326	233	481
1983	205	743	456	317	1109	1099	851	488	553	778	495	377	622
1984	246	628	498	311	634	1339	588	521	440	434	299	284	517
1985	295	695	432	238	246	1013	649	514	101	216	414	283	422
1986	177	495	574	319	737	751	709	449	102	350	357	242	439
1987	165	407	595	510	733	656	527	312	179	548	478	382	458
1988	209	484	594	359	577	1154	640	274	140	241	447	254	447
1989	199	725	425	225	510	905	399	173	69	505	584	350	420
1990	201	526	561	414	427	985	598	224	100	531	482	331	447
1991	180	441	598	355	348	913	575	311	111	205	526	285	403
1992	219	254	698	387	341	1160	722	596	481	303	372	192	477
1993	182	174	684	399	495	711	562	134	191	310	404	281	378
1994	197	549	536	299	379	1053	998	580	323	303	447	291	495
1995	205	142	719	432	662	983	553	198	66	65	234	302	382
1996	225	526	545	324	625	1081	831	525	208	71	553	424	494
1997	275	467	592	338	554	1215	1163	556	213	295	369	256	525
1998	159	366	661	403	838	1228	646	444	239	328	580	354	521
1999	212	220	64	454	983	1500	824	276	248	306	501	332	494
2000	187	318	696	427	567	1153	760	534	167	118	159	267	446
2001	232	441	607	356	680	1004	410	388	195	400	544	392	470
2002	274	313	677	403	312	1183	852	464	401	559	450	344	520
2003	241	173	692	420	482	921	745	393	147	330	374	355	441
2004	231	622	529	326	396	1517	1276	471	216	148	154	156	502
2005	156	734	494	304	662	777	273	177	371	580	443	400	445
Mean	206	443	497	338	560	1062	712	443	301	389	430	300	473

5. Meteorology

5.1 General

The determination of the meteorological parameters used as inputs to the 1999 PMF study for the Lower Churchill Basin by Atmospheric Environment Branch (AEB) of Atlantic Region, Environment Canada, was used as the starting point for this update. The detailed report from AEB regarding the meteorological studies undertaken to derive the inputs to the PMF was included as Appendix A in the 1999 report. The methodologies used by AEB to estimate the parameters follow currently accepted practice and 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. [13, 14] in 1994 and 1995.
2. The World Meteorological Organization's (WMO) Manual for Estimation of Probable Maximum Precipitation, second edition, published in 1986. [15]

It was decided that there was no need to repeat the analyses performed in 1999. Instead, the values obtained in that study were updated using data collected since the completion of that study, adjusted to account for inclusion of the entire Churchill Basin and modified to provide spatial information suitable for incorporation into GIS products and input to the hydrologic model. Additional analyses for two sequences not considered in the 1999 study were also required. Consistent with requirements of the Canadian Dam Association Guidelines, data for three scenarios were prepared:

1. A probable maximum precipitation (PMP) event in early June occurring with snowmelt from the 100-year snow accumulation.
2. 100-year rain storm in early June occurring with melt from the probable maximum snow accumulation.
3. A PMP event concurrent with maximum atmospheric moisture in mid-summer preceded by a 100-year antecedent rain storm.

In the 1999 study only values averaged over the Lower Churchill basin were supplied. For this update, information on the spatial distribution of the meteorological parameters over the entire Churchill River Basin was required for input to GIS surfaces and the hydrologic model. This was accomplished utilizing historical climate information and GIS surfaces provided by the Great Lakes Forest Research Centre (Dan McKenney, personal communication).

5.2 Precipitation

Four extreme precipitation sequences were required for the PMF analysis, the Probable Maximum Precipitation for both early June and end-July and the 100-year extreme precipitation for the same periods.

The PMP study for the original Churchill Falls Project was completed in 1969 by Sparrow using basically the same methodology as described in the current WMO PMP manual. That analysis formed the basis for the Gull Island PMP undertaken in 1975 and for the 1999 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 1999. Five of these events were used in the 1969 and 1975 studies. Examination of data between 1999 and 2006 did not reveal any additional storms for inclusion in the PMP computation. The additional years of data were used in the calculation of 100-year rainfall, however.

The events were maximized using records at upper air data stations. This is a departure from the WMO recommendations, but is consistent with Canadian practice as recommended by the CDA Guidelines and in Hydrology of Floods in Canada[16] . The WMO recommends use of surface dewpoint measurements to determine atmospheric moisture in the entire column of atmosphere. However, in the presence of extensive snow cover a surface inversion develops. The surface dewpoint is then not representative of the moisture at higher altitudes and upper air data is considered a better measure of total atmospheric moisture. The precipitable water available to the actual storm was compared to the 100-year precipitable water at the representative station. This ratio is used as a multiplicative factor to maximize the storm precipitation. In the 1999 study AEB found that the maximization factors based on upper air data were lower than those used by Sparrow in the 1969 study, which were based on surface dewpoints. These lower factors were accepted for PMP determination in both the 1999 study and this update. Table 5.1 demonstrates the maximization process and Figure 5.1 shows the depth-area-duration curve from the 1999 study.

It was originally intended that the storm precipitation would be adjusted for orographic enhancement by incorporating patterns observed in average May and June precipitation. Orographic enhancement occurs where saturated air is forced to rise by a topographic barrier such as hills or mountains. The rising airflow accelerates, is compressed and cools, reducing the moisture holding capacity of the air column and giving rise to increased precipitation. However, there were no strong associations with orography observed in these maps of monthly rainfall and it was decided to assume no significant orographic enhancement of precipitation in the basin.

5.2.1 Spring PMP

The depth-area relationship for the spring PMP, recommended in the 1999 study, was accepted for this update. To facilitate determination of the spatial distribution of PMP rainfall over the basin, elliptical isohyets in units of % storm centre rain, which preserved the depth-area relation of the PMP event, were prepared as a GIS grid, which could be rotated and moved over the basin to produce the PMF event (Figure 5.2). The central storm amount of 286 mm over 10 km^2 was chosen so that depth-area values consistent with the 1999 study were maintained.

The chronological sequence of rainfall also had to be determined. Examination of spring storms in the general area of the basin (Storm Rainfall in Canada series) indicated that a wide variety of depth-duration relations are possible, but that there was a tendency for rainfall not to be concentrated too much in short periods. The depth-duration relationship recommended by the 1999 study was accepted as a reasonable compromise that was within depth-duration relationships that have been experienced, and maximized peakedness for PMF determination. Because of the size of the basin, the depth-duration relationship is not expected to be critical for PMF determination. Consistent with recommendations by the WMO, a late peaking time sequence that maintained the depth-duration relation for all durations was chosen as shown in Table 5.2. In nature the depth-area relation varies for each duration, but it was found that differences between the time varying depth-area relations and the total storm depth-area for the PMP event were small, so the total storm depth-area relation was accepted for all durations and the entire storm made to grow based upon values in Table 5.2, without changing the relative shape of the isohyets shown in Figure 5.2.

5.2.2 All-Season PMP

Determination of the probable maximum precipitation event during the warm season when no snow is present was problematic. A review of the Storm Rainfall in Canada series and rainfall records in and near the basin identified five significant storms in the June to September period which were transposable to the basin. The two largest events (August 16, 1953 and September 2, 1960), when maximized to summer precipitable water, produced central amounts no larger than the largest spring storm maximized to spring moisture.

Since historical floods on the Churchill River have always been associated with rain plus snowmelt events, the lack of larger warm-season storms in the historical record may well be indicative of climate conditions in the basin. Still, the relatively poor climate station records in the region may not be sufficient to have sampled a potential design summer storm. Therefore the decision was made to assess the sensitivity of the basin to a rain-only PMP by assuming a conservatively large event and examining the resultant flood. If this conservatively large event did not generate flows greater than those generated by the spring rain plus snowmelt event then it was believed that this would be sufficient evidence that a more rigorous determination of the rain-only PMP was not necessary.

The usual method for increasing the number of available storms in the absence of recorded events in the immediate area of the basin is to transpose storms spatially from other areas. Since no summer storms that generated an event larger than the spring PMP for the basin were found, it was decided to temporally transpose the largest spring storm that had occurred in the immediate vicinity of the basin, to the period of maximum available precipitable water. It is not normally advisable to transpose a storm more than 15 days from its date of occurrence, but this restriction was waived to allow examination of the sensitivity of the basin to a summer rain-only event as discussed above. Consequently, the spring PMP event was assumed to be possible in mid-July over the basin. Maximization was performed by increasing the spring PMP event by the ratio of early June precipitable water to annual maximum precipitable water at Goose Bay ($53/41.5 = 1.28$). The net result was to create a summer PMP event which was 1.28 times bigger than the spring PMP event for all durations and areas.

The isohyetal pattern presented in Figure 5.2 and the chronological rainfall sequence of Table 5.2 were considered appropriate for the purpose of this sensitivity analysis. This resulted in a value of 366 mm being used as the storm centre 10 km^2 all-season PMP, which was distributed spatially and temporally in the same way as the spring event.

5.2.3 Spring 100-year Rainfall

Rainfall statistics for a point are relatively easy to obtain, but determination of the 100-year return period amount of areal rainfall for a specific basin is difficult at the best of times, and even more difficult in the data-sparse Churchill River basin. This is because the necessary time series of areal rainfall obtained from all gauges in the basin has never been compiled, would be inaccurate because of the few stations available, and would not meet conditions of stationarity due to varying station record lengths. The 1999 study attempted to solve the problem by comparing point PMP estimates to point 100-year estimates and applying this ratio to estimate the 100-year spring rainfall, on the assumption that this ratio would be constant for both point and areal rainfall and for all-season and spring events. The current study employed a different approach to attempt a solution.

Only data from the spring months (April-June) were considered. Point rainfall probabilities for all stations in and near the basin were determined assuming a Gumbel distribution fitted by the method of moments. No attempt was made to determine the areal amount for each event but it was noted that for the majority of events, the rain was widespread. An overall basin 100-year return period point rainfall was determined both by averaging the individual station estimates and by combining all time series into a single basin time series. No significant difference in the final basin value was identified. The 24-hour, point 100-year estimate was 53 mm. It was then assumed that this point 100-year rainfall for a single location in the basin could be converted into an estimate of areal 100-year rainfall over the basin by assuming the same relative depth-area-duration relation determined from historical spring storms and used in the PMP determination. This very conservative assumption yielded an estimate for the 22,300 km^2 Lower Churchill basin of 50 mm over 66 hours compared to the 1999 study value of 53 mm. The 100-year spring rainfall for input to the hydrologic model was defined by using the depth-area relation of Figure 5.2 and the depth-duration relation of Table 5.2 combined with the 10 km^2 storm centre value of 76 mm over 66 hours.

5.2.4 All-Season 100-year Rainfall

The 100-year all-season basin rain event was determined in a manner completely analogous to the spring 100-year rainfall except rainfall data from all months of the year were included in the probability calculation. The 10 km^2 all-season 100-year rainfall was estimated to be 70 mm over 24 hours and 100 mm over 66 hours. The values for input to the hydrologic model were determined employing the relationships of Figure 5.2 and Table 5.2.

5.3 Temperatures

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. The 1999 study used a sequence derived using procedures similar to the CEA methodology, in both the PMP and PMSA cases.

In the 1999 study, 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 5.3.

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

These sequences are, in part, determined by the historical limits of maximum and minimum daily temperatures with snow on the ground throughout the spring period. These limits were reviewed including the 9 additional years of data collected since the completion of the 1999 study. Temperature sequences with snow on the ground reached maximum values about one week earlier when data from the last 8 years was included but these maxima were not higher than those calculated for data to 1999, presumably because the snow cover melted earlier in the more recent years. Therefore, the sequence proposed by the 1999 study for the Lower Basin (reproduced here as Figure 5.4) was accepted as representative of a location near the centre of that portion of the basin.

Additional information was required to spatially distribute these temperatures across the entire basin for input to the hydrologic model. A GIS based grid of normal May Labrador temperature determined using a sophisticated interpolation procedure by Great Lakes Forest Research Centre (GLFRC) was used as the template of temperature variation across the basin. The grids, provided by Dr. D. McKenney[17], were produced using the best available data from Environment Canada and a thin-plate smoothing spline algorithm that includes effects due to elevation developed by the Australian National University. An adjustment map for the basin (Figure 5.5) was produced by subtracting the temperature at the centre of the Lower Basin from values for all other grids within the Churchill River Basin. Values for the temperature sequence at each grid in the basin were then determined by adding the Lower Basin temperature sequence values to the adjustment grid for all parts of the basin, thereby including the effects of elevation and latitude as defined by the GLFRC grids.

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 35 years of record between 1959 and 2007 were examined. Most are located in the Churchill River Basin, mostly in the upper basin. The maximum snowpack reading, regardless of date, was noted for each year and a frequency analysis was carried out. Since the maximum snow accumulation is closer to a seasonal total than to an extreme value of a sample, the log-normal distribution was assumed, as it is more appropriate for monthly or seasonal totals of precipitation. The 100-year estimates were then mapped to the basin and values interpolated to a 10 km grid covering the basin area (Figure 5.6). This grid provided the input to the hydrologic model.

A maximization analysis of snowfall during several peak snowfall years was undertaken in the 1999 study to assess the probable maximum snow accumulation (PMSA). Historic snow events were maximized using the same methodology used 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 with >8 cm accumulation within those years was maximized using upper air data to calculate maximum precipitable water available to the event. In the current study, additional data for the 1999-2007 period were examined to see if snowstorm maximization of more recent years would affect the period of record maximum. As can be seen in Table 5.3, maximized data from 2005-06 were larger than any other year for Wabush Lake, but were not the maximum for Goose Bay, the only other station in the basin collecting the necessary data in 2006. Since the procedure requires the selection of maximized snow accumulation from a single year for the entire basin, accumulations for the 1980-81 spring were selected as representative of the PMSA for the basin, as was done in the 1999 study. The station values were mapped to the basin and values interpolated to the 10 km grid covering the basin area (Figure 5.7) to generate the data for input to the hydrologic model.

5.5 Climate Change

No study attempting to consider the effects of weather and climate on hydrologic structures in the mid-21st century would be complete without consideration of greenhouse gas induced climate change. Anthropogenic climate change may well impact PMP estimates for the future. Climate scientists generally agree that temperatures over much of the earth will increase by 3-5° C over the coming century. A commensurate increase in dewpoint temperatures is a logical assumption supported by observations since 1988, Solomon et al[18]. Temperatures over much of the globe have increased by an average of about 1° C over the past century, but temperatures in Labrador have not followed this trend, due probably to a strengthening of the Icelandic low pressure area. Solomon et al also report that precipitation amounts and frequencies of heavy precipitation events have increased in many parts of the northern hemisphere, but again, Labrador is not included in these areas of increase. Snow cover has decreased globally, especially in the spring, since about 1980 and model projections all agree on the continuation of this trend. Solomon et al report that “increases in the amount of precipitation are very likely at high latitudes” and that “available research indicates a tendency for an increase in heavy daily rainfall events in many regions”, but that responses of precipitation to climate change will be slower and with more regional variation than temperature.

These uncertainties make it very difficult to quantify the impact of climate change on PMP estimates. Acceptance of an increase in atmospheric moisture commensurate with climate change projections would result in increases in the maximization factor and hence in the PMP of 15-20% by 2100. However, it is not clear that the efficiency of future storms in the region will be the same as historical ones or how regional changes in climate will affect heavy precipitation events. In addition, snow accumulation, a dominant factor in the current PMF projection, is expected to decrease. Most scenarios suggest smaller snow packs in the region, which will melt earlier, meaning that the relevant spring storm will occur earlier in the season at a time when atmospheric moisture can be expected to be less, off-setting projected increases expected due to climate change. This could result in a reduction in the expected PMF for Labrador. Considering all of these factors, it was decided that it was not reasonable to introduce an additional, explicit adjustment to account for possible future climate change. Instead, it was assumed that the conservative assumptions employed in the PMP calculation, along with the uncertainties of the PMF estimation process, would ensure that changes due to climate change would be within the uncertainty bounds of the current estimates.

5.6 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 meteorological 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 and the 1999 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 1999 AEB study was carried out for the Lower Churchill Basin only. Moving the elliptical PMP storm over the Churchill River Basin yields a maximum basin average PMP of 136 mm over the whole Churchill River Basin.

The temperature sequence derived for this study is similar to the 1999 study, but 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 flood. The number of degree days before the PMP are similar in all studies, ranging only from 104 for the present and 1999 studies 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.
4. The 1999 study derived 100-year snowpack water equivalents of 580 mm and 550 mm for the lower and upper basins, respectively, using upper air precipitable water, rather than surface dew points, for maximization. The PMSA was estimated as 725 mm for the Lower Basin.

The current study made use of the same data sets used in the 1999 study, extended with more recent data and mapped over the Churchill River basin according to the available snow course network, using a 10 km^2 GIS grid. The basin area-weighted average100-year snowpacks resulting from the GIS mapping are 533 mm and 536 mm, for the lower and upper basins, respectively, or 535 mm for the entire basin. Similarly, the PMSA values resulting from the GIS mapping are 618 mm and 624 mm, for the lower and upper basins, respectively, or 623 mm for the entire basin.

The 100-year snowpack and the PMSA values are slightly lower than the values used in the previous studies.

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	-	-

Notes

1. PWC - Precipitable Water Content
2. UA - Upper Air
3. Sparrow - 1969 Meteorology Study for Upper Churchill Basin
4. DAD - Depth Area Duration

Table 5.2
Design Storm Rainfall Depth Duration

Duration (hours)	Maximum Incremental Rainfall (% Total)	Ordered Incremental Rainfall (% Total)	Ordered Incremental Rainfall Depth[1] (mm)			
			Spring PMP	Spring 100-year	Summer PMP	Summer 100-year
6	34	2	6	2	7	2
12	15	3	9	2	11	3
18	12	3	9	2	11	3
24	9	5	14	4	18	5
30	6	6	17	5	22	6
36	6	9	26	7	33	9
42	5	15	43	11	55	15
48	5	34	97	26	124	34
54	3	12	34	9	44	12
60	3	6	17	5	22	6
66	2	5	14	4	18	5
Total	100	100	286	76	366	100

Note

1. Rainfall depths for 10 km^2

Table 5.3
Probable Maximum Snow Accumulation[1]

Year	Churchill Falls		Schefferville		Wabush Lake		Goose Bay		Nitchequon	
	Measured	Maximum	Measured	Maximum	Measured	Maximum	Measured	Maximum	Measured	Maximum
1971-72	506	662	430	551	567	737	422	568	251	336
1976-77	474	607	562	722	516	659	441	591	429	580
1980-81	446	589	592	784	507	672	552	736	374	489
1982-83	527	648	442	558	535	660	528	647	346	404
2005-06	-	-	-	-	613	768	412	535	-	-

Note
1. Total snow water equivalent accumulation in mm.

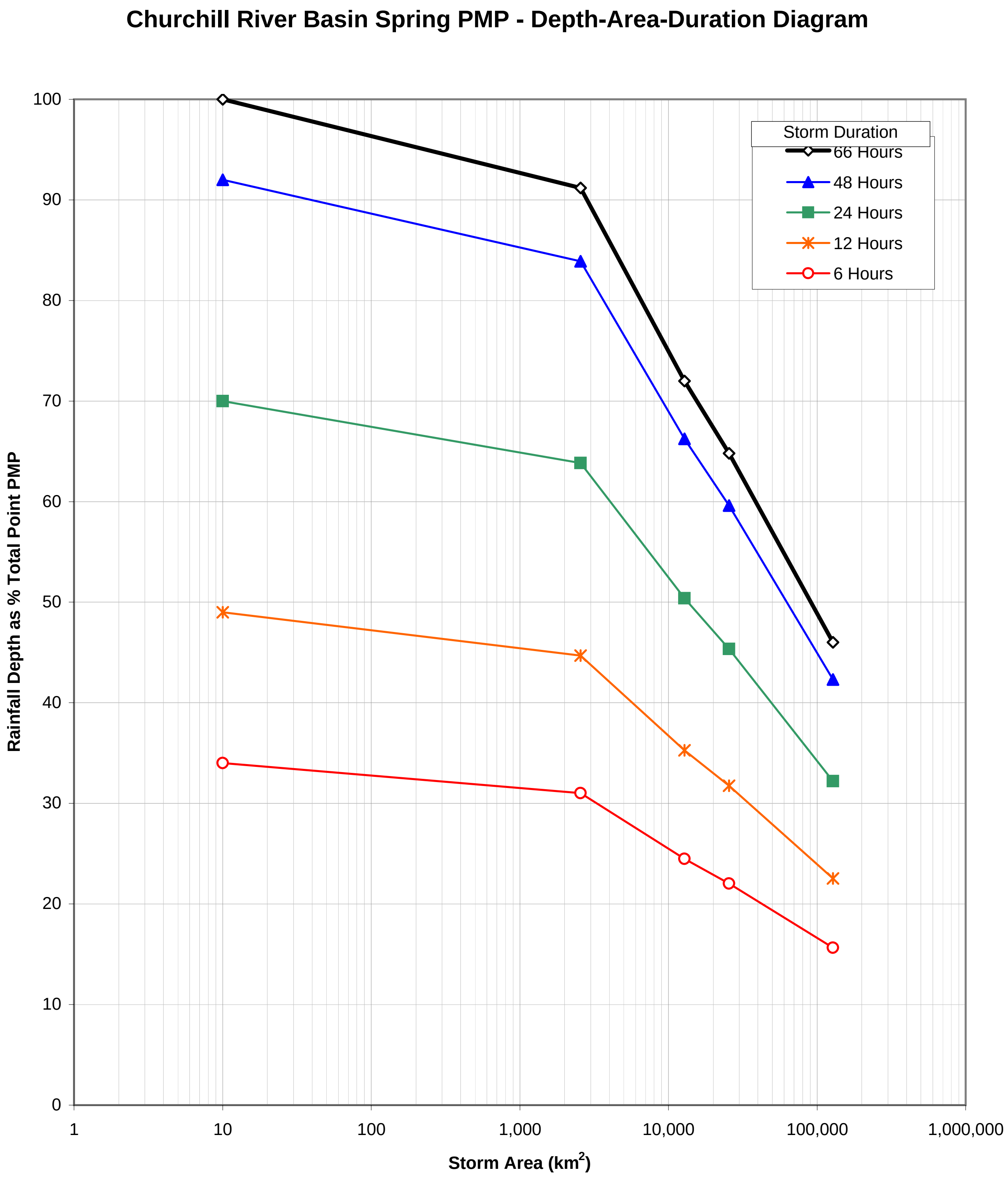

Figure 5.1
Lower Churchill Project
PMF and Construction Design Flood Study
CHURCHILL RIVER BASIN SPRING PMP - DEPTH-AREA-DURATION DIAGRAM

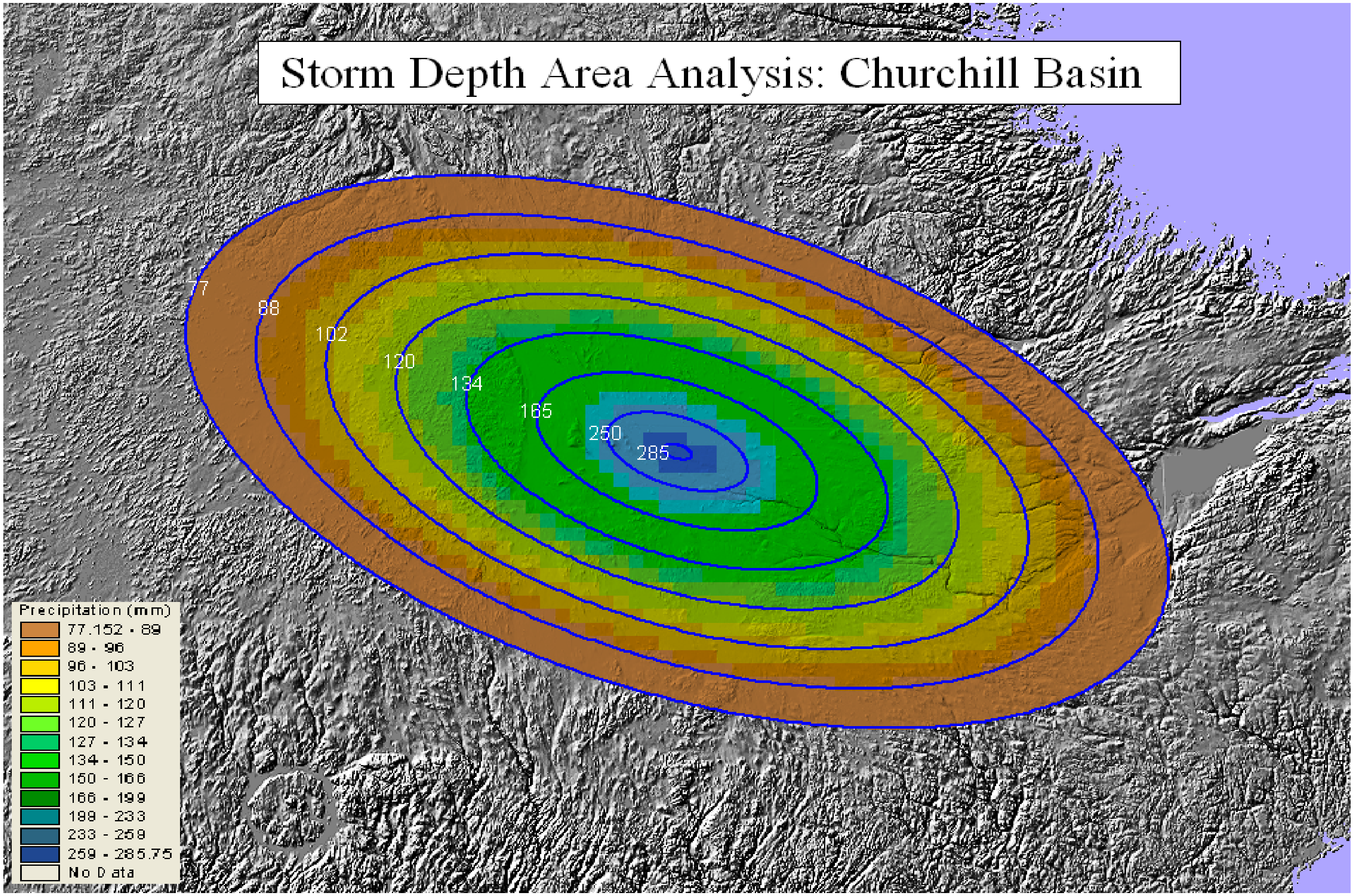

Figure 5.2
Lower Churchill Project
PMF and Construction Design Flood Study
STORM DEPTH AREA ANALYSIS: CHURCHILL BASIN

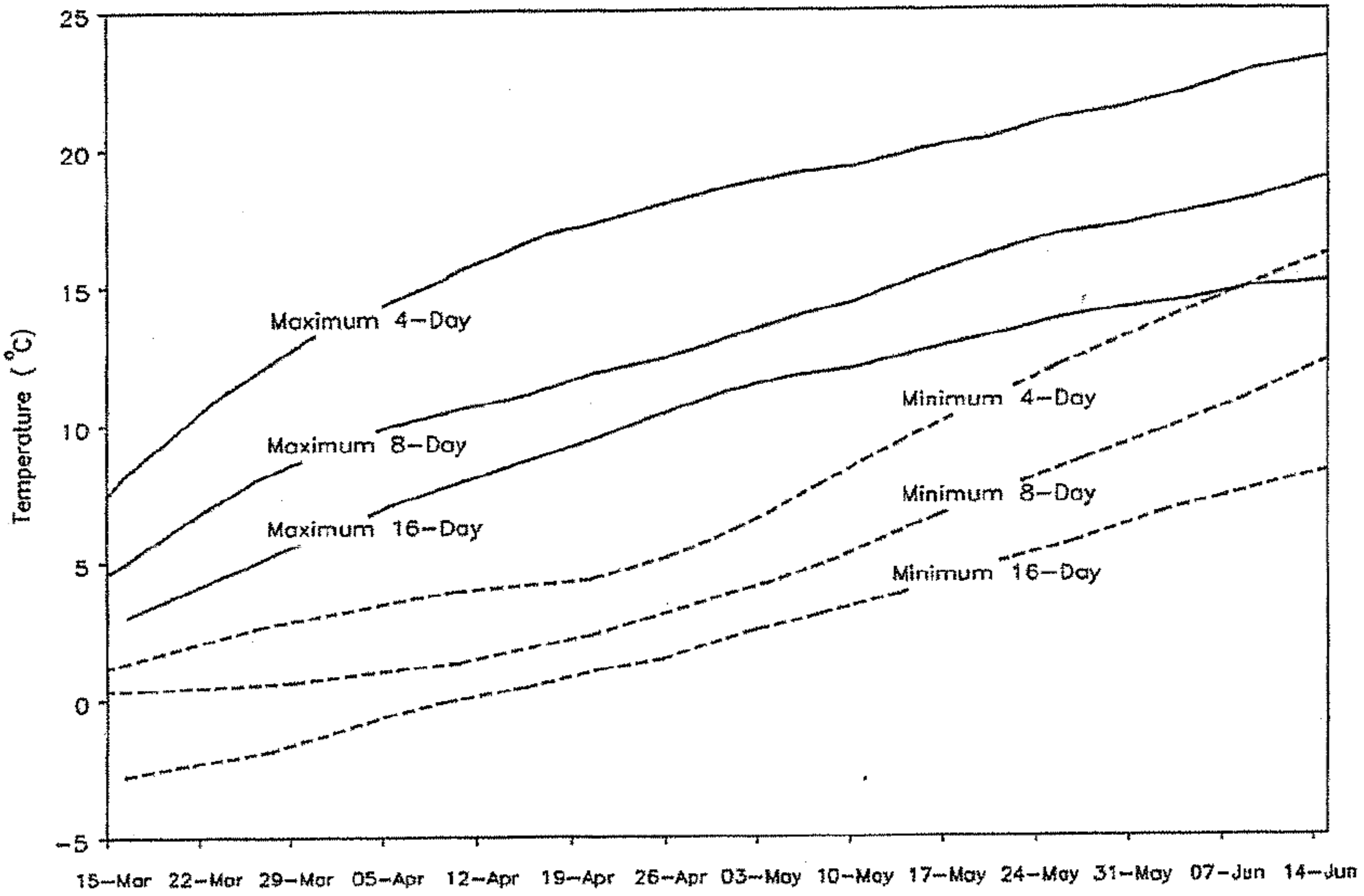

Figure 5.3
Lower Churchill Project
PMF and Construction Design Flood Study
MAXIMUM TEMPERATURE ENVELOPES

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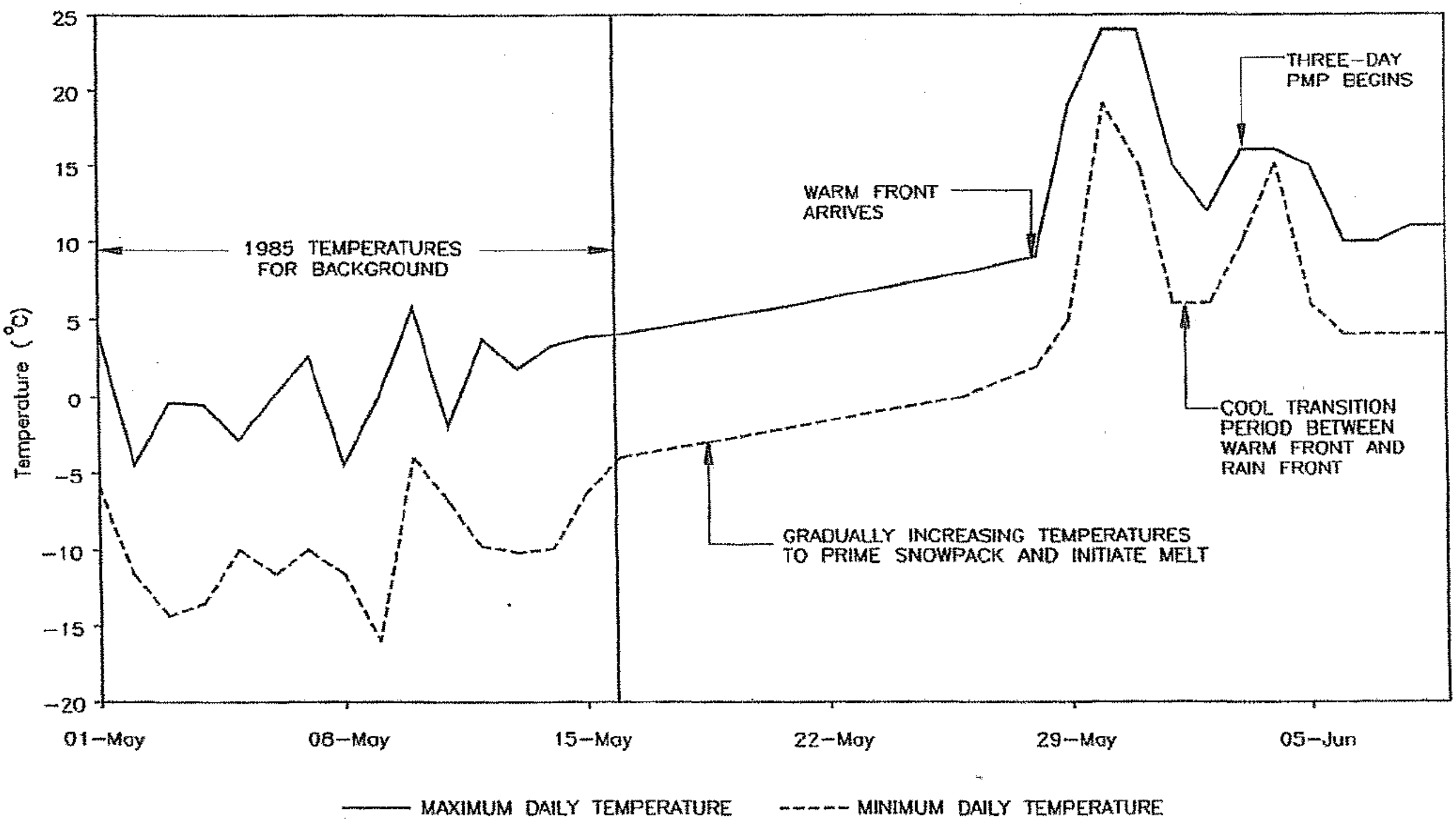

Figure 5.4
Lower Churchill Project
PMF and Construction Design Flood Study
TEMPERATURE SEQUENCE FOR LOWER CHURCHILL BASIN PMF

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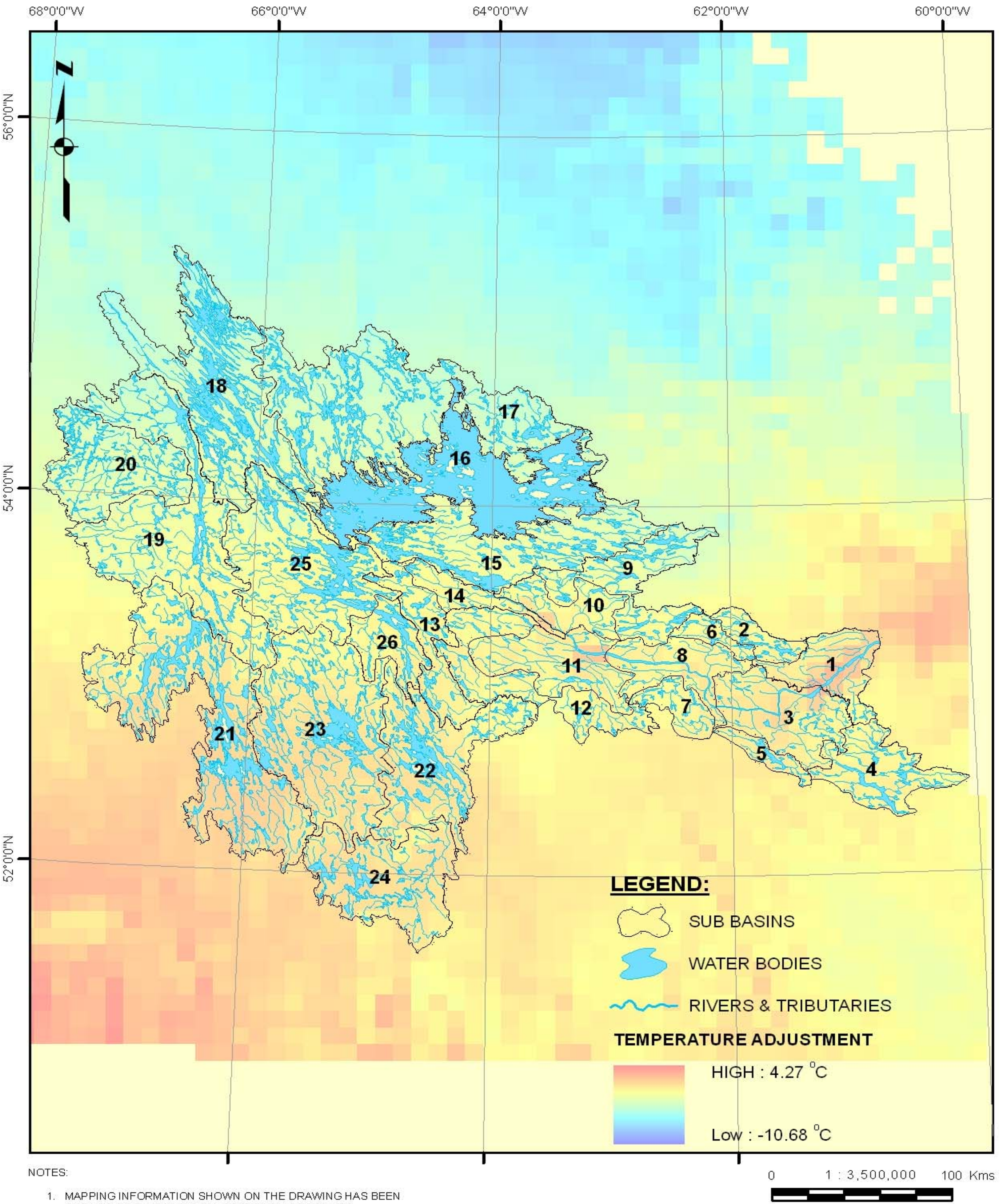

NOTES:

1. MAPPING INFORMATION SHOWN ON THE DRAWING HAS BEEN DERIVED FROM THE DIGITAL DATA FROM GEOGRATIS
2. PROJECTED COORDINATE SYSTEM IS NAD 1983, UTM ZONE 20N.

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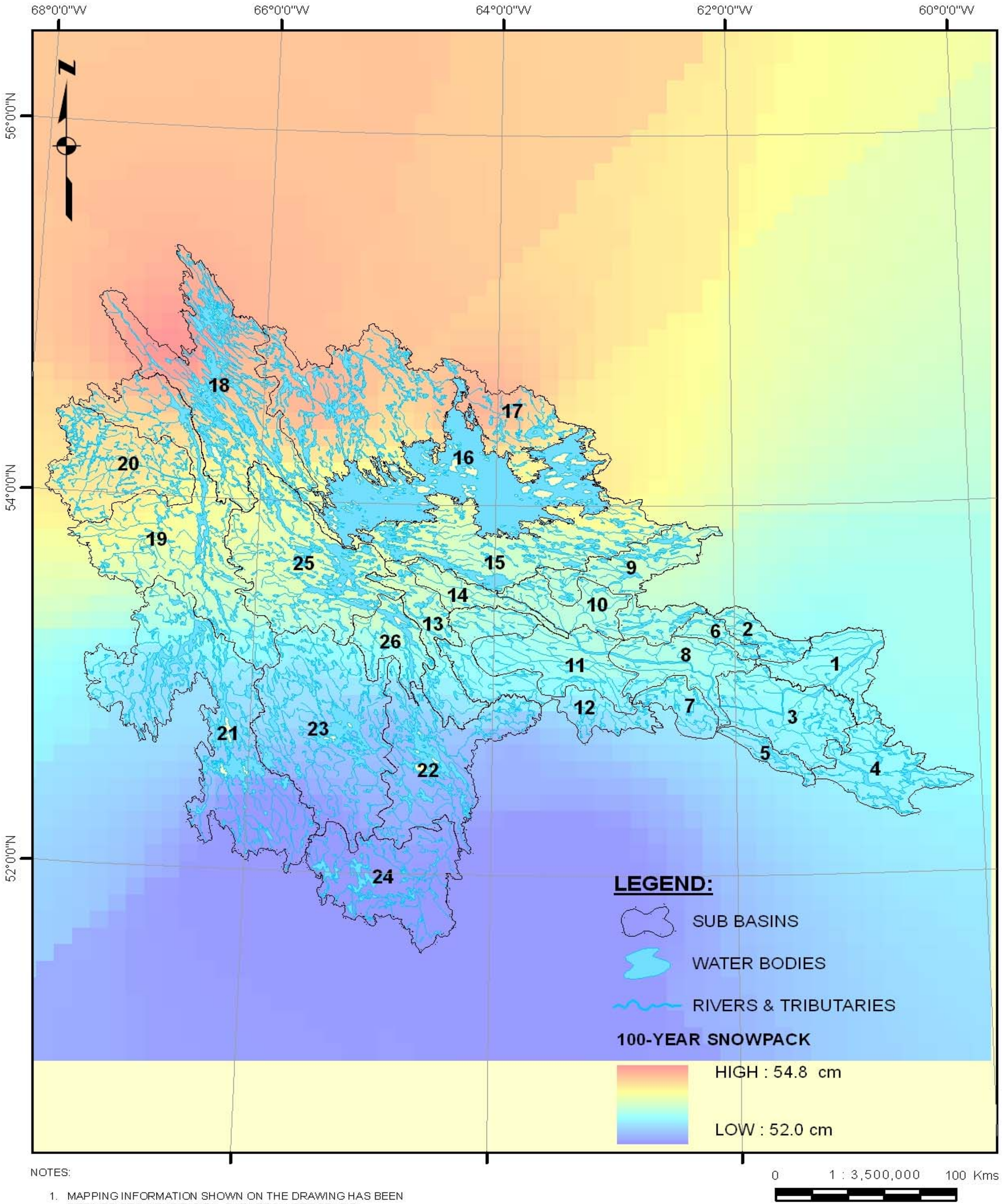
Figure 5.5
Lower Churchill Project
PMF and Construction Design Flood Study
TEMPERATURE ADJUSTMENT



NOTES:

1. MAPPING INFORMATION SHOWN ON THE DRAWING HAS BEEN DERIVED FROM THE DIGITAL DATA FROM GEOGRATIS
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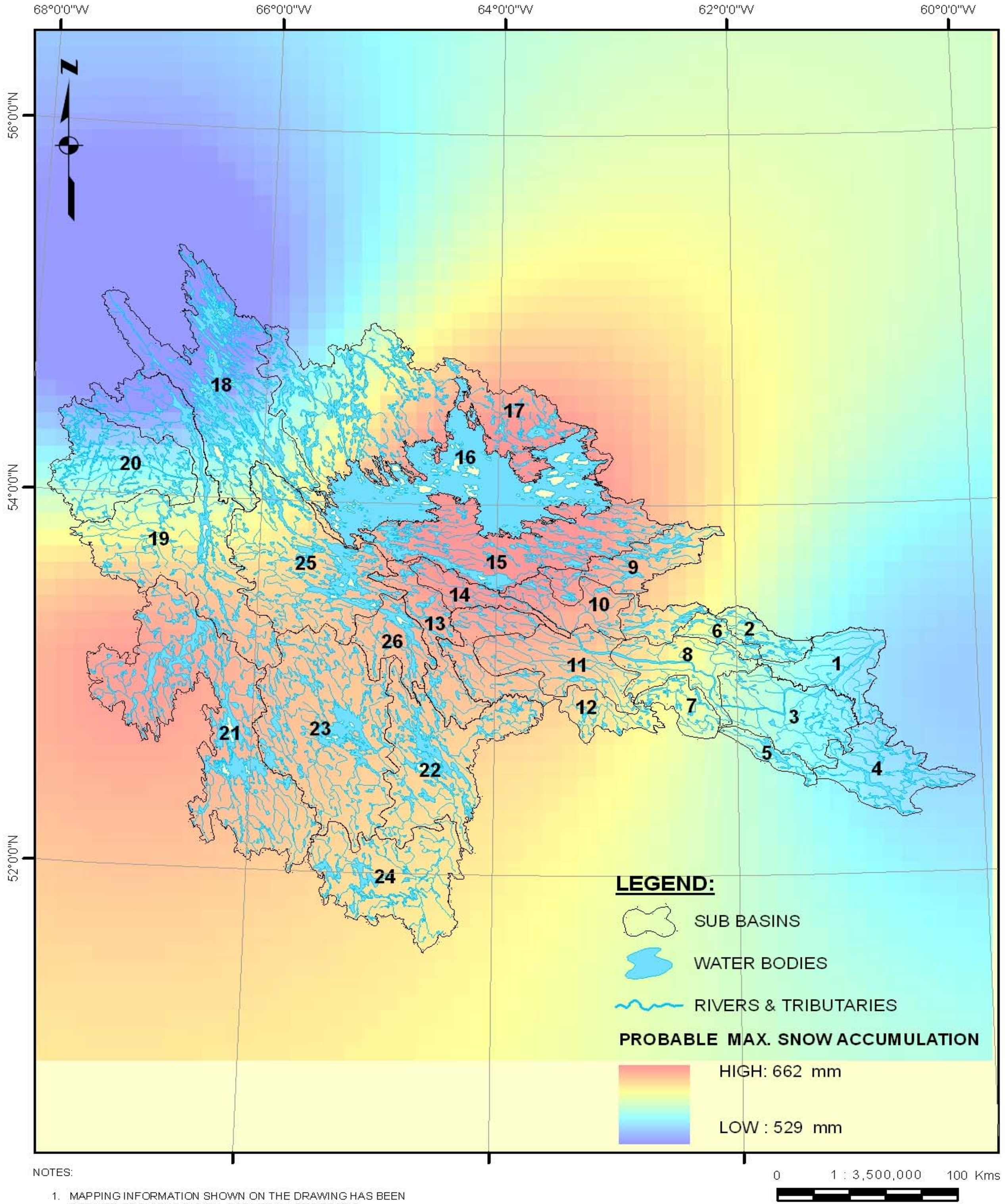
Figure 5.6
Lower Churchill Project
PMF and Construction Design Flood Study
100-YEAR SNOWPACK



NOTES:

1. MAPPING INFORMATION SHOWN ON THE DRAWING HAS BEEN DERIVED FROM THE DIGITAL DATA FROM GEOGRATIS
2. PROJECTED COORDINATE SYSTEM IS NAD 1983, UTM ZONE 20N.

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Figure 5.7
Lower Churchill Project
PMF and Construction Design Flood Study
PROBABLE MAXIMUM SNOW ACCUMULATION

6. Churchill River Basin Watershed Model

6.1 The SSARR Model

A watershed model of the Churchill River 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"[8]. 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 snow band option of SSARR was used. The integrated snow band 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, baseflow and lower zone 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 Model Configuration

The configuration and complexity of a watershed model depends on the homogeneity of the overall drainage basin being represented and the level of data available to describe physical and climatic variability within the basin. Ideally in a watershed model, physical characteristics should be homogeneous within each hydrologic sub-basin and it should be possible to represent climate parameters by average values over the entire sub-basin area. As sub-basin areas increase and major hydrological features, such as large lakes, are added this assumption of homogeneity starts to break down. However, if a watershed is divided into too many sub-basins there is insufficient data to calibrate individual sub-basins and the complexity of hydraulic routing between sub-basins is introduced.

For the current watershed model of the Churchill River Basin the SSARR model(s) derived in the 1999 PMF study have been disaggregated into multiple sub-basins to better represent the effects of flood attenuation by natural lakes and to capture the variation of storm rainfall throughout the basin.

In 1999 the Churchill River Basin was divided into three main sub-basins:

- The Smallwood Reservoir Basin
- The Ossokmanuan/Gabbro Lake Basin
- The Lower Churchill Basin.

In the current study each of these basins has been further sub-divided and each model has been calibrated independently. Figure 6.2 shows the sub-basins used in the SSARR models. The final watershed model used for the PMF simulations recombines these models as shown schematically in Figure 6.3.

6.2.1 The Smallwood Reservoir Basin

The Smallwood Reservoir Basin has been sub-divided in into seven sub-basins on the basis of the availability of WSC gauge data for calibration, location and hydrological characteristics. These seven sub-basins are:

1. Ashuanipi River below Wightman Lake (03OA004). This sub-basin is at the head of the Ashuanipi River and has a published drainage area of 8,310 km^2. Flows at (03OA004) also include regulation by Ashuanipi, Wabush and Shabogamo Lakes, which have been modeled as a single lake.
2. McPhayden River near the mouth (03OA003). This sub-basin is a tributary to the Ashuanipi River and represents the response of a sub-basin with small lakes at the head of the basin, but no major lake routing. The McPhayden River has a published drainage area of 3,610 km^2 at (03OA003).
3. Ashuanipi River at Menihek Rapids (03OA001). This gauge location includes outflows from the sub-basins above and has a published drainage area of 19,000 km^2. The sub-basin has a net area of 7,080 km^2, largely unregulated by lakes. Flows at (03OA001) represent nearly half of the drainage to Smallwood Reservoir, excluding the reservoir surface.
4. Ashuanipi River between (03OA001) and Smallwood Reservoir. This sub-basin has a high proportion of lake cover and drains directly to Smallwood Reservoir.
5. North Shore of Smallwood Reservoir. Flows from this sub-basin are only slightly lake affected and drain directly to Smallwood Reservoir.
6. South Shore of Smallwood Reservoir. Flows from this sub-basin are only slightly lake affected and drain directly to Smallwood Reservoir. For the purpose of the model this sub-basin includes drainage to the West and East Forebays.
7. The surface of Smallwood Reservoir. Smallwood Reservoir has a surface area of over 6,000 km^2 and storm rainfall and snowmelt on its surface will produce an instant response in the reservoir, long before flows arrive from the other sub-basins. Smallwood Reservoir storage is also included in the SSARR model for reservoir regulation modelling.

The final component of the Smallwood Reservoir model is the river routing from the upper sub-basins to Smallwood Reservoir. Two Ashuanipi River routing reaches were simulated:

- From Wabush Lake (03OA004) to Menihek Rapids (03OA001)
- From Menihek Rapids (03OA001) to Smallwood Reservoir.

The separation of Smallwood Reservoir catchment area into the seven sub-basins above enables the response timing of different parts of the basin to be modeled more accurately, from the near instantaneous response of the reservoir surface to the slow, attenuated response of the upper Ashuanipi River Basin. Calibration data for the McPhayden River also helps to calibrate the three sub-basins draining directly to the reservoir, which have similar characteristics.

Figure 6.4 shows flood hydrographs in the Upper Basin for 1975, a high flood year when all of the WSC stations were active. The effect of large lakes on flood peaks can be seen by comparison of the hydrographs from the McPhayden River (03OA003), which has little lake attenuation, the Ashuanipi River at the outlet of Wabush Lake (03OA004), which has significant lake attenuation and the Ashuanipi River at Menihek Rapids (03OA001), which is a mixture of both catchment types:

- The McPhayden River peaks on 4 June 1975 with a unit runoff peak of 0.4 $m^3/s/km^2$
- The Ashuanipi River at the outlet of Wabush Lake peaks on 10 June 1975 with a unit runoff peak of 0.08 $m^3/s/km^2$
- The Ashuanipi River at Menihek Rapids peaks on 5 June 1975 with a unit runoff peak of 0.17 $m^3/s/km^2$.

Thus, the “unregulated” McPhayden River sub-basin contributes to the flood inflows to Smallwood Reservoir at five times the unit rate of the Ashuanipi River below Wabush Lake, because of the difference in the degree of lake coverage in the two basins. This observation is important when calibrating the other, ungauged, sub-basins draining to Smallwood Reservoir.

6.2.2 The Ossokmanuan/Gabbro Lake Basin

The Ossokmanuan/Gabbro Lake Basin has been sub-divided in into five sub-basins on the basis of the availability of WSC gauge data for calibration, location and hydrological characteristics. These five sub-basins are:

1. Atikonak River above Atikonak Lake (03OC005). This sub-basin is at the head of the Atikonak River and has a published drainage area of 3,680 km^2. Flows at (03OC005) include some natural lake attenuation, typical of the Upper Basin sub-basins.
2. Kepimits River below Kepimits Lake (03OC004). Flows in the Kepimits River include significant attenuation by Lac Joseph, which is included as a natural lake in the model. The Kepimits River has a published drainage area of 7,070 km^2 at (03OC004).
3. Atikonak River above Panchia Lake (03OC003). This gauge location includes outflows from the sub-basins above, as well as attenuation by Atikonak Lake, and has a published drainage area of 15,100 km^2. The local sub-basin has a net area of 4,350 km^2. Atikonak Lake is included explicitly as a natural lake in the watershed model. Flows at (03OC003) represent two-thirds of the drainage to Ossokmanuan/Gabbro Lake.
4. Ossokmanuan Lake local drainage. Flows from this sub-basin are only slightly lake affected and drain directly to Ossokmanuan Lake.

5. Gabbro Lake local drainage. Flows from this sub-basin include some lake attenuation and drain directly to Gabbro Lake.

The separation of the Ossokmanuan/Gabbro Lake catchment area into the five sub-basins above enables the response timing of different parts of the basin to be modelled more accurately, from the relatively fast response of the local drainage to Ossokmanuan/Gabbro Lake to the slow, attenuated response of the Atikonak River Basin. Calibration data for the Atikonak River above Atikonak Lake (03OC005) also help to calibrate the two sub-basins draining directly to Ossokmanuan/Gabbro Lake, which have similar characteristics. Ossokmanuan/Gabbro Lake storage is also included in the SSARR model for reservoir regulation modelling.

Figure 6.4 shows that the flood response of the Atikonak River is generally slower than the Ashuanipi River due to the greater degree of natural lake regulation, i.e.

- The Atikonak River above Atikonak Lake peaks on 7 June 1975 with a unit runoff peak of 0.19 $m^3/s/km^2$
- The Kepimits River below Lac Joseph peaks on 9 June 1975 with a unit runoff peak of 0.11 $m^3/s/km^2$
- The Atikonak River below Atikonak Lake peaks on 10 June 1975 with a unit runoff peak of 0.10 $m^3/s/km^2$.

Thus, the less regulated Atikonak River sub-basin above Atikonak Lake peaks at twice the unit rate of the Atikonak River at the outlet of Atikonak Lake, because of the difference in the degree of lake attenuation in the two basins. This observation is important when calibrating the other, ungauged, sub-basins draining to Ossokmanuan/Gabbro Lake.

Figure 6.4 also shows that floods to Ossokmanuan/Gabbro Lake will arrive later than those to Smallwood Reservoir.

6.2.3 *The Lower Churchill Basin*

The Lower Churchill Basin is characterized by six major tributaries that flow laterally into the Churchill River and are conveyed downstream at rates varying in accordance with the elevation profile of the river. Each of the tributaries flows through a series of chain lakes on the plateau before descending into the valley and joining the Churchill River.

To capture the influence of the chain lakes and the variable travel times through different reaches of the main river, the Lower Churchill Basin has been sub-divided according to the six main tributaries, with each tributary represented by an upper sub-basin, a natural lake and a lower sub-basin. The six tributaries are:

1. Unknown River. The Unknown River flows through a series of lakes and will exhibit moderate lake attenuation. Outflows from the Ossokmanuan Control Structure will flow to the Unknown River in the complete SSARR model, but will avoid most of the lake attenuation.
2. Metchin River. The Metchin River sub-basin shows the highest density of lake coverage in the lower basin, though the East Metchin River gauge (03OD007) shows only slight lake attenuation.
3. Fig River. The Fig River (and Elizabeth River) sub-basin has light lake coverage and will exhibit moderate lake attenuation.

4. Cache River. The Cache River (and Shoal River) sub-basin has light lake coverage and will exhibit moderate lake attenuation.
5. Minipi River. The Minipi River sub-basin has two large lakes, Minipi Lake and Dominion Lake and will exhibit significant lake attenuation. The Minipi River gauge below Minipi Lake (03OE003) shows that flood outflows from the lake generally peak ten days after the peak on the Churchill River above Upper Muskrat Falls (03OE001).
6. Pinus River. The Pinus River sub-basin has light lake coverage and exhibits only moderate lake attenuation. The gauge on the Pinus River (03OE011) provides useful data for the calibration of those sub-basins that are only moderately affected by lake routing.

The SSARR model of the Lower Churchill River also includes river routing of the cumulating flood hydrograph from Churchill Falls to Muskrat Falls. Eight routing reaches were used to simulate the three day travel time through Winokapau Lake, Gull Lake and the main channel of the Lower Churchill River.

The flow data on the tributaries and the Churchill River above Upper Muskrat Falls (03OE001), together with the powerhouse releases at Churchill Falls (03OD005) provide a useful database for the calibration of the Lower Churchill Basin watershed model.

Figures 6.5 and 6.6 demonstrate the less obvious effects of natural lake regulation at the WSC stations in the Lower Basin during the high flood year, 1999:

- The Pinus River, at the lower end of the basin, is partially regulated by a chain of small to moderate sized lakes. The flood hydrograph shows a main flood hydrograph, peaking on the 11 May, followed by a second slight rise in the hydrograph about a week later.
- The East Metchin River basin contains a number of medium to large lakes that regulate about two-thirds of the basin at the WSC station. The flood hydrograph comprises two pronounced peaks, an initial peak from the unregulated third of the basin on 10 May, and a second peak from the regulated two-thirds of the basin ten days later. The first peak not only occurs much earlier than the second peak, but also has a unit runoff three times that of the lake attenuated peak.
- The Minipi River station is located at the outlet of Minipi Lake, so all flows have been attenuated. The 1999 outflow peak from Minipi Lake occurred on 23 May, nearly two weeks after the unregulated peaks from the East Metchin and Pinus Rivers.

Figure 6.6 shows that this twin peak effect is reflected in the flow record of the Lower Churchill River above Muskrat Falls. Releases from Churchill Falls powerhouse were virtually constant during the 1999 flood period, so the twin peak effect is clearly due to the different contributing rates of the unregulated and lake regulated areas of the Lower Basin.

It is important to capture the attenuating effect of this natural lake regulation in the SSARR model, so each tributary sub-basin was split into lake controlled and unregulated sub-basins, using the flood hydrographs from the three WSC stations as a guide to the degree of regulation to apply in each sub-basin.

6.3 Calibration

The SSARR model contains many variables and relationships input by the user to describe each 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 modeller 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 Churchill Basin models were chosen from the following sources:

- the calibrated models from the 1999 PMF study;
- 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; and
- values used in other applications.

The snowmelt season was modelled from April 1 to September 30 using a 6-hour time step.

6.3.1 Calibration Criteria

The objective in calibrating the SSARR models for the Upper and Lower Basins was to reproduce historically observed floods for a range of years, with only the input data changing for each year. However, in a catchment of 92,500 km^2, with only a few point observations of input parameters, recorded at varying, discrete intervals, this objective can only be partially achieved.

Instead, calibration criteria must be established and the model parameters adjusted to meet these criteria as well as possible for the calibration years selected. The result is a model where the simulated results, averaged over the years of calibration, meet the established criteria within acceptable limits.

The calibration criteria adopted in this study compared simulated and published values of:

1. Runoff volumes at the active WSC streamflow stations
2. Flood peaks and timing at the active WSC streamflow stations
3. Water levels in Smallwood Reservoir and Ossokmanuan/Gabbro Lake.

6.3.2 Calibration Data

Calibration of the Churchill River SSARR models used meteorological and flow data for the years 1980 to 1982, for continuity with the 1999 PMF study, and for 1999, to reflect the change in flood operating procedures following the 1989 Flood Handling Study and to capture a high runoff year in the Lower Basin. The following data were used in the calibration of the three basin models:

- Topographic data. Drainage areas and elevation data for snow band areas were taken from a digital elevation model (DEM) of southern Labrador. Figure 6.7 shows the hypsometric curves of basin elevation versus area. The Upper Basin is generally flat with all the area on the Labrador Plateau. The Lower Basin combines areas on the plateau with steeper areas as the tributaries drop off the plateau down into the Churchill River valley.

- Temperature data. Temperature data were available from AEB stations at Goose Bay, Churchill Falls, Schefferville and Wabush on a daily basis as maximum, minimum and mean daily values. Hourly temperature values were also available at Goose Bay. Values for the 6-hourly compute periods were taken from the hourly values at Goose Bay, adjusted according to the maximum and minimum temperatures at each gauge. Temperatures within SSARR are lapsed from the AEB station elevations to common sea level values and then lapsed again to the median snow band elevations in each sub-basin. The temperatures in each sub-basin were calculated as the weighted average of the nearest AEB stations.
- Snowpack data. Snowpack water equivalent data were available from CF(L)Co at the end of March each year from fifteen snow courses in the Upper Basin and two in the Lower Basin, at Metchin and Fig West. Snowpack water equivalent data for Goose Bay[2] were available from AEB. In the Upper Basin, on the Labrador Plateau, there is no obvious variation of snowpack depth or water equivalent with elevation, so snow water equivalent values for each sub-basin were calculated as the weighted average of the nearest CF(L)Co stations. In the Lower Basin below the plateau elevation (± 400m) snowpack data for each snow band were calculated thus:
    - Band 1 (median elevation 90m) = Goose Bay
    - Band 2 (median elevation 225m) = Average of Goose Bay and Metchin
    - Band 3 (median elevation 335m) = Metchin
    - Band 4 (median elevation 415m) and above = Average of Fig West and Churchill Falls.
- Precipitation data. Precipitation data were available on a daily basis for the same four AEB stations as temperature, although in recent years data for the Churchill Falls gauge were frequently missing. 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. Monthly precipitation data were also available at the CF(L)Co snow course locations. These gauges provide a good coverage of precipitation in the Upper Basin, but not at the interval required in the watershed model. To make use of the CF(L)Co precipitation data, the weighted average precipitation for each sub-basin was computed for the modelling period (April through September) each year and the available AEB stations were weighted to give these amounts. This means that the precipitation station weights vary from year to year, but should give a more accurate estimate of sub-basin precipitation.
- Flow data. Daily flow data were available for the following principal stations continuously from 1980 to 2005:
    - 03OA001 Ashuanipi River at Menihek Rapids – Lake regulated flows in Smallwood Reservoir Basin;

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[2] Snow water equivalent (SWE) data collection was discontinued in 1995. SWE values for subsequent years were taken from published snow depth data and average snow density data from previous years.

- 03OC006 Atikonak River at Gabbro Lake (Control Structure) – Outflows from the Ossokmanuan/Gabbro Lake Basin;
- 03OD005 Churchill River at Churchill Falls Powerhouse – Outflows from the Smallwood Reservoir and Forebays (+Ossokmanuan/Gabbro Lake) Basin;
- 03OE001 Churchill River above Muskrat Falls - Outflows from the entire Churchill River Basin.

Flow data from these stations enable the following calibration checks to be performed:

- Magnitude and timing of flood peaks
- Monthly water balance
- Water levels from reservoir operations.

Most of the other Upper Basin streamflow gauges have data for the early 1980s, but have since been discontinued. Three tributary gauges in the Lower Basin have data since 1999, except for the Minipi River, which has data from 1979.

- Water level data. CF(L)Co monitors the water level at Lobstick Control Structure and other locations on Smallwood Reservoir and at Gabbro Control Structure on Gabbro Lake. Daily water levels at these structures were compared to those generated by the SSARR model, using the elevation-storage curves in the 1989 Flood Handling study.
- Storage data. Elevation-storage curves from the 1989 Flood Handling study were included in the SSARR model for reservoir routing through Smallwood Reservoir and Ossokmanuan/Gabbro Lake. Figures 6.8 and 6.9 show the elevation-area-storage curves for the two reservoirs.
- Operations data. Elevation-discharge curves for the Churchill Falls control structures were taken from the 1989 Flood Handling Study for reservoir routing through Smallwood Reservoir and Ossokmanuan/Gabbro Lake to simulate the PMF routing in the SSARR model. The various discharge curves for each storage were combined into a composite discharge rating and adjusted to represent the effective discharge ratings based on the actual flood handling procedures implemented in the PMF Base Case example in the 1989 Flood Handling Study report. Figures 6.10 and 6.11 show the discharge rating curves used in the SSARR model.
- Initial Conditions. Initial conditions for each calibration year were taken from the following sources:
    - Snowpack water equivalents were taken from CF(L)Co. data described above;
    - Starting flows were taken from WSC station records at the end of March and distributed between the four routing zones in proportions typical to this time of year;
    - Starting values of soil moisture index, cold content and base flow percent were taken from preliminary runs undertaken in the 1999 PMF Study. Starting the calibration runs on April 1st, allows the starting conditions to stabilize before the main snowmelt sequence begins in May.
- River Routing. The Lower Churchill River flows 285 km and drops 120m from Churchill Falls to Muskrat Falls and releases from Churchill Falls Powerhouse take approximately three days to reach Muskrat Falls. The river has a gentle slope with values ranging from near zero through Winokapau

Lake to 0.17% through Mouni Rapids. Channel routing has a strong influence on flood peaks along the river so river routing was modelled explicitly as eight separate reaches in SSARR. Each reach was split into a number of storage phases depending on the length of the reach. Routing uses the continuity equation:

$$O_2 = O_1 + t\,(I_m - O_1)/(T_s + t/2)$$

Where: O_1, O_2 are outflows at the beginning and end of the time period

I_m is the average inflow during the period

t is the time duration of the period

T_s the time of storage

The time of storage T_s varies with flow and is given by:

$$T_s = KTS/Q^n$$

Where: KTS is a constant calibrated using the estimated May1999 flood flows in each reach

Q is flow

n is a coefficient (= 0.2) calibrated using May1999 flood flows.

- Natural Lakes. The only information available to represent natural lakes or chains of lakes in the SSARR model is the approximate drainage area controlled by the lakes and the normal surface areas of the lakes. Both of these quantities were measured approximately from topographic mapping for most of the lakes, although the surface areas of Ashuanipi Lake, Lac Joseph and Atikonak Lake were taken from The Atlas of Canada[19].

  A dimensionless elevation-area curve was derived from the elevation-area curves for Ossokmanuan and Gabbro Lakes. This dimensionless elevation-area curve was then used to generate an elevation-area curve for each "natural lake" using the equation:

$$\text{Surface Area} = C.S.f[h] \qquad (\text{km}^2)$$

Where: f[h] is the dimensionless elevation-area curve for Ossokmanuan and Gabbro Lakes as a function of lake elevation rise h (m)
S is the measured combined surface area of the lake(s) from topographic mapping (km^2)
C is a calibration coefficient.

The discharge rating for each lake assumes a weir flow equation and an effective crest length proportional to the size of the drainage area divided by the surface area of the lake(s). i.e.

$$Q = k.A.S^{-1}.h^{1.5} \qquad (\text{m}^3/\text{s})$$

Where: Q is the outflow from the lake (m^3/s)
A is the drainage area of the lake (km^2)
S is the measured combined surface area of the lake(s) from topographic mapping (km^2)
h is the elevation of the lake above the outlet "crest"
k is a calibration coefficient.

6.3.3 *Calibration Adjustments*

Calibration of the SSARR model for each sub-basin requires two types of adjustments:

System wide adjustments, such as melt rate, lapse rate, etc.

Sub-basin specific adjustments, such the number of routing phases and the storage times for each runoff zone. This class of adjustment also includes the adjustment of the storage and discharge curves synthesized for each natural lake modeled.

The three basin models from the 1999 PMF Study provided a good starting point in which many of the basic parameter values were established. Only a few changes were made to these system wide parameters:

The lapse rate[3] between Goose Bay and Churchill Falls was found to decrease through the snowmelt period with a value of 4˚C/1000m appropriate for the main melt period of late May/early June. This lapse rate replaced the default value of 6˚C/1000m in the model.

The effectiveness of evaporation loss in the previous models was reduced through the summer to better match the summer/fall recession.

In the Upper Basin the proportion of runoff going to baseflow was increased due to the flatter terrain and the higher percent of lake coverage than in the Lower Basin.

These general adjustments were reviewed in the SSARR model, in terms of flood peaks, but also by comparing the runoff at the various WSC gauges with the monthly water balance breakdown given by SSARR.

The sub-basin specific adjustments were limited to adjustment of the storage hours for each routing zone. Where a natural lake, or a chain of lakes, attenuates the flows at a WSC gauge, the storage and discharge coefficients for the synthetic lake included in the SSARR model were also adjusted to improve the magnitude and timing of the peak outflow from the lake.

6.3.4 *The Smallwood Reservoir Basin*

The SSARR model of the Smallwood Reservoir basin modelled the runoff and routing of all flows entering Smallwood Reservoir, including the direct drainage to the forebays. The Gabbro CS (03OC006) flows were included as inflows to Smallwood Reservoir and the powerhouse (03OD005) flows were included as outflows from Smallwood Reservoir. The basin was divided into seven sub-basins, as shown in Figure 6.2, to capture the impacts of varying storm centres and travel times on inflows to Smallwood Reservoir. These sub-basins are:

Sub-Basin Number	**Sub-Basin Description**	**Drainage Area (km^2)**
15	South shore of Smallwood Reservoir	5209
16	Surface of Smallwood Reservoir	6286
17	North shore of Smallwood Reservoir	9346

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[3] The lapse rate is the decrease in temperature with elevation. It causes snow cover to remain longer at high elevations than at low elevations.

Sub-Basin Number	Sub-Basin Description	Drainage Area (km^2)
18	Mouth of Ashuanipi River (net*)	6714
19	Ashuanipi River at WSC 03OA001 (net)	7296
20	McPhayden River at WSC 03OA003	3609
21	Ashuanipi River at WSC 03OA004	8309

** Net drainage between this location and the next gauge upstream on the river.*

Table 6.1 summarises the observed and simulated runoffs to Smallwood Reservoir and Ossokmanuan/Gabbro Lake between April and September for each calibration year.

Table 6.2 compares the magnitude of the flood peaks at the active WSC stations and the maximum water levels in Smallwood Reservoir for each calibration year.

Figures 6.12 to 6.15 show the published and simulated inflows, outflows and water levels for Smallwood Reservoir for 1980, 1981, 1982 and 1999.

6.3.5 The Ossokmanuan/Gabbro Lake Basin

The SSARR model of the Ossokmanuan/Gabbro Lake basin modelled the runoff and routing of all flows entering the Ossokmanuan/Gabbro Lake. The Gabbro CS (03OC006) flows were included as outflows from Ossokmanuan/Gabbro Lake to Smallwood Reservoir. The basin was divided into five sub-basins, as shown in Figure 6.2, to capture the impacts of varying storm centres and travel times on inflows to Ossokmanuan/Gabbro Lake. These sub-basins are:

Sub-Basin Number	Sub-Basin Description	Drainage Area (km^2)
22	Atikonak River at WSC 03OC003	4458
23	Kepimits River at WSC 03OC004	6968
24	Atikonak River at WSC 03OC005 (net)	4023
25	Gabbro Lake	5547
26	Ossokmanuan Lake	1436

** Net drainage between this location and the next gauge upstream on the river.*

Table 6.1 summarises the observed and simulated runoffs at the active WSC stations between April and September for each calibration year.

Table 6.3 compares the magnitude of the flood peaks at the active WSC stations and the maximum water levels in Ossokmanuan/Gabbro Lake for each calibration year.

Figures 6.16 to 6.19 show the published and simulated inflows, outflows and water levels for Ossokmanuan/Gabbro Lake for 1980, 1981, 1982 and 1999.

6.3.6 The Lower Churchill Basin

The SSARR model of the Lower Churchill basin modelled the runoff and routing of all flows in the Lower Churchill River above Muskrat Falls. The Churchill Falls powerhouse (03OD005) flows were included as outflows from Smallwood Reservoir. The basin was divided into twelve sub-basins, as shown in Figure 6.2, to capture the impacts of varying storm centres, natural lake attenuation and travel times on flows in the Lower Churchill River above Muskrat Falls. These sub-basins are:

Sub-Basin Number	**Sub-Basin Description**	**Drainage Area (km^2)**
1	Lower Pinus River	1799
2	Upper Pinus River	759
3	Lower Minipi River	2768
4 + 5	Upper Minipi River	2771
6 + 7	Upper Cache (+Shoal) River	1377
8	Lower Cache (+Shoal) River	1881
9	Upper Metchin River	2651
10	Lower Metchin River	1330
11	Upper Fig (+Elizabeth) River	2508
12	Lower Fig (+Elizabeth) River	2711
13	Upper Unknown River	1815
14	Lower Unknown River	928

The published flows for the Lower Churchill River above Muskrat Falls (03OE001) were included to compare with the SSARR simulated flows.

Table 6.4 summarises the observed and simulated peaks and runoff volumes at the Upper Muskrat Falls WSC station 03OE001 between April and September for each calibration year.

Figures 6.20 to 6.23 show the published and simulated flows for the Lower Churchill River above Muskrat Falls for 1980, 1981, 1982 and 1999.

6.3.7 Commentary

6.3.7.1 The Smallwood Reservoir Basin

In calibrating the SSARR model for the Smallwood Reservoir Basin it has been assumed that flows for the entire basin pass through Smallwood Reservoir before being released to the Lower Basin through the Churchill Falls powerhouse. In practice ±4% of the runoff from the Smallwood Reservoir Basin bypasses Smallwood Reservoir and flows directly to the West and/or East Forebays. This will not significantly affect the calibration as the outflows from Churchill Falls powerhouse are from the total basin area.

SSARR water levels in Smallwood Reservoir have been compared to observed levels at the Lobstick Control Structure. These levels frequently differ from those at Hook Bay and Orma, other gauge locations on the reservoir, by as much as 0.3m. Thus some variation in measured and simulated levels may be due to natural variations in level across the reservoir surface.

Comments on each of the calibration years follow.

1980 – An average runoff year and one of the best years of calibration. The recession limb of the water level hydrograph is slightly steep, but overall the peak and volume are well matched with less than 2 % discrepancy.

1981 – A high runoff year. The timing of the hydrograph is good, but the maximum water level is overestimated by 0.3m. The runoff volume is within 4 % of the actual volume.

1982 - An average runoff year. The simulated reservoir level hydrograph follows the measured levels well, but is consistently 0.25m below the actual levels. In contrast the estimated runoff is 5% higher than measured.

1999 – A high flood year. The simulated water level rises faster than the measured levels, but peaks at a similar level. The simulated runoff volume was 2% higher than measured.

Overall the average runoff from SSARR from the calibration years was 2.3% higher than actual and the average reservoir peak level was 0.01m higher than measured. The calibration for Smallwood Reservoir Basin is considered good.

6.3.7.2 The Ossokmanuan/Gabbro Lake Basin

Ossokmanuan/Gabbro Lake has approximately one half the drainage area of Smallwood Reservoir, but only one tenth of the storage. This makes variations in water level far more sensitive to inflow estimates than Smallwood Reservoir.

SSARR water levels in Ossokmanuan/Gabbro Lake have been compared to observed levels at the Gabbro Control Structure. There is a flow constriction between Ossokmanuan and Gabbro lakes and this can sometimes result in differences in water level between Ossokmanuan and Gabbro Control Structure gauges. The gauge at Ossokmanuan Control Structure is no longer monitored, but in the early years of operation differences in level of up to 0.8m were recorded. This may have some influence on the comparison of simulated and observed levels for Ossokmanuan/Gabbro Lake.

Comments on each of the calibration years follow.

1980 – An average runoff year. Unlike Smallwood, this is the worst year of calibration. The runoff is underestimated by almost 10% and the maximum Ossokmanuan water level simulated was 1.4m below actual.

1981 – A high runoff year. The timing of the hydrograph is good and the maximum water level is virtually the same as measured. The lake level drops of after the peak, rather than remaining level, but the runoff volume is within 0.5 % of actual.

1982 - An average runoff year. The simulated reservoir level hydrograph rises earlier than the measured levels, but then matches the summer levels almost exactly before rising in September. The estimated runoff is 7% higher than measured.

1999 – A high flood year. The timing of the simulated water level is good, but the variation is greater than the measured levels, although the lake level peaks at a similar level. The simulated runoff volume was 2% lower than measured.

Overall the average runoff from SSARR from the calibration years was 1.4% lower than actual and the average reservoir peak level was 0.30m lower than measured, though this was mainly due to 1980. The calibration for Ossokmanuan/Gabbro Lake Basin was more variable than for Smallwood Reservoir Basin, but the model parameters were similar. Overall the calibration is considered reasonable.

The total runoff simulated from the Upper Basin in the calibration years was 1.1% higher than measured.

6.3.7.3 The Lower Churchill Basin

Comments on each of the calibration years follow.

1980 – An average local flood year. Like Ossokmanuan, this is the worst year of calibration. The runoff is underestimated by almost 6% and the simulated flood peak at Muskrat Falls was 9% below actual.

1981 – A high local flood year. The timing of the hydrograph is good and the peak and runoff volume are both within 3% of actual.

1982 - An average local flood year. The simulated hydrograph follows the measured hydrograph well and peaks on the same day. However, a warm spell in mid-May results in early melt in the SSARR model that was not seen in reality. As a result the peak is underestimated by 6%, although the estimated runoff is less than 1% below measured.

1999 – A very high local flood year. The timing of the simulated flood hydrograph is good, but the peak is overestimated by nearly 10%. The simulated runoff volume was less than 2% higher than measured.

Overall the average floods from SSARR from the calibration years were 0.2% lower than actual in terms of flood peak and runoff volume was 0.7% lower than measured. The timing of the flood peaks was the same as recorded. Overall the calibration is considered good.

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, 1981, 1982 and 1999. Three recent years, 2000, 2002 and 2004 were simulated with no additional alterations to the SSARR models to verify the calibration. The initial snowpacks and soil moisture content were calculated using the same method as used for the calibration.

The verification simulations for the Smallwood Reservoir Basin are shown in Figures 6.24 to 6.26. The hydrographs show good agreement with the shape of the observed water level hydrographs, but overestimated the maximum water levels. Maximum discrepancies were 0.54m in peak reservoir level and 15% in runoff volume.

The verification simulations for the Ossokmanuan/Gabbro Lake Basin are shown in Figures 6.27 to 6.29. The hydrograph for 2000 shows good agreement with the shape of the observed water level hydrograph, but 2002 and 2004 diverge from recorded levels. Maximum discrepancies were 0.93m in peak reservoir level and 11% in runoff volume.

With the inclusion of the three verification years the seven year average runoff volume simulated for the upper basin is 3.6% higher than measured and the SSARR model can be considered slightly conservative in the upper basin.

The verification simulations for the Lower Churchill River at Muskrat Falls are shown in Figures 6.30 to 6.32. The hydrographs show good agreement with the recorded flow hydrographs, although the timing of the peaks is slightly delayed. Maximum discrepancies were 8% in flood peak and 6% in runoff volume. Overall the seven flood years simulated by SSARR were 0.5% less than observed in terms of peak and 0.3% lower in terms of volume, with the flood peaks occurring on the same day on average.

The input data coverage for the large drainage areas that comprise the Churchill River Basin is sparse and interpolation between point measurements cannot accurately capture the hydrometeorological variation across the sub-basins in individual years. However, as more years are simulated the interpolation of hydrometeorological averages becomes more valid and differences due to the model itself can be evaluated. When the average differences have been reduced to an acceptably small value the underlying model can be considered a good representation of how the basin would respond if the hydrometeorological inputs were accurately known. When design values of each hydrometeorological parameter are applied to this model the resulting outputs can then be viewed with the same confidence as the input values.

The results presented above for the seven years of simulation show that the three SSARR models produce good average agreement with the observed information and can be used with confidence to simulate the PMF scenarios.

Table 6.1
Upper Basin SSARR Calibration - April to September Runoff

Year	Smallwood Reservoir			Ossokmanuan/Gabbro Lake			Upper Basin		
	Measured[1] (mm)	SSARR (mm)	SSARR/ Measured (%)	Measured[1] (mm)	SSARR (mm)	SSARR/ Measured (%)	Measured[1] (mm)	SSARR (mm)	SSARR/ Measured (%)
Calibration									
1980	504	498	98.7%	527	475	90.2%	511	490	95.9%
1981	553	572	103.5%	586	583	99.5%	564	576	102.1%
1982	482	507	105.1%	499	536	107.4%	488	516	105.9%
1999	488	498	102.0%	550	539	97.9%	508	511	100.5%
Average	507	519	102.3%	541	533	98.6%	518	523	101.1%
Verification									
2000	372	427	114.8%	452	464	102.6%	398	439	110.3%
2002	465	454	97.6%	483	490	101.4%	471	466	98.9%
2004	530	599	113.0%	544	603	110.8%	535	600	112.3%
Overall Average	485	508	104.7%	520	527	101.3%	496	514	103.6%

Note

1. Water Survey of Canada runoff adjusted for storage change in reservoirs.

Table 6.2
Smallwood Basin SSARR Calibration - Flood Peaks

Year	Ashuanipi River below Wightman Lake (03OA004)			McPhayden River near the Mouth (03OA003)			Ashuanipi River at Menihek Rapids (03OA001)			Smallwood Reservoir - Maximum Water Level at Lobstick Gauge		
	Measured (m^3/s)	SSARR (m^3/s)	SSARR/ Measured (%)	Measured (m^3/s)	SSARR (m^3/s)	SSARR/ Measured (%)	Measured (m^3/s)	SSARR (m^3/s)	SSARR/ Measured (%)	Measured (m)	SSARR (m)	SSARR - Measured (m)
Calibration												
1980	569	675	118.6%	-	629	-	2250	1860	82.7%	472.78	472.72	-0.06
1981	818	876	107.1%	-	736	-	2860	2110	73.8%	472.81	473.14	0.33
1982	464	660	142.2%	425	613	144.2%	1670	1860	111.4%	471.01	470.75	-0.26
1999	-	625	-	-	1010	-	1740	2730	156.9%	471.25	471.27	0.02
Calibration Average	617	737	119.4%	425	613	144.2%	2130	2140	100.5%	471.96	471.97	0.01
Verification												
2000	-	576	-	-	421	-	1580	1720	108.9%	470.95	471.35	0.40
2002	-	611	-	-	733	-	2510	1950	77.7%	470.39	470.52	0.13
2004	-	891	-	-	748	-	2430	2440	100.4%	471.65	472.19	0.54
Overall Average	617	737	119.4%	425	613	144.2%	2149	2096	97.5%	471.55	471.71	0.16

Table 6.3
Ossokmanuan Basin SSARR Calibration - Flood Peaks

Year	Atikonak River above Atikonak Lake (03OC005)			Kepimits River below Kepimits Lake (03OC004)			Atikonak River above Panchia Lake (03OC003)			Ossokmanuan/Gabbro Lake - Maximum Water Level at Gabbro Gauge		
	Measured (m^3/s)	SSARR (m^3/s)	SSARR/ Measured (%)	Measured (m^3/s)	SSARR (m^3/s)	SSARR/ Measured (%)	Measured (m^3/s)	SSARR (m^3/s)	SSARR/ Measured (%)	Measured (m)	SSARR (m)	SSARR - Measured (m)
Calibration												
1980	609	555	91.1%	535	525	98.1%	1170	1170	100.0%	479.21	477.79	-1.42
1981	733	621	84.7%	841	842	100.1%	1750	1620	92.6%	479.18	479.15	-0.03
1982	-	505	-	555	681	122.7%	1390	1440	103.6%	479.18	479.37	0.19
1999	759	807	106.3%	757	685	90.5%	1500	1400	93.3%	478.68	478.74	0.06
Calibration Average	700	661	94.4%	672	683	101.7%	1453	1408	96.9%	479.06	478.76	-0.30
Verification												
2000	353	567	160.6%	508	599	117.9%	1030	1120	108.7%	477.67	477.54	-0.13
2002	-	646	-	-	674	-	1240	1410	113.7%	478.86	478.71	-0.15
2004	-	585	-	-	831	-	1420	1710	120.4%	478.40	479.33	0.93
Overall Average	614	638	103.9%	639	666	104.3%	1357	1410	103.9%	478.74	478.66	-0.08

Table 6.4
Lower Churchill Basin SSARR Calibration at Muskrat Falls[1]

Year	Flood Peak			Date of Flood Peak			May-July Flood Volume		
	Measured (m^3/s)	SSARR (m^3/s)	SSARR/ Measured (%)	Measured	SSARR	SSARR - Measured (days)	Measured (hm^3)	SSARR (hm^3)	SSARR/ Measured (%)
Calibration									
1980	5230	4760	91.0%	23-May	22-May	-1	29168	27476	94.2%
1981	4810	4951	102.9%	1-Jun	1-Jun	0	28322	29091	102.7%
1982	5200	4868	93.6%	6-Jun	6-Jun	0	25670	25498	99.3%
1999	6220	6833	109.9%	12-May	11-May	-1	22765	23162	101.7%
Average	5365	5353	99.8%	26-May	26-May	0	26481	26307	99.3%
Verification									
2000	3680	3969	107.9%	28-May	29-May	1	22139	20873	94.3%
2002	4970	4707	94.7%	1-Jun	3-Jun	2	19899	20480	102.9%
2004	3890	3747	96.3%	23-May	23-May	0	21019	21900	104.2%
Overall Average	4857	4834	99.5%	27-May	27-May	0	24140	24068	99.7%

Note

1. Measured and simulated flows at Muskrat Falls (03OE001) include Churchill Falls Powerhouse releases.

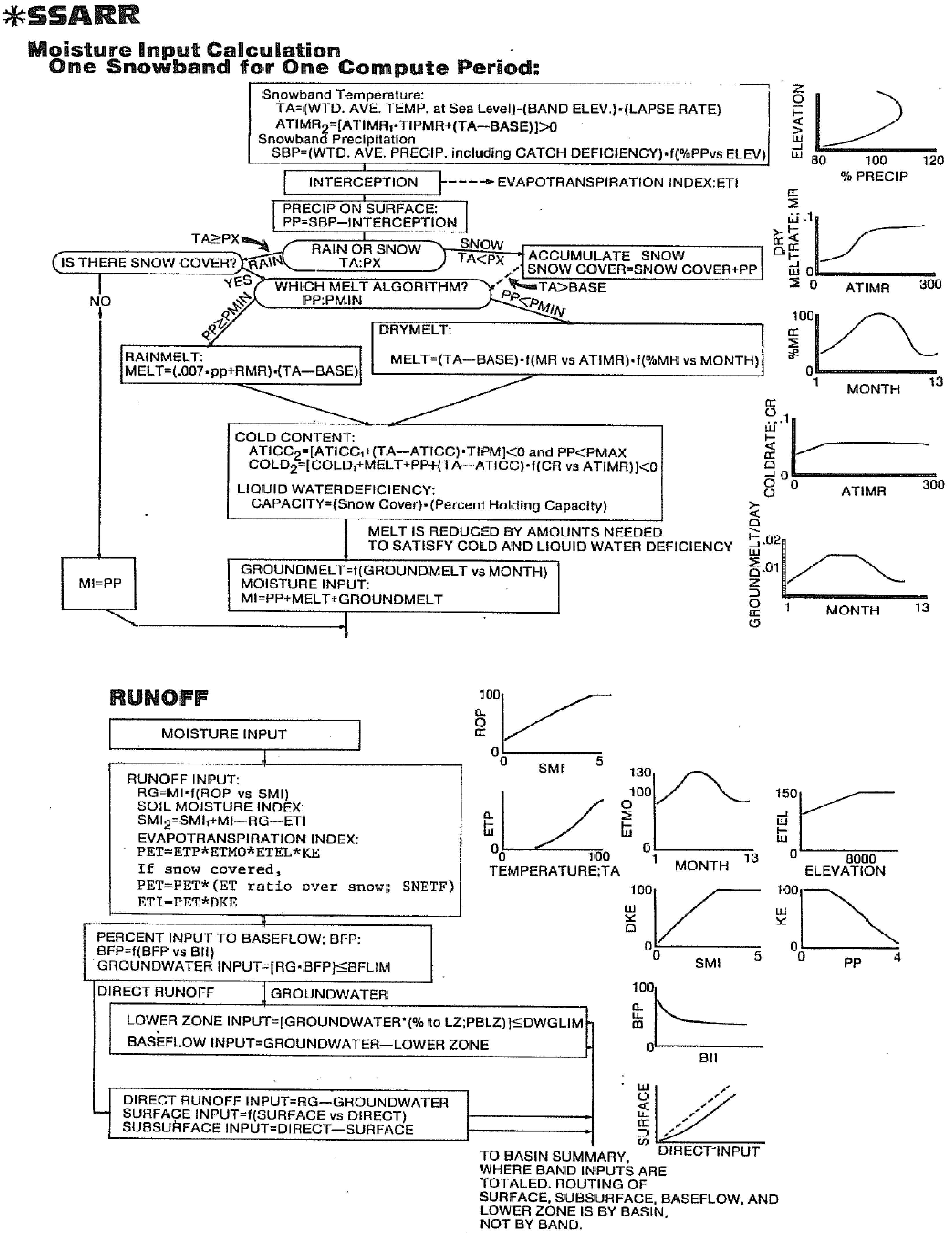
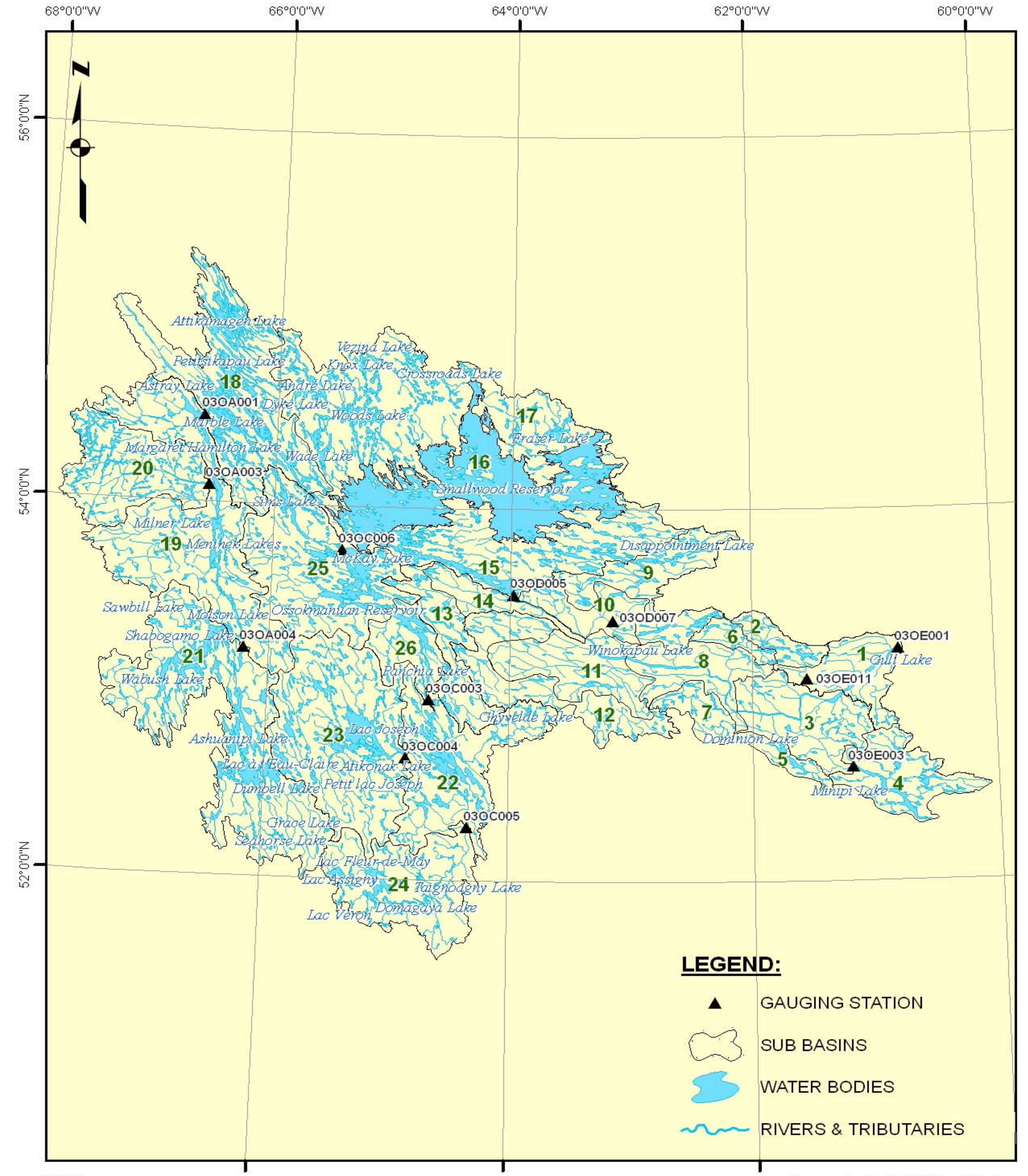


Figure 6.1
Lower Churchill Project
PMF and Construction Design Flood Study
SSARR METHODOLOGY SCHEMATIC



NOTES:

1. MAPPING INFORMATION SHOWN ON THE DRAWING HAS BEEN DERIVED FROM THE DIGITAL DATA FROM GEOGRATIS
2. PROJECTED COORDINATE SYSTEM IS NAD 1983, UTM ZONE 20N.

HATCH™

Figure 6.2
Lower Churchill Project
PMF and Construction Design Flood Study
SUB-BASIN MAP

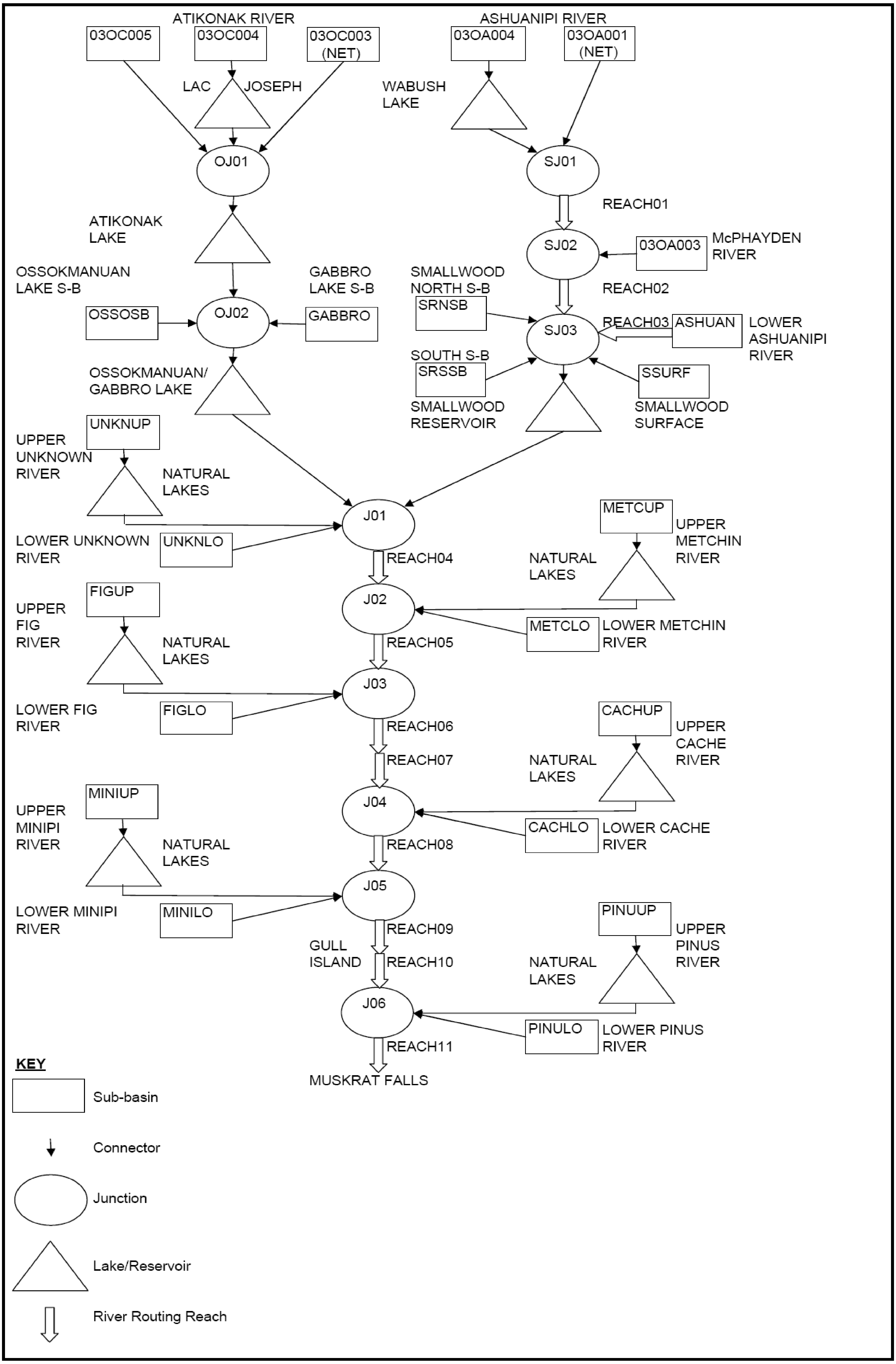


Figure 6.3
Lower Churchill Project
PMF and Construction Design Flood Study
CHURCHILL RIVER BASIN - SSARR MODEL SCHEMATIC

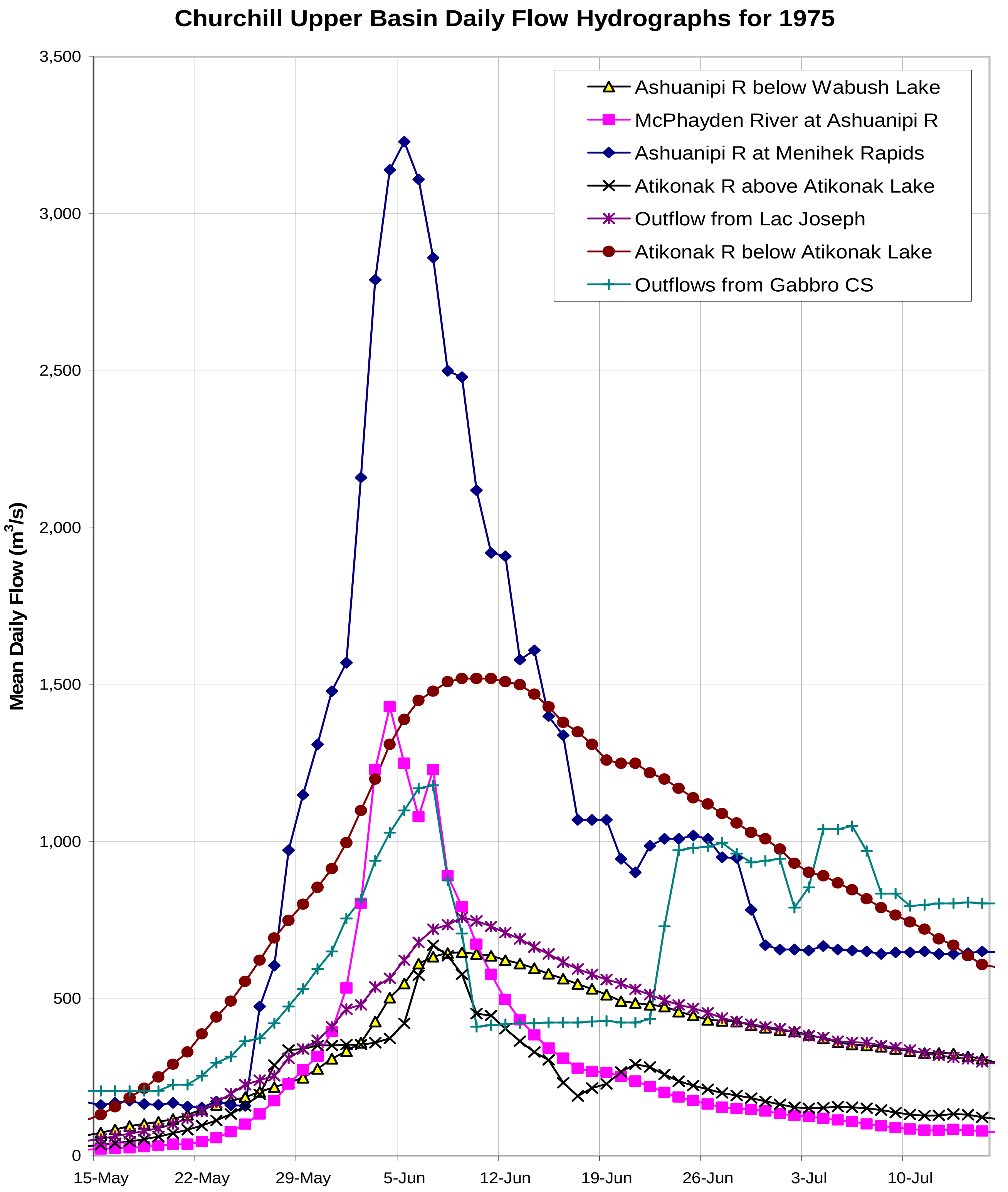


Figure 6.4
Lower Chruchill Project
PMF and Construction Design Flood Study
CHURCHILL UPPER BASIN DAILY FLOW HYDROGRAPHS FOR 1975

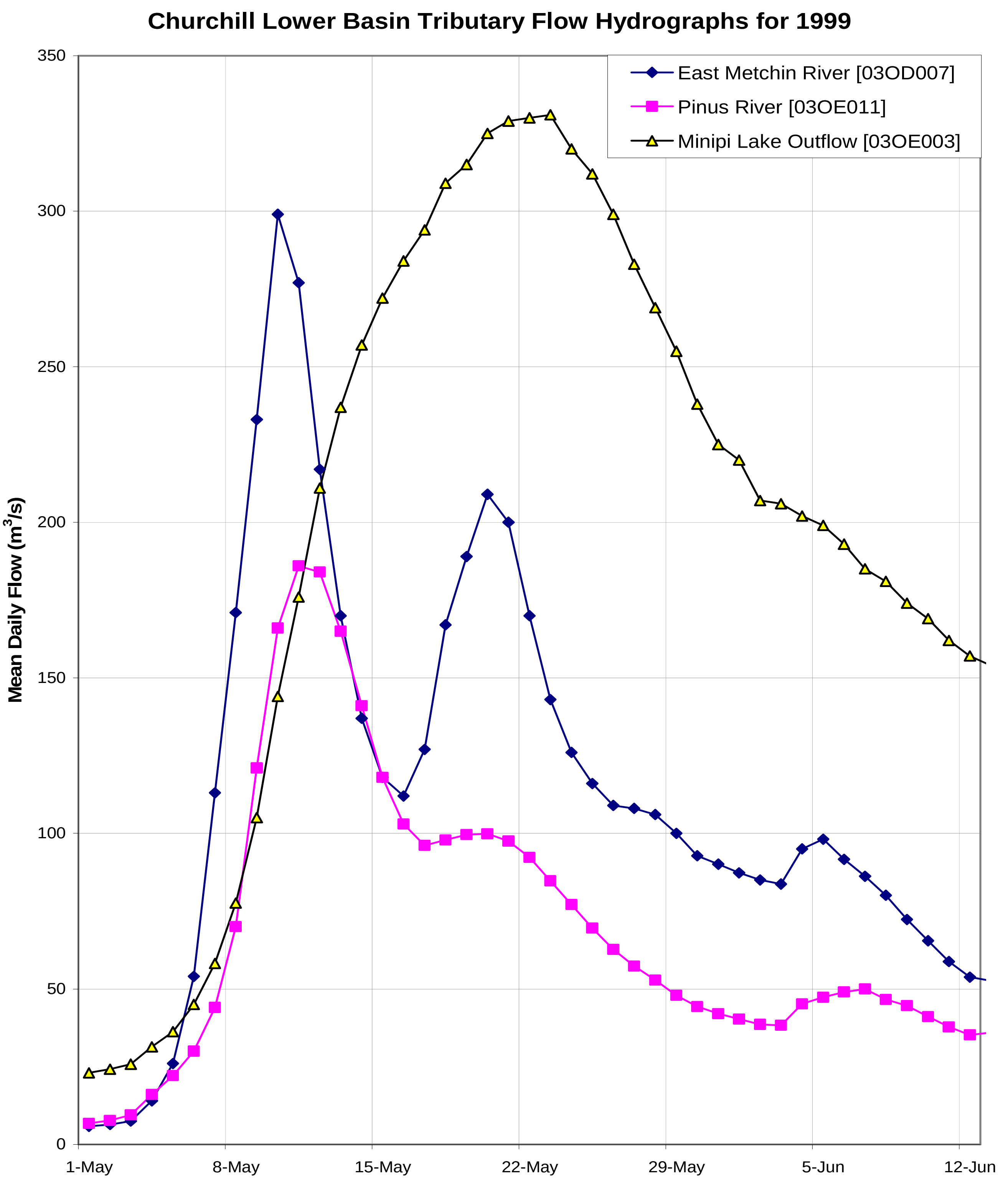


Figure 6.5
Lower Chruchill Project
PMF and Construction Design Flood Study
CHURCHILL LOWER BASIN TRIBUTARY FLOW HYDROGRAPHS FOR 1999

Churchill Lower Basin Daily Flow Hydrographs for 1999

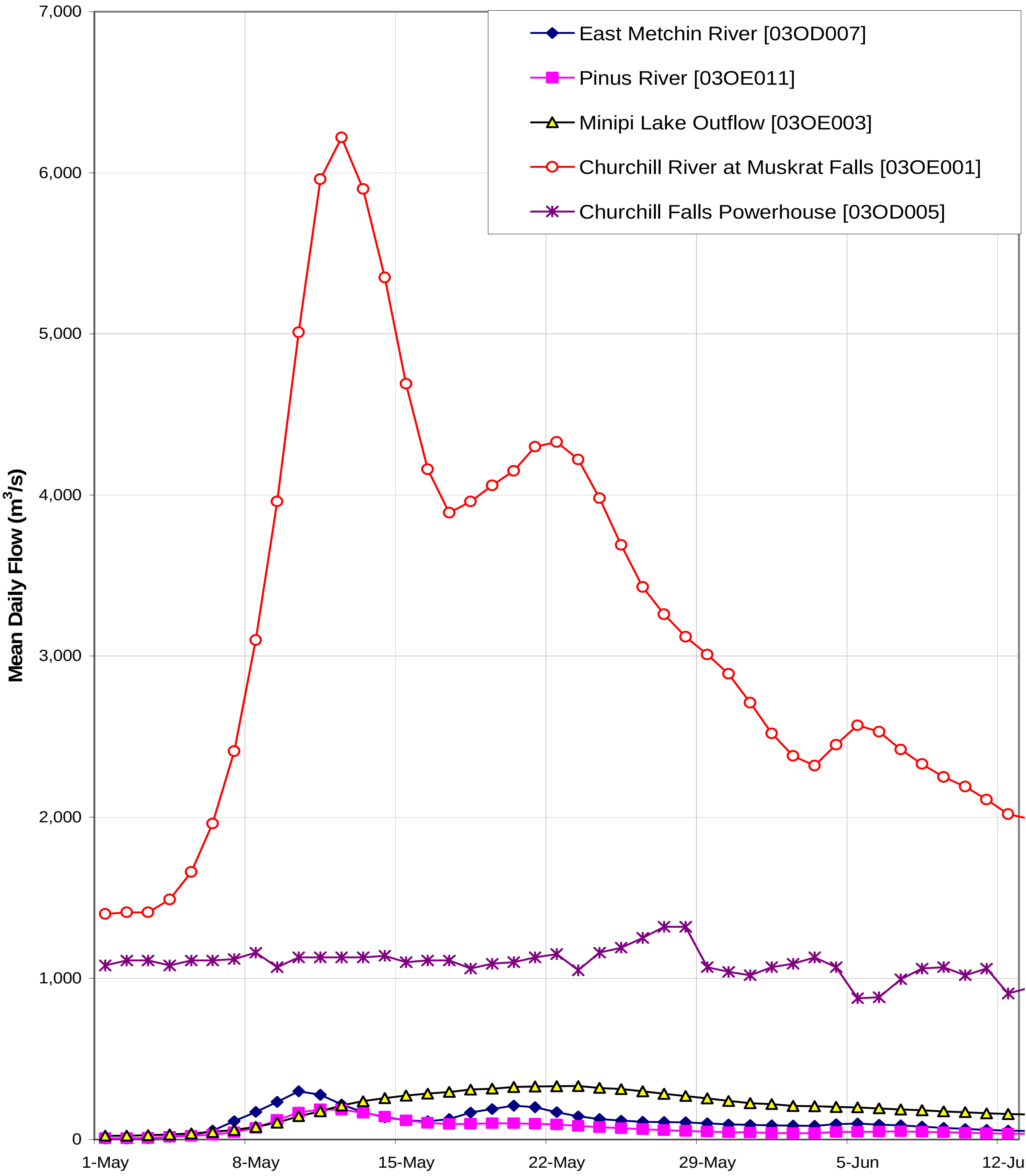


Figure 6.6
Lower Chruchill Project
PMF and Construction Design Flood Study
CHURCHILL LOWER BASIN DAILY FLOW HYDROGRAPHS FOR 1999

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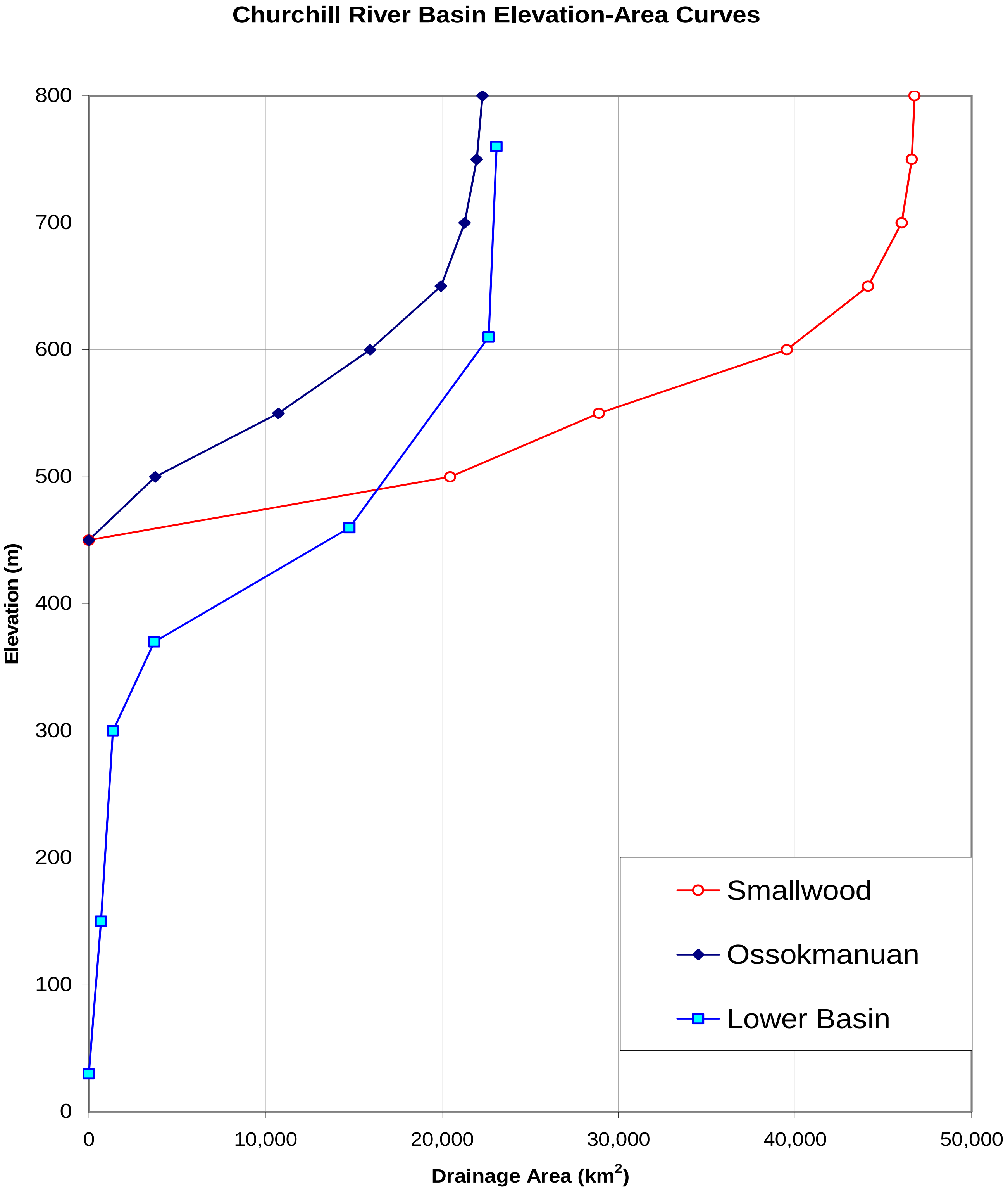

Figure 6.7

Lower Chruchill Project

PMF and Construction Design Flood Study

CHURCHILL RIVER BASIN ELEVATION-AREA CURVES

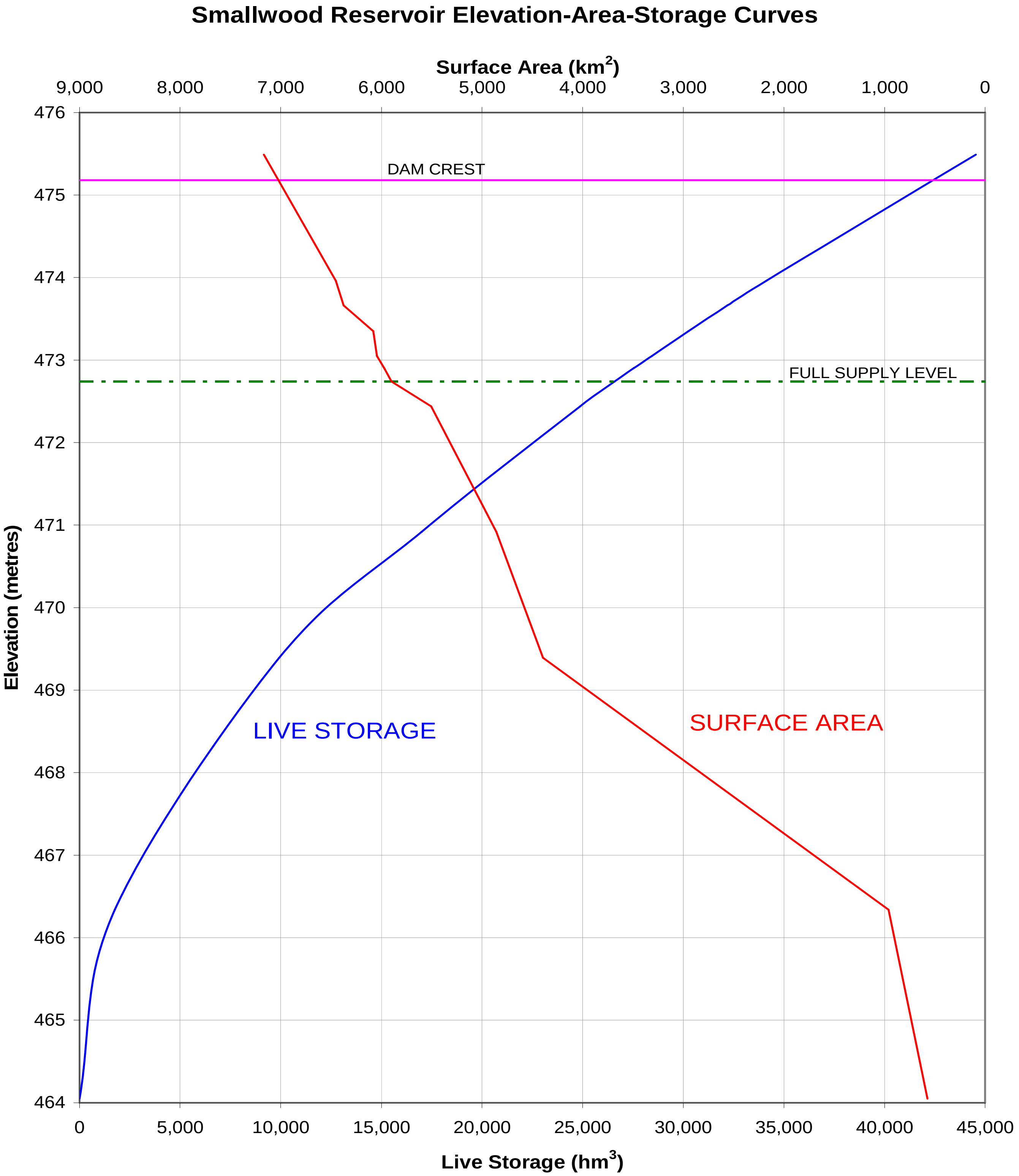

Figure 6.8
Lower Chruchill Project
PMF and Construction Design Flood Study
SMALLWOOD RESERVOIR ELEVATION-AREA-STORAGE CURVES

Ossokmanuan/Gabbro Lake Elevation-Area-Storage Curves

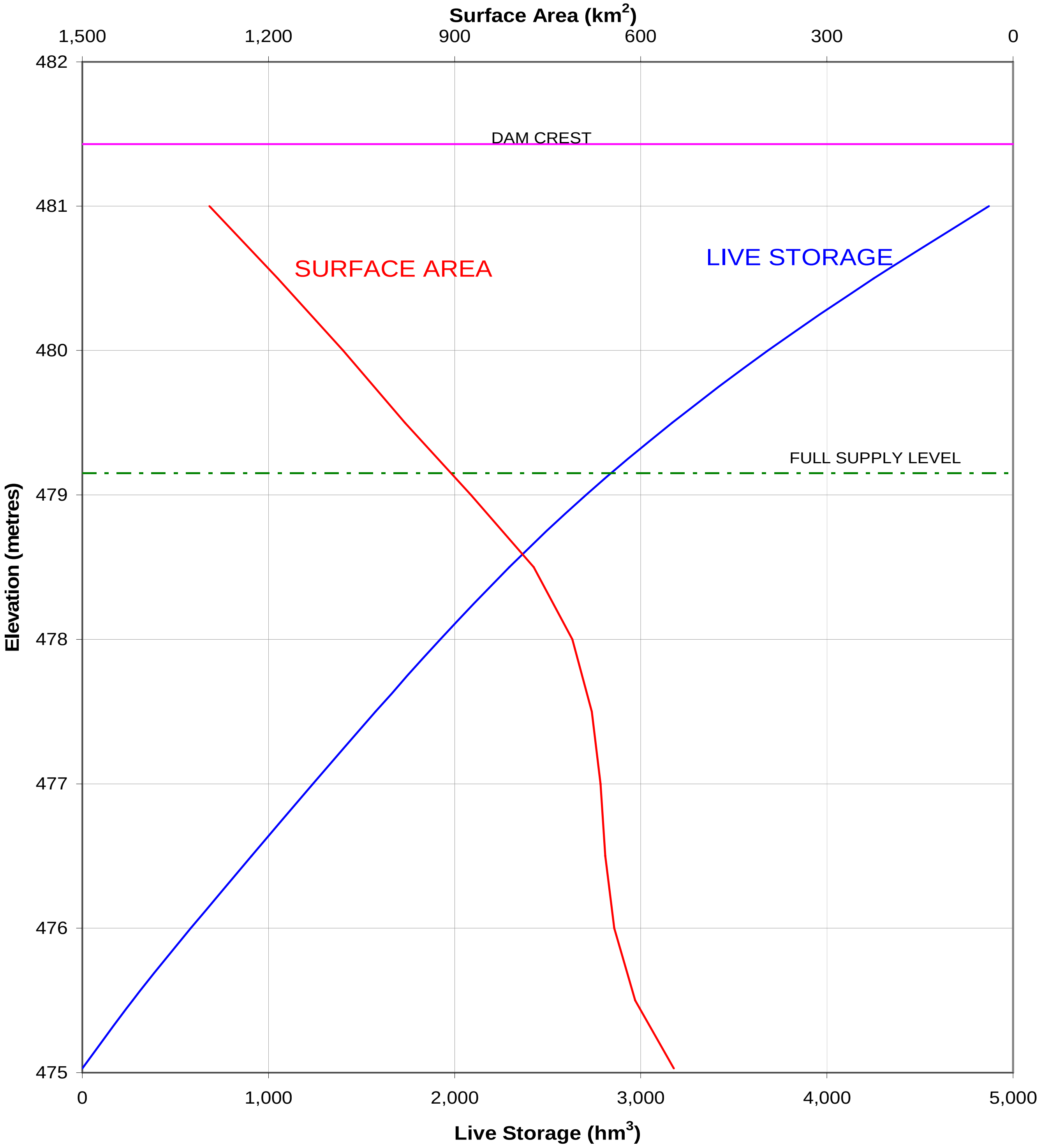

Figure 6.9

Lower Chruchill Project

PMF and Construction Design Flood Study

OSSOKMANUAN/GABBRO LAKE ELEVATION-AREA-STORAGE CURVES

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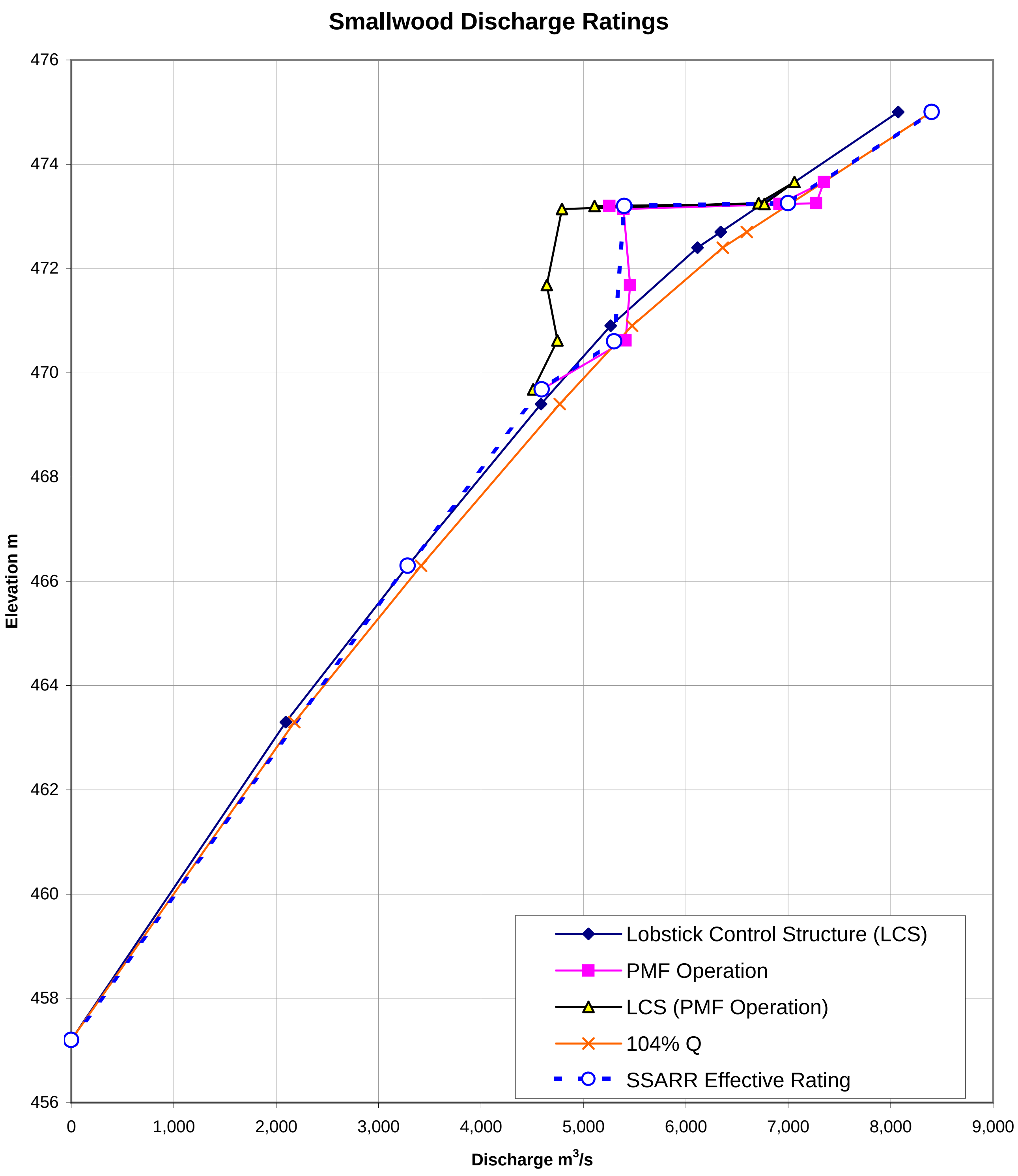


Figure 6.10
Lower Chruchill Project
PMF and Construction Design Flood Study
SMALLWOOD DISCHARGE RATINGS

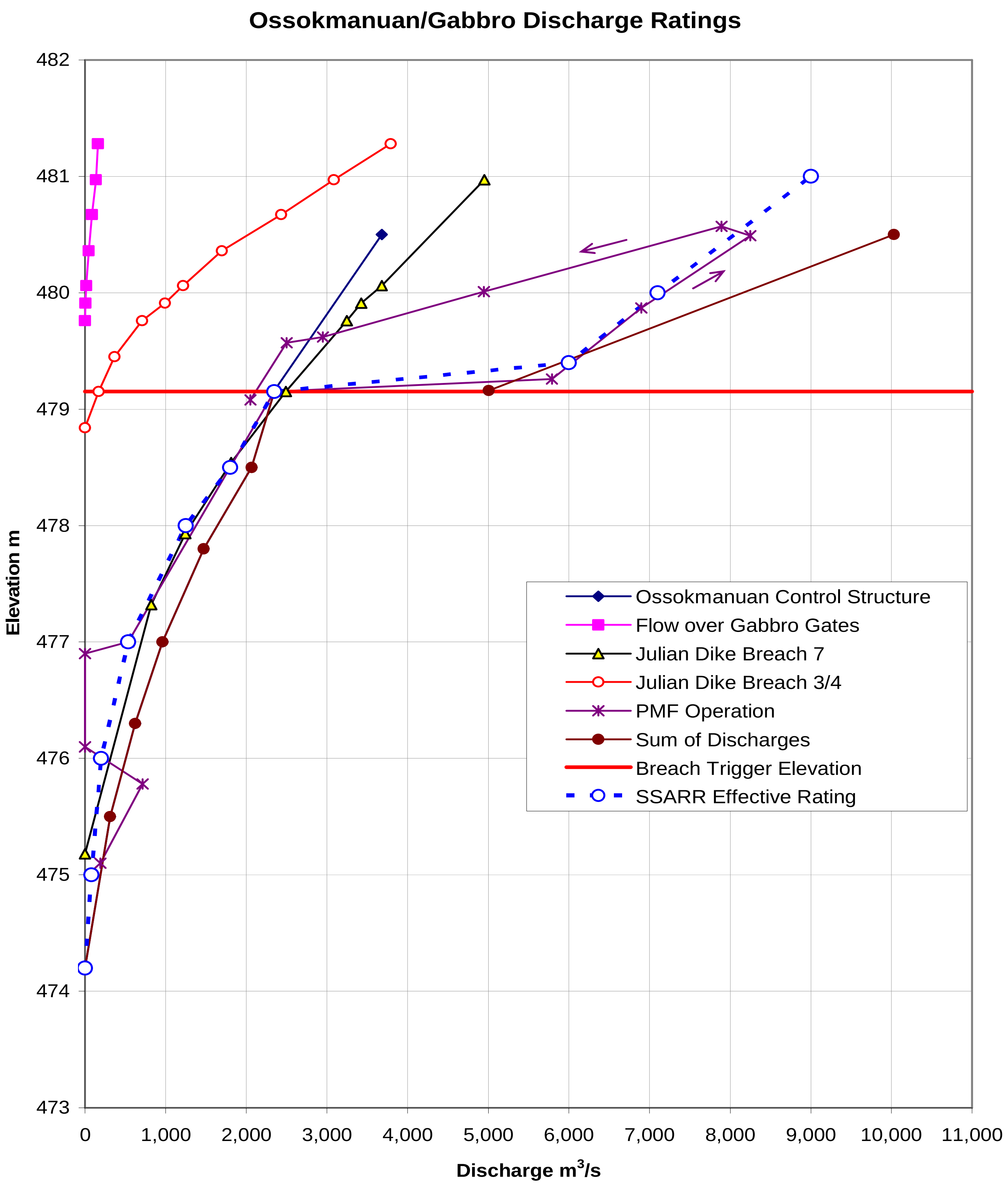


Figure 6.11
Lower Chruchill Project
PMF and Construction Design Flood Study
OSSOKMANUAN/GABBRO DISCHARGE RATINGS

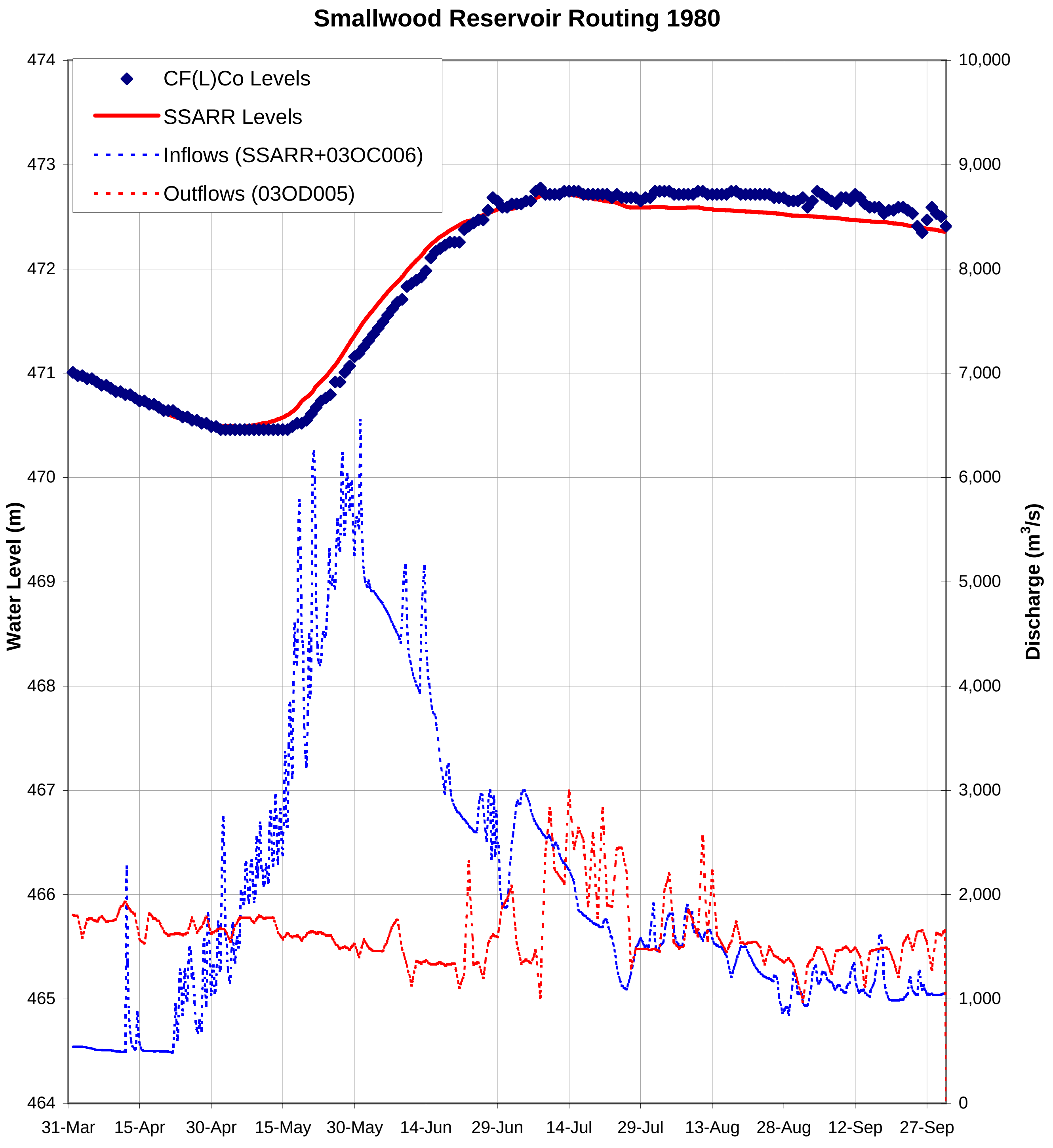


Figure 6.12
Lower Chruchill Project
PMF and Construction Design Flood Study
SMALLWOOD RESERVOIR ROUTING 1980

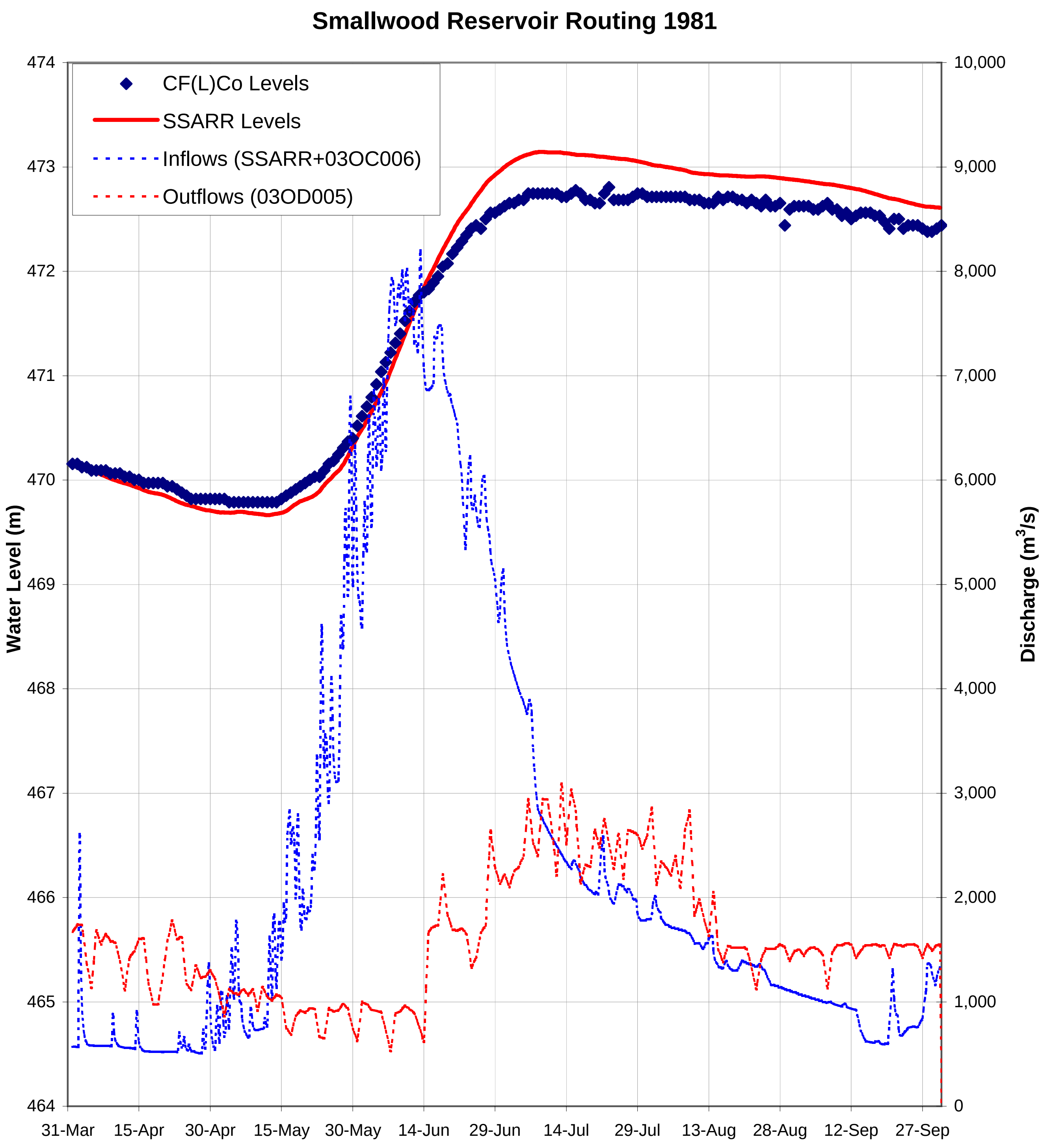


Figure 6.13
Lower Chruchill Project
PMF and Construction Design Flood Study
SMALLWOOD RESERVOIR ROUTING 1981

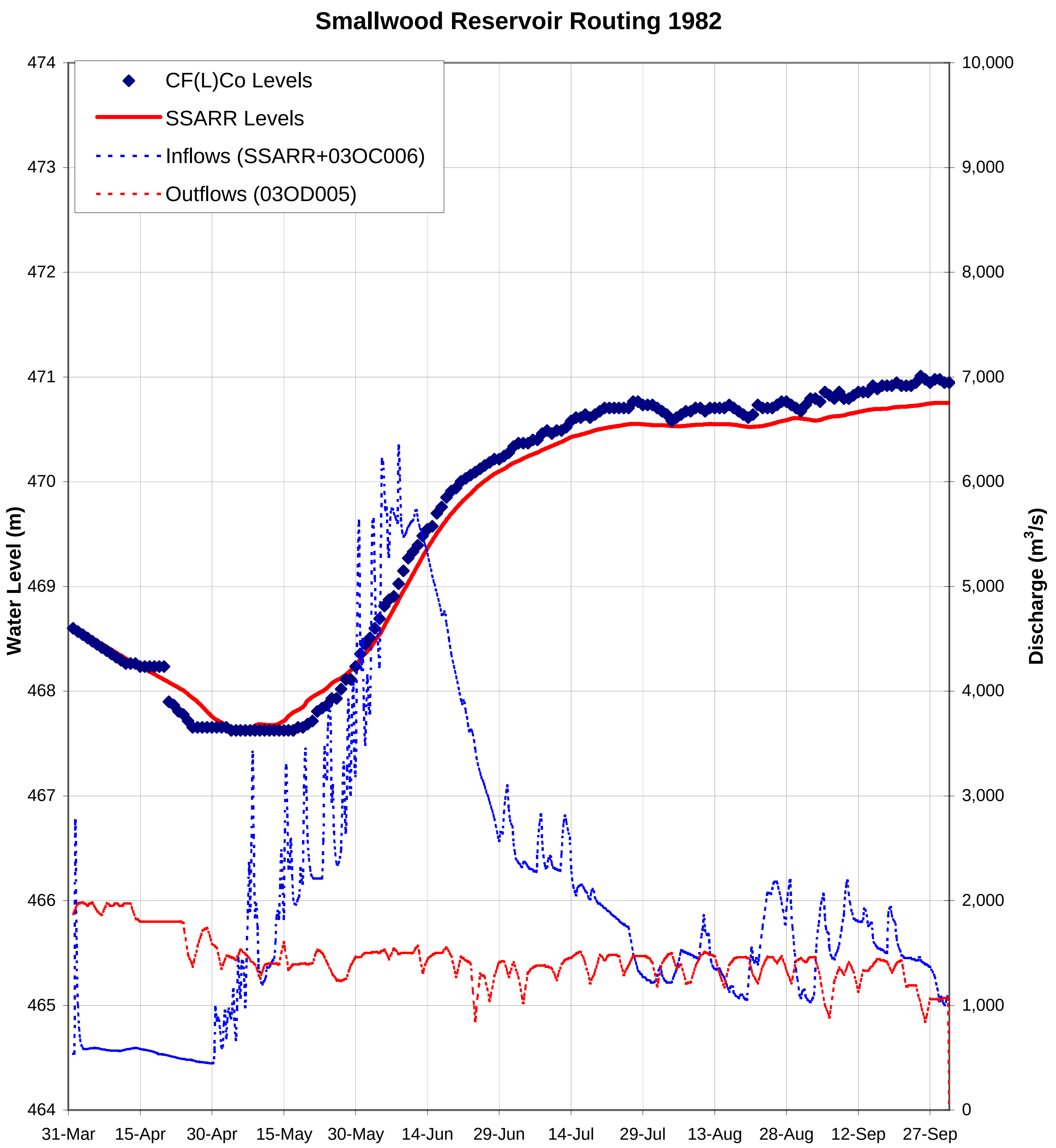


Figure 6.14
Lower Chruchill Project
PMF and Construction Design Flood Study
SMALLWOOD RESERVOIR ROUTING 1982

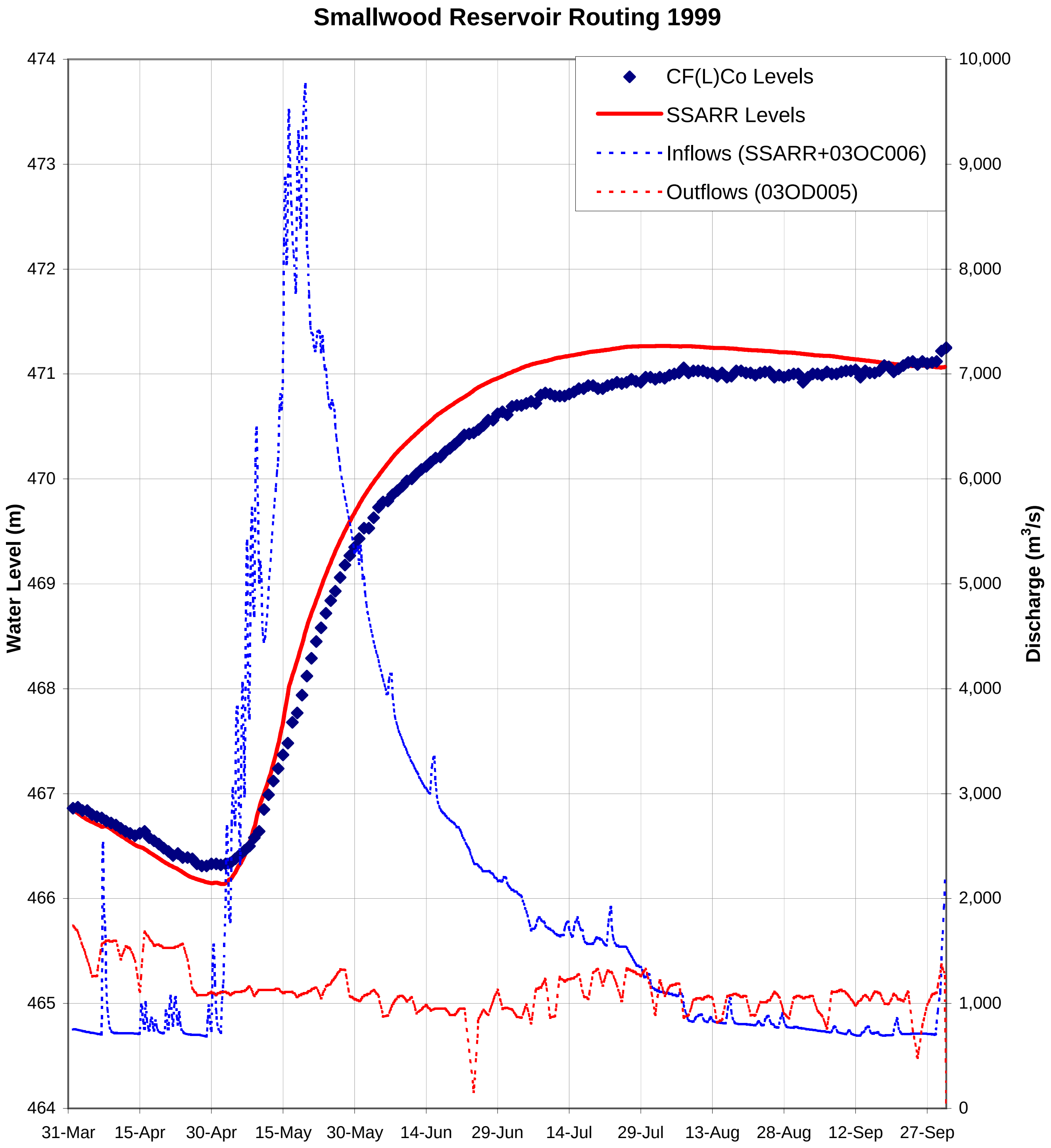


Figure 6.15
Lower Chruchill Project
PMF and Construction Design Flood Study
SMALLWOOD RESERVOIR ROUTING 1999

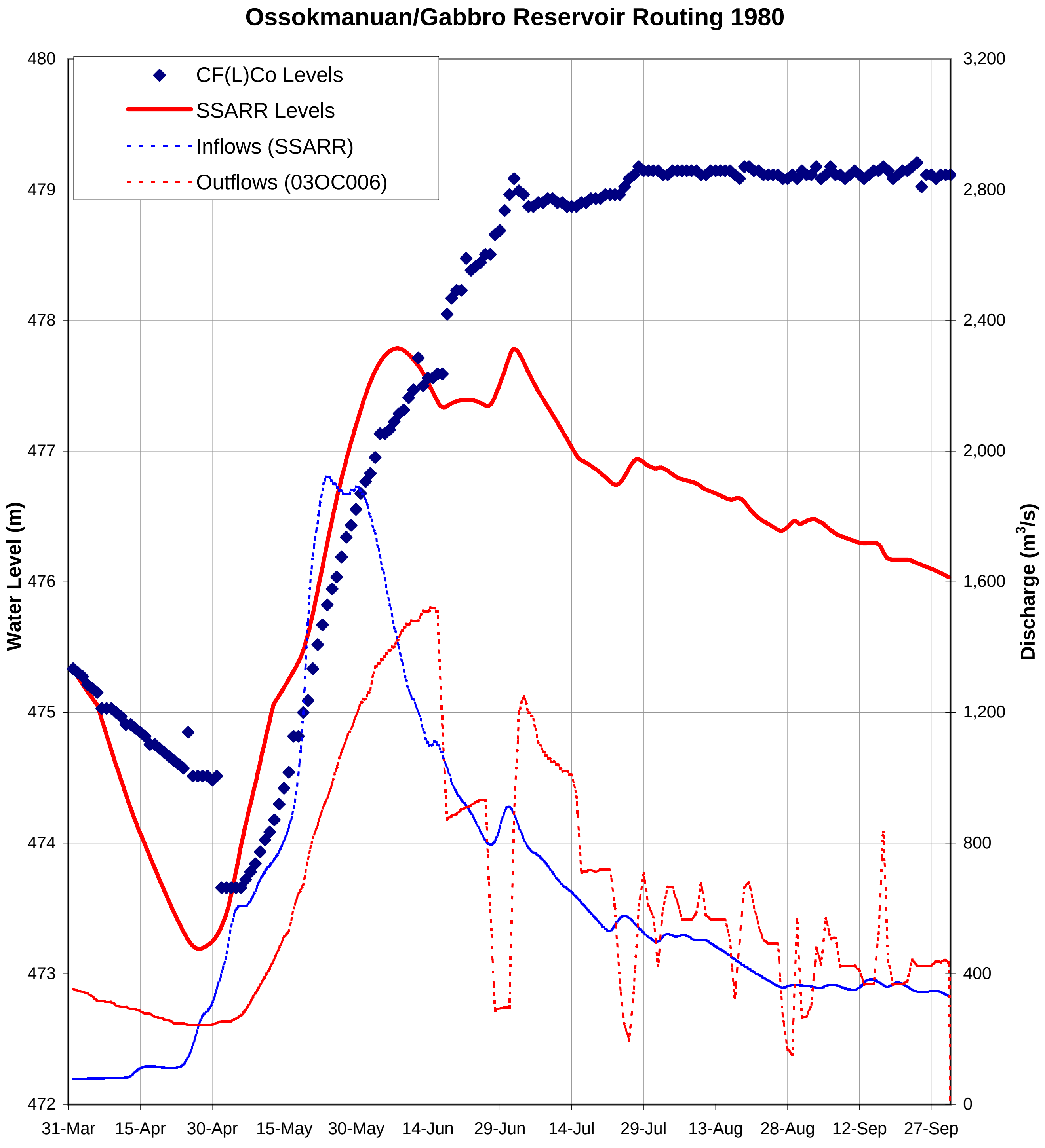


Figure 6.16
Lower Chruchill Project
PMF and Construction Design Flood Study
OSSOKMANUAN/GABBRO RESERVOIR ROUTING 1980

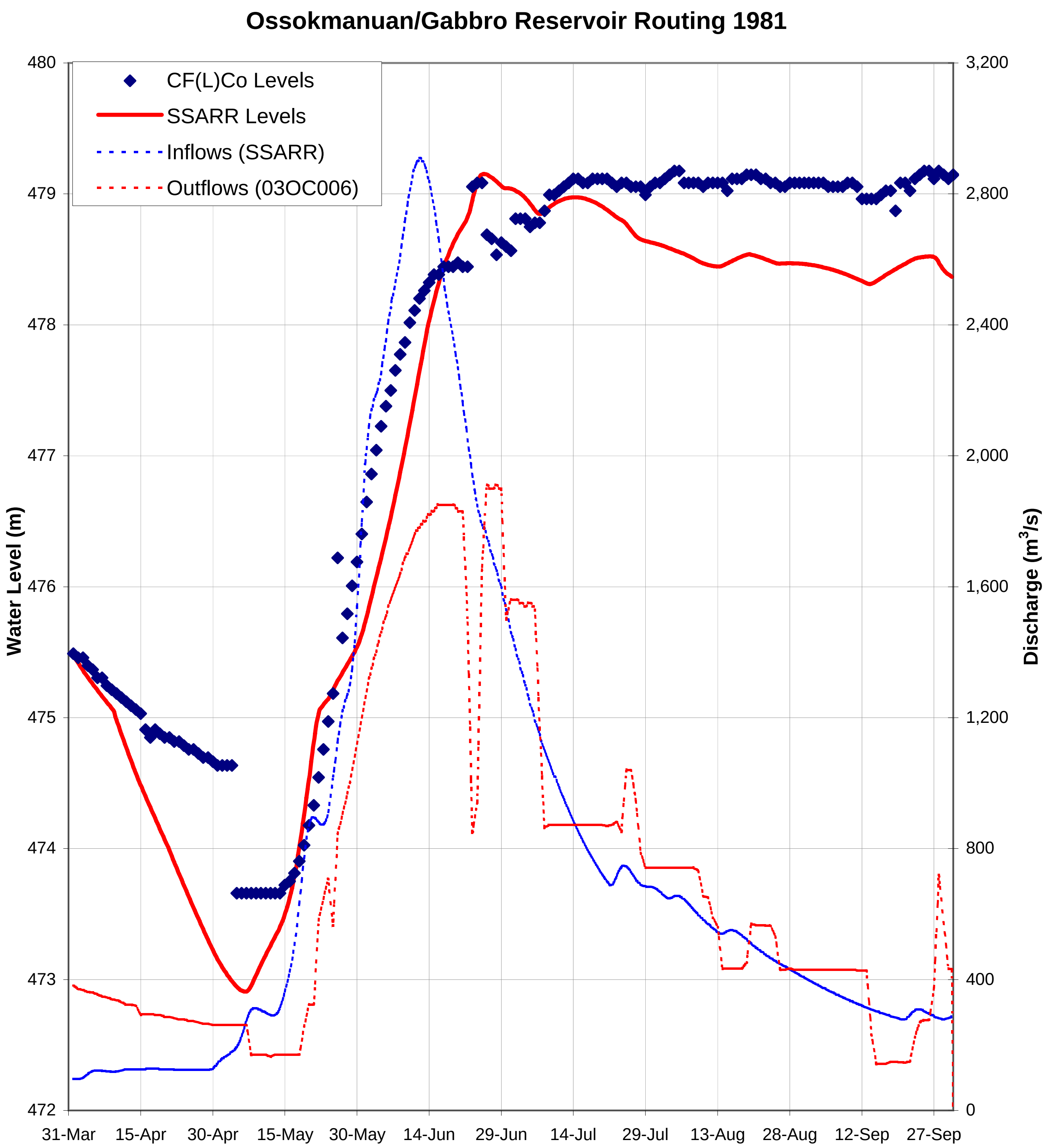


Figure 6.17
Lower Chruchill Project
PMF and Construction Design Flood Study
OSSOKMANUAN/GABBRO RESERVOIR ROUTING 1981

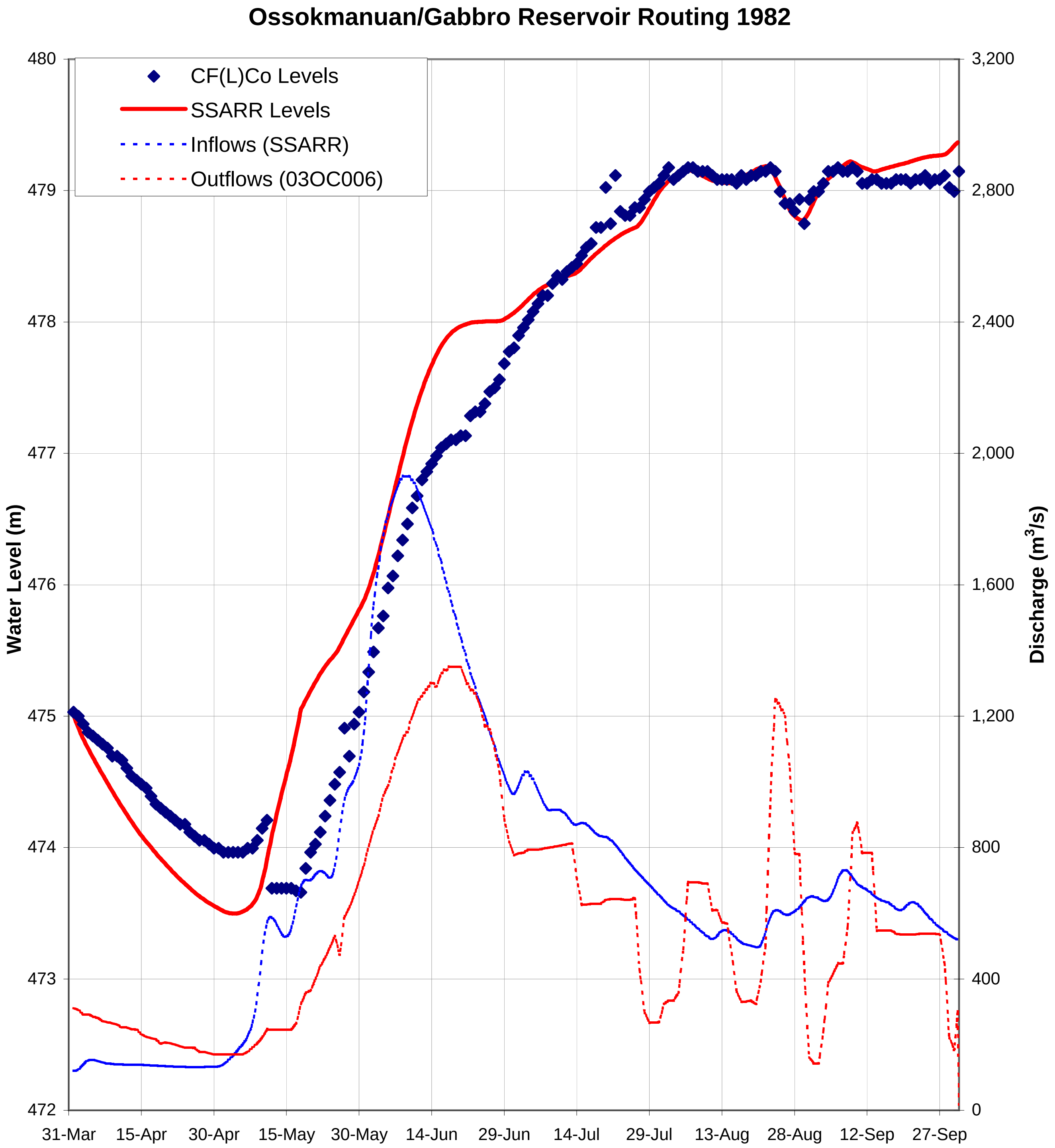


Figure 6.18
Lower Chruchill Project
PMF and Construction Design Flood Study
OSSOKMANUAN/GABBRO RESERVOIR ROUTING 1982

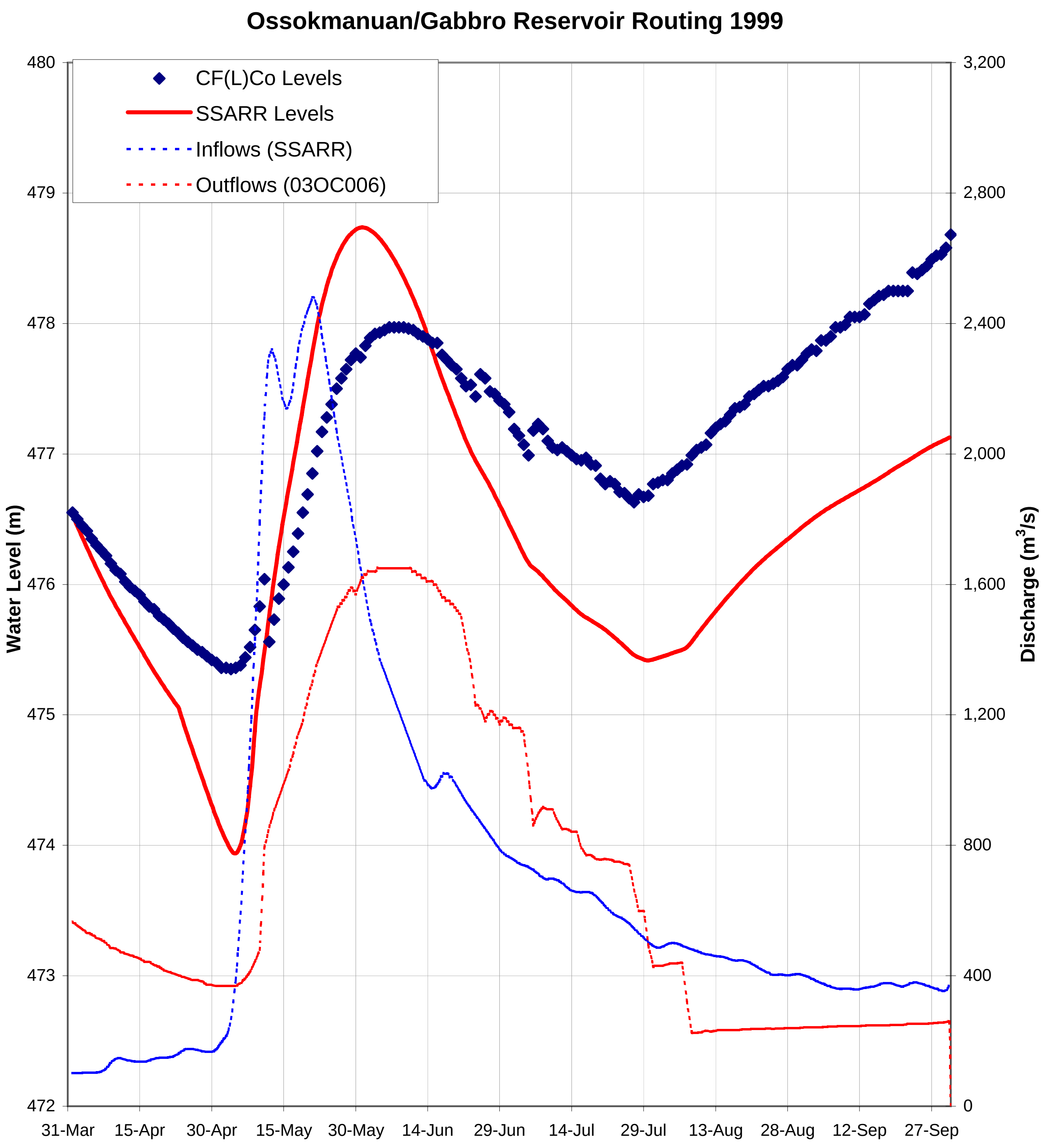


Figure 6.19
Lower Chruchill Project
PMF and Construction Design Flood Study
OSSOKMANUAN/GABBRO RESERVOIR ROUTING 1999

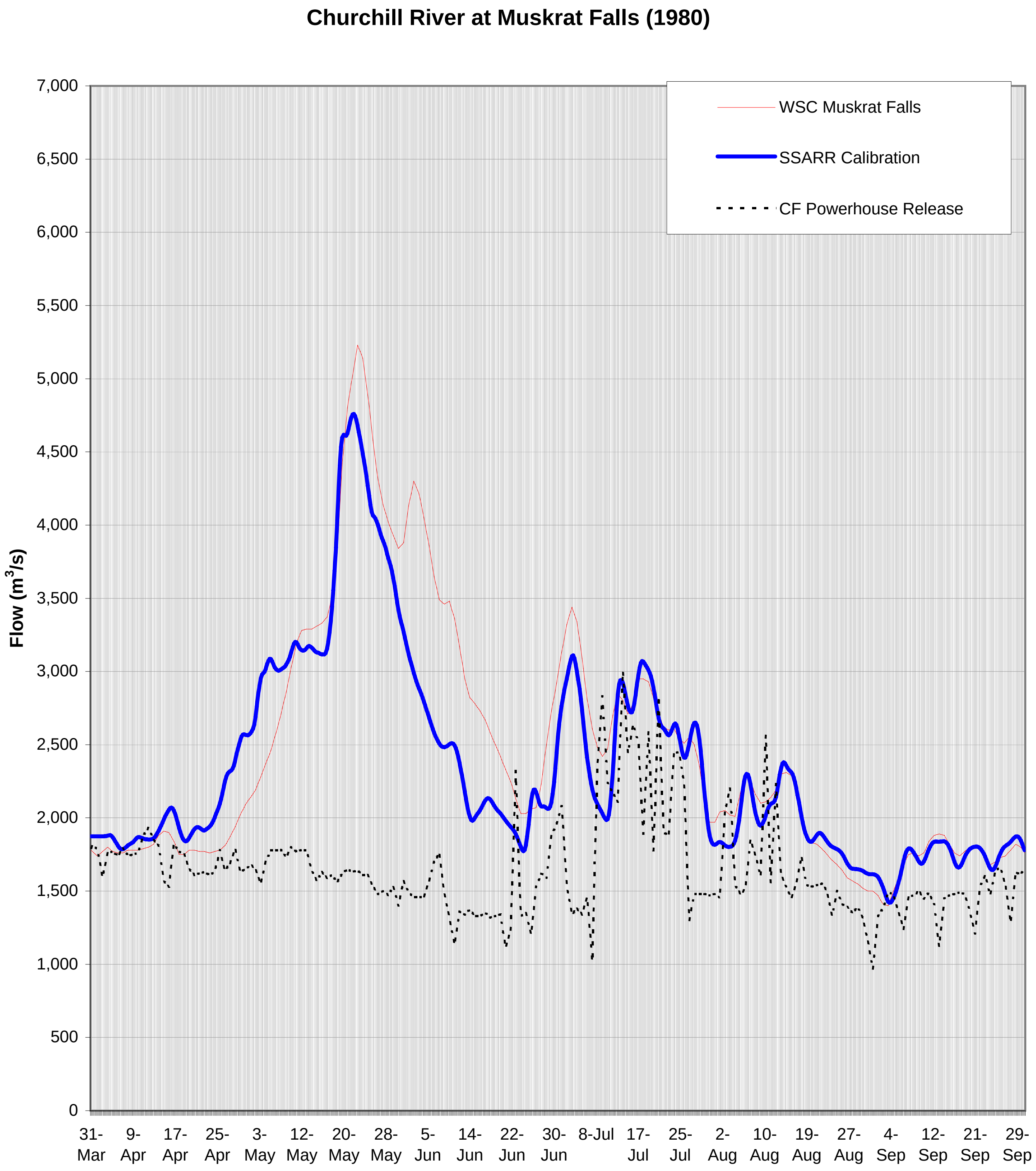


Figure 6.20
Lower Chruchill Project
PMF and Construction Design Flood Study
CHURCHILL RIVER AT MUSKRAT FALLS (1980)

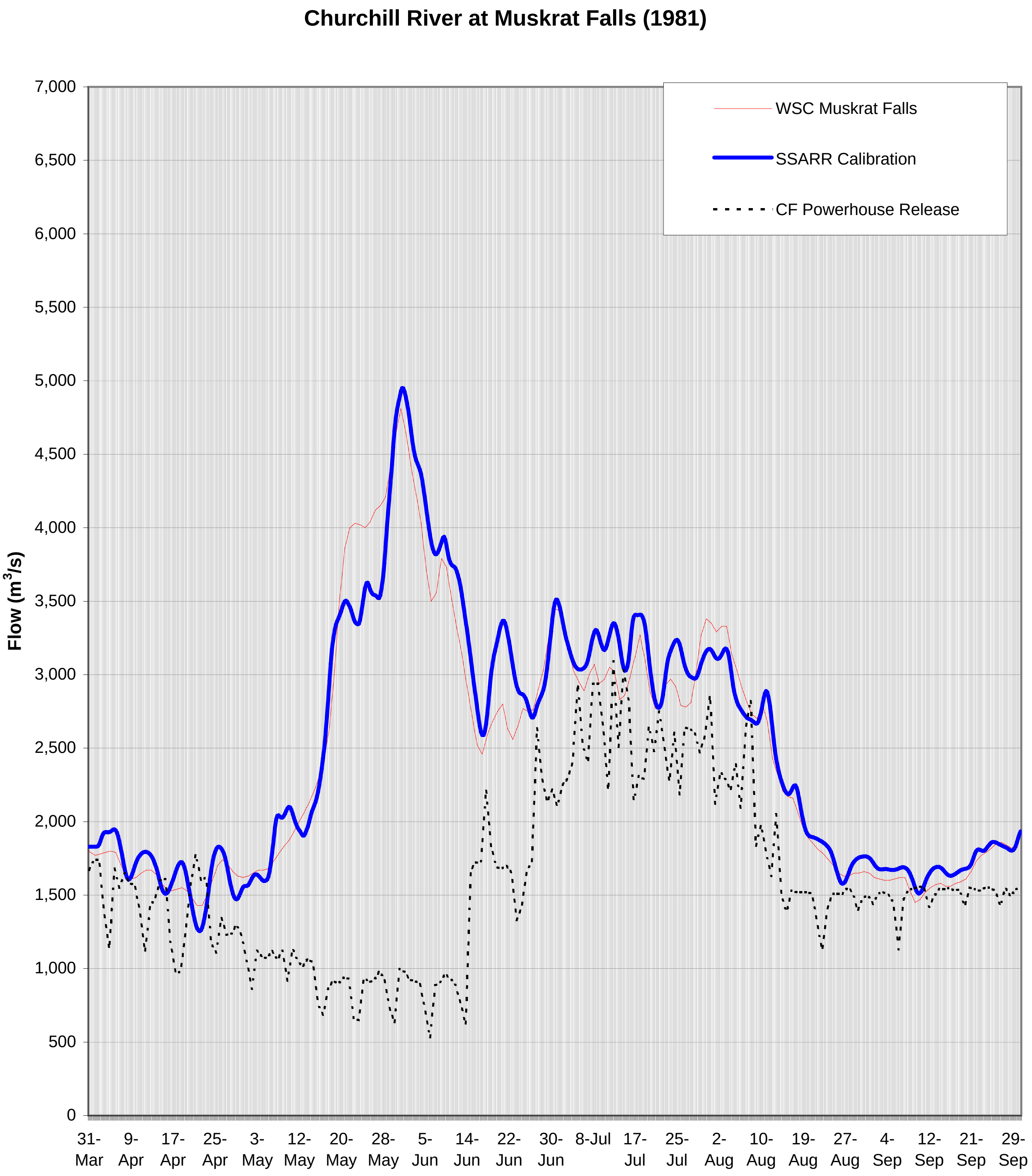


Figure 6.21
Lower Chruchill Project
PMF and Construction Design Flood Study
CHURCHILL RIVER AT MUSKRAT FALLS (1981)

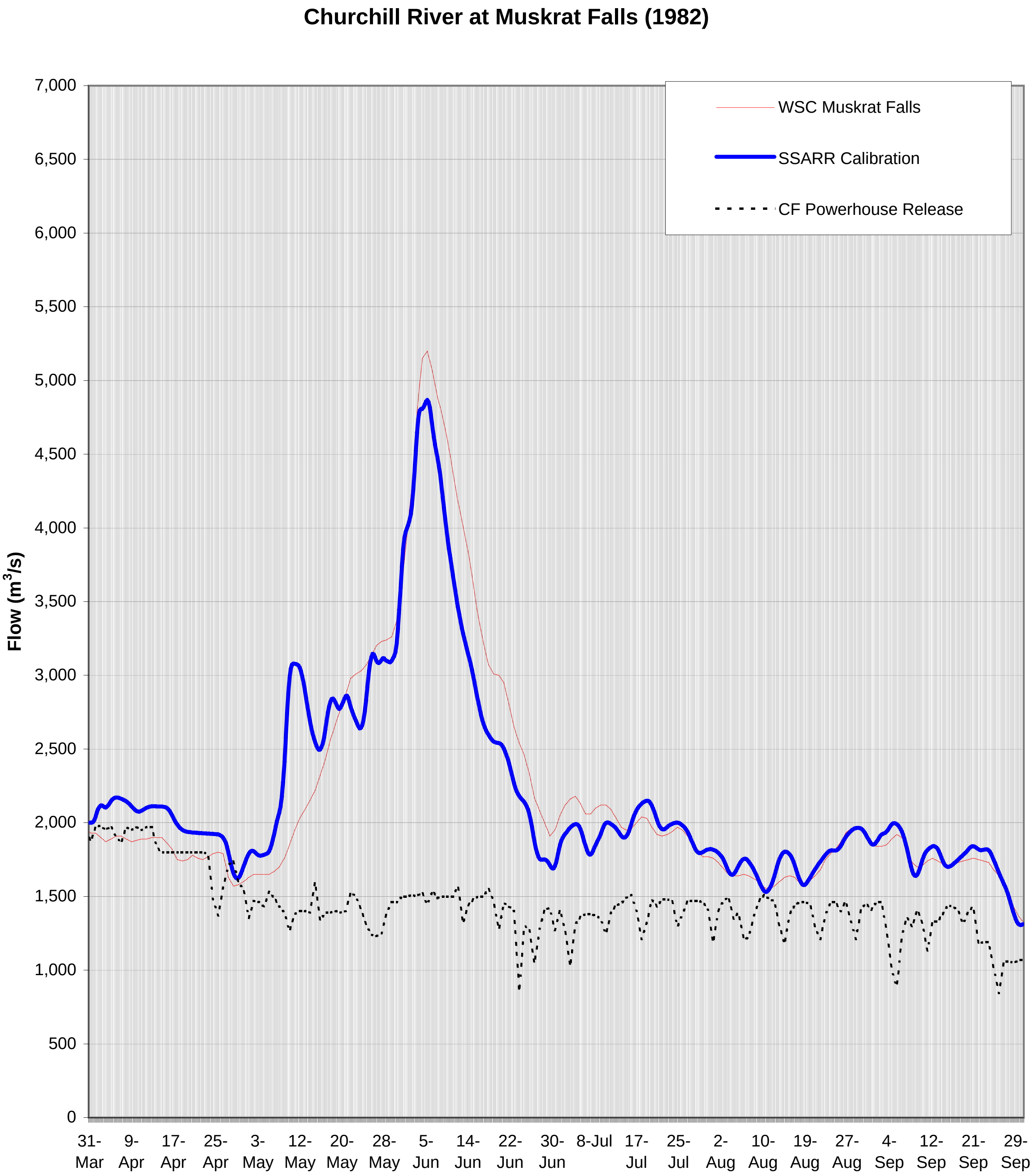


Figure 6.22
Lower Chruchill Project
PMF and Construction Design Flood Study
CHURCHILL RIVER AT MUSKRAT FALLS (1982)

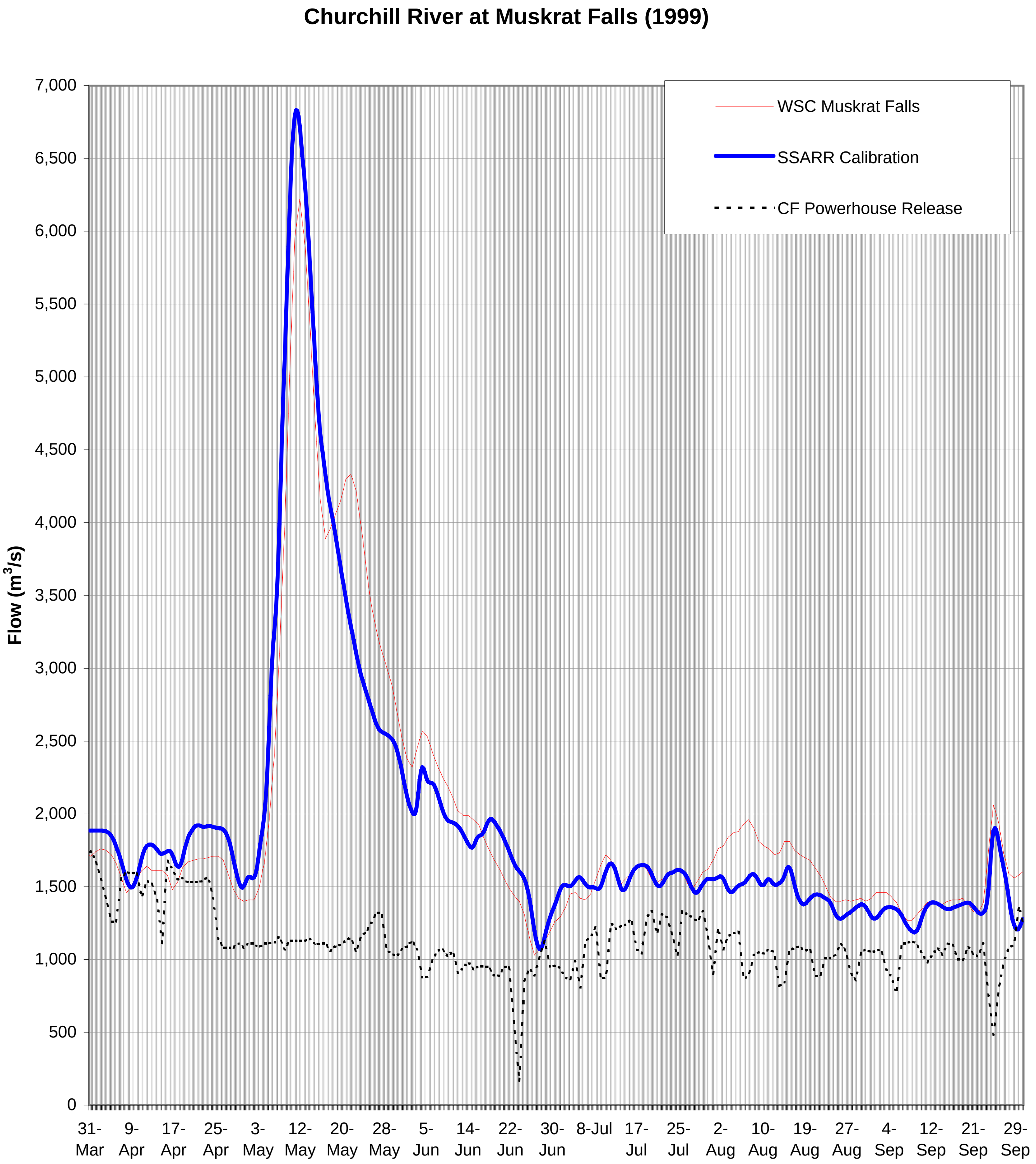


Figure 6.23
Lower Chruchill Project
PMF and Construction Design Flood Study
CHURCHILL RIVER AT MUSKRAT FALLS (1999)

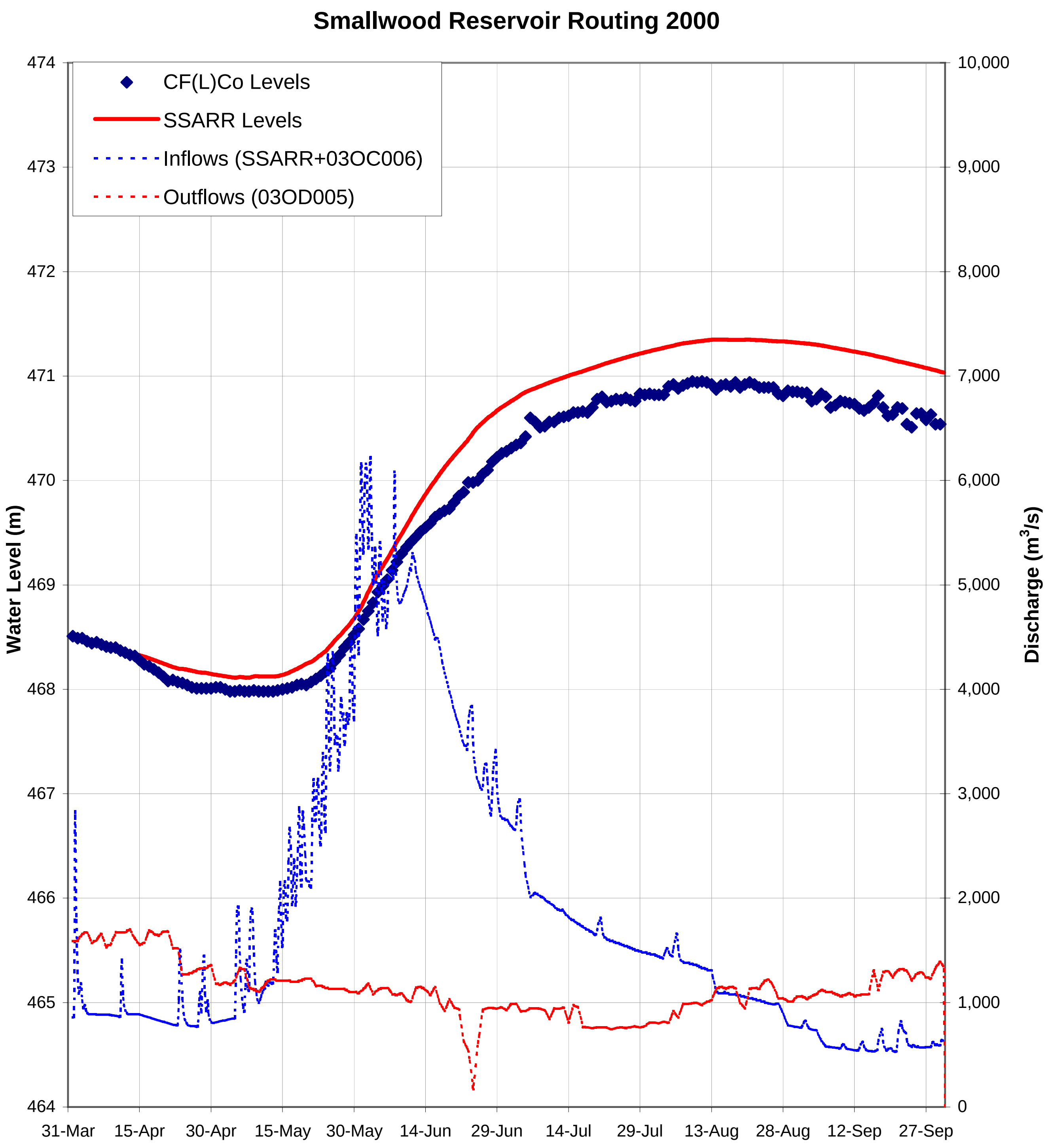


Figure 6.24
Lower Chruchill Project
PMF and Construction Design Flood Study
SMALLWOOD RESERVOIR ROUTING 2000

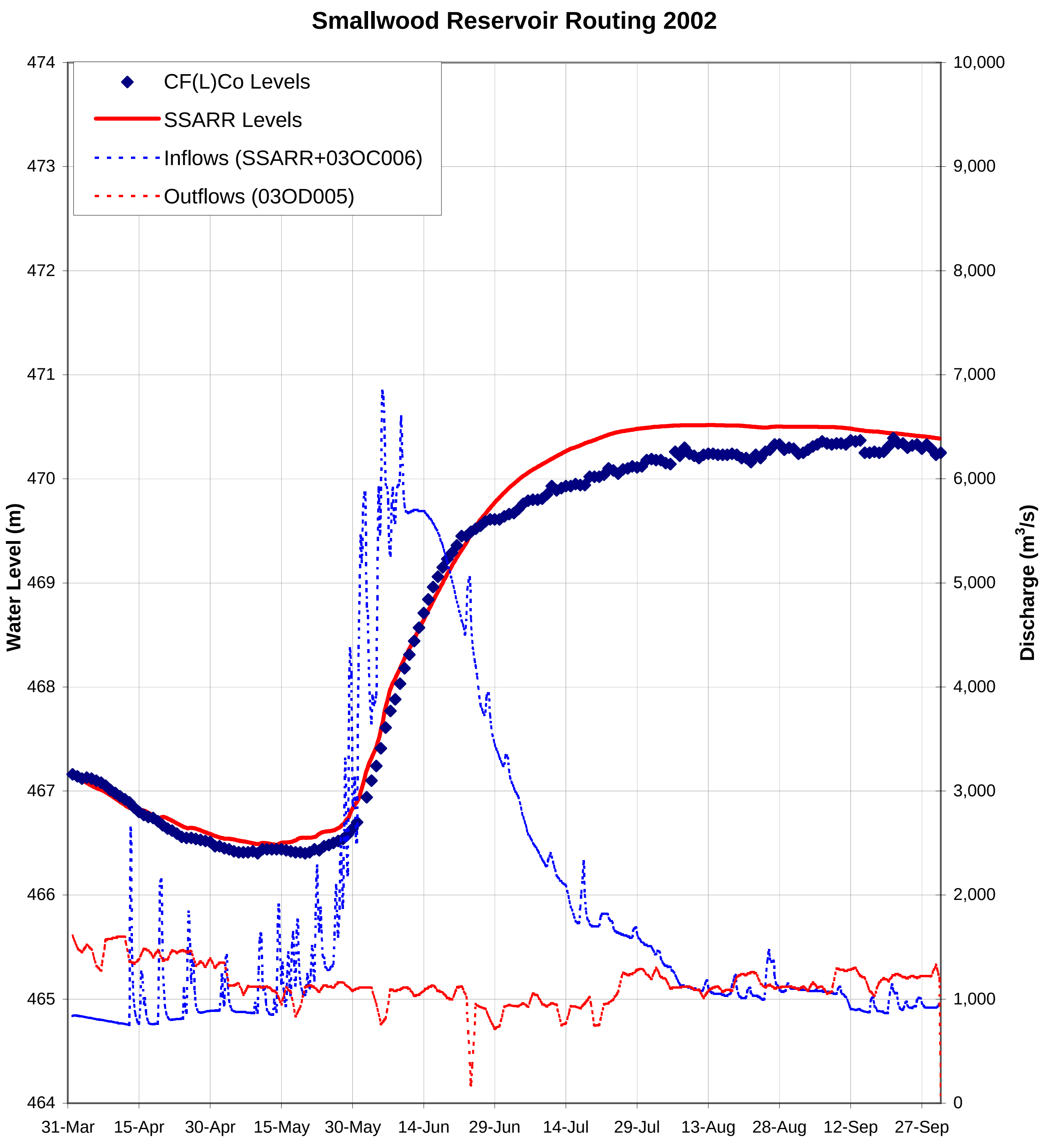


Figure 6.25
Lower Chruchill Project
PMF and Construction Design Flood Study
SMALLWOOD RESERVOIR ROUTING 2002

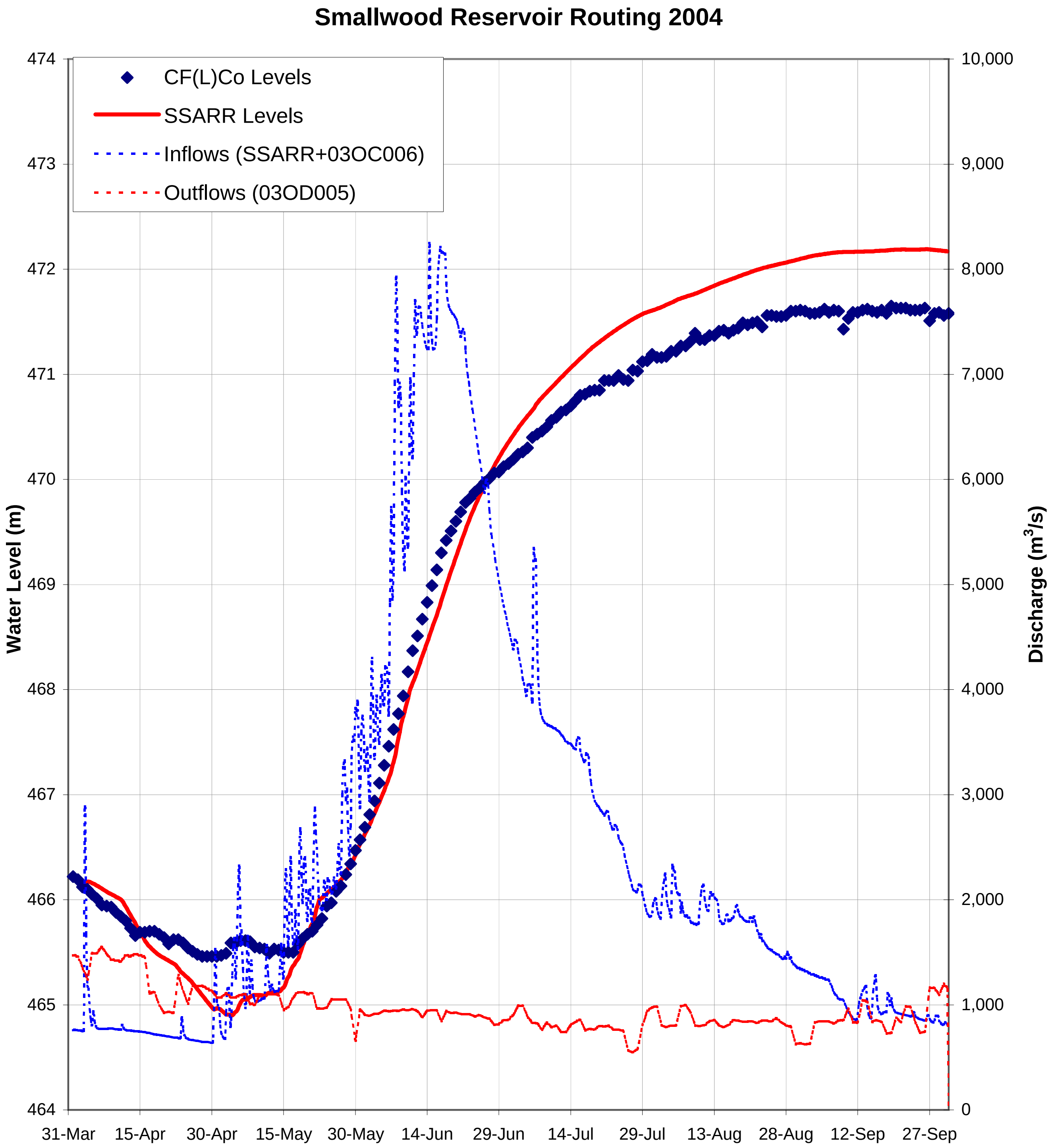


Figure 6.26
Lower Chruchill Project
PMF and Construction Design Flood Study
SMALLWOOD RESERVOIR ROUTING 2004

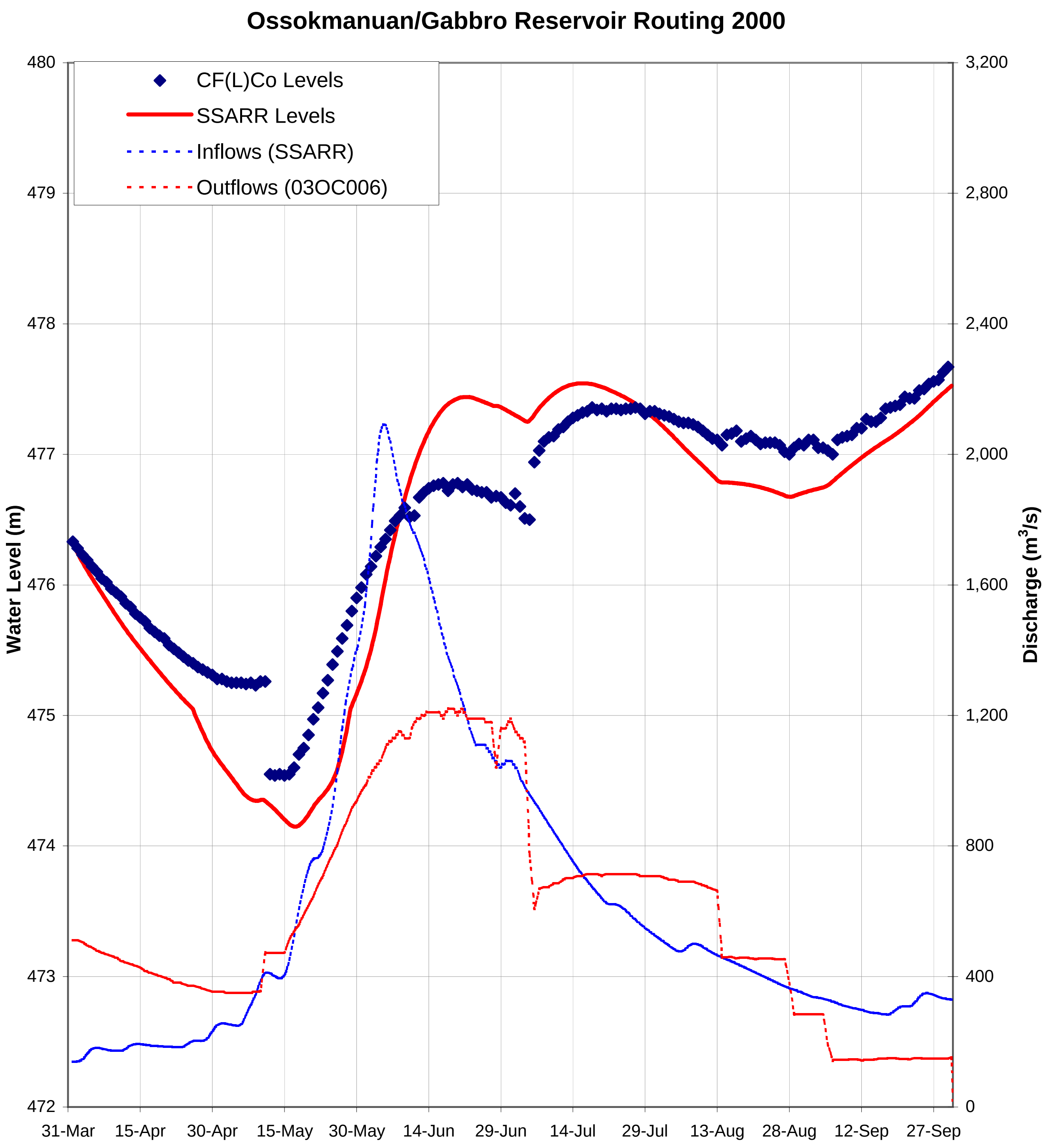


Figure 6.27
Lower Chruchill Project
PMF and Construction Design Flood Study
OSSOKMANUAN/GABBRO RESERVOIR ROUTING 2000

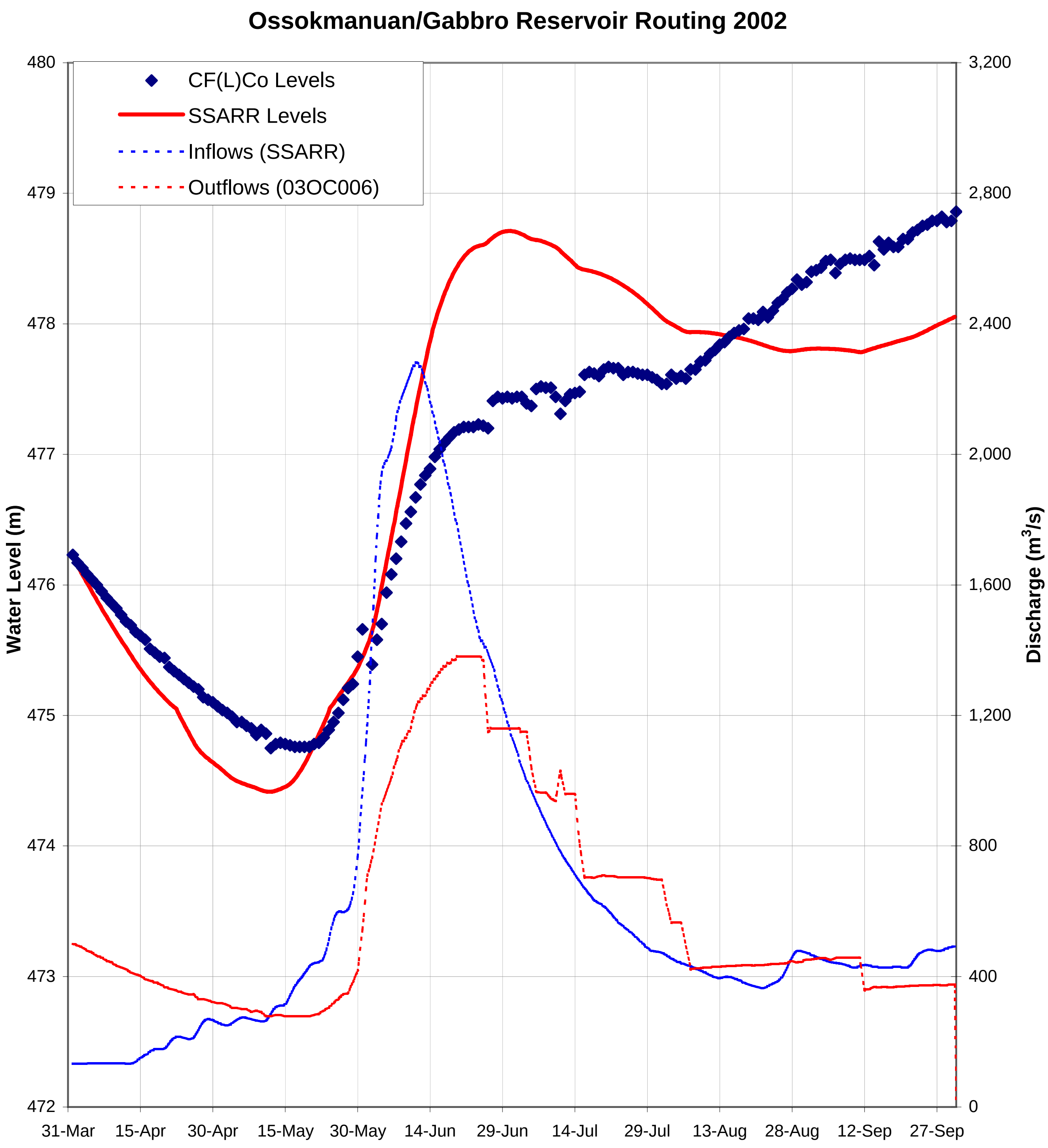


Figure 6.28
Lower Chruchill Project
PMF and Construction Design Flood Study
OSSOKMANUAN/GABBRO RESERVOIR ROUTING 2002

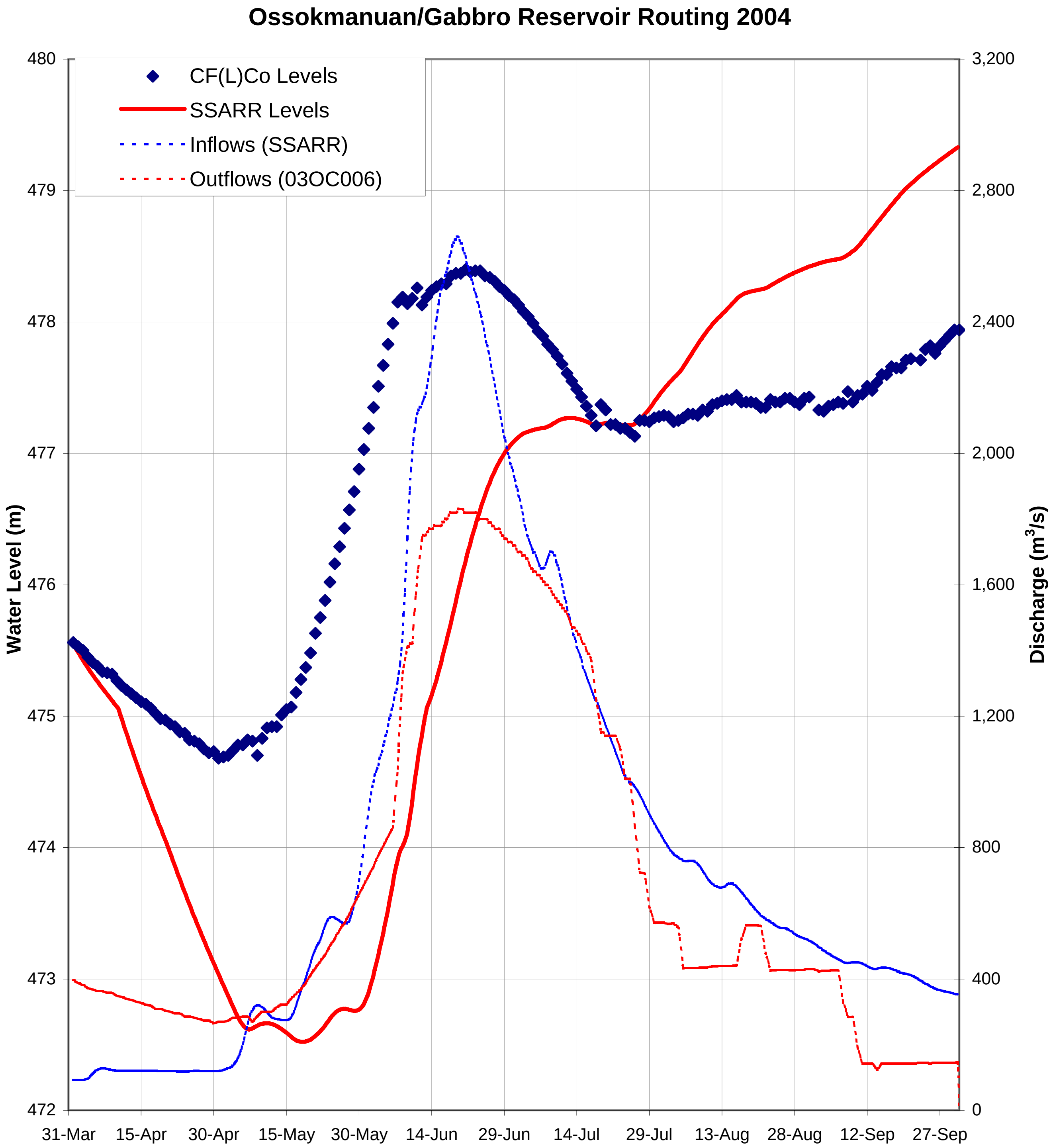


Figure 6.29
Lower Chruchill Project
PMF and Construction Design Flood Study
OSSOKMANUAN/GABBRO RESERVOIR ROUTING 2004

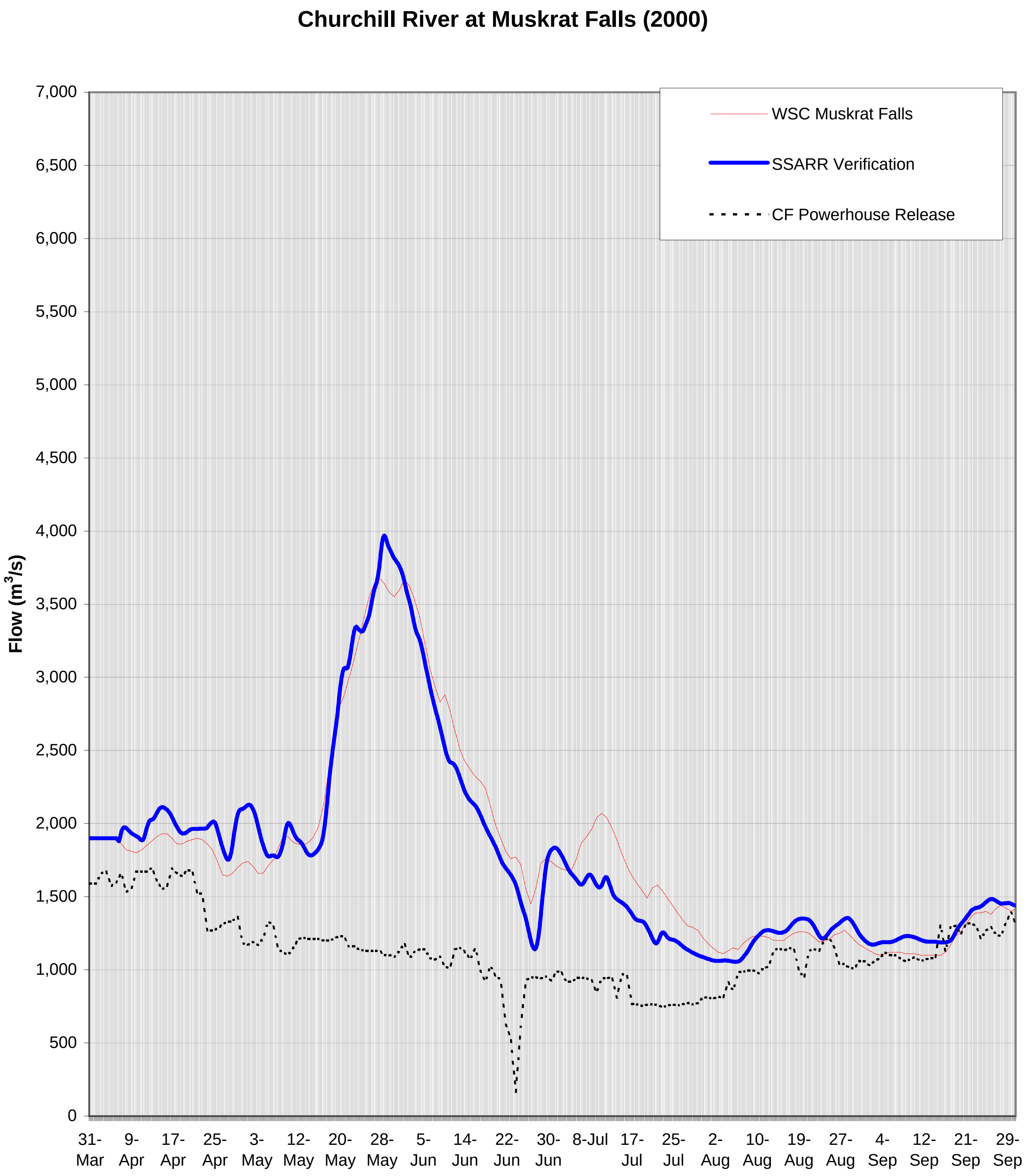


Figure 6.30
Lower Chruchill Project
PMF and Construction Design Flood Study
CHURCHILL RIVER AT MUSKRAT FALLS (2000)

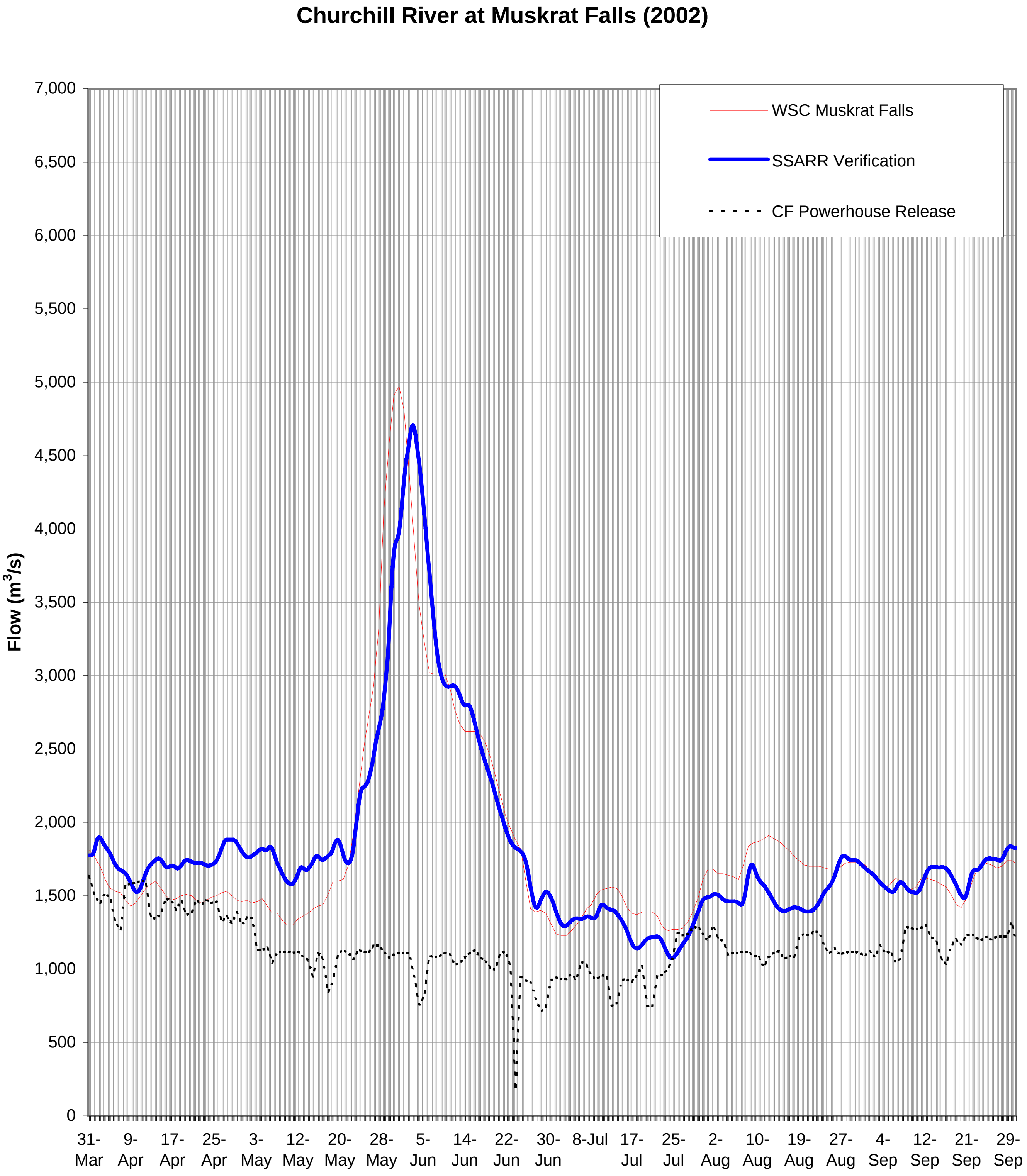


Figure 6.31
Lower Chruchill Project
PMF and Construction Design Flood Study
CHURCHILL RIVER AT MUSKRAT FALLS (2002)

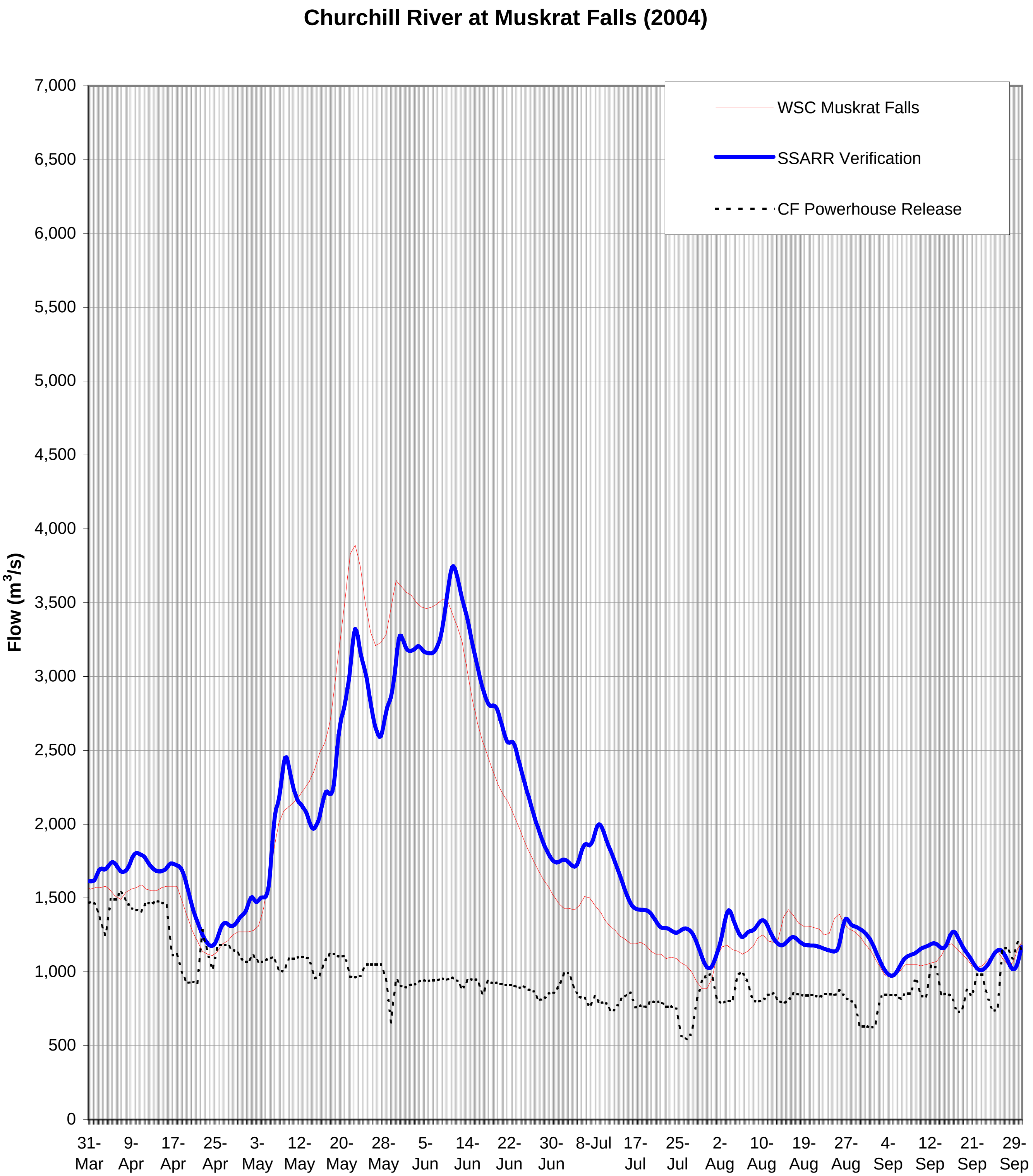


Figure 6.32
Lower Chruchill Project
PMF and Construction Design Flood Study
CHURCHILL RIVER AT MUSKRAT FALLS (2004)

7. PMF Simulations

7.1 General

The calibrated SSARR models described in Section 6 were combined into a single model as shown in SSARR schematic (Figure 6.3) for the PMF simulations. The only changes required from the calibration models relate to the treatment of outflows from Smallwood Reservoir and Ossokmanuan/Gabbro Lake. The operation of the spill facilities at Churchill Falls during extreme flood conditions is governed by guidelines in the1989 Flood Handling Study report. These guidelines require a continuous monitoring of the snowpack and rising water levels to make operating decisions. This process cannot be modelled directly in SSARR. Instead effective discharge ratings were developed that mimic the application of the1989 Flood Handling guidelines during a PMF.

In the calibration models for the Upper Basin outflows from Ossokmanuan/Gabbro Lake to Smallwood Reservoir were represented by the flow records for Gabbro Control Structure (03OC006). There were no spills out of Ossokmanuan/Gabbro Lake during the calibration and verification years. In the SSARR PMF model the Gabbro Control Structure is closed and outflows are modelled through the Ossokmanuan Control Structure and via breaches in the Julian Dykes. These outflows bypass Smallwood Reservoir and flow via the Twin Falls project to the Unknown River and into the Lower Churchill River upstream of Churchill Falls tailrace. The effective elevation-discharge rating curve used to represent Ossokmanuan/Gabbro Lake in the SSARR PMF model is shown in Figure 6.11.

In the calibration model for Smallwood Reservoir inflows from Ossokmanuan/Gabbro Lake were represented by the flow records for Gabbro Control Structure (03OC006) and outflows via the powerhouse were represented by records for Churchill Falls Powerhouse (03OD005). There were no spills out of Smallwood Reservoir during the calibration and verification years. In the SSARR PMF model the Gabbro Control Structure is closed and all inflows to Smallwood Reservoir are from Smallwood Reservoir drainage area. Spills out of Smallwood Reservoir would be regulated by Lobstick Control Structure, flow through Jacopie Spillway and enter the Lower Churchill River upstream of Churchill Falls tailrace. The effective elevation-discharge rating curve used to represent Smallwood Reservoir in the SSARR PMF model is shown in Figure 6.10.

In the calibration model for the Lower Basin outflows from Smallwood Reservoir were represented by records for Churchill Falls Powerhouse (03OD005). In the combined SSARR model these flows and those from Ossokmanuan/Gabbro Lake enter the Lower Churchill River as described above.

The schematic for the SSARR PMF model is shown in Figure 6.3.

Three PMF scenarios were modelled:

- A combination of a 100-year snow accumulation with the spring PMP and a 100-year temperature sequence;
- A combination of the PMSA with a 100-year rainstorm and a 100-year temperature sequence;
- A summer/autumn PMF resulting from a summer/autumn PMP, with no snow on the ground, preceded by a 100-year rainfall.

Each of these PMF scenarios comprises a fixed component, such as the initial snowpack and the temperature sequence, and a flexible component, the storm rainfall. So each of these PMF scenarios was further refined by considering ten different storm rainfall centres and, for each storm centre, the timing of the rain storm was varied to find the maximum flood peaks at the new dam locations.

These simulations have two main purposes:

- to test various meteorological alternatives to determine which gives the highest flow and is therefore the critical 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 Section 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 Section 7.4.

7.2 Meteorological Input

The basic meteorological information is described in Section 5. The remainder of this Section explains how the information was interpreted for use in the SSARR PMF simulations.

7.2.1 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 or the 100-year rainfall. The temporal distribution of the rain storms is given in Table 5.2 in terms of the percentage of total rainfall in each six-hour period. The total rainfall received by each of the 24 sub-basins in the SSARR model depends on the storm centre of the rainfall event.

Ten storm centres were modelled to consider the variation of PMF peaks with storm location. These storm centres are shown in Figure 7.1. The rainfall associated with each storm centre is expressed as a percentage of the 10 km^2 maximum rainfall for each 10 km^2 grid square over Churchill River Basin. Using GIS the average precipitation over each of the 24 sub-basins can then be determined. Table 7.1 shows the spring PMP values for each sub-basin, for the ten storm centres in Figure 7.1.

Figure 7.2 shows the base case distribution of the 6-hourly rainfall increments given in Table 5.2. The start date and time for each storm and storm centre was varied to maximize the PMF peak. Table 7.2 shows the precipitation values used for each 6-hour period in the 22-day simulation of the spring PMP with storm centre 2.

Other temporal distributions which advanced or delayed the peak period of rain in the sequence were considered during the sensitivity simulations.

7.2.2 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 the PMF simulations, the historic temperatures for the duration of the critical meteorological sequence were replaced by the maximized melt temperatures. For most of the sequence, 6-hourly values were estimated from provided maximums and minimums. In 1999 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. This temperature sequence has been retained in the current analysis. The base 6-hourly temperatures for the critical period are shown in Table 7.3. Adjustments to this base temperature sequence over the Churchill River were distributed using a GIS grid and averaged for each sub-basin. Figure 5.5 shows the GIS distribution of these adjustments and Table 7.4 summarises the adjustments for each sub-basin.

The same temperature sequence was used for 100-year snow accumulation with the spring PMP and the PMSA with a 100-year rainstorm PMF scenarios. The actual 1985 temperatures were used for the PMF resulting from a summer/autumn PMP, with no snow on the ground, preceded by a 100-year pre-storm.

7.2.3 Snowpack

May 1st 100-year snow water equivalent estimates for each sub-basin were derived from the snow course frequency analysis as described in Section 5.4. The GIS distribution of 100-year snowpack water equivalent estimates is shown in Figure 5.3. Table 7.5 summarizes these snow water equivalent estimates for each sub-basin. These snowpack values were entered in the SSARR model as initial conditions for the 100-year snow accumulation with the spring PMP PMF scenario. These snowpack estimates lead to a 100-year lower basin average snowpack of 533 mm and an upper basin average snowpack of 536 mm.

The PMSA analysis described in Section 5.4 resulted in the snowfall maximization of 1980-81 snowfalls for the PMSA. Figure 5.7 shows the station values of PMSA mapped to the basin and interpolated to the 10 km^2 grid covering the basin area. Table 7.6 summarizes these PMSA snow water equivalent estimates for each sub-basin. These PMSA snowpack values were entered in the SSARR model as initial conditions for the PMSA with the 100-year rainstorm PMF scenario. These snowpack estimates lead to a PMSA lower basin average of 618 mm and an upper basin average PMSA of 624 mm.

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 66 hour 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; and
- the starting water level in Smallwood Reservoir, Ossokmanuan/Gabbro Lake and the natural lakes.

The SSARR PMF model is a pre-project model calibrated for the existing basin conditions. The model includes natural river routing of the tributary hydrographs down the Lower Churchill River, but it does not include Gull Island Dam or Muskrat Dam. The routing effects of these dams were later modelled dynamically, using the inflow hydrographs generated by SSARR, as the final step in the spillway design analysis. In the SSARR PMF model the magnitude of the flood peak at Muskrat Falls, the downstream node of the model, was used as the measure of the critical PMF.

The dynamic hydraulic model was subsequently run with the hydrographs from a number of storm centres to confirm the critical PMF at each dam.

7.3.1 100-year Snowpack and Spring PMP

The 100-year snowpack and spring PMP has proved to be the critical PMF scenario in previous PMF studies for the Churchill River Basin. Consequently, this PMF scenario received the greatest attention in the current study in terms of the number of storm centres and PMP start time/date options modeled.

The starting snowpack, temperature sequence, soil moisture index, flow rates and starting water levels were common to all SSARR runs for this PMF scenario. The soil moisture index and sub-basin flow rates on May 1st were estimated from a review of the calibration simulations, which started on April 1st and had stabilized by May 1st. Starting water levels in the natural lakes included in the model were defined by SSARR to agree with the flow rate specified for the sub-basin draining to the lake.

Water levels for Smallwood Reservoir and Ossokmanuan/Gabbro Lake were taken from the operating rule curves from the 1989 Flood Handling Study assuming the potential PMF starting levels, i.e.

- 469.68 m in Smallwood Reservoir
- 475.03 m in Ossokmanuan/Gabbro Lake.

For each PMP storm centre the timing of the PMP rainfall was advanced or delayed until the maximum flood peak was achieved at Muskrat Falls.

Table 7.7 shows the critical start time/date for each PMP storm centre, the peak outflows from Smallwood Reservoir and Ossokmanuan/Gabbro Lake and the PMF peak at Muskrat Falls. Figure 7.3 shows the critical PMF flood hydrographs for storm centre 2.

7.3.2 PMSA and 100-year Spring Rainfall

The PMSA and 100-year spring rainfall PMF scenario used the same initial conditions and approach as the 100-year snowpack and spring PMP scenario, except that the PMSA snow water equivalents replaced the 100-year values and the 100-year spring rainfall replaced the spring PMP.

Table 7.8 shows the critical start time/date for each PMP storm centre, the peak outflows from Smallwood Reservoir and Ossokmanuan/Gabbro Lake and the PMF peak at Muskrat Falls. Figure 7.4 shows the critical PMF flood hydrographs for storm centre 3.

7.3.3 Summer/Autumn PMP Preceded by 100-year Rainfall

The summer/autumn PMF scenario resulting from a summer/autumn PMP, with no snow on the ground, preceded by a 100-year pre-storm is probably the least accurate of the PMF models. Although the SSARR model calibrations included the summer/autumn seasons there are no examples of major flood events for these seasons among the available data sets. Similarly, as noted in Section 5.2, there are no summer/autumn rain storms greater than the maximum spring rain storms in the vicinity of the project and the all-season PMP was pro-rated from the spring PMP by the precipitable water in each season.

The summer/autumn PMF simulations started on August 1st, with Smallwood Reservoir and Ossokmanuan/Gabbro Lake water levels conservatively set at full supply level, the upper limit of the operating rule curve, i.e.

- 472.74 m in Smallwood Reservoir
- 479.15 m in Ossokmanuan/Gabbro Lake.

The soil moisture index and sub-basin flow rates on August 1st were estimated from a review of the calibration simulations, which started on April 1st and ran till September 30th each year. The 100-year all-season rainfall was followed four days later by the all-season PMP. No other rainfall was included during this period.

Table 7.9 shows the critical start time/date for each PMP storm centre, the peak outflows from Smallwood Reservoir and Ossokmanuan/Gabbro Lake and the PMF peak at Muskrat Falls. Figure 7.5 shows the critical PMF flood hydrographs for storm centre 4.

7.4 Results Summary

A review of the Muskrat Falls flood peak results in Tables 7.7 to 7.9, summarized below, confirms that the critical PMF scenario for the Lower Churchill River is the 100-year snowpack and a spring PMP, i.e.

- Summer PMP preceded by 100-year storm - Peak at Muskrat Falls 10,800 m^3/s
- PMSA plus 100-year spring rainfall - Peak at Muskrat Falls 14,600 m^3/s
- 100-year snowpack plus spring PMP - Peak at Muskrat Falls 22,800 m^3/s

At Muskrat Falls the critical pre-project PMF results from PMP storm centre 1, 35 km upstream of Gull Island. At Gull Island the critical pre-project PMF results from PMP storm centre 2, near the Shoal River confluence, 70 km west of the site.

Figure 7.3 shows that the critical PMF peak would result from snowmelt and PMP runoff from the unregulated sub-basins of the Lower Churchill River Basin. Flood peak contributions from the natural lake regulated sub-basins of the Lower Churchill River Basin and Smallwood Reservoir and Ossokmanuan/Gabbro Lake outflows would not arrive until 5 to 7 days after this initial runoff peak.

The inflow “spike” to Smallwood Reservoir shown in Figure 7.3 is the result of snowmelt and PMP rainfall on the surface of Smallwood Reservoir and does not contribute to the initial PMF peak at Muskrat Falls.

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 made using the critical pre-project PMF results from PMP storm centre 1. At Gull Island the critical pre-project PMF results from PMP storm centre 2, but the conclusions drawn from one case would apply to both.

The lower Minipi River sub-basin below Minipi Lake was chosen to illustrate the results of the sensitivity analysis. This sub-basin is typical of the unattenuated sub-basins in the Lower Churchill Basin. The historical year 1981 was chosen as the calibration year for comparison for continuity with the 1999 study. Table 7.10 summarizes the maximum and minimum values for Snow band 4 (the elevation band with the highest proportion of the basin area) and Table 7.11 shows the basin averages. Several points should be noted:

1. The PMF simulation has a much higher maximum 6-hour value of precipitation and therefore much higher rainfall 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 and the antecedent temperature indices in the two runs are not significantly different; however the antecedent temperature index for the PMF is reached in two weeks, compared to one month 1981. This results from the sustained warm temperatures in the warm front just before the PMP and results in more rapid melting of the snowpack.
3. The PMF simulation has a much higher maximum melt rate. Melt rate is a function of the antecedent temperature index, but is also increased by the intensity of rainfall. 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. It also confirms the timing of the PMP towards the end of the melt sequence.
4. The snow melts much more quickly in the PMF simulation than in 1981, but starts much later due to the assumption of a maximum snowpack on May 1st and a 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. Both 1981 and the PMF simulations reach the limit of subsurface runoff. Again, it is high intensity rainfall 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.
8. The greatest difference between 1981 and the PMF is the maximum 6 hour moisture input and runoff generated, which are five times higher during the PMF than in 1981. This is a result of the rainfall intensity at the peak of the PMP and the accelerated melt rate this generates in the ripe snow pack.

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; and

- 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 or the exact timing of the start of the PMP.

The sensitivity of other parameters 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.

It should be noted that no changes were made to the timing of the PMP in the sensitivity analyses. This means that, while the base case PMF peak is optimal (i.e. the highest possible), the peaks for the sensitivity runs may be sub-optimal, due to the non-coincidence of snowmelt and rainfall peaks.

Table 7.12 shows the sensitivity to the external parameters, i.e., the meteorological input. The impacts of changes in meteorological inputs to the PMF were examined at Muskrat Falls, the downstream node in the SSARR model. Some comments follow:

1. The peak of the PMF varies non-linearly to a change in snowpack. However, this probably has more to do with the non-coincidence of snowmelt and rainfall peaks, noted above, than the absolute water equivalent of the snowpack. In reality the maximum PMF peak would vary by approximately 1%/cm of snowpack, the same as the PMF volume.
2. The peak of the PMF is not particularly sensitive to the maximum temperatures used on individual days of the sequence.
3. The initial soil moisture condition shows a small linear effect on both the PMF peak and volume. This is an indication of the initial losses that must be satisfied before saturated runoff can occur.
4. The PMF is sensitive to the PMP, as expected, with a 10% change in PMP resulting in a 5% change in PMF peak.
5. Averaging the PMP to a uniform intensity over 66 hours demonstrates the significance of the higher rainfall intensity during the peak hours of the PMP. The uniform PMP results in a PMF peak that is 11% lower, though the runoff volume remains the same.

To summarize, the water equivalent of the snowpack and the depth and intensity of the PMP are the principal factors determining the peak of the PMF.

Table 7.13 presents the results of the sensitivity analysis to internal parameters, i.e., the value of the SSARR parameters. The lower Minipi River sub-basin was selected from the 24 sub-basins in the SSARR PMF model for this comparison. This table includes the sensitivity of the 1981 calibration years to the same changes. Some comments follow:

1. The maximum melt rate and, to a lesser extent, the cold rate have a significant impact on the simulated 1981 flood peak, but not on the PMF peak. This is because the 1981 flood peak is due almost completely to snowmelt, and is thus very sensitive to the maximum melt rate used, whereas

the PMF peak is due to a combination of PMP rainfall and snowmelt, which occurs at a higher rate due to the PMP, irrespective of the basic melt rate.

2. Both the PMF and the calibration year are sensitive to the runoff response to soil moisture and the limit placed on the subsurface runoff intensity. This is because 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 calibration year peak is sensitive to both the number and storage time of the surface and subsurface routing phases, with the subsurface phase being more sensitive. This is because, during most floods, the surface and subsurface phases both contribute significantly to peak. The PMF peak is also sensitive to the number of surface routing phases and the routing time assigned to each phase, but not to the subsurface phases. This occurs because, at the peak of the PMF, runoff to the subsurface phase has reached the limit, the subsurface hydrograph has plateaued and all excess runoff occurs as surface flow, which has no upper limit.

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% lower than the 1999 estimate of 21,700 m^3/s and 22% less than present pre-project estimate of 20,900 m^3/s, as shown in Figure 7.6. The difference between the 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 2,900 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 spill from Jacopie Spillway and Ossokmanuan Control Structure contributing to the Lower Churchill Basin PMF peak is $\pm$5,000 m^3/s.

The 1999 study used a similar approach to the current study except that the Lower Churchill Basin was modelled as a single basin terminating between Gull Island and Muskrat Falls and the PMF peaks at each location were pro-rated according to drainage area. Contributions from the Upper Churchill Basin of 5,000 m^3/s were added to the lower basin peaks to give Gull Island and Muskrat Falls PMF peaks of 21,700 m^3/s and 24,400 m^3/s. These values are 4% and 7%, respectively, higher than the current study estimates.

The changes in the in the PMF peaks are due primarily to:

1. The use of a distributed storm pattern that results in a slightly lower areal PMP over the lower basin.
2. Modelling the entire Churchill River Basin to automatically simulate the contributions from the upper basin for different storm centres.

3. The inclusion of natural lake regulation to recognize the attenuating influence lakes have on the floods in the Churchill River.
4. The introduction of river routing reaches in the SSARR model to capture the attenuating effects of Lake Winokapau and Gull Lake on flows in the Lower Churchill River.

7.7 Comparison with Historic Events

To put the Lower Churchill PMF estimates in context, the values were 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 4,000 m^3/s and 25,000 m^3/s. The estimated local Lower Churchill PMF of approximately 16,000 m^3/s is within the range of these values.

The historic maximum inflow to the lower basin based on the calculated 28 year period of record since full operation commenced 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 flood frequency analysis of local inflows to the Lower Churchill River at Muskrat Falls predicted extreme floods of:

- 100-year = 5,200 m^3/s
- 10,000-year = 6,730 m^3/s

Ratios of 3.4 between the PMF and the 100-year event and 2.6 between the PMF and the 10,000-year event are reasonable.

Table 7.1
Spring PMP Variation with Storm Centre

Sub-Basin No.	Sub-Basin Name	Area (km2)	Total Storm Depth over Sub-Basin (mm)									
			Centre 1	Centre 2	Centre 3	Centre 4	Centre 5	Centre 6	Centre 7	Centre 8	Centre 9	Centre 10
1	Lower Pinus	1799	213	165	141	118	91	114	77	87	96	248
2	Upper Pinus	759	254	195	167	130	105	126	88	93	109	242
3	Lower Minipi	2768	228	207	159	124	88	126	86	101	101	253
4 + 5	Upper Minipi	2771	155	148	131	106	74	112	74	92	88	187
6 + 7	Upper Cache	1377	231	250	212	142	101	146	100	114	118	204
8	Lower Cache	1881	252	265	244	152	106	154	103	115	123	170
9	Upper Metchin	2651	183	192	213	171	127	147	101	104	132	186
10	Lower Metchin	1330	167	201	251	241	130	202	118	122	152	192
11	Lower Fig	2508	158	203	229	204	113	244	125	144	142	146
12	Upper Fig	2711	140	163	181	183	109	229	131	164	147	139
13	Upper Unknown	1815	121	132	147	196	117	229	152	200	185	133
14	Lower Unknown	928	136	153	186	265	137	247	143	138	224	126
15	Smallwood South	5209	131	139	156	203	162	157	120	111	188	109
16	Smallwood Surface	6285	115	118	128	153	205	128	115	99	173	118
17	Smallwood North	9346	94	97	105	120	206	104	104	84	141	118
18	Ashuanipi Mouth	6714	78	82	90	109	162	101	116	86	135	103
19	Ashuanipi 03OA001	7296	79	88	98	117	121	117	196	131	140	83
20	McPhayden 03OA003	3609	72	80	90	110	124	107	148	108	132	68
21	Ashuanipi 03OA004	8309	70	78	83	93	69	104	135	140	97	70
22	Atikonak 03OC003	4458	101	111	116	117	80	139	125	190	111	69
23	Kepimits 03OC004	6968	86	98	104	110	80	125	147	201	110	73
24	Atikonak 03OC005	4023	66	73	73	73	35	86	89	113	68	94
25	Gabbro Lake	5547	101	112	123	153	135	153	226	157	208	81
26	Ossokmanuan Lake	1436	114	126	138	161	116	205	180	246	164	64
Basin Average	Upper Basin	69200	91	98	106	124	130	121	139	130	138	91
	Lower Basin	23300	183	188	186	164	105	171	106	123	130	185
	Total Basin	92500	114	121	126	134	124	133	131	128	136	114

Table 7.2
Critical Spring PMP Rainfall Sequence
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	0	6	9	9
4-Jun	14	17	26	43
5-Jun	97	34	17	14
6-Jun	0	0	0	0

Notes

1. Depths are for 10 km^2 at the storm centre.
2. 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 Spring Temperature Sequence
6-Hour Instantaneous Values (^oC)

Day	6-Hour Period			
	6:00	12:00	18:00	24:00
16-May	-1.0	2.5	-0.8	-4.0
17-May	-0.6	2.8	-0.4	-3.6
18-May	-0.3	3.0	-0.1	-3.3
19-May	0.0	3.3	0.2	-2.9
20-May	0.3	3.5	0.5	-2.5
21-May	0.7	3.9	0.9	-2.1
22-May	1.1	4.3	1.3	-1.7
23-May	1.5	4.6	1.7	-1.3
24-May	1.9	5.0	2.1	-0.8
25-May	2.4	5.7	2.6	-0.4
26-May	2.9	6.2	3.1	0.0
27-May	3.7	7.3	4.2	1.0
28-May	5.0	9.0	5.5	2.0
29-May	10.5	19.0	12.0	5.0
30-May	14.5	24.0	21.5	19.0
31-May	21.5	24.0	19.5	15.0
1-Jun	15.0	15.0	10.5	6.0
2-Jun	9.0	12.0	9.0	6.0
3-Jun	11.0	16.0	13.0	10.0
4-Jun	13.0	16.0	15.5	15.0
5-Jun	15.0	15.0	10.5	6.0
6-Jun	8.0	10.0	7.0	4.0

Note

1. The Spring temperature sequence was adjusted to each sub-basin using the values in Table 7.4.

Table 7.4
Sub-Basin Adjustments to Critical Temperature Sequence

Sub-Basin No.	Sub-Basin Name	Area (km2)	Temperature Adjustment (˚ C)		
			Minimum	Maximum	Mean
1	Lower Pinus	1799	-0.2	1.8	0.7
2	Upper Pinus	759	-0.1	0.3	0.1
3	Lower Minipi	2768	0.0	1.2	0.4
4+5	Upper Minipi	2771	-0.1	0.3	0.1
6+7	Upper Cache	1377	-0.2	0.3	0.0
8	Lower Cache	1881	-0.1	0.6	0.2
9	Upper Metchin	2651	-1.6	-0.1	-0.7
10	Lower Metchin	1330	-0.7	1.1	0.0
11	Lower Fig	2508	-0.2	1.5	0.3
12	Upper Fig	2711	-0.6	0.3	-0.1
13	Upper Unknown	1815	-0.3	0.4	0.1
14	Lower Unknown	928	-0.2	0.3	-0.1
15	Smallwood South	5209	-1.5	0.1	-0.7
16	Smallwood Surface	6285	-1.8	-0.4	-1.0
17	Smallwood North	9346	-2.4	-0.4	-1.6
18	Ashuanipi Mouth	6714	-3.0	-0.8	-1.6
19	Ashuanipi 03OA001	7296	-2.0	0.4	-0.7
20	McPhayden 03OA003	3609	-1.6	-0.7	-1.1
21	Ashuanipi 03OA004	8309	-0.3	1.3	0.7
22	Atikonak 03OC003	4458	-0.5	0.8	0.4
23	Kepimits 03OC004	6968	-0.4	1.0	0.5
24	Atikonak 03OC005	4023	0.0	1.0	0.6
25	Gabbro Lake	5547	-1.2	0.1	-0.3
26	Ossokmanuan Lake	1436	-0.1	0.4	0.1
Basin Average	Upper Basin	69200	-3.0	1.3	-0.5
	Lower Basin	23300	-1.6	1.8	0.1
	Total Basin	92500	-3.0	1.8	-0.3

Table 7.5
100-year Snowpack Water Equivalents by Sub-Basin

Sub-Basin No.	Sub-Basin Name	Area (km2)	100-year Snowpack Water Equivalent (mm)		
			Minimum	Maximum	Mean
1	Lower Pinus	1799	532	533	532
2	Upper Pinus	759	532	534	533
3	Lower Minipi	2768	531	533	532
4+5	Upper Minipi	2771	531	532	531
6+7	Upper Cache	1377	531	534	532
8	Lower Cache	1881	531	534	533
9	Upper Metchin	2651	534	537	535
10	Lower Metchin	1330	534	535	535
11	Lower Fig	2508	531	534	533
12	Upper Fig	2711	528	535	532
13	Upper Unknown	1815	529	537	533
14	Lower Unknown	928	534	537	536
15	Smallwood South	5209	535	541	537
16	Smallwood Surface	6285	536	545	540
17	Smallwood North	9346	538	546	543
18	Ashuanipi Mouth	6714	539	548	544
19	Ashuanipi 03OA001	7296	530	545	539
20	McPhayden 03OA003	3609	539	542	541
21	Ashuanipi 03OA004	8309	522	536	528
22	Atikonak 03OC003	4458	524	532	527
23	Kepimits 03OC004	6968	523	533	528
24	Atikonak 03OC005	4023	523	525	524
25	Gabbro Lake	5547	533	541	537
26	Ossokmanuan Lake	1436	530	536	533
Basin Average	Upper Basin	69200	522	548	536
	Lower Basin	23300	528	537	533
	Total Basin	92500	522	548	535

Table 7.6
Probable Maximum Snow Accumulation (PMSA) by Sub-Basin

Sub-Basin No.	Sub-Basin Name	Area (km^2)	PMSA (mm)		
			Minimum	Maximum	Mean
1	Lower Pinus	1799	574	592	580
2	Upper Pinus	759	589	611	601
3	Lower Minipi	2768	579	604	591
4+5	Upper Minipi	2771	575	587	580
6+7	Upper Cache	1377	604	623	614
8	Lower Cache	1881	601	632	617
9	Upper Metchin	2651	625	652	637
10	Lower Metchin	1330	638	653	645
11	Lower Fig	2508	625	646	638
12	Upper Fig	2711	621	649	638
13	Upper Unknown	1815	635	648	642
14	Lower Unknown	928	642	653	650
15	Smallwood South	5209	638	660	652
16	Smallwood Surface	6285	628	662	652
17	Smallwood North	9346	557	660	622
18	Ashuanipi Mouth	6714	530	622	563
19	Ashuanipi 03OA001	7296	543	642	610
20	McPhayden 03OA003	3609	560	612	587
21	Ashuanipi 03OA004	8309	634	650	643
22	Atikonak 03OC003	4458	626	638	632
23	Kepimits 03OC004	6968	631	641	636
24	Atikonak 03OC005	4023	623	633	628
25	Gabbro Lake	5547	602	642	630
26	Ossokmanuan Lake	1436	637	643	640
Basin Average	Upper Basin	69200	530	662	624
	Lower Basin	23300	574	653	618
	Total Basin	92500	530	662	623

Table 7.7
Spring PMF (100-year Snowpack and PMP) Variation with Storm Centre

PMF Peak Location	**PMF Peak (m^3/s)**									
	Centre 1	**Centre 2**	**Centre 3**	**Centre 4**	**Centre 5**	**Centre 6**	**Centre 7**	**Centre 8**	**Centre 9**	**Centre 10**
Smallwood Reservoir Outflow	5,320	5,320	5,320	5,330	**5,340**	**5,340**	5,330	5,320	5,320	5,320
Ossokmanuan/Gabbro Lake Outflow	4,920	5,130	5,270	5,670	5,060	5,060	**6,190**	6,090	6,060	4,760
Gull Island (pre-project)	20,700	**20,900**	20,100	18,900	15,600	15,600	15,700	16,100	16,500	20,000
Muskrat Falls (pre-project)	**22,800**	22,500	21,500	19,700	16,600	16,600	16,500	17,000	17,300	22,500

Table 7.8
Spring PMF (PMSA and 100-year Rainfall) Variation with Storm Centre

PMF Peak Location	PMF Peak (m^3/s)									
	Centre 1	**Centre 2**	**Centre 3**	**Centre 4**	**Centre 5**	**Centre 6**	**Centre 7**	**Centre 8**	**Centre 9**	**Centre 10**
Smallwood Reservoir Outflow	5,310	5,310	5,310	5,310	**5,320**	**5,320**	5,310	5,310	5,310	5,310
Ossokmanuan/Gabbro Lake Outflow	4,520	4,500	4,530	4,600	4,530	4,530	**4,750**	4,670	4,700	4,500
Gull Island (pre-project)	13,600	14,200	**14,300**	14,200	13,600	13,600	13,700	13,800	13,900	13,500
Muskrat Falls (pre-project)	14,600	14,500	**14,600**	14,500	13,900	13,900	13,900	14,000	14,100	14,500

Table 7.9
Summer PMF (100-year Rainfall and PMP) Variation with Storm Centre

PMF Peak Location	PMF Peak (m^3/s)									
	Centre 1	**Centre 2**	**Centre 3**	**Centre 4**	**Centre 5**	**Centre 6**	**Centre 7**	**Centre 8**	**Centre 9**	**Centre 10**
Smallwood Reservoir Outflow	4,890	5,050	5,360	5,360	**5,370**	5,360	4,960	4,210	5,360	4,320
Ossokmanuan/Gabbro Lake Outflow	1,050	1,230	1,410	1,930	1,420	2,160	**3,020**	2,510	2,650	881
Gull Island (pre-project)	8,490	9,200	10,400	**10,700**	8,260	10,500	7,070	6,760	9,370	7,770
Muskrat Falls (pre-project)	9,200	9,440	10,600	**10,800**	8,410	10,500	7,150	6,850	9,520	9,150

Table 7.10
Comparison of Calibration and PMF Parameters (Snow Band 4)
Lower Minipi River Sub-basin SSARR Snowband 4 - May 1 to September 30

Parameter	Maximum		Minimum		Total	
	1981	PMF	1981	PMF	1981	PMF
Precipitation, cm	1.00	7.78	0	0	60	60
Interception, cm	***0.51***	0.46	0	0	15	17
Snow Water Equivalent, cm	43	53	0	0		
Antecedent Temperature Index (for cold content), degree days	0	1	-5	-5		
Cold Content, cm	0	0	-0.1	-0.1		
Liquid Water Deficiency, cm	0	0	0	-0.9		
Air Temperature with snow, °C	22.3	24.2	-7.3	-7.8		
Antecedent Temperature Index (for melt rate), degree-days	129	135	0	0		
Melt Rate, cm/degree-day	0.37	0.73	0	0		
Snowmelt, cm	2.05	2.73	0	0	44	50
Moisture Input, cm	2.09	10.5	0	0	88	87
Potential Evapotranspiration, cm/day	0.64	0.64	0	0.01		
Evapotranspiration, cm/day	0.64	0.64	0	0.01		
Soil Moisture Index, cm	10.79	11.82	2.65	0.54		
Runoff Percent, %	94	99	18	10		
Runoff Generated, cm	1.96	10.23	0	0	67	81
Baseflow Infiltration Index, cm/day	***2.50***	***2.50***	0	0		
Baseflow Percent, %	***80***	***80***	***12***	***12***		
Surface Runoff, cm	1.00	8.31	0	0	22	38
Subsurface Runoff, cm	**0.72**	**0.72**	0	0	22	19
Baseflow Runoff, cm	0.26	0.96	0	0	18	11
Lower Zone Runoff, cm	0.07	0.24	0	0	5	3

Notes

1. Values from 6-hourly simulation
(eg. maximum precipitation in 1981 was 1.00 cm in 6 hours).
2. Bold, italicized values governed by a user defined limit.

Table 7.11
Comparison of Calibration and PMF Parameters (SSARR Summary)
Lower Minipi River Sub-Basin SSARR Summary - May 1 to September 30

Parameter	Maximum		Minimum		Total	
	1981	PMF	1981	PMF	1981	PMF
Precipitation, cm	1.00	7.75	0	0	59	49
Interception, cm	***0.51***	0.45	0	0	15	15
Snowline, m	535	535	90	90		
Snow Water Equivalent, cm	37	53	0	0		
Air Temperature with snow, ^{o}C	24	26	-6	-6		
Melt Rate, cm/degree-day	0.37	0.73	0	0		
Runoff Generated, cm	1.24	9.87	0	0	60	71
Evapotranspiration, cm/day	0.64	0.65	0	0.01		
Soil Moisture Index, cm	10.4	11.8	2.5	0.5		
Runoff Percent, %	92	99	18	10		
Baseflow Percent, %	***80***	***80***	15	***12***		
Discharge from Surface Zone, m^3/s (total in million m^3)	484	5890	0	0	530	1020
Discharge from Subsurface Zone, m^3/s (total in million m^3)	299	772	0	0	520	550
Discharge from Baseflow Zone, m^3/s (total in million m^3)	79	110	6	1	467	309
Discharge from Lower Zone, m^3/s (total in million m^3)	6	4	1	1	57	41
Total Discharge, m^3/s (total in million m^3)	786	6640	12	5	1580	1920

Notes

1. Values from 6-hourly simulation
(eg. maximum precipitation in 1981 was 1.00 cm in 6 hours).
2. Bold, italicized values governed by a user defined limit.

Table 7.12
External Parameter Sensitivity Analysis Results

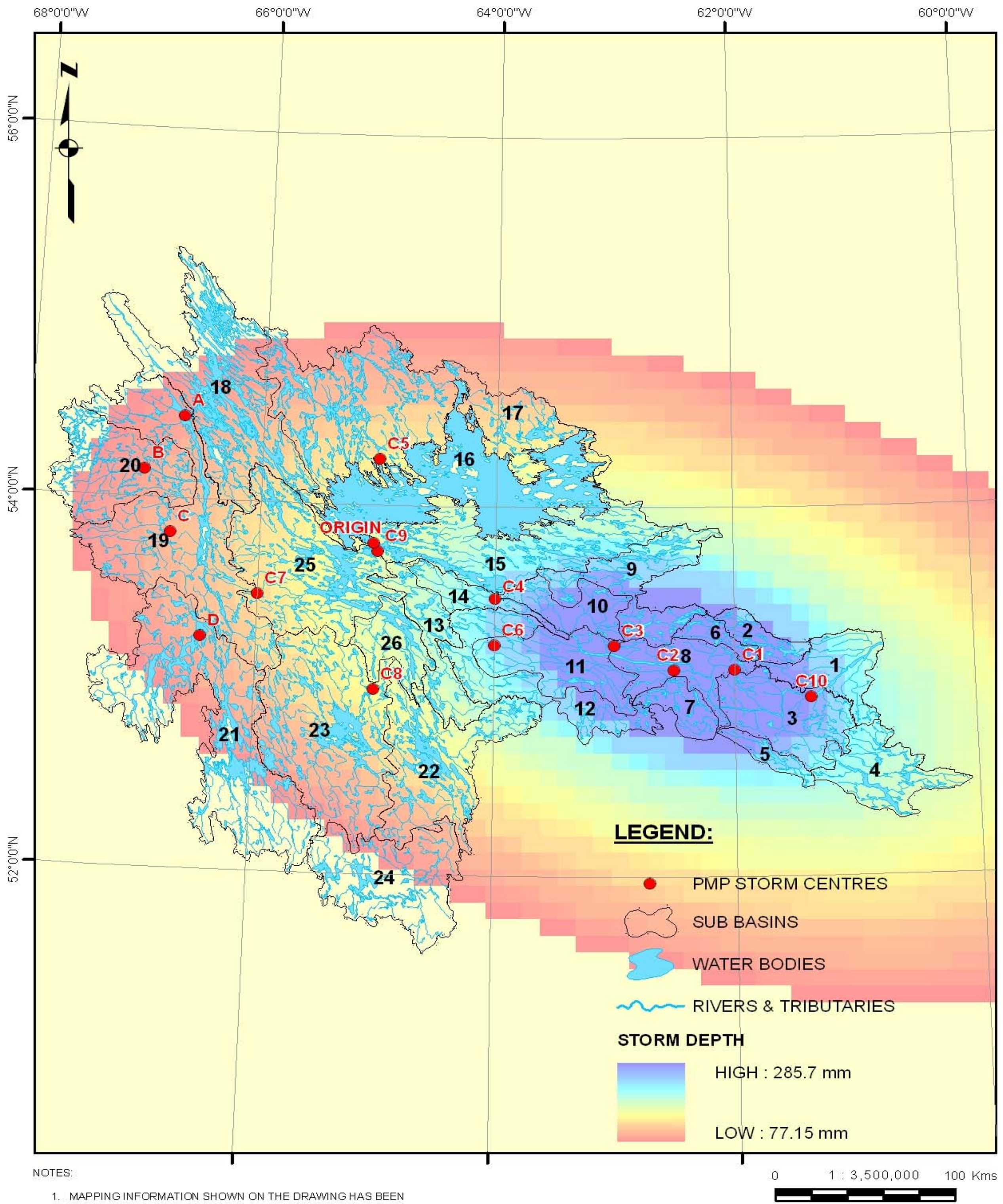
Parameter	Condition	Probable Maximum Flood[1]			
		Peak[2] (m^3/s)	Change	Volume[3] (million m^3)	Change
Base Case		22800		30060	
Snowpack (53.5 cm)[4]	43.5 cm	18930	-17%	26600	-12%
	63.5 cm	23620	4%	33250	11%
Temperatures					
Maximum Value (24°C)	22°C	22790	0%	30050	0%
	26°C	22810	0%	30060	0%
Value During PMP (16°C)	14°C	22490	-1%	30010	0%
	18°C	23070	1%	30090	0%
Initial Soil Moisture (7 cm)	5 cm	22390	-2%	29480	-2%
	9 cm	23200	2%	30640	2%
PMP					
66-Hour 10 km^2 Value (286 mm)	257 mm	21640	-5%	29500	-2%
	315 mm	23980	5%	30600	2%
6-Hour Distribution (typical pattern)	Uniform	20240	-11%	30070	0%

Notes
1. PMF results are for 100-yr SWE + Spring PMP Storm Centre 1.
2. Pre-project values at Muskrat Falls.
3. Volumes are maximum 28-day volumes.
4. Values in parentheses are base case values.

Table 7.13
Internal Parameter Sensitivity Analysis Results

Parameter	Condition	1981 Calibration				Probable Maximum Flood[1]			
		Peak[2] (m^3/s)	Change	Volume[3] (million m^3)	Change	Peak[2] (m^3/s)	Change	Volume[3] (million m^3)	Change
Base Case		786		912		6640		1700	
Melt Rates (max = 0.37 cm/°day)[4]	0.23	628	-20%	897	-2%	6730	1%	1680	-1%
Cold Rates (max = 0.04 cm/°day)	0.14	833	6%	943	3%	6740	2%	1730	2%
Baseflow									
Percent Curve	- 10%	792	1%	919	1%	6710	1%	1710	1%
	+ 10%	780	-1%	905	-1%	6610	0%	1700	0%
Input Limit (0.2 cm/hr)	0.15	786	0%	912	0%	6750	2%	1710	1%
	0.25	786	0%	912	0%	6630	0%	1700	0%
Runoff % vs Soil Moisture	- 10%	750	-5%	875	-4%	6110	-8%	1600	-6%
(Typical)	+ 10%	797	1%	927	2%	6790	2%	1740	2%
Surface/Sub-Surface Split	0.08 cm/hr	850	8%	912	0%	6810	3%	1700	0%
(SS limit = 0.12 cm/hr)	0.3 cm/hr	750	-5%	912	0%	6250	-6%	1700	0%
Hydrologic Routing									
Surface Phases (4)	3	813	3%	910	0%	7160	8%	1700	0%
	5	766	-3%	913	0%	6150	-7%	1700	0%
Surface Time (4 hrs)	3 hrs	816	4%	911	0%	7230	9%	1700	0%
	5 hrs	763	-3%	913	0%	6030	-9%	1700	0%
Sub-Surface Phases (5)	4	835	6%	916	0%	6710	1%	1700	0%
	6	755	-4%	909	0%	6610	0%	1700	0%
Sub-Surface Time (15 hrs)	10 hrs	875	11%	920	1%	6760	2%	1700	0%
	20 hrs	758	-4%	909	0%	6600	-1%	1700	0%

Notes
1. PMF results are for 100-yr SWE + Spring PMP Storm Centre 1.
2. Pre-project values for Lower Minipi River sub-basin.
3. Volumes are maximum 28-day volumes.
4. Values in parentheses are base case values.



NOTES:

1. MAPPING INFORMATION SHOWN ON THE DRAWING HAS BEEN DERIVED FROM THE DIGITAL DATA FROM GEOGRATIS
2. PROJECTED COORDINATE SYSTEM IS NAD 1983, UTM ZONE 20N.

Figure 7.1
Lower Chruchill Project
PMF and Construction Design Flood Study
PMP STORM CENTRES

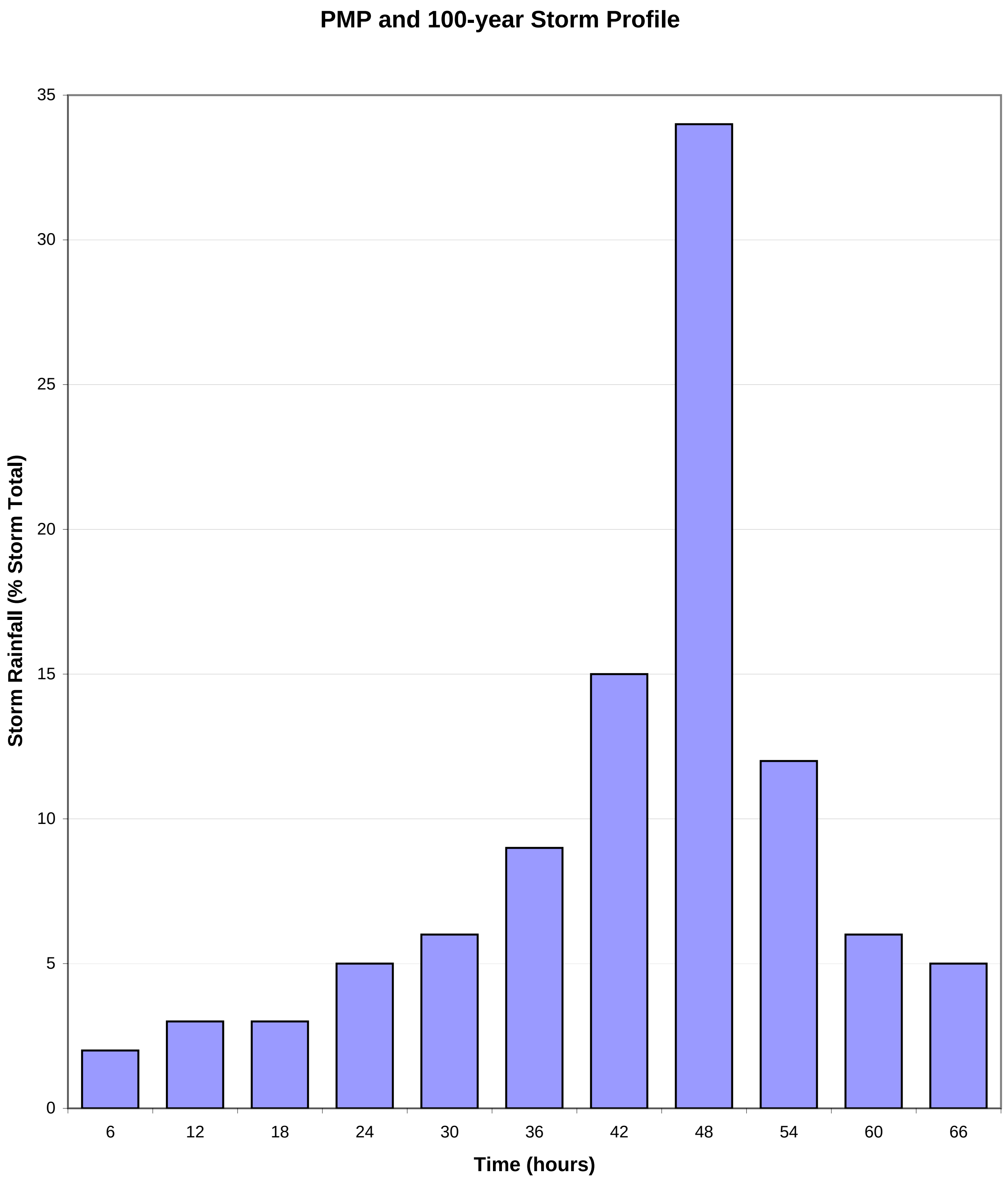


Figure 7.2
Lower Chruchill Project
PMF and Construction Design Flood Study
PMP AND 100 YEAR STORM PROFILE

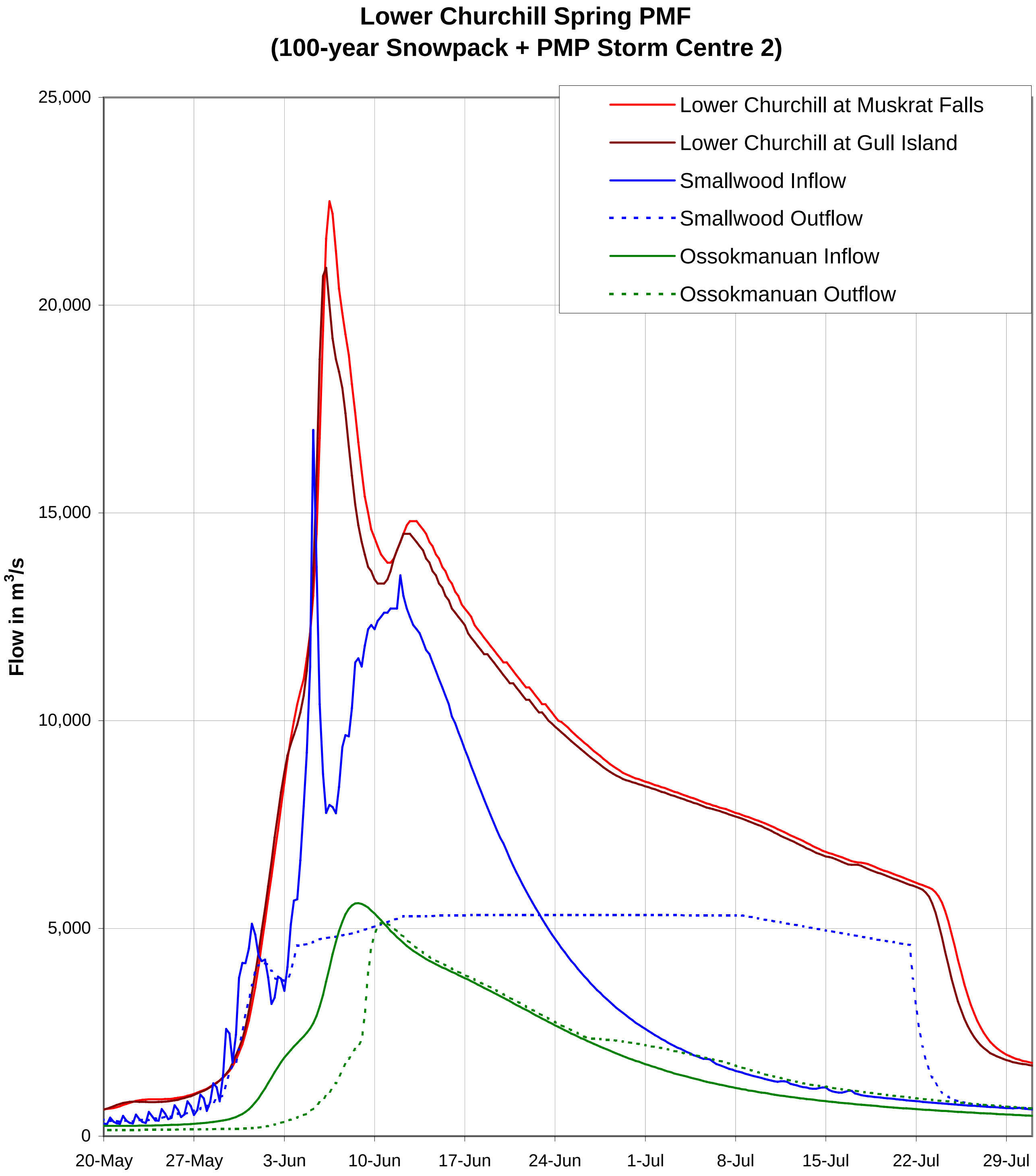


Figure 7.3
Lower Chruchill Project
PMF and Construction Design Flood Study
LOWER CHURCHILL SPRING PMF (PMP)

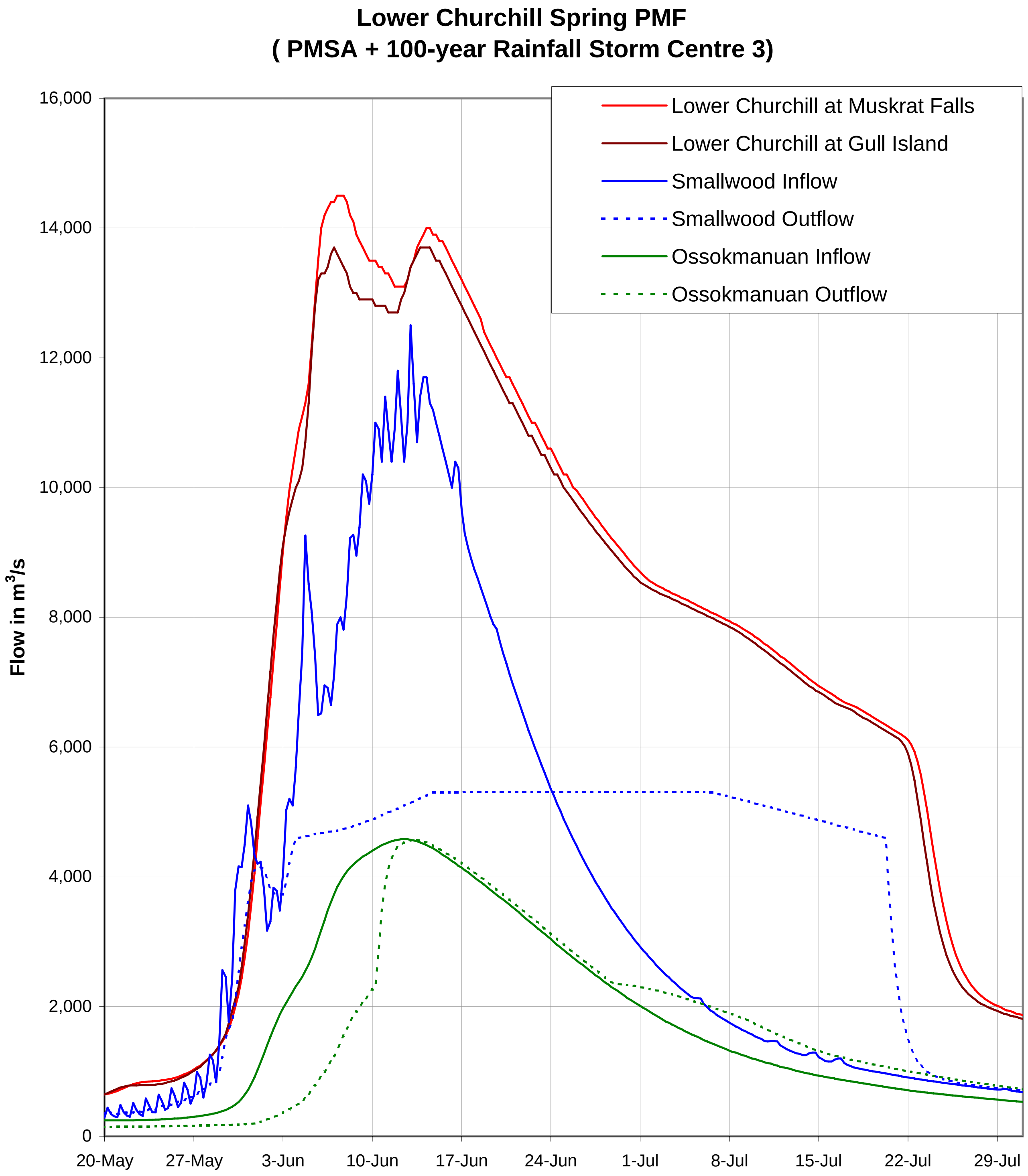


Figure 7.4
Lower Chruchill Project
PMF and Construction Design Flood Study
LOWER CHURCHILL SPRING PMF (PMSA)

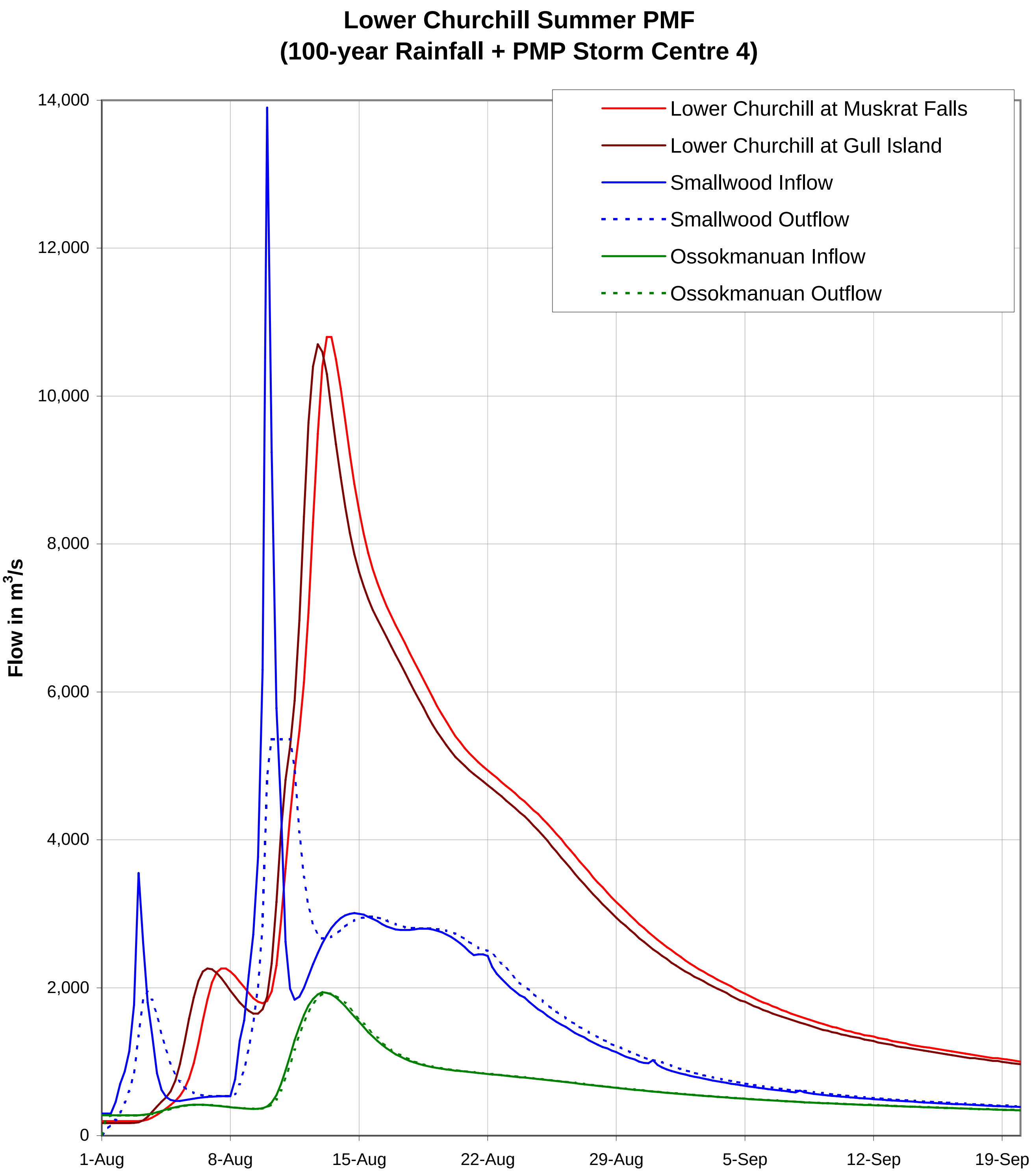


Figure 7.5
Lower Chruchill Project
PMF and Construction Design Flood Study
LOWER CHURCHILL SUMMER PMF

8. Churchill Falls Flood Routing

The flood handling operation of the Churchill Falls Project employs decision based procedures defined by Acres[6] in 1989. These procedures include:

- Determination of May 1st maximum starting water levels in Smallwood Reservoir and Ossokmanuan/Gabbro Lake;
- Upper rule curves that determine when pre-spill procedures must be implemented;
- Shut down of Gabbro Control Structure and activation of Ossokmanuan Control Structure;
- Shut down of Churchill Falls Powerhouse; and
- Trigger elevations for breaching various fuse plug dykes.

In the hydrological modelling of the PMF scenarios and storm centre comparisons these flood handling procedures were represented by effective stage-discharge rating relationships. However, for the critical PMF/storm centre scenario, routing through the Churchill Falls complex was undertaken using the ARSP operational model to get the most accurate estimate of the Upper Basin contribution to the Lower Basin PMF.

8.1 Upper Basin Operational Model

The model used to define the flood handling operation of the Churchill Falls Project in 1989 was the Acres Reservoir Simulation Program (ARSP). ARSP is a general multipurpose, multi-reservoir simulation program that represents the water resource system as a capacitated flow network. Operating policies and priorities are defined through a penalty structure associated with each element of the flow network, and optimal operating decisions can be made given the initial state of the system and estimates of net inflows to the system.

The 1989 ARSP model for Churchill Falls was recompiled for the present study using PMF inflows to Smallwood Reservoir and Ossokmanuan/Gabbro Lake from the integrated basin-wide SSARR model. Figure 8.1 shows a schematic of the ARSP model and Table 8.1 provides a description of the numbered components of the model.

Table 8.2 provides a summary of the flood routing through Smallwood Reservoir and Ossokmanuan/Gabbro Lake for the PMF generated by a 100-year snowpack and a spring PMP centred over storm centre 2, upstream of Gull Island in the Lower Basin. Model nodes in Figure 8.1 that are not used in the routing have been omitted from the table for clarity.

Figure 8.2 shows Smallwood Reservoir water level profile during the PMF routing from the ARSP and SSARR models. The water level on May 1st is 469.68m, the PMF rule curve starting level. Spill commences around June 3 and both ARSP and SSARR give similar results until the rule curve is encountered on June 27th. After this date the simplified elevation-discharge rating in the SSARR model results in continued spill through Lobstick Control Structure and Jacopie Spillway and Smallwood water level continues to fall. In ARSP the drop below the rule curve triggers the closure of Lobstick Control Structure and Smallwood Reservoir is allowed to rise to store the remaining PMF inflow for later release through the powerhouse.

This difference in operation between ARSP and SSARR does not affect the Lower Basin PMF peak, which occurs three weeks earlier on June 6th.

Figure 8.3 shows Ossokmanuan/Gabbro Lake water level profile during the PMF routing from the ARSP and SSARR models. The water level on May 1st is 475.03m, the PMF rule curve starting level. Spill through Ossokmanuan Control Structure to the Lower Basin commences immediately in the SSARR model and gradually increases as the lake level increases. However, in the ARSP model flow continues through the Gabbro Control Structure to Smallwood Reservoir until June 2nd, holding the water level near to 475.03m. On June 3rd Gabbro Control Structure is closed. Ossokmanuan Control Structure is opened on June 6th and spill to the Lower Basin commences.

The inability of SSARR to model the changing outflow direction from Ossokmanuan/Gabbro Lake means that the lake level reaches the dyke breach trigger level three days earlier than in the ARSP model. Breaching the Julian Dykes results in a rapid increase in outflow from Ossokmanuan/Gabbro Lake and a corresponding drop in lake level. This is modelled accurately in ARSP, but cannot be represented correctly by the simplified elevation-discharge rating in the SSARR model.

After June 27th the simplified elevation-discharge rating in the SSARR model results in continued spill through Ossokmanuan Control Structure and water levels continue to fall. In ARSP the drop below the rule curve triggers the closure of Ossokmanuan Control Structure and the opening of Gabbro Control Structure to transfer as much of the storage remaining in Ossokmanuan/Gabbro Lake to Smallwood Reservoir, for later release through the powerhouse. At the same time outflows to the Lower Basin continue through the breached dykes.

The differences in operation between ARSP and SSARR result in SSARR peak outflows from the Upper Basin three days earlier, but 3% lower than from the ARSP model. However, at the time of the Upper Basin contribution to the Lower Basin PMF peak, which would occur 2-3 days earlier than the June 6th peak due to travel times, both models give an outflow of ± 5,000 m^3/s. This confirms the use of the simplified elevation-discharge ratings in the SSARR to determine the critical PMF scenario and storm centre.

Figure 8.4 shows the SSARR PMF outflow hydrograph from the Upper Basin and the ARSP PMF outflow hydrograph used in the dynamic hydraulic routing model.

Table 8.1
ARSP Schematic Description

Schematic No.	Description
1	Ossokmanuan/Gabbro Lake Inflow (from SSARR)
2	Ossokmanuan Control Structure Outflow
3	Julian Dyke 7 Breach Outflow
4	Julian Dykes 3&4 Breach Outflow
7	Gabbro Control Structure Outflow
8	Gabbro Control Structure Overflow
9	Smallwood Reservoir Inflow (from SSARR)
10	Orma/Sail Dykes Outflow
11	Lobstick Control Structure Outflow
12	Lobstick Dyke Breach Outflow
13	West Forebay Inflow
14	Jacopie Spillway Outflow
15	Jacopie Dyke Breach Outflow
16	Whitefish Control Structure Outflow
17	East Forebay Inflow
18	East Forebay Spillway Outflow
19	Churchill Falls Power Flow
20	Churchill River Flow downstream of Jacopie Spillway
21	Total Ossokmanuan/Gabbro Lake Outflow to Lower Basin
22	Total Upper Churchill Outflow to Lower Basin (to HEC_RAS)

Note

1. Nodes 5 and 6 no longer included in ARSP Model.

Table 8.2

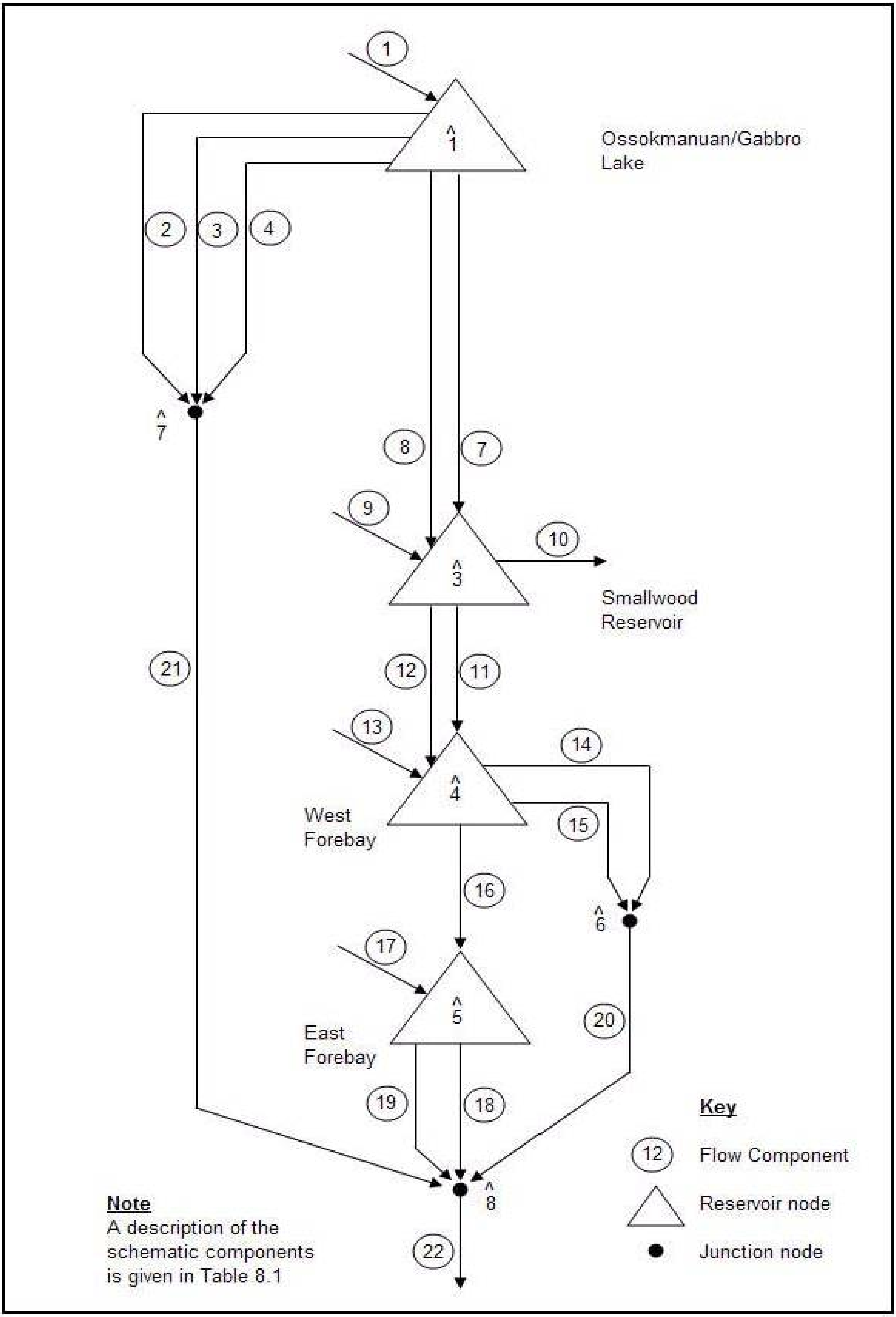
ARSP Model PMF Routing through Upper Churchill Project

(100-year Snowpack + PMP Storm Centre 2; Flows in m^3/s)

Schematic No.	1	2	3	4	7	9	11	13	14	17	18	20	21	22
Date	**Ossok/Gabbro Inflow**	**Ossok CS**	**Julian Dyke 7 Breach**	**Julian Dykes 3&4 Breach**	**Gabbro CS**	**Smallwood Inflow**	**Lobstick CS**	**West Forebay Inflow**	**Jacopie Spillway**	**East Forebay Inflow**	**East Forebay Spillway**	**Churchill R d/s of Jacopie**	**Total Ossok Outflow to Lower Basin**	**Total Upper Churchill Outflow**
26-May	291	0	0	0	735	625	1,360	15	1,376	9	0	1,376	0	1,376
27-May	314	0	0	0	717	757	1,474	19	1,492	10	0	1,492	0	1,492
28-May	348	0	0	0	700	990	1,690	24	1,715	14	0	1,715	0	1,715
29-May	403	0	0	0	686	1,994	2,680	49	2,729	27	0	2,729	0	2,729
30-May	518	0	0	0	677	3,511	4,187	86	4,274	48	0	4,274	0	4,274
31-May	773	0	0	0	0	4,530	4,530	111	4,596	62	0	4,596	0	4,596
1-Jun	1,218	0	0	0	718	3,722	4,440	92	4,577	51	0	4,577	0	4,577
2-Jun	1,718	0	0	0	750	3,482	4,232	86	4,317	48	30	4,317	0	4,347
3-Jun	2,113	0	0	0	0	4,944	4,714	122	4,650	68	68	4,650	0	4,718
4-Jun	2,450	0	0	0	0	8,454	4,731	208	4,762	116	116	4,762	0	4,877
5-Jun	3,035	0	0	0	0	11,994	4,778	295	4,864	164	164	4,864	0	5,028
6-Jun	4,208	740	0	0	0	7,570	4,821	186	4,935	104	104	4,935	740	5,778
7-Jun	5,228	1,132	0	0	0	8,918	4,851	219	4,978	122	122	4,978	1,132	6,232
8-Jun	5,588	1,475	0	0	0	10,715	4,893	264	5,035	147	147	5,035	1,475	6,656
9-Jun	5,460	1,853	0	0	0	11,678	4,947	287	5,106	160	160	5,106	1,853	7,118
10-Jun	5,155	2,117	0	0	0	12,063	5,007	297	5,178	165	165	5,178	2,117	7,460
11-Jun	4,830	2,246	0	0	0	12,424	4,907	306	5,211	170	170	5,211	2,246	7,627
12-Jun	4,553	2,358	0	0	0	12,159	4,912	299	5,211	167	167	5,211	2,358	7,736
13-Jun	4,335	2,406	2,564	209	0	11,533	4,928	284	5,211	158	158	5,211	5,178	10,548
14-Jun	4,160	2,342	2,470	160	0	10,883	4,944	268	5,211	149	149	5,211	4,972	10,332
15-Jun	4,008	2,307	2,386	119	0	10,089	4,963	248	5,211	138	138	5,211	4,812	10,162
16-Jun	3,860	2,274	2,300	76	0	9,270	4,983	228	5,211	127	127	5,211	4,651	9,989
17-Jun	3,710	2,239	2,210	32	0	8,478	5,003	209	5,211	116	116	5,211	4,480	9,807
18-Jun	3,550	2,204	2,120	1	0	7,717	5,022	190	5,211	106	106	5,211	4,324	9,641
19-Jun	3,390	2,168	2,027	0	0	7,014	5,039	173	5,211	96	96	5,211	4,195	9,502
20-Jun	3,225	2,130	1,931	0	0	6,357	5,055	156	5,211	87	87	5,211	4,062	9,360
21-Jun	3,060	2,091	1,833	0	0	5,758	5,070	142	5,211	79	79	5,211	3,924	9,214
22-Jun	2,890	2,034	1,740	0	0	5,225	5,083	129	5,211	72	72	5,211	3,774	9,057
23-Jun	2,730	1,949	1,646	0	0	4,741	5,095	117	5,211	65	65	5,211	3,594	8,871
24-Jun	2,570	1,864	1,553	0	0	4,315	5,105	106	5,211	59	59	5,211	3,417	8,688
25-Jun	2,418	1,781	1,463	0	0	3,930	5,115	97	5,211	54	54	5,211	3,244	8,509
26-Jun	2,275	1,701	1,375	0	0	3,588	5,123	88	5,211	49	49	5,211	3,076	8,336
27-Jun	2,138	1,622	1,288	0	0	3,284	3,771	81	4,924	45	45	4,924	2,910	7,879
28-Jun	2,008	0	1,208	0	1,634	3,013	0	74	116	41	41	116	1,208	1,366
29-Jun	1,885	0	1,136	0	1,594	2,774	0	68	68	38	38	68	1,136	1,242
30-Jun	1,773	0	1,062	0	1,555	2,557	0	63	63	35	35	63	1,062	1,160

Note

1. Refer to Table 8.1 and Figure 8.1 for description and location of each schematic component.



Note
A description of the schematic components is given in Table 8.1

Figure 8.1
Lower Churchill Project
PMF and Construction Design Flood Study
ARSP MODEL SCHEMATIC

HATCH™

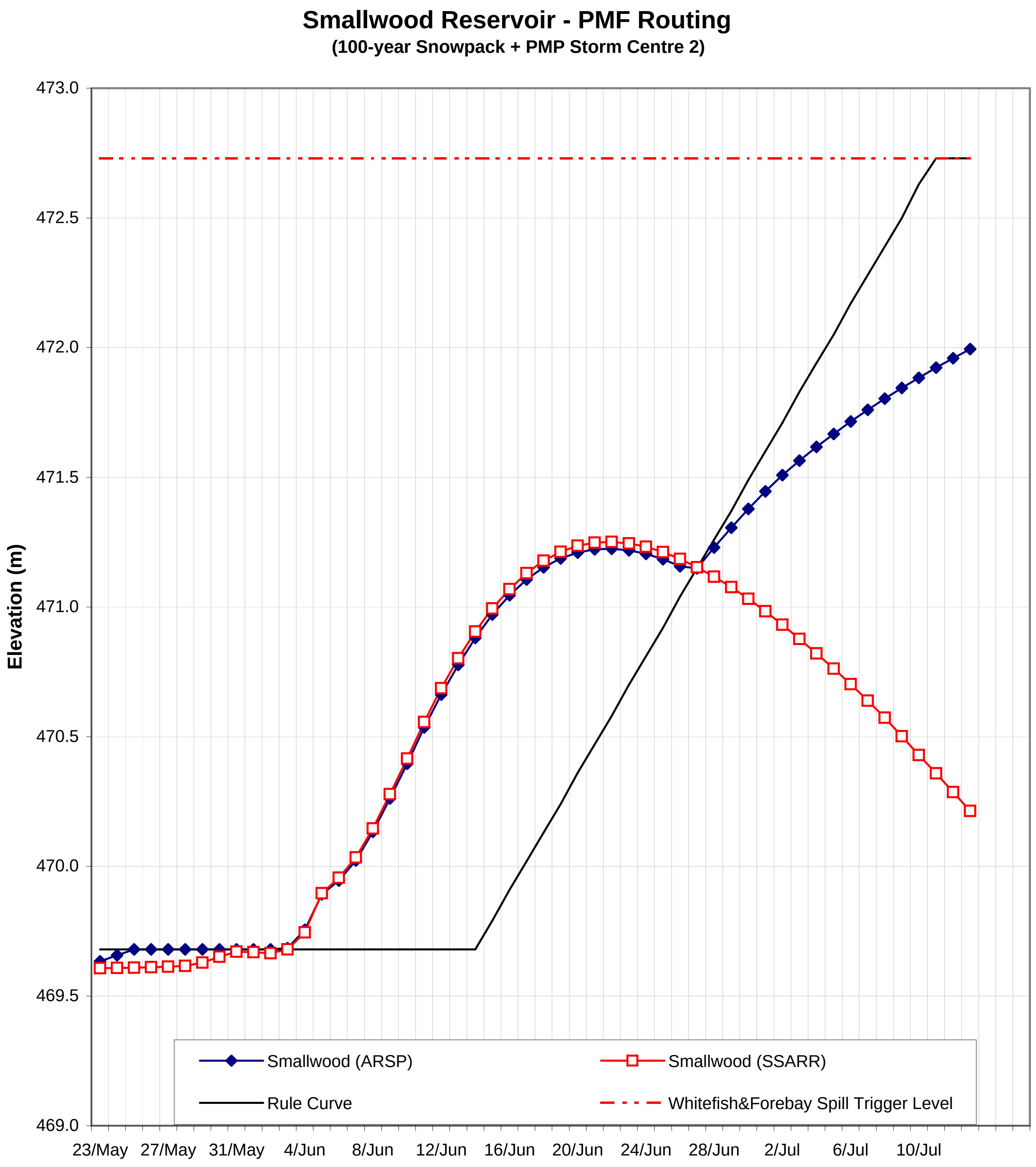


Figure 8.2
Lower Chruchill Project
PMF and Construction Design Flood Study
SMALLWOOD RESERVOIR - PMF ROUTING

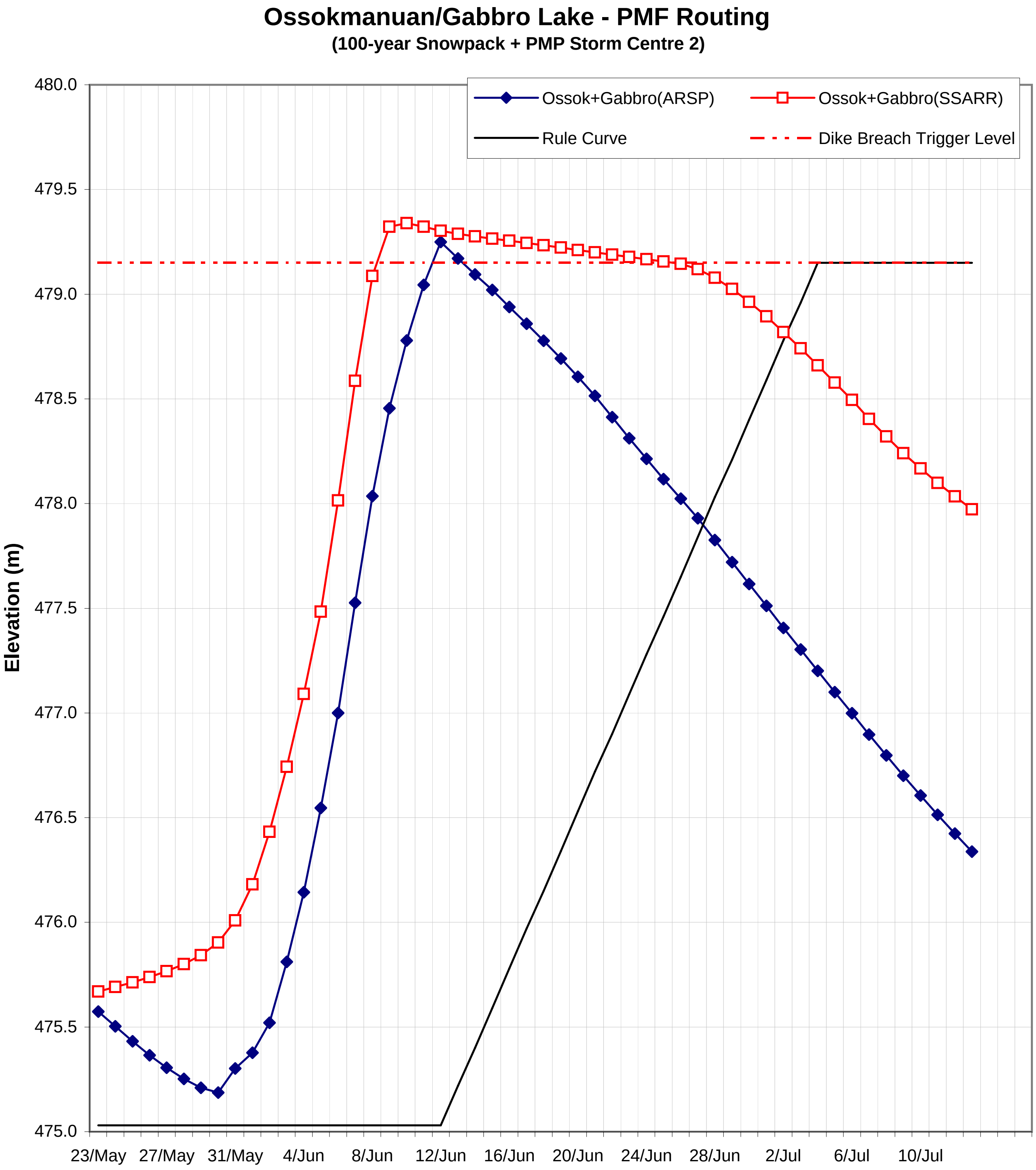


Figure 8.3

Lower Chruchill Project

PMF and Construction Design Flood Study

OSSOKMANUAN/GABBRO LAKE - PMF ROUTING

Churchill Falls Project - PMF Routing

(100-year Snowpack + PMP Storm Centre 2)

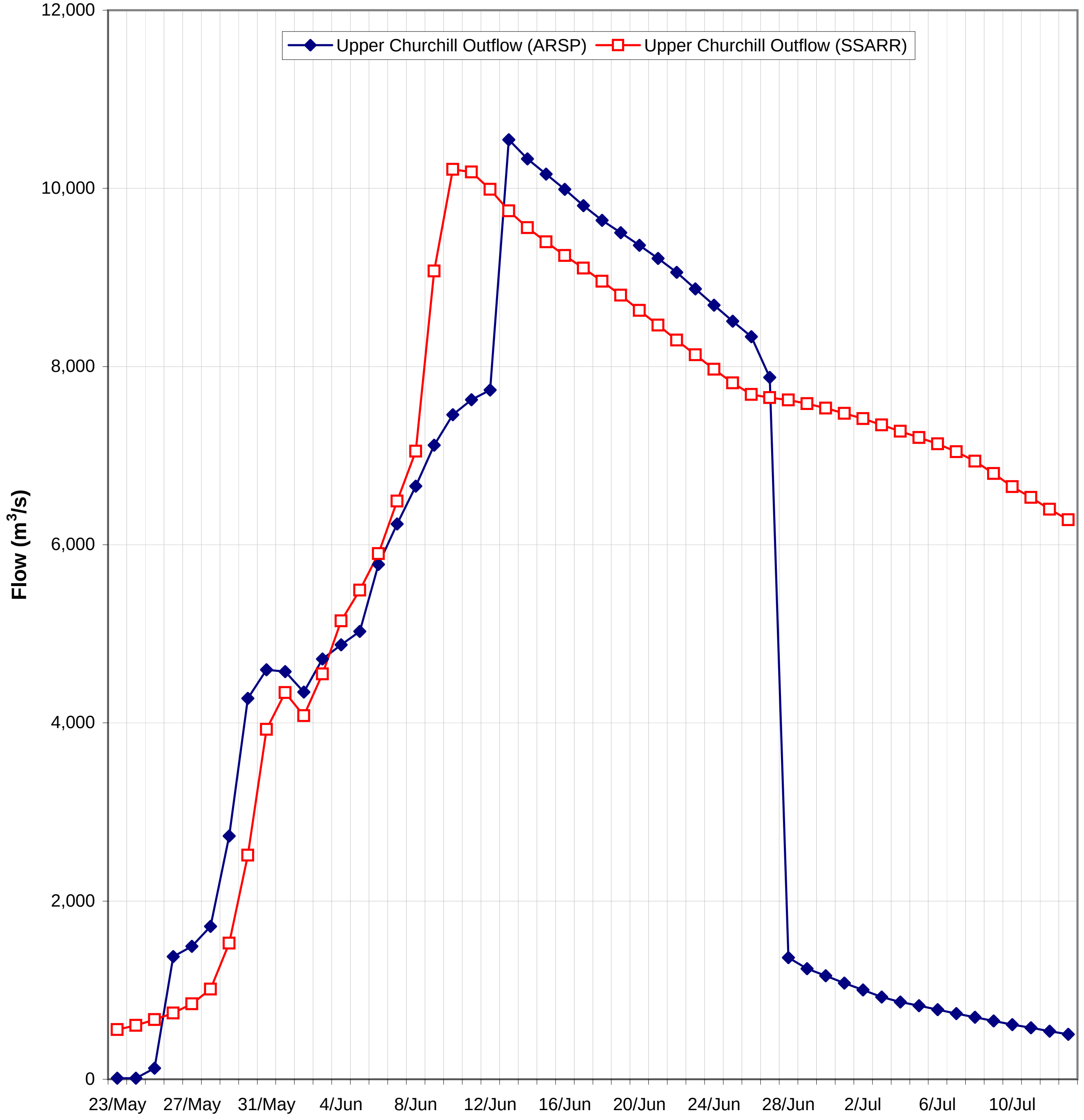


Figure 8.4

Lower Chruchill Project

PMF and Construction Design Flood Study

CHURCHILL FALLS PROJECT - PMF ROUTING

9. Lower Churchill River Dynamic Hydraulic Modelling

The Lower Churchill River is a long, deeply inscribed channel that receives flood inflow peaks from it's tributaries at approximately the same time along its length. Thus, the time of travel and the flood peak attenuation along the Lower Churchill River have a significant and critical impact on the PMF peaks at Gull Island and Muskrat Falls.

Channel routing through eight separate reaches is included as part of the SSARR model and appears to duplicate the observed travel time from Churchill Falls Powerhouse to Upper Muskrat Falls during historical floods. The SSARR channel routing is hydrological and empirical and cannot be calibrated for floods of the magnitude of the PMF, as no such flow records exist.

Consequently it was decided to employ a dynamic hydraulic model to remove the uncertainty implicit in the extrapolation of the SSARR channel routing functions. Dynamic hydraulic models are based on the physical characteristics of the river channel and solution of the Saint-Venant equations of unsteady flow and are not subject to the uncertainties of extrapolation applicable to hydrological routing approaches.

9.1 The HEC-RAS Model

A HEC-RAS dynamic hydraulic model of the Lower Churchill River was developed as part of the GI1110 Hydraulic Modeling of River report. The GI1110 report covers surveys, cross section extraction, model set up and calibration of the model from Churchill Falls tailrace to Goose Bay. Figures 9.1 and 9.2 show calibration plots for the HEC-RAS model from the GI1110 report.

The GI1110 HEC-RAS model was used to undertake the following simulations in the PMF study:

- Route the outflows from Churchill Falls powerhouse (03OD005) and lateral inflow hydrographs from the SSARR model to Muskrat Falls for a historical year, to verify the model calibration.
- Route the PMF outflows from the Upper Basin (from the ARSP model) and lateral inflow hydrographs from the SSARR model to Muskrat Falls for the critical PMF scenario, for pre-project conditions.
- Route the PMF outflows from the Upper Basin (from the ARSP model) and lateral inflow hydrographs from the SSARR model to Muskrat Falls for the critical PMF scenario, for post-project conditions to assess the attenuating effect of the reservoirs.

9.1.1 Historical Year Calibration

1981 was selected to test the calibration of the HEC-RAS model because the SSARR hydrograph at Muskrat Falls showed the closest agreement with recorded flows and the lateral inflow hydrographs were therefore likely close to actual.

Figure 9.3 shows the recorded (03OE001), SSARR and HEC-RAS hydrographs at Muskrat Falls for 1981. The agreement between the three hydrographs is very good, particularly at the peak of the flood. This confirms the calibration of the HEC-RAS model, but also endorses the runoff hydrographs and channel routing in SSARR, which could only be calibrated in combination in the SSARR model. i.e. if the lateral hydrographs from SSARR were incorrect the HEC-RAS routing would not agree with the WSC hydrograph at Muskrat Falls and, if the lateral hydrographs from SSARR are correct, the channel routing in SSARR must also be correct (at this flood level) otherwise the SSARR hydrograph at Muskrat Falls would not agree with the WSC hydrograph.

9.1.2 Pre-Project PMF Routing

In the pre-project HEC-RAS PMF model the only changes to the calibrated model were to the input hydrographs used. The outflow hydrograph from the Upper Basin from the ARSP model and the Lower Basin lateral inflow hydrographs from the SSARR model were input for the critical PMF (100-year snowpack + storm centre 2 PMP).

Figure 9.4 shows the Lower Churchill River with Gull Island and Muskrat Falls Dams in place. After development the depth of flow in the river will increase and slope of the water surface will be flattened. This will slow flows down and attenuate flood peaks.

Figures 9.5 and 9.6 show the pre-project SSARR and HEC-RAS PMF hydrographs at Gull Island and Muskrat Falls, respectively.

The pre-project HEC-RAS flood peaks are 16% higher than those from the SSARR model. The reason for the increase is the increased slope of the water surface on the rising limb of the flood hydrograph during the PMF.

The Saint-Venant equations comprise a continuity equation and a momentum equation. The momentum equation is made up of the following terms:

- The local acceleration term, which describes the change in momentum due to change in velocity over time;
- The convective acceleration term, which describes the change in momentum due to change in velocity along the channel;
- The pressure force term, proportional to the change in the water depth along the channel;
- The gravity force term, proportional to the bed slope; and
- The friction force term, proportional to the friction slope.

The HEC-RAS model includes all of these terms. The hydrological routing model used by SSARR includes the continuity equation, but neglects all momentum terms except the gravity force term and the friction force term, which are assumed to be equal. i.e. the energy slope is assumed to equal to the bed slope.

This is approximately equal for gradually rising flows, but on the rising limb of the PMF hydrograph the water slope will be steeper, increasing flow velocities, reducing travel times and reducing the attenuation of flood peaks at the dam sites.

9.1.3 Post-Project PMF Routing

In the post-project HEC-RAS PMF model the salient features of Gull Island and Muskrat Falls dams and spillways from SNC-AGRA[20],[21] were added to the model definition data set. In the post-project model the water level at each dam is maintained at full supply level by opening gates until the gate capacity is exceeded, when the reservoirs are allowed to surcharge and emergency spillway facilities come into play. The full supply levels used in the model were 125 m and 39 m, for Gull Island and Muskrat Falls dams, respectively.

Figures 9.7 and 9.8 show the pre-project and post-project HEC-RAS PMF hydrographs at Gull Island and Muskrat Falls, respectively. The introduction of the dams reduces the PMF peaks by 14%, from 24,260 m^3/s to 20,800 m^3/s at Gull Island and from 26,020 m^3/s to 22,420 m^3/s at Muskrat Falls.

The introduction of the dams widens the live storage area of the valley above each dam. This means that the area of flow will be much wider than in the pre-project condition and, as a consequence, the increase in depth during the PMF will be less than in the pre-project condition. This and the loss of momentum to reservoir storage will reduce the slope of the water surface and slow the flow down. In turn the reduced velocity of flow will increase travel times and increase attenuation of the flood peak.

Comparison of the pre- and post-project hydrographs shows that the flow volume attenuated from the peak of the pre-project hydrographs is displaced to the recession limb of the post-project hydrographs over several days until the both hydrographs revert to approximately the same profile on the recession limb.

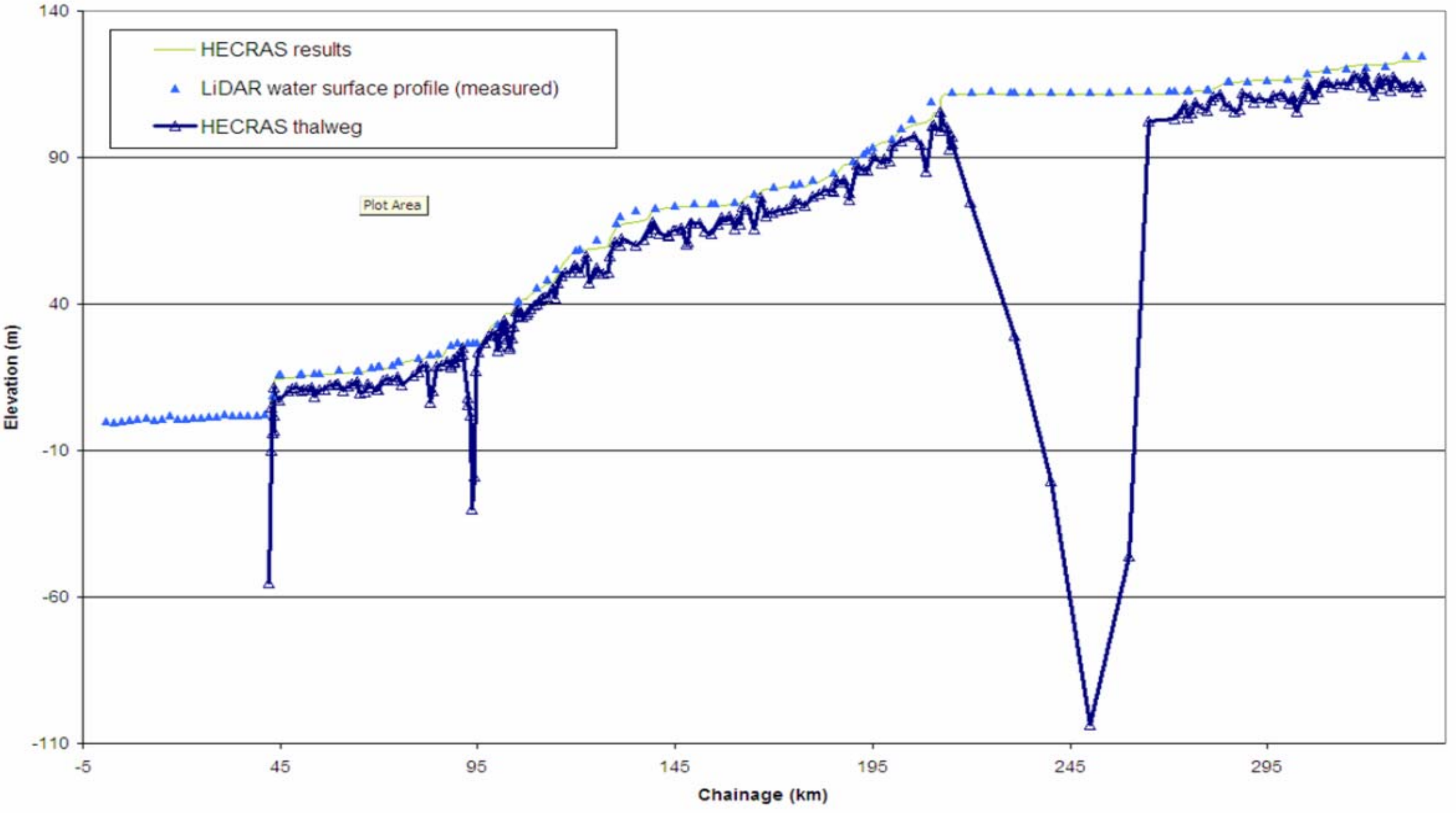


Figure 9.1

Lower Churchill Project

PMF and Construction Design Flood Study

HEC-RAS MODEL CALIBRATION

HATCH™

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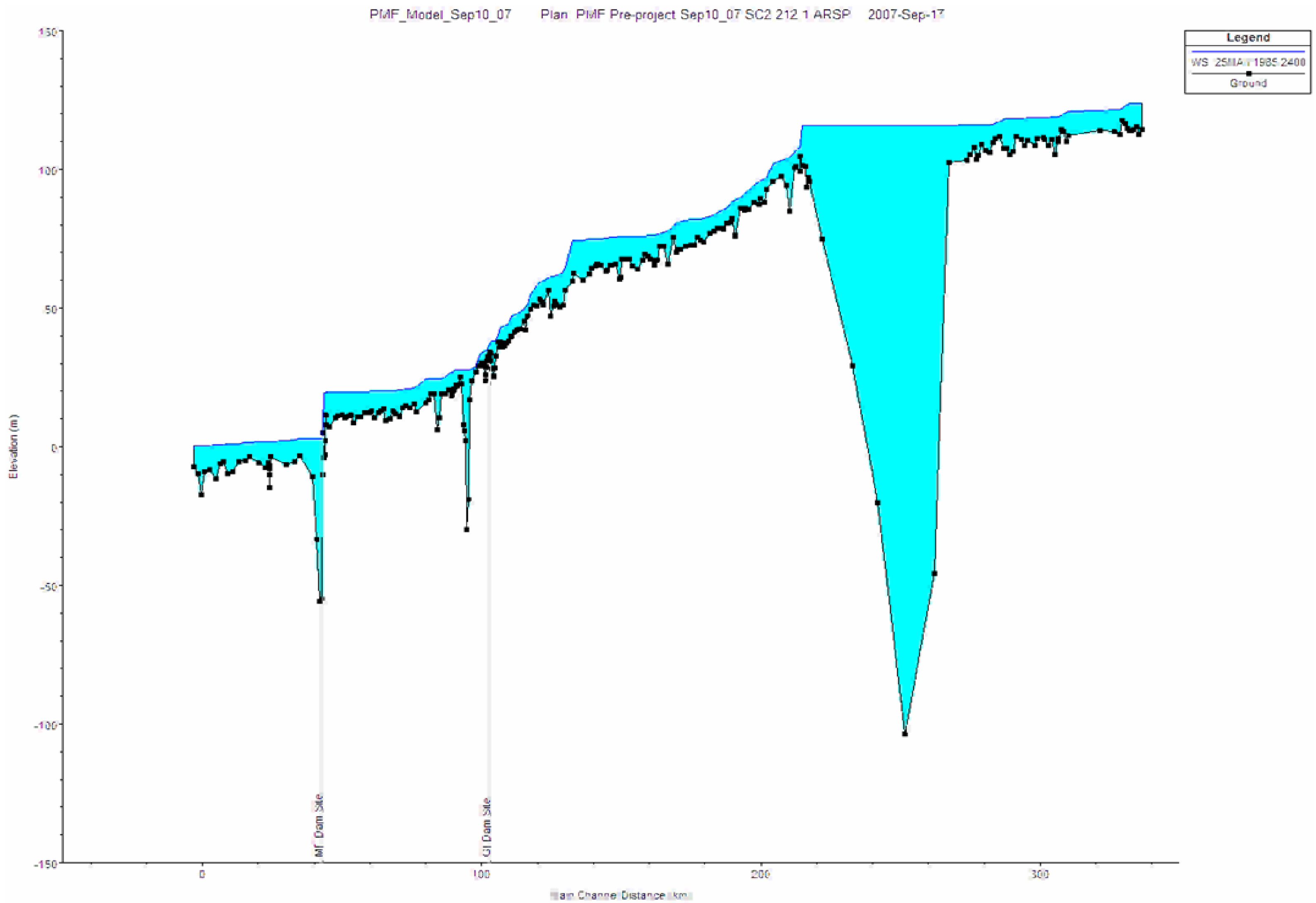

Figure 9.2

Lower Churchill Project

PMF and Construction Design Flood Study

HEC-RAS PRE-PROJECT PROFILE

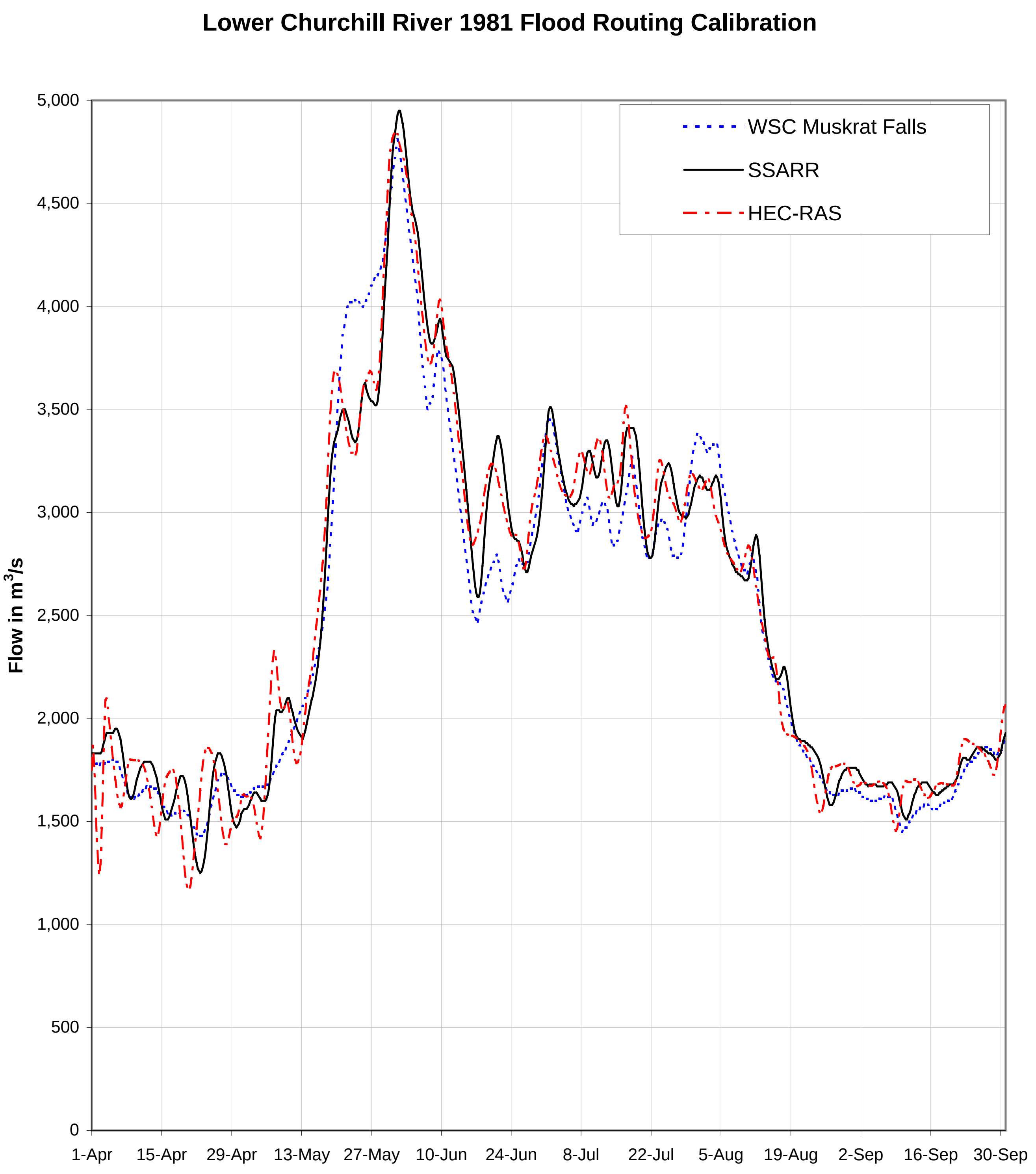

Figure 9.3
Lower Churchill Project
PMF and Construction Design Flood Study
LOWER CHURCHILL RIVER 1981 FLOOD ROUTING CALIBRATION

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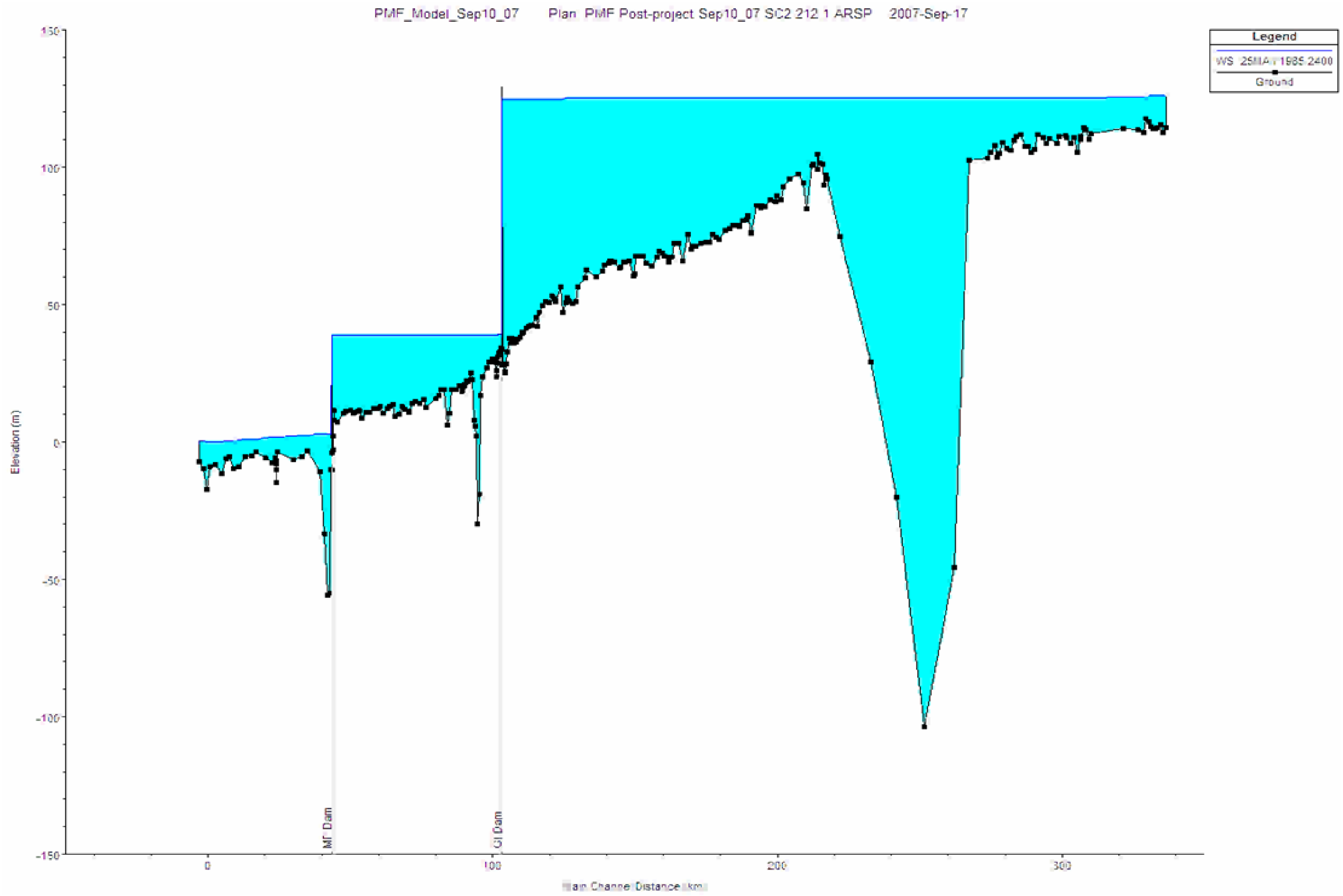

Figure 9.4
Lower Churchill Project
PMF and Construction Design Flood Study
HEC-RAS POST-PROJECT PROFILE

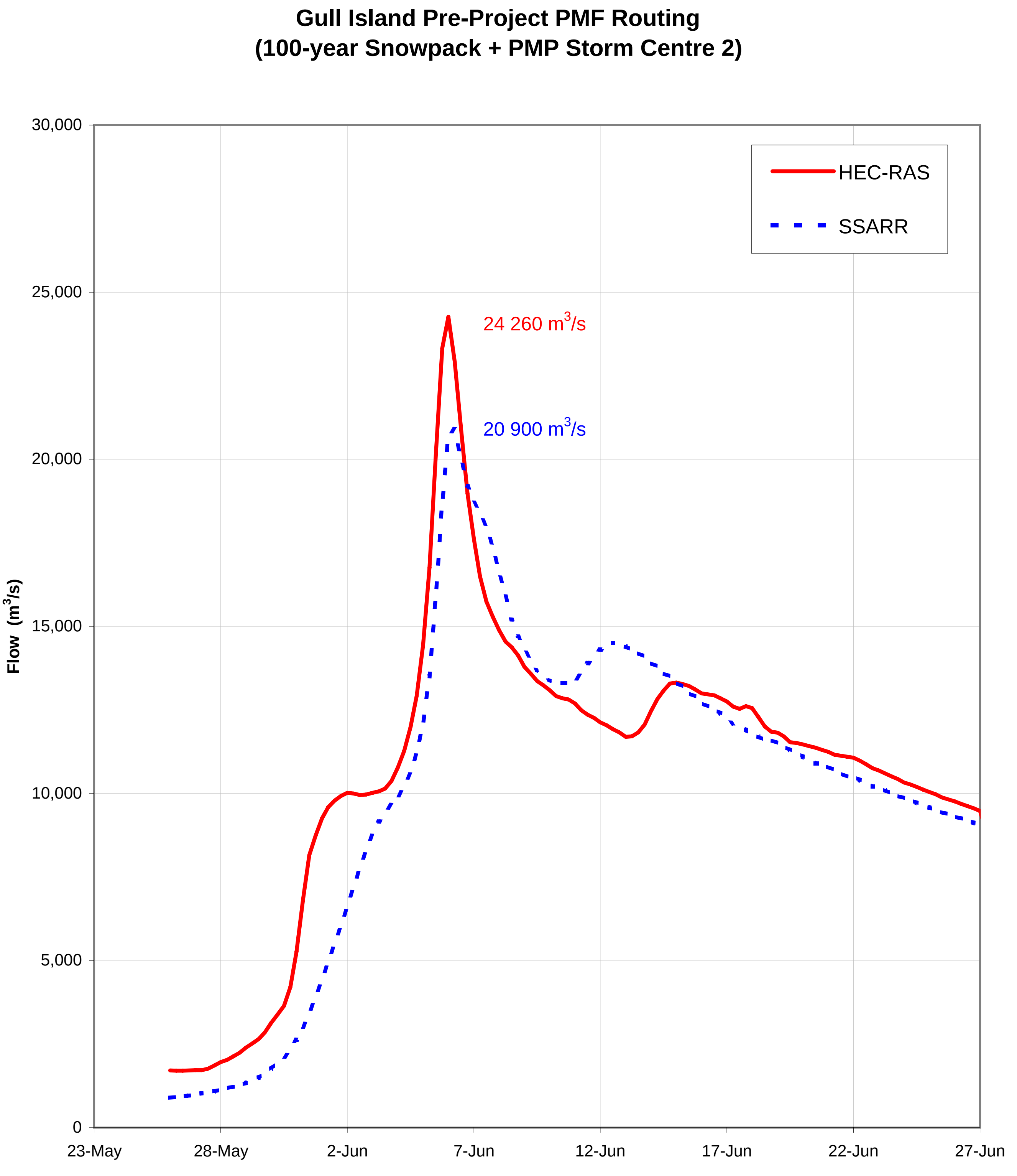

Figure 9.5
Lower Churchill Project
PMF and Construction Design Flood Study
GULL ISLAND PRE-PROJECT PMF ROUTING

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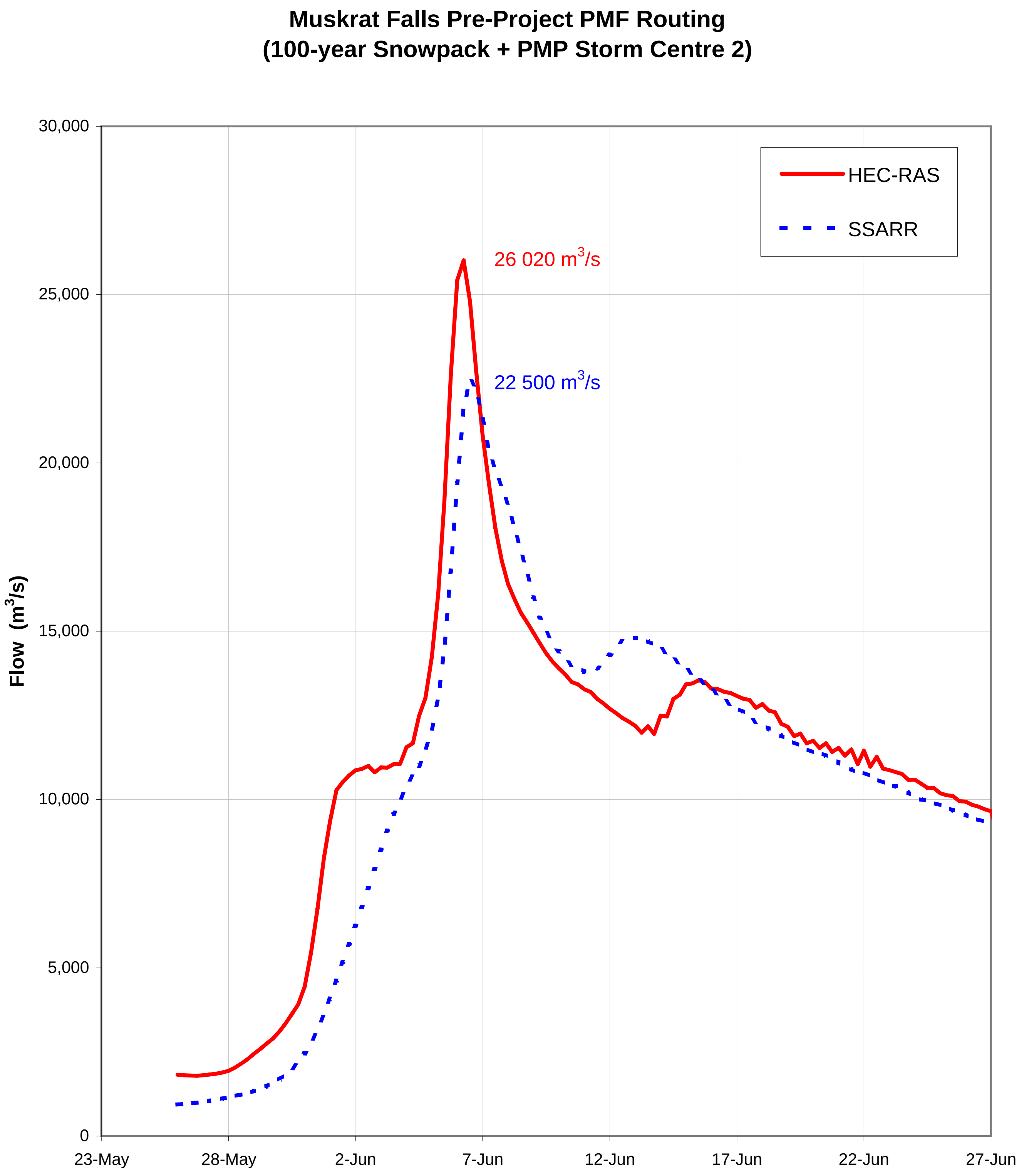

Figure 9.6
Lower Churchill Project
PMF and Construction Design Flood Study
MUSKRAT FALLS PRE-PROJECT PMF ROUTING

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Gull Island Pre- and Post-Project PMF Dynamic Routing (100-year Snowpack + PMP Storm Centre 2)

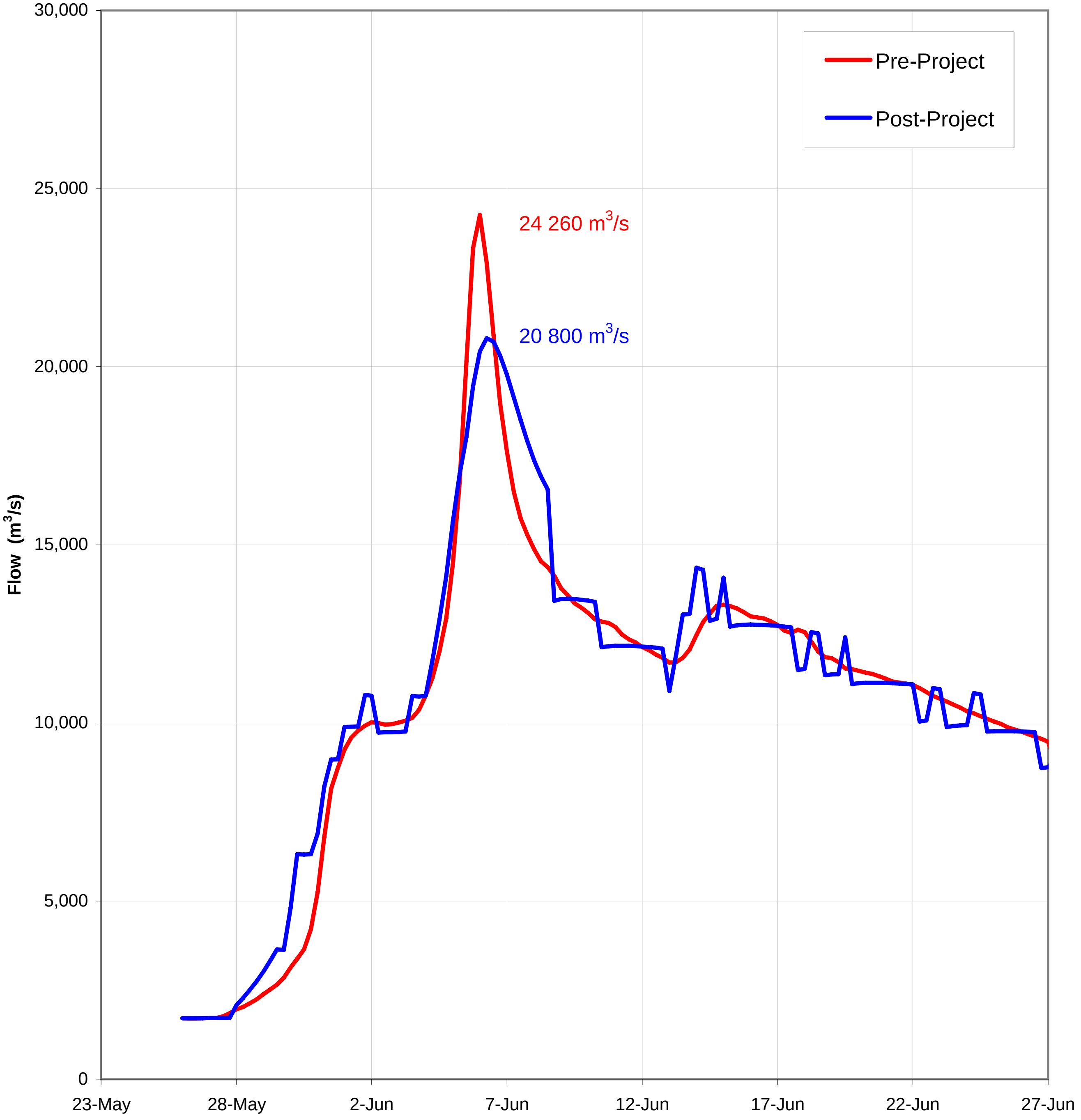

Figure 9.7
Lower Churchill Project
PMF and Construction Design Flood Study
GULL ISLAND PRE AND POST PROJECT PMF DYNAMIC ROUTING

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Muskrat Falls Pre- and Post-Project PMF Dynamic Routing (100-year Snowpack + PMP Storm Centre 2)

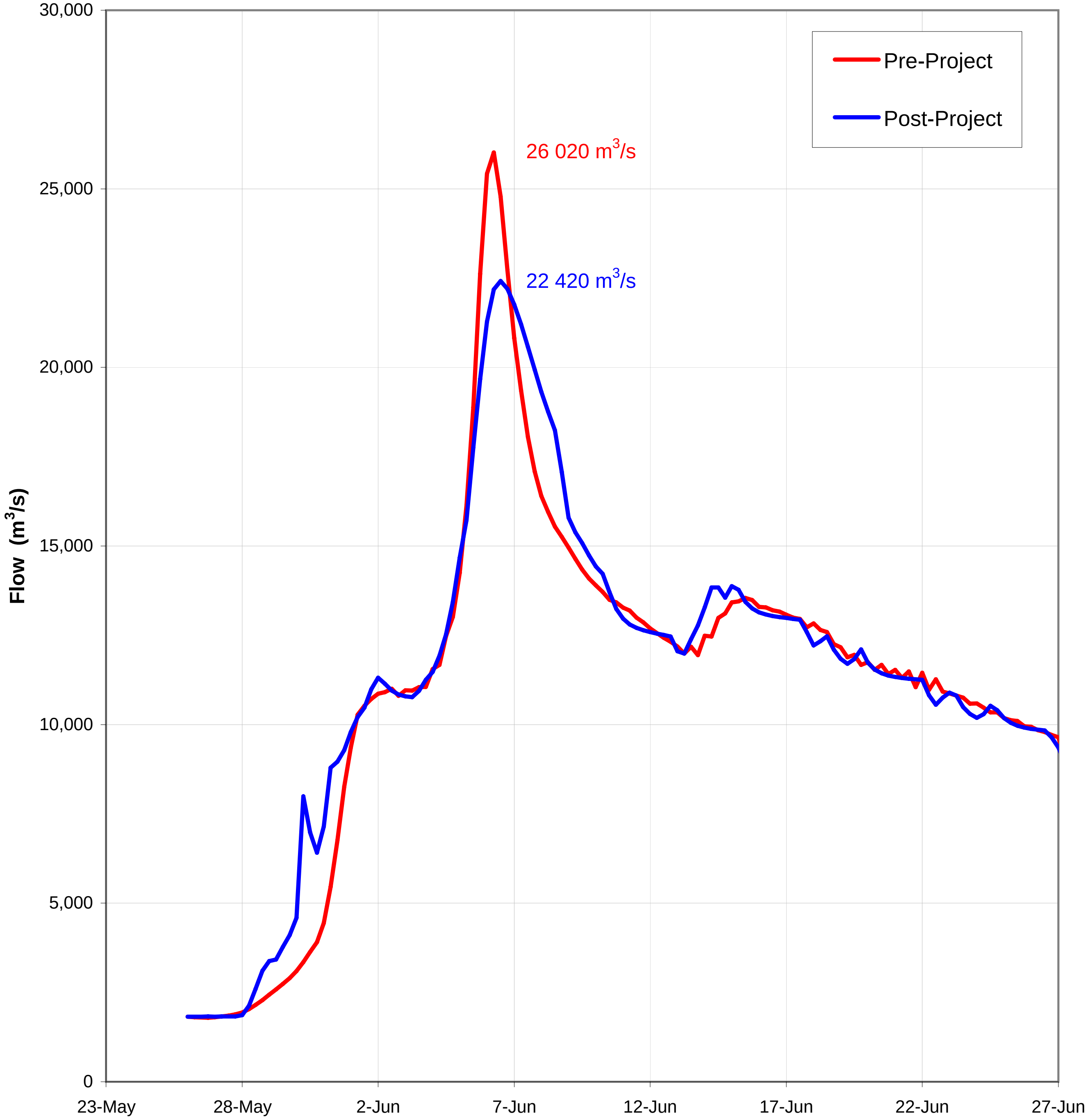

Figure 9.8
Lower Churchill Project
PMF and Construction Design Flood Study
MUSKRAT FALLS PRE AND POST PROJECT PMF DYNAMIC ROUTING

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10. Construction Design Floods

10.1 Previous Studies

The construction design floods for Gull Island and Muskrat Falls were considered by SNC-AGRA[20],[21] during the Feasibility Studies for the two projects.

SNC-AGRA conducted statistical flood studies of the inflow volumes and peaks to Smallwood Reservoir and Ossokmanuan/Gabbro Lake, as well as local inflows to the Lower Churchill River at Muskrat Falls. In the SNC-AGRA analysis flood events of 20-year and 40-year return periods were assumed to occur simultaneously in all three basins, with the routed floods having the same return periods at each dam site.

Floods into the Upper Basin storages included diverted flows from the Saint-Jean and Romaine rivers. The 1:20 and 1:40 year floods were extrapolated graphically from 1:100, 1:1,000 and 1:10,000-year floods from Acres 1989 Flood Handling Study. Hydrographs for these floods were then pro-rated to each reservoir from the 1:100-year flood hydrographs. Flood peaks in the Lower Churchill River were estimated from a frequency analysis of net inflows, i.e. Churchill River at Upper Muskrat Falls (03OE001) – Churchill Falls Powerhouse releases (03OD005). Nineteen years of data (1975 – 1995) were used in the analysis and a negatively skewed GEV distribution gave a 1:40-year flood peak of 4,410 m^3/s at Muskrat Falls.

Two flood routing scenarios were considered for the Upper Basin projects:

1. May 1st starting water levels at the PMF maximum rule curve level, i.e. 469.68m in Smallwood Reservoir and 475.03m in Ossokmanuan/Gabbro Lake. Flood routing was then conducted in strict accordance with the 1989 Flood Handling Procedures. This scenario would result in a 1:40-year flood peak of 8,800 m^3/s at Muskrat Falls.
2. Diversions from Saint-Jean and Romaine rivers shut down if the snowpack at the start of the flood is greater than 300 mm. The maximum starting water level in Smallwood Reservoir on May 1st is lowered to 468.50m. Churchill Falls Powerhouse releases are stepped down to 500 m^3/s during the construction flood. Ossokmanuan Control Structure would remain closed and Smallwood Reservoir and Ossokmanuan/Gabbro Lake would be allowed to surcharge above the rule curves to temporarily store the Upper Basin floods. This scenario yielded a 1:40-year diversion design capacity of 5,300 m^3/s at Muskrat Falls.

Construction design flood peaks at Gull Island, 8,100 m^3/s from routing scenario 1 and 4,800 m^3/s from routing scenario 2, were simply pro-rated from those at Muskrat Falls by the ratio of their net drainage areas.

10.2 Changes Since 1999

There have been a number of changes since the SNC-AGRA feasibility studies were completed:

- Diversion of the Saint-Jean and Romaine rivers is no longer included.
- The available flow records include eleven more years of data since 1995.
- The current, more detailed PMF study has been completed for the Churchill River Basin.

Removal of the Saint-Jean and Romaine river diversions reduces the Upper Basin drainage area by 12%, reducing the potential flood inflows to the Upper Basin during the construction period. This will make flood handling in the Upper Basin easier and will reduce the potential for spill to the Lower Basin.

The addition of eleven years of data, including the highest flood at Muskrat Falls since Churchill Falls began operating, provides a better understanding of operating levels in Smallwood Reservoir and a more reliable estimate of the 1:20 and 1:40-year floods in the Lower Churchill River.

The detailed hydrological modelling of the Upper and Lower Churchill River Basins in the current PMF study has demonstrated that natural lake attenuation and flood routing through the storage reservoirs results in non-coincidence of flood peaks from the Upper and Lower Basins.

10.3 2007 Construction Flood Estimates

The two Upper Basin flood routing scenarios propounded by SNC-AGRA were examined in detail in the current analysis to determine which is more likely and the impact this would have on the construction design floods.

10.3.1 Upper Basin Spilling

The possibility of the Upper Basin spilling during a 1:40-year flood event has been reduced since 1999 with the abandonment of the proposed diversion options from the Saint-Jean and Romaine rivers. This reduces the area draining to the Upper Basin by 12% and to Ossokmanuan/Gabbro Lake by 30%.

The potential for spill from the Upper Basin is predicated on a May 1st starting water level in Smallwood Reservoir of 469.68m. As Figure 10.1 shows this level has not been reached on May 1st since the 1989 Flood Handling Study was completed. In fact the May 1st starting level has not reached the reduced operating level of 468.50m, recommended by SNC-AGRA.

This indicates that the combined probability of a May 1st starting level of 469.68m in Smallwood Reservoir and a 1:40-year local inflow flood in the Lower Basin would have a return period greatly in excess of a 1:40-year event.

Further, the occurrence of a 1:40-year flood event in the Upper Basin at the same time as the 1:40-year event in the Lower Basin, as predicated by SNC-AGRA, is not very likely. For example, the 1999 local inflow peak in the Lower Basin had a return period of approximately 40 years, whereas the 1999 flood in the Ashuanipi River at Menihek Rapids (03OA001), the major tributary to Smallwood Reservoir, had a return period of only 2 years. Conversely, the 1975 flood in the Ashuanipi River at Menihek Rapids had a return period between 50 and 100 years, whereas the 1975 local inflow peak in the Lower Basin had a return period of approximately 5 years. This comparison of Upper and Lower Basin flood peaks suggests that it is most unlikely that a 40-year return period flood would occur simultaneously on both basins.

SNC-AGRA state that under flood routing scenario 1 it would be necessary to spill flows from Ossokmanuan Control Structure. Figure 10.2 shows the flood hydrographs for 1975 and 1999, for the Lower Churchill River at Muskrat Falls and the Atikonak River below Atikonak Lake (03OC003), the main inflow to Ossokmanuan Lake. The Lower Churchill River peaks on June 5 in 1975 and June 10 in 1999, 5 days and 13 days, respectively ahead of the Atikonak River. This means that any spills from Ossokmanuan Control Structure will occur after the peak of the flood hydrograph at Muskrat Falls. This echoes the PMF findings in Figures 7.3 and 7.4 where the peak outflow from Ossokmanuan and Smallwood occurs almost one week after the peak at Muskrat Falls.

Thus, any flood in the Lower Basin that would include spill from the Upper Basin would have to have a return period greater than 40 years and would not coincide with the flood peak from local runoff to the Lower Churchill River.

10.3.2 Lower Basin Floods

The statistical flood frequency analysis undertaken by SNC-AGRA was updated with a 28-year data set for the Lower Churchill River at Muskrat Falls from 1978 – 2006 (1989 missing). The analysis was performed for the recorded data set, which incorporates past operation of Churchill Falls Project, and for the local inflows only, i.e. Muskrat Falls (03OE001) - Churchill Falls Powerhouse releases (03OD005).

Figures 10.3 and 10.4 show the results of the frequency analyses using the 3-Parameter LogNormal distribution. The additional years of data, in particular the high flood peak of 6,280 m^3/s in 1999, result in un-skewed frequency distributions and increased return period flood peaks, compared to the SNC-AGRA estimates from the negatively skewed GEV distribution.

The estimated 1:20 and 1:40-year flood peaks at Muskrat Falls are shown below:

Return Period (years)	**20**	**40**
Local Inflow (m^3/s)	4,510	4,900
Total Flow (m^3/s)	5,930	6,500

There are no flood data for the Lower Churchill River at Gull Island, so appropriate pro-ration factors were required to transpose the Muskrat Falls floods to Gull Island. SNC-AGRA used a simple ratio of drainage areas at the two dams giving a factor of 0.86. However, this implies all tributaries would peak at both dams at the same time. In reality floods from tributaries at the west end of the Lower Basin will take longer to reach the dams than floods from tributaries close to the dams. Thus, when the cumulating flood reaches Muskrat Falls the flood peak from the Pinus River, which joins the Lower Churchill River between Gull Island and Muskrat Falls, will already have peaked and will be in recession. This means that the local inflow peaks estimated by SNC-AGRA for Gull Island were underestimated.

Table 10.1 shows a comparison of the historical flood peaks at Gull Island and Muskrat Falls from the calibrated SSARR model used in the PMF analysis. The average ratios of flood peaks at the two locations are 0.91 and 0.93, for local flood peaks and total flood peaks, respectively. Applying these ratios to the Muskrat Falls flood peaks above gives the following values for Gull Island:

Return Period (years)	**20**	**40**
Local Inflow (m^3/s)	4,120	4,480
Total Flow (m^3/s)	5,540	6,070

For design purposes the critical construction flood peaks at each site will be the sum of the local inflow flood peak given above, plus the minimum acceptable generation flow through Churchill Falls Powerhouse.

The total return period flood peaks estimated for Gull Island and Muskrat Falls represent the expected flood peaks with Churchill Falls operation following the historical pattern, i.e. with no downstream constraints. This historical operation could add between 1,400 m^3/s and 1,600 m^3/s to the flood peak at each dam site. To avoid this increase in flood peaks, generation flow through Churchill Falls Powerhouse would have to be cut back and the unreleased flow would have to be stored in Smallwood Reservoir.

The potential surcharging of Smallwood Reservoir that would result from reducing powerhouse flows during the 1:40-year flood was analyzed for the 5,300 m^3/s diversion capacity previously proposed for Muskrat Falls, SNC-AGRA[21]. Flood hydrographs at Muskrat Falls were analyzed to define an average flood volume and a maximum flood volume for a given flood peak. These two hydrographs were then pro-rated to the 1:40-year total flood peak of 6,500 m^3/s at Muskrat Falls.

Figure 10.5 shows average and maximum 1:40-year hydrographs at Muskrat Falls together with the previous diversion capacity. All flow above the 5,300 m^3/s diversion capacity would have to be retained in Smallwood Reservoir. The impacts on Smallwood Reservoir are shown below:

Hydrograph Shape	Average	Maximum
Retained Volume (hm^3)	362	591
No. of Days	6	10
Reservoir Rise (cm)	6	10

Thus, restricting powerhouse outflows during the peak of the 1:40-year construction design flood would have a negligible impact on Smallwood Reservoir. There could also be the possibility of using Gull Island surcharge to reduce peak at Muskrat Falls.

10.4 Conclusion

SNC-AGRA presented two potential construction flood scenarios:

- A strict application of the current flood handling procedures combined with:
  - A May 1st starting level of 469.68m in Smallwood Reservoir
  - Coincident 1:40-year floods in the Upper and Lower Basins
  - Coincident timing of these flood peaks at Muskrat Falls
- A modified flood handling procedure to be adopted during construction:
  - A May 1st starting level of 468.50m in Smallwood Reservoir
  - Powerhouse releases stepped down to 500 m^3/s during the peak of the flood
  - No releases from Ossokmanuan Control Structure.

The first of these two scenarios produced a diversion requirement of 8,800 m^3/s at Muskrat Falls, but is overly conservative, requiring the coincidence of extreme conditions that have not been demonstrated since commissioning Churchill Falls Project. This combination of conditions would have a return period well in excess of 40 years and can be dismissed as unrealistic.

The second flood scenario is reasonable and produced diversion design capacities of 5,300 m^3/s at Muskrat Falls and 4,800 m^3/s at Gull Island. This modified operation requires very little change to historical spring operation at Churchill Falls other than stepping down the powerhouse releases during the peak of the flood. However, there are several issues related to this scenario that will affect the diversion design capacities recommended by SNC-AGRA:

1. The 1:40-year local inflow peak to Muskrat Falls was previously estimated as 4,410 m^3/s from a negatively skewed distribution based on 19 years of data. The current frequency analysis using an un-skewed distribution based on 28 years of data results in 1:40-year local inflow peak to Muskrat Falls of 4,900 m^3/s. This change will increase the diversion design capacities recommended by SNC-AGRA by ± 500 m^3/s.
2. The minimum acceptable turbine flow at Churchill Falls, and how long it can be sustained, must be negotiated with CF(L)Co.
3. The timing of turbine flow reductions in the SNC-AGRA flood routing appears to have been selected with complete foreknowledge of local inflows and without any lag for the travel time from Churchill Falls to Muskrat Falls. The typical travel time from Churchill Falls to Muskrat Falls is three days. In May 1999 the flow at Muskrat Falls rose from 2,000 m^3/s to 6,000 m^3/s in five days. Thus a flood forecasting procedure is required to enable turbine flows to be reduced at least three days ahead of the natural flood peak at Muskrat Falls. This flood forecasting analysis should also include the use of a dynamic hydraulic model of the Lower Churchill River to ensure that a reduction in powerhouse releases at Churchill Falls will result in a corresponding reduction in flows at Gull Island and Muskrat Falls within the expected timeframe.

Table 10.1
Flood Peak Comparison from SSARR Model

Year	Total Peaks (m^3/s)			Local Peaks (m^3/s)			
	MF	GI	Ratio	CF	MF	GI	Ratio
1980	4760	4457	0.94	1600	3160	2857	0.90
1981	4951	4617	0.93	850	4101	3767	0.92
1982	4868	4441	0.91	1500	3368	2941	0.87
1999	6833	6239	0.91	1140	5693	5099	0.90
2000	3969	3701	0.93	1130	2839	2571	0.91
2002	4707	4489	0.95	1110	3597	3379	0.94
2004	3747	3676	0.98	940	2807	2736	0.97
Average	**4834**	**4517**	**0.93**	**1181**	**3652**	**3336**	**0.91**
PMF	**22500**	**20900**	**0.93**	**5000**	**17500**	**15900**	**0.91**

Notes

1. MF	Muskrat Falls
2. GI	Gull Island
3. CF	Churchill Falls Powerhouse

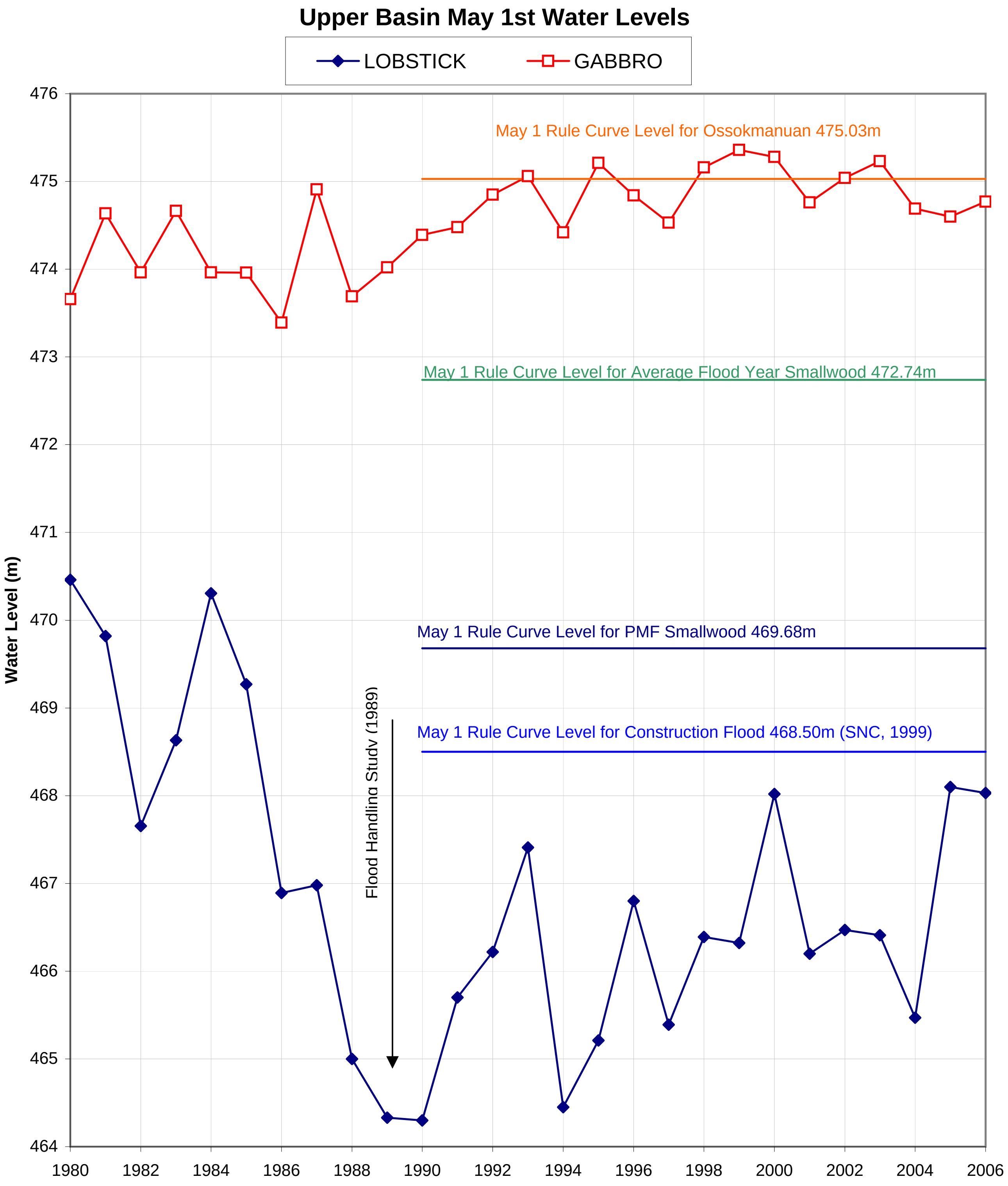

Figure 10.1
Lower Churchill Project
PMF and Construction Design Flood Study
UPPER BASIN MAY 1st WATER LEVELS

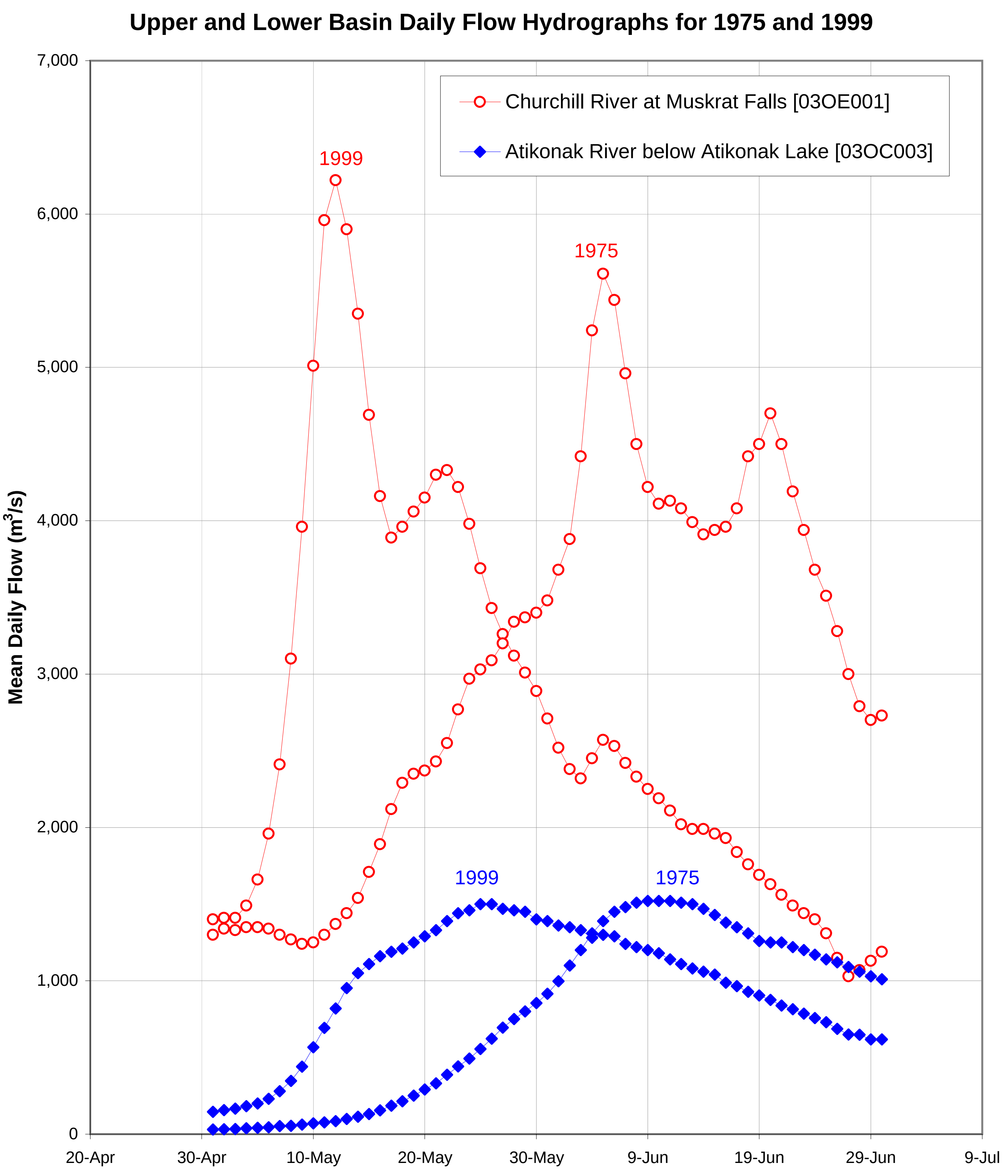

Figure 10.2
Lower Churchill Project
PMF and Construction Design Flood Study
UPPER AND LOWER BASIN DAILY FLOW HYDROGRAPHS FOR 1975 AND 1999

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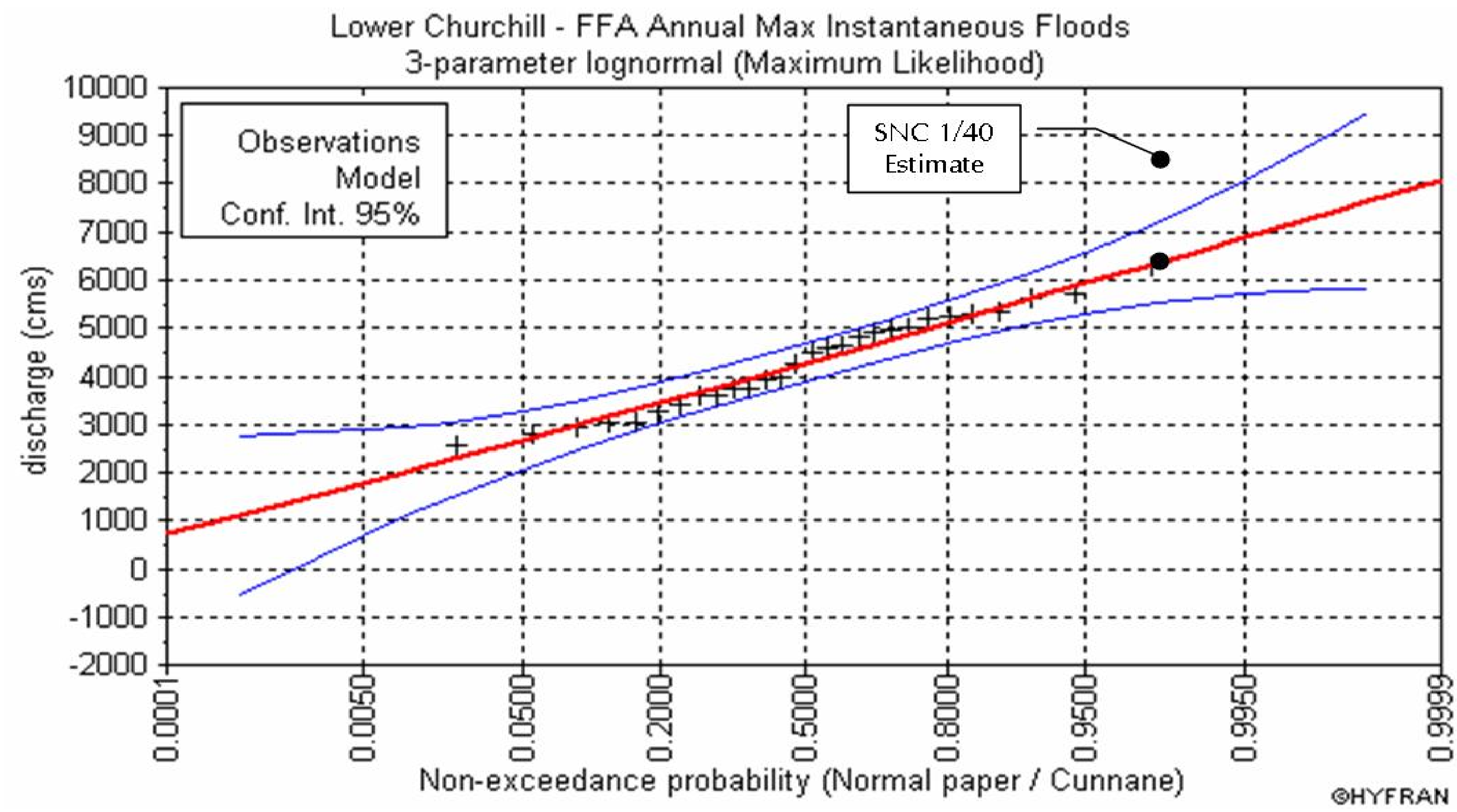

Figure 10.3
Lower Churchill Project
PMF and Construction Design Flood Study
MUSKRAT FALLS - TOTAL FLOOD FREQUENCY DISTRIBUTION

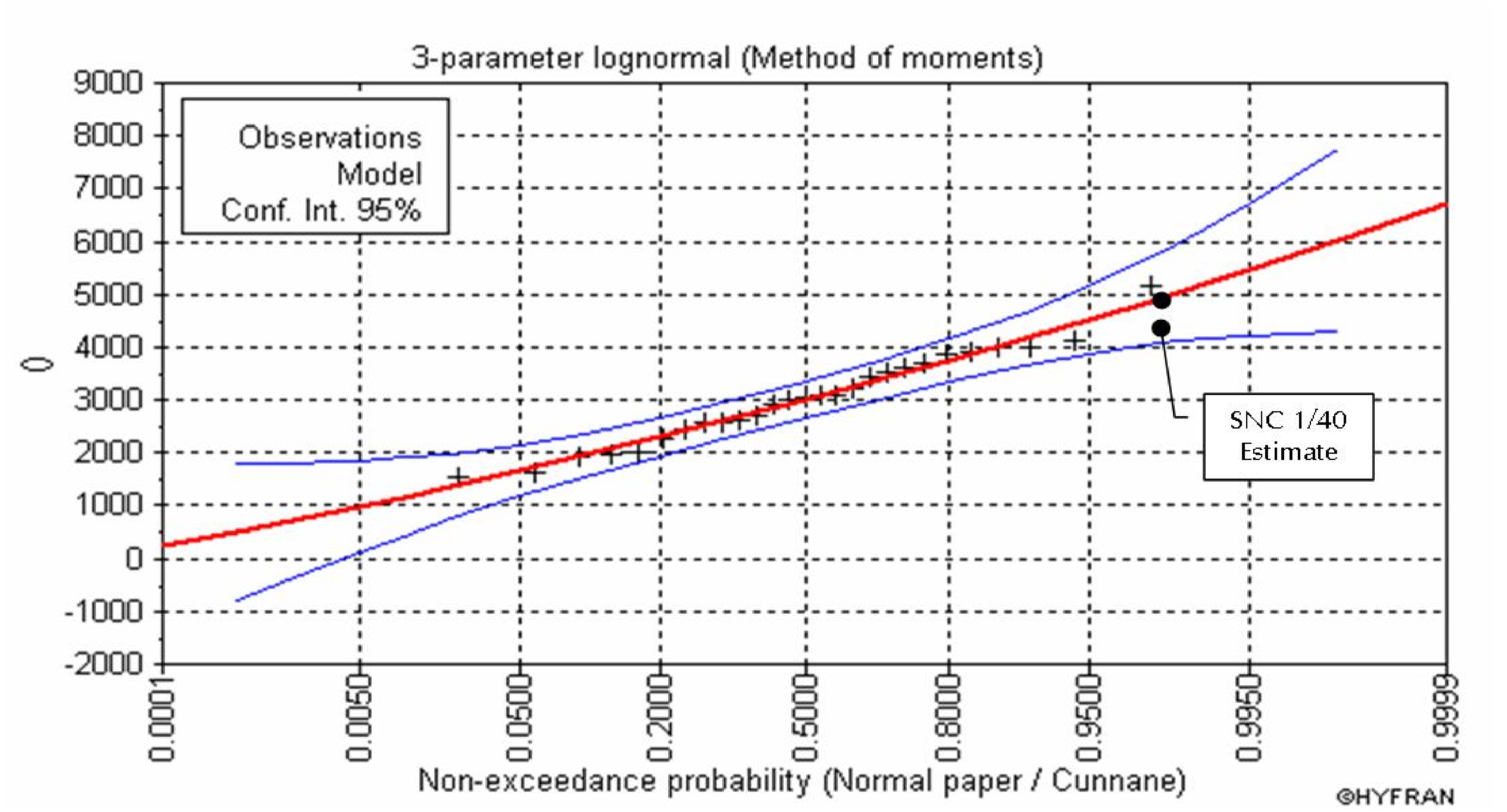

Figure 10.4
Lower Churchill Project
PMF and Construction Design Flood Study
MUSKRAT FALLS - LOCAL FLOOD FREQUENCY DISTRIBUTION

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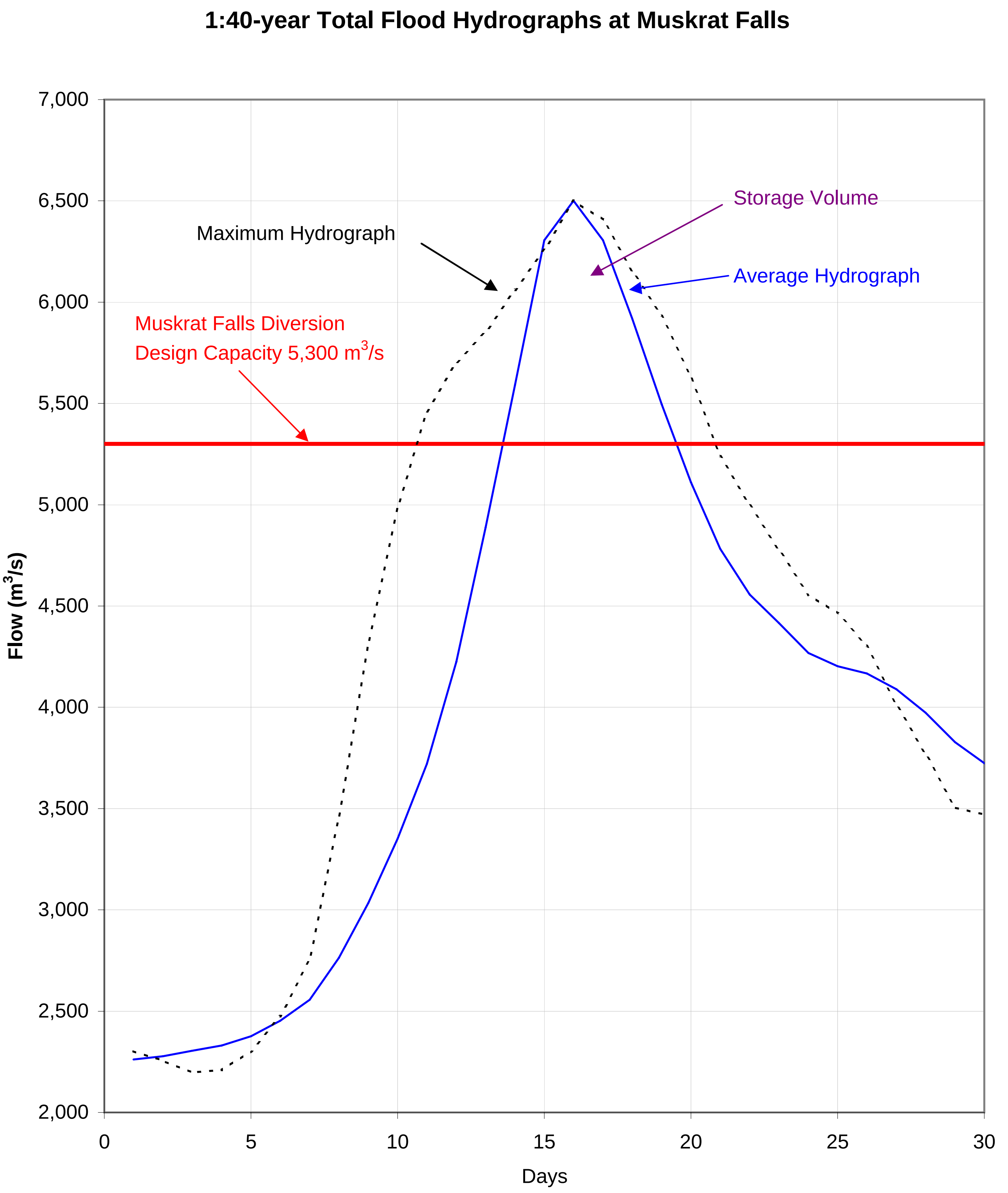

Figure 10.5

Lower Churchill Project

PMF and Construction Design Flood Study

1:40 YEAR TOTAL FLOOD HYDROGRAPHS AT MUSKRAT FALLS

11. Future Flood Handling Procedures at Churchill Falls Project

11.1 Current Flood Handling Procedures

The current operating procedures for the Churchill Falls Project during floods are based on the Flood Handling Study prepared by Acres[6] in 1989. A brief description of these procedures is given in Section 8.

The 1989 Flood Handling Study was based on the 1969 PMF, comprising:

• May 1st snowpack	687 mm (767 mm in total – PMSA)
• PMP (5 days)	172 mm
• May to July Volume	$68,180 \times 10^6$ m^3
• Maximum Smallwood Reservoir water level	473.66 m.

The PMF for the Churchill Falls Project has not been maximized in the current study, but the following numbers apply for PMP storm centre 5, centered over Smallwood Reservoir:

• May 1st snowpack	536 mm (100-year SWE)
• PMP (66-hours)	151 mm
• May to July Volume	$39,200 \times 10^6$ m^3
• Maximum Smallwood Reservoir water level	471.72 m.

The differences between these PMF estimates can be attributed to three factors:

1. In 1969 the PMSA was combined with the spring PMP; the CDA guidelines now dictate that any secondary component of the PMF should not be greater than a 100-year event. This accounts for 23% of the difference between the 1969 and 2007 estimates.
2. The 1969 PMP was the maximum for this area from the DAD curve over 5-days. The 2007 PMP storm was not oriented for maximum areal precipitation over the Upper Basin. This accounts for 2% of the difference between the 1969 and 2007 estimates.
3. The reported May to July runoff volume in 1969 was $68,180 \times 10^6$ m^3 from 67,558 km^2 (does not include Forebays). This is equivalent to 1009 mm of runoff from 939 mm snowmelt and PMP. An additional 130 mm precipitation between May and July was included in the 1969 model giving 94% runoff May-July. The 2007 May to July runoff volume was $39,200 \times 10^6$ m^3 from 69,200 km^2 (includes Forebays). This is equivalent to 566 mm of runoff from 687 mm snowmelt and PMP, or 83% runoff. In 2007 the large natural lakes were included explicitly in the model and these lakes attenuate the PMF runoff beyond the end of July.

Thus, the detailed PMF modelling for the Upper Basin following the current CDA guidelines suggests that the PMF used to define the flood handling procedures for the Churchill Falls Project are overly conservative. As a result the operating rule curves for the PMF are also too conservative and should be revised using the PMF models from the current study.

11.2 Future Flood Handling Procedures

It has been assumed, based on conversations, that CF(L)Co. has no plans to modify the flood handling operation of the Churchill Falls Project when the Lower Churchill Projects are constructed.

However, the PMF comparison above suggests that Smallwood Reservoir could safely be surcharged a further 1.5 m up to the Maximum Flood Level 473.23 m during a PMF centred over the Upper Basin.

The critical PMF for the Lower Churchill Projects, with the PMP over storm centre 2, only raises Smallwood Reservoir level to 471.25 m, so there would be a further 0.47 m freeboard available in Smallwood Reservoir during this PMF scenario.

Thus, the Churchill Falls Project appears to have the potential to reduce the PMF peaks in the Lower Basin by retaining the initial PMF runoff in the Upper Basin until the peak of the local PMF in the Lower Basin has passed.

Reference to the ARSP model results in Section 8 indicates that the release from the Upper Basin three days ahead of the peak at Muskrat Falls is ±5,000 m^3/s and the PMF peaks at Gull Island and Muskrat Falls are 24,300 m^3/s and 26,000 m^3/s pre-project; 20,800 m^3/s and 22,400 m^3/s post-project. Running the HEC-RAS model with zero outflows from the Upper Basin reduces these PMF peaks to 20,250 m^3/s and 21,730 m^3/s pre-project at Gull Island and Muskrat Falls; 18,650 m^3/s and 20,160 m^3/s post-project. Thus, the reduction in outflow from the Upper Basin is attenuated to ±4,200 m^3/s pre-project at the downstream sites and ±2,200 m^3/s post-project.

To take advantage of the flood surcharge available in Smallwood Reservoir to minimize the PMF peaks at the downstream projects the Operating Rule Curves for the Upper Churchill Project need to be revised for the benefit of the Upper and Lower Basin Projects using the latest PMF models.

To test whether the rule curve for Smallwood can be modified to benefit the Lower Basin projects without endangering the Churchill Falls Project, the starting level in Smallwood Reservoir was lowered from 469.68 m to 468.00 m for the PMF routing, but the existing rule curves were retained. Lowering the May 1st starting level would delay the spill from Jacopie Spillway by 5 days and the only outflow from the Churchill Falls Project would be via the Forebay spillways.

When this modified outflow hydrograph was entered in the HEC-RAS model for the Lower Churchill Projects the spillway peaks were reduced by ±2,000 m^3/s. The maximum water level reached in Smallwood Reservoir was 470.81m. If the reduction in starting level (469.68 – 468.00 = 1.68m) was added to this simulated Smallwood Reservoir level, the maximum level would be 472.49 m. Adding a further 0.47m for the difference between Storm Centres 2 and 5 would give a maximum Smallwood PMF level of 472.96 m, still below the maximum flood level of 473.23m.

In practice raising the rule curve instead of lowering the starting level would result in a smaller surcharge because the incremental storage increases with elevation as the reservoir surface increases.

The form of rule curve required to protect the lower projects as well as the Churchill Falls Project would be slightly different from the current rule curves; there would still be a May 1st maximum water level, depending on the snowpack water equivalent in the basin, but the rule curve would be 1-2 metres above this level to allow the reservoir to surcharge, delaying spills to the Lower Basin. This would have an added benefit that unnecessary pre-spills could more easily be avoided by the additional of the buffer zone between the May 1st maximum starting level and the rule curve level at which spills must commence.

This appears to be the de facto way in which CF(L)Co. actually operates Smallwood Reservoir, as historical May 1st water levels have always been well below the rule curve levels on this date.

12. Conclusions and Recommendations

12.1 Conclusions

The Lower Churchill River Probable Maximum Flood and Construction Design Flood Study has been completed with the following conclusions.

1. The Lower Churchill Basin Probable Maximum Flood would occur as the result of a warm front melting a 100-year snowpack, followed by a spring Probable Maximum Precipitation.
2. The 100-year basin average snowpack is 535 mm, varying from 533 mm in the Lower Basin to 536 mm in the Upper Basin.
3. The maximum temperatures would be 24° C during the melt period and 16° C during the PMP.
4. The critical spring PMP would have a 66-hour rainfall depth of 286 mm over the central 10 km^2 and would be centered over the Lower Churchill River approximately 70 km west of Gull Island. This PMP would have an average depth of 121 mm, varying from 188 mm in the Lower Basin to 98 mm in the Upper Basin.
5. The SSARR pre-project PMF peaks from a 100-year snowpack and spring PMP would be 20,900 m^3/s at Gull Island and 22,500 m^3/s at Muskrat Falls.
6. The dynamically routed PMF would have pre-project peaks of 24,260 m^3/s at Gull Island and 26,020 m^3/s at Muskrat Falls.
7. Adding the dams, with the configurations given in the feasibility studies, reduces the dynamically routed PMF peaks to 20,800 m^3/s at Gull Island and 22,420 m^3/s at Muskrat Falls.
8. The PMSA basin average snowpack is 623 mm, varying from 618 mm in the Lower Basin to 624 mm in the Upper Basin.
9. The 100-year spring rain storm would have a 66-hour rainfall depth of 76 mm over the central 10 km^2 and would be centered over the Lower Churchill River approximately 100 km west of Gull Island. This 100-year rainfall would have an average depth of 33 mm, varying from 49 mm in the Lower Basin to 28 mm in the Upper Basin.
10. The SSARR pre-project PMF peaks from a PMSA and 100-year rainfall would be 14,300 m^3/s at Gull Island and 14,600 m^3/s at Muskrat Falls.
11. The critical summer/autumn PMP would have a 66-hour rainfall depth of 366 mm over the central 10 km^2 and would be centered over the Churchill Falls Powerhouse. This PMP would have an average depth of 171 mm, varying from 210 mm in the Lower Basin to 159 mm in the Upper Basin.
12. The all-season 100-year rainfall preceding the summer/autumn PMP would have a 66-hour rainfall depth of 100 mm over the central 10 km^2 and would also be centered over the Churchill Falls Powerhouse. This 100-year rainfall would have an average depth of 47 mm, varying from 57 mm in the Lower Basin to 43 mm in the Upper Basin.
13. The SSARR pre-project PMF peaks resulting from a 100-year rainfall followed by a summer/autumn PMP would be 10,700 m^3/s at Gull Island and 10,800 m^3/s at Muskrat Falls.

14. Allowing for travel time from Churchill Falls the Upper Basin contribution to the PMF peaks at Gull Island and Muskrat Falls is ± 5,000 m^3/s.
15. The post-project flood peaks are compared to the Feasibility Studies values and 1999 PMF study values (with 5,000 m^3/s from the Upper Basin) below.

Dam	Feasibility Studies	1999 PMF Study	2007 Study
Gull Island	19,700 m^3/s	21,700 m^3/s	20,800 m^3/s
Muskrat Falls	22,100 m^3/s	24,400 m^3/s	22,420 m^3/s

16. The 20-year and 40-year local inflow flood peak estimates in the Lower Basin have increased with the extension of the flood data set from 19 to 28 years. A comparison of the Lower Basin local inflow flood peaks with the Feasibility Studies values is shown below.

Dam	Feasibility Studies		2007 Study	
	20-year Flood	40-year Flood	20-year Flood	40-year Flood
Gull Island	3,690 m^3/s	3,790 m^3/s	4,120 m^3/s	4,480 m^3/s
Muskrat Falls	4,290 m^3/s	4,410 m^3/s	4,510 m^3/s	4,900 m^3/s

17. SNC-AGRA recommended 40-year diversion design floods of 4,800 m^3/s at Gull Island and 5,300 m^3/s at Muskrat Falls. The increases in 40-year local inflow peaks found in the current study would require the timely reduction of generation at Churchill Falls to one or two units to continue with the Feasibility Study diversion capacities and the same level of risk.
18. The significant decrease in the Upper Basin PMF from 1969 to the current study means that the 1989 Flood Handling Procedures for the Churchill Falls Project are overly conservative at the PMF level.
19. Revision of the flood operating procedures for the Churchill Falls Project could reduce the PMF peaks at Gull Island and Muskrat Falls by approximately 2,000 m^3/s.

12.2 Recommendations

The PMF peaks at Gull Island and Muskrat Falls have been modelled in great detail in the current study, including variable storm centres, hydrological modelling of the entire Churchill Basin, decision-based operation modelling of the Churchill Falls Project and dynamic hydraulic modelling of the Lower Churchill River with both dams in place.

It is recommended that:

1. The 1989 Flood Handling Study be updated using the current PMF models to improve the flood operating procedures at the Churchill Falls Project and to delay spills to the Lower Basin to reduce flood peaks at Gull Island and Muskrat Falls.
2. If any changes are made to the spillway configurations of either dam presented in the Feasibility Studies the HEC-RAS post-project model should be used to test the new spillway variants.

The 40-year local inflow flood peaks at each dam site have increased by 500 m^3/s above the Feasibility Studies values. This may necessitate an increase in the proposed diversion capacities at each dam.

It is recommended that:

1. A flood forecasting analysis be undertaken to allow early prediction of local flood inflows.
2. The minimum acceptable turbine flow at Churchill Falls during construction should be established with CF(L)Co.
3. The necessary timing of turbine discharge reduction should be verified using the HEC-RAS pre-project model.
4. The capacity of the diversion tunnels should be reviewed upon completion of recommendations 1 to 3.

List of References

1. Canadian Dam Association, “Dam Safety Guidelines”, [draft], September 2006.
2. Acres Canadian Bechtel of Churchill Falls, “Churchill Falls Snowmelt and Frequency Studies for Design Floods”, September 1969.
3. Sparrow, D.M. Department of Transport, Meteorological Branch, “Critical Meteorological Conditions for Maximum Inflow, Churchill Falls Power Development, Newfoundland”, March 1968.
4. Acres Consulting Services Ltd., “Gull Island Hydro-electric Project, Maximum Probable Flood Study”, October, 1975.
5. Pollock, D.M. and Ranahan, W.L., Atmospheric Environment Service, “A Study of the Meteorological Factors for Maximum Flows in the Churchill River at Gull Island, Labrador”, August 1975.
6. Acres International Limited, “Flood Handling Study of the Churchill Falls System”, Main Report, March 1989.
7. Acres International Limited, “Churchill River Complex, PMF Review and Development Study”, January 1999.
8. US Army Corps of Engineers, North Pacific Division, “User Manual – SSARR Model: Streamflow Synthesis and Reservoir Regulation”, January 1991.
9. Acres International Limited, “User’s Manual – ARSP Model: ACRES Reservoir Simulation Package”, 1989.
10. US Army Corps of Engineers, Hydrologic Engineering Center (HEC), “User’s Manual – HEC_RAS Model: River Analysis System”, November, 2006.
11. Banfield, C.E. “The Climatic Environment of Newfoundland”, “The Natural Environment of Newfoundland: Past and Present”, Edited by Macpherson, J.B. and Macpherson, A.G. Department of Geography, Memorial University of Newfoundland, 1981.
12. Acres International Limited, “Flood Handling Study of the Churchill Falls System”, Manual for Spring Operating Procedure for Smallwood Reservoir, March 1989.
13. SNC-Shawinigan, for the Canadian Electrical Association, “Probable Maximum Precipitation (PMP) in Boreal Regions”, CEA No. 9137G929, September 1995.
14. Atria Engineering Hydraulics Inc, for the Canadian Electrical Association, “Probable Maximum Precipitation (PMP) in Boreal Regions”, CEA No. 9111G839, January 1994.
15. World Meteorological Organization, “Manual for Estimation of Probable Maximum Precipitation, Second Edition, Operational Hydrology Report No. 1 WMO-No 332, WMO, Geneva, 1986.
16. Watt, W.E, K.W. Lathem, C.R. Neill, T.L. Richards, J. Rousselle, “Hydrology of Floods in Canada: A Guide to Planning and Design”, NRC, Ottawa, 1989.

17. McKenney, D.W., Hutchinson, M.F., Kesteven, J.L., Venier, L.A., "Canada´s Plant Hardiness Zones Revisited Using Modern Climate Interpolation Techniques", Can. J. Plant Sci. 81: 129-143, 2001.
18. Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood and D. Wratt, "Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change", [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.
19. Natural Resources Canada, "Atlas of Canada (web site)", 2006.
20. SNC-AGRA Joint Venture, "Gull Island Hydro Electric Development, Design Update and Optimization", December 2000.
21. SNC-AGRA Joint Venture, "Muskrat Falls Hydroelectric Development, Final Feasibility Study", January 1999.