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Nalcor Energy - Lower Churchill Project

North Spur Dam Break Analysis

Final Report

MFA-HE-CD-2800-CV-RP-0001-01
Rev. B1
June 26, 2015

Hatch Ref No.: H347178-0000-00-124-0001

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REGISTERED PROFESSIONAL ENGINEER
MICHAEL M. ROSALES
SIGNATURE
June 26, 2015
DATE
NEWFOUNDLAND & LABRADOR

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1. Introduction

Nalcor Energy – Lower Churchill Project (NE-LCP) is undertaking construction of the Muskrat Falls hydroelectric development on the lower Churchill River in Labrador. The site is located approximately 34 km upriver of the town of Happy Valley-Goose Bay. In May 2014, NE-LCP engaged Hatch to undertake a dam break study of the North Spur, a natural feature that along with the dams at Muskrat Falls will retain the Muskrat Falls Reservoir.

In 2010, Hatch completed the Muskrat Falls Dam Break Study (MF1330) which simulated the downstream consequences of a hypothetical breach of the North Dam at Muskrat Falls. The purpose of the present study (MF1626) is to investigate the sensitivity of the simulated results to a hypothetical breach of the North Spur.

The scope of work included updating the existing dam break model to include the North Spur; simulation of a hypothetical breach of the North Spur, including assessment of the sensitivity of the results to assumed breach formation time, breach width, and breach bottom elevation; and analysis of results.

Hypothetical dam failures during the predetermined Inflow Design Flood (Probable Maximum Flood – PMF) as well as during “fair weather” conditions were considered in the current study, as specified by the 2007 Canadian Dam Association Dam Safety Guidelines (CDA Guidelines). The PMF inflow hydrograph for Muskrat Falls was determined in the PMF and Construction Design Flood Study (GI1140) completed by Hatch for NE-LCP in 2007. The same inflow hydrology has been used in the current study.

All elevation values cited in this report are referenced to Canadian Geodetic Vertical Datum (CGVD).

2. Model Updates and Breach Parameter Selection

The HEC-RAS dam break model used in MF1330 was updated to add the North Spur to the model geometry and include additional bathymetric detail in the reservoir. The North Spur was represented in HEC-RAS as a "lateral structure" upstream of the North Dam. A "lateral structure" is a geometric element in HEC-RAS that may be used to represent an artificial structure (dam, levee, weir) or similar natural feature on the side of a river channel.

2.1 Breach Scenario and Parameter Selection

The dam breach parameter values selected for the model in MF1330 were applicable to the North Dam, which is a Roller Compacted Concrete (RCC) structure. The North Spur is an earth structure, which would have a different failure mode and different breach characteristics from those of the North Dam. Therefore, an alternative approach was required for estimating the breach width and time of breach formation parameters.

The mode of failure assumed for analysis of the North Spur entailed a progressive landslide that would eventually reduce the crest elevation of the North Spur to that of the upstream water level. At that point, an overtopping breach of the North Spur would commence.

"Base case" breach parameters were calculated using an empirical methodology developed from historic data, published by David C. Froehlich in the technical paper "Embankment Dam Breach Parameters and Their Uncertainties" (Journal of Hydraulic Engineering, December 2008). The breach shape was assumed to be trapezoidal, with side slopes of 1:1. The assumed breach bottom elevation for the analysis was specified by NE-LCP to be 20.5 m, which is the elevation of the top of the bentonite cutoff wall.

The time of breach formation as defined by Froehlich (and in the HEC-RAS breach formation computations) does not include the "breach initiation phase", during which the landslide displaces material from the downstream face and reduces the crest elevation. The time of breach formation starts only with the initiation of the overtopping flow from the reservoir, and represents the length of time for the breach to grow to its full width.

The uncertainties of parameter estimates obtained using an empirical method can be large; therefore, sensitivity analysis was carried out to establish a credible range of hypothetical scenarios. Sensitivity values were as follows.

- Breach width: maximum 600 m (i.e., approximately the full length of the North Spur)
- Time of breach formation: minimum 1.0 hours
- Breach bottom elevation: minimum 10.0 m (i.e., approximate minimum elevation of the river bed upstream of the North Spur)

The various dam breach parameters are summarized in Tables 2-1 and 2-2 below.

Table 2-1: "Fair Weather" Breach Parameters

Scenario	Time of Breach Formation (h)	Average Breach Width (m)	Breach Bottom Elevation (m)
Base Case	11.3	391	20.5
Breach Width Sensitivity	11.3	600	20.5
Formation Time Sensitivity	1.0	391	20.5
Breach Bottom Elevation Sensitivity[1]	7.5	402	10.0

Note:

1. The equations for breach formation time and average breach width are dependent on breach height; therefore these values change as a result of the lower breach bottom elevation.

Table 2-2: PMF Breach Parameters

Scenario	Time of Breach Formation (h)	Average Breach Width (m)	Breach Bottom Elevation (m)
Base Case	10.3	446	20.5
Breach Width Sensitivity	10.3	600	20.5
Formation Time Sensitivity	1.0	446	20.5
Breach Bottom Elevation Sensitivity[1]	7.4	454	10.0

Note:

1. The equations for breach formation time and average breach width are dependent on breach height; therefore these values change as a result of the lower breach bottom elevation.

3. HEC-RAS Analysis Results

3.1 "Fair Weather" Conditions Breach Results

Simulations were undertaken to estimate the impacts of a hypothetical breach of the North Spur on downstream water levels during "fair weather" conditions. The analysis included simulations to test the sensitivity of the results to variations in individual parameters. Table 3-1 below summarizes the results for a number of key downstream locations. For comparison, results from MF1330 for a hypothetical breach of the North Dam are included. Figures 3.1 to 3.4 present the stage hydrographs for key locations, and Figures 3.5 to 3.8 present the flow hydrographs.

General observations from the simulations follow.

- The North Spur base case breach scenario resulted in peak water levels lower than those of the North Dam breach scenario.
- The differences between the peak water levels for the various sensitivities progressively diminish in the downstream direction.
- Among the sensitivity simulations, the highest peak water levels resulted from the breach bottom elevation sensitivity scenario. In that case, the peak water levels were similar to those of the North Dam breach scenario.
- Flood arrival times were generally very similar to the flood arrival times for a hypothetical breach of the North Dam.
- Times to peak water level were typically longer than for a hypothetical breach of the North Dam, because of the longer breach formation time for the North Spur. The North Dam had an assumed time of breach formation of 1 hour, representing a hypothetical monolithic displacement of the RCC structure. When the North Spur time of breach formation was set to the minimum sensitivity value (also 1 hour), it resulted in shorter times to peak water level, closer to those for a hypothetical breach of the North Dam.
- Appendix A includes the results of additional sensitivity simulations that consider possible combinations of the breach widths, breach bottom elevations, and formation times. The most extreme combination of sensitivity parameters resulted in a peak water level at Happy Valley-Goose Bay that was 0.5 m higher and a time to peak that was 0.4 h shorter than for a hypothetical failure of the North Dam.

Table 3-1: HEC-RAS Results – "Fair Weather" Conditions

Scenario	Distance Downstream of Muskrat Falls (km)	Cross Section Description	Maximum Water Level without Breach (m)	Breach Flood Summary				
				Breach Flood Arrival Time (hr)	Peak Water Level (m)	Incremental Depth of Flooding (m)	Maximum Discharge (m^3/s)	Time to Peak Water Level (hr)
North Dam (MF1330)	1.5	D/S Muskrat Falls	2.6	0.0	15.4	12.8	62,200	3.4
	18.7	U/S Blackrock Bridge	1.6	0.6	11.7	10.1	42,000	3.8
	33.6	Happy Valley - Goose Bay	0.7	1.4	6.4	5.7	38,200	6.8
	40.0	Mud Lake	0.5	1.7	5.2	4.7	35,200	7.3
North Spur Base Case	1.5	D/S Muskrat Falls	2.6	0.0	11.1	8.5	28,200	12.6
	18.7	U/S Blackrock Bridge	1.6	0.8	7.8	6.2	24,000	13.5
	33.6	Happy Valley - Goose Bay	0.7	1.6	4.8	4.1	22,300	15.8
	40.0	Mud Lake	0.5	2.1	3.6	3.1	21,000	16.5
North Spur Breach Width Sensitivity	1.5	D/S Muskrat Falls	2.6	0.0	12.3	9.7	33,600	12.0
	18.7	U/S Blackrock Bridge	1.6	0.8	8.7	7.1	29,100	12.7
	33.6	Happy Valley - Goose Bay	0.7	1.6	5.3	4.6	26,800	14.9
	40.0	Mud Lake	0.5	2.1	4.1	3.6	25,000	15.5
North Spur Formation Time Sensitivity	1.5	D/S Muskrat Falls	2.6	0.0	11.6	9.0	35,500	4.3
	18.7	U/S Blackrock Bridge	1.6	0.6	8.2	6.6	26,600	5.3
	33.6	Happy Valley - Goose Bay	0.7	1.3	5.0	4.3	24,100	8.0
	40.0	Mud Lake	0.5	1.7	3.8	3.3	22,400	8.7
North Spur Breach Bottom Elevation Sensitivity	1.5	D/S Muskrat Falls	2.6	0.0	15.2	12.6	53,100	8.8
	18.7	U/S Blackrock Bridge	1.6	0.7	11.5	9.9	41,000	9.1
	33.6	Happy Valley - Goose Bay	0.7	1.5	6.4	5.7	37,700	11.8
	40.0	Mud Lake	0.5	1.8	5.2	4.7	34,900	12.3

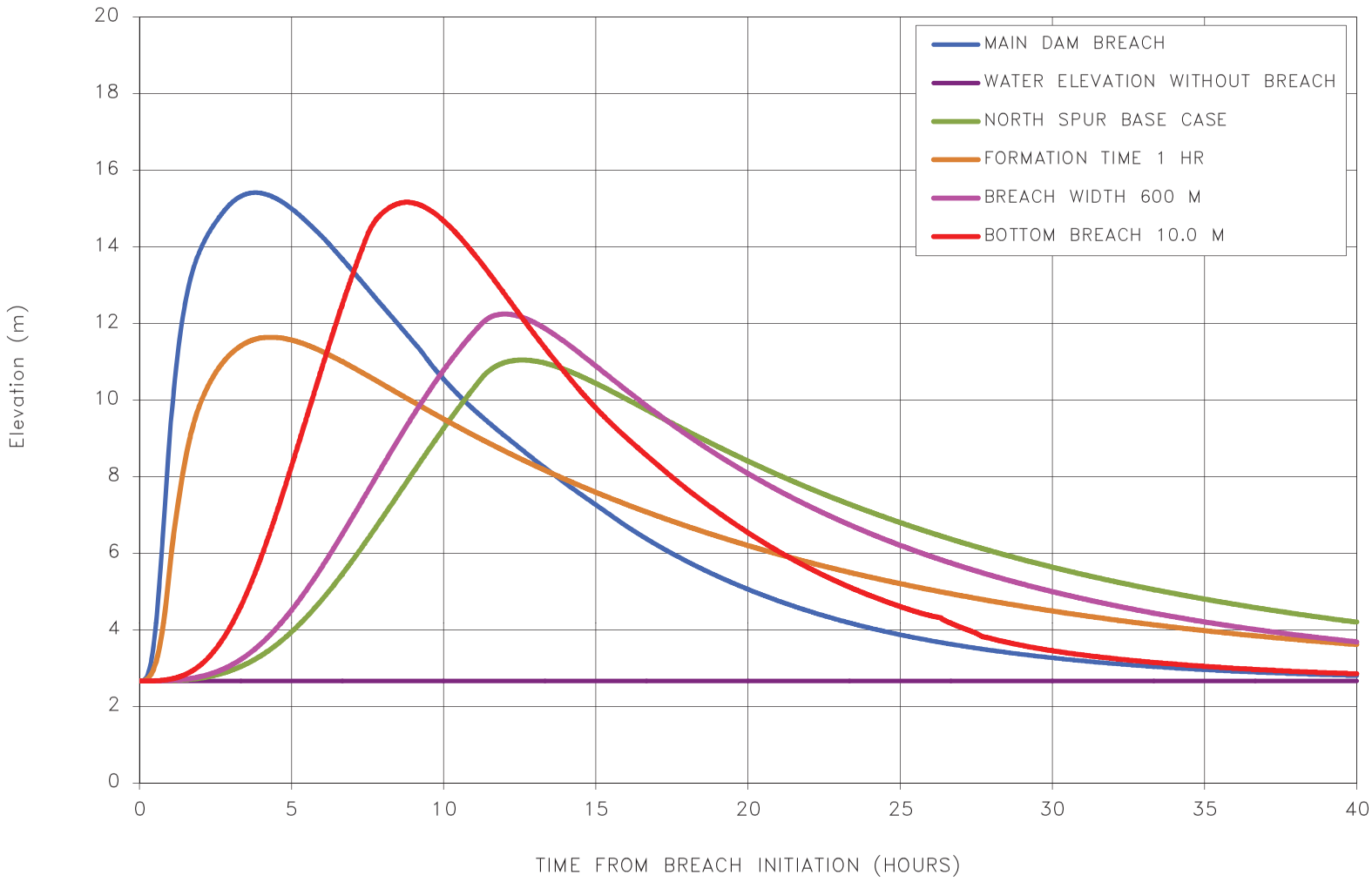

Figure 3.1
Fair Weather Conditions
Stage Hydrographs 1.5 km d/s of Muskrat Falls
North Spur Dam Break Analysis
Nalcor Energy - Lower Churchill Project

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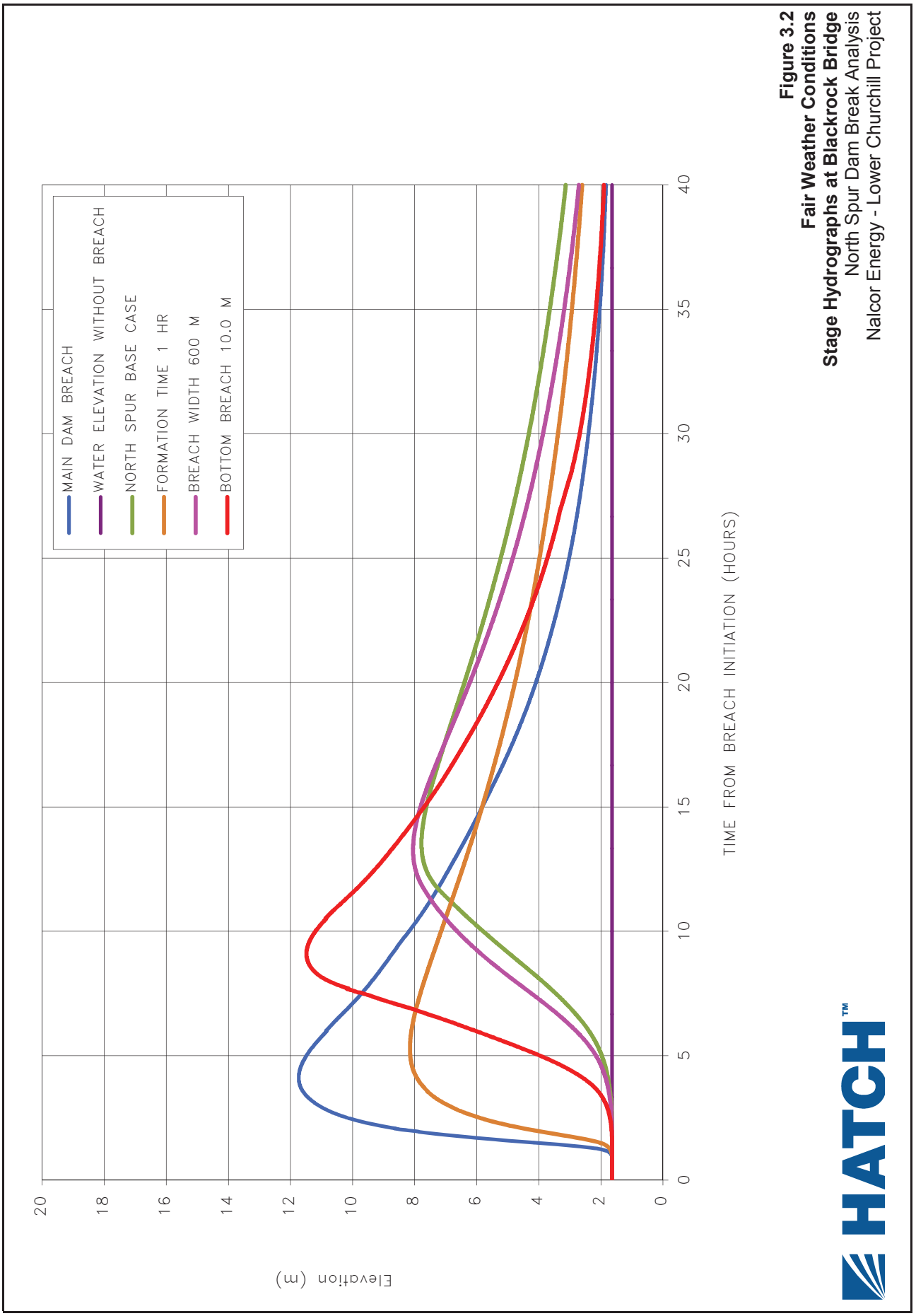

Figure 3.2
Fair Weather Conditions
Stage Hydrographs at Blackrock Bridge
North Spur Dam Break Analysis
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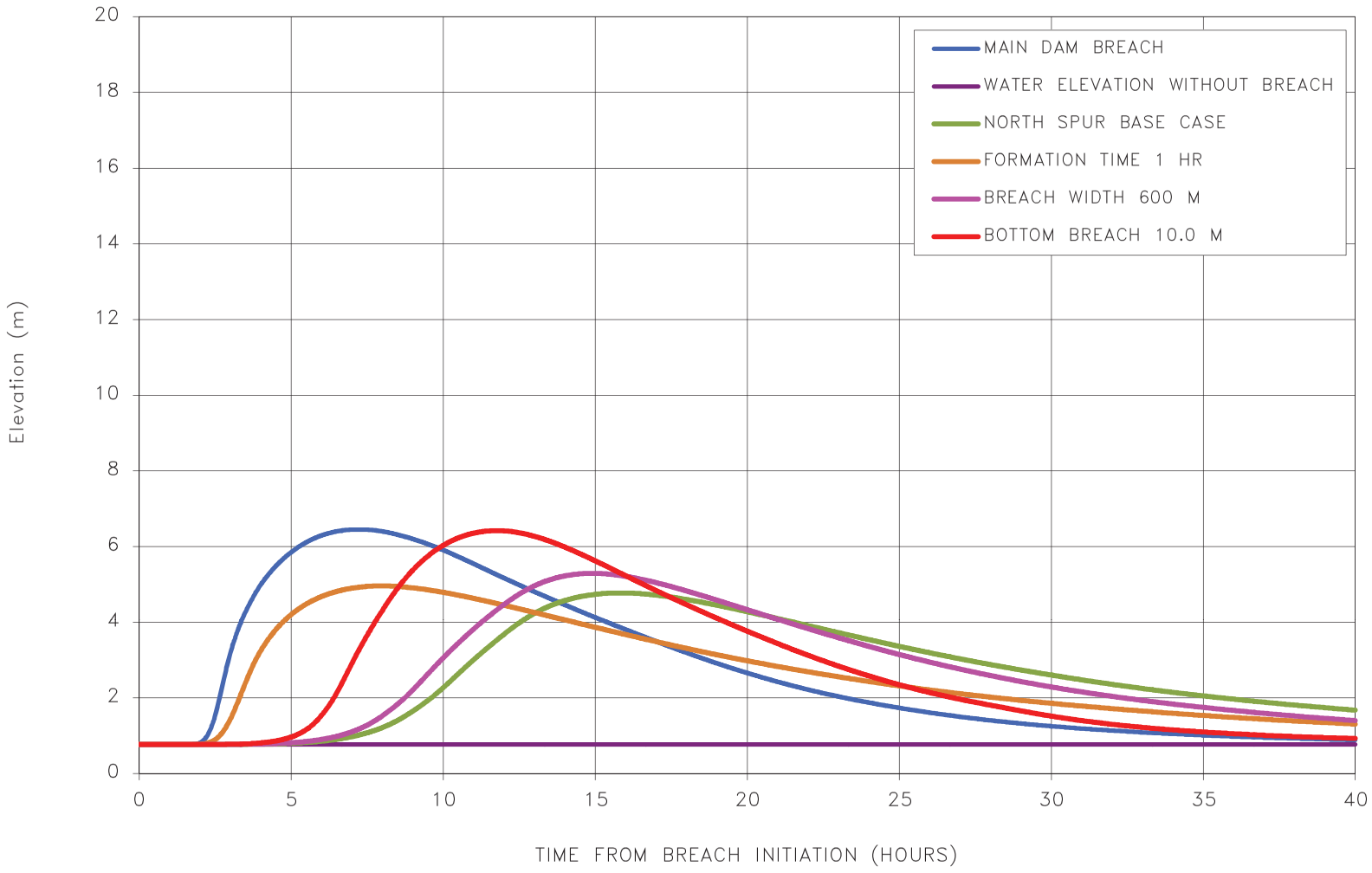

Figure 3.3
Fair Weather Conditions
Stage Hydrographs at Happy Valley - Goose Bay
North Spur Dam Break Analysis
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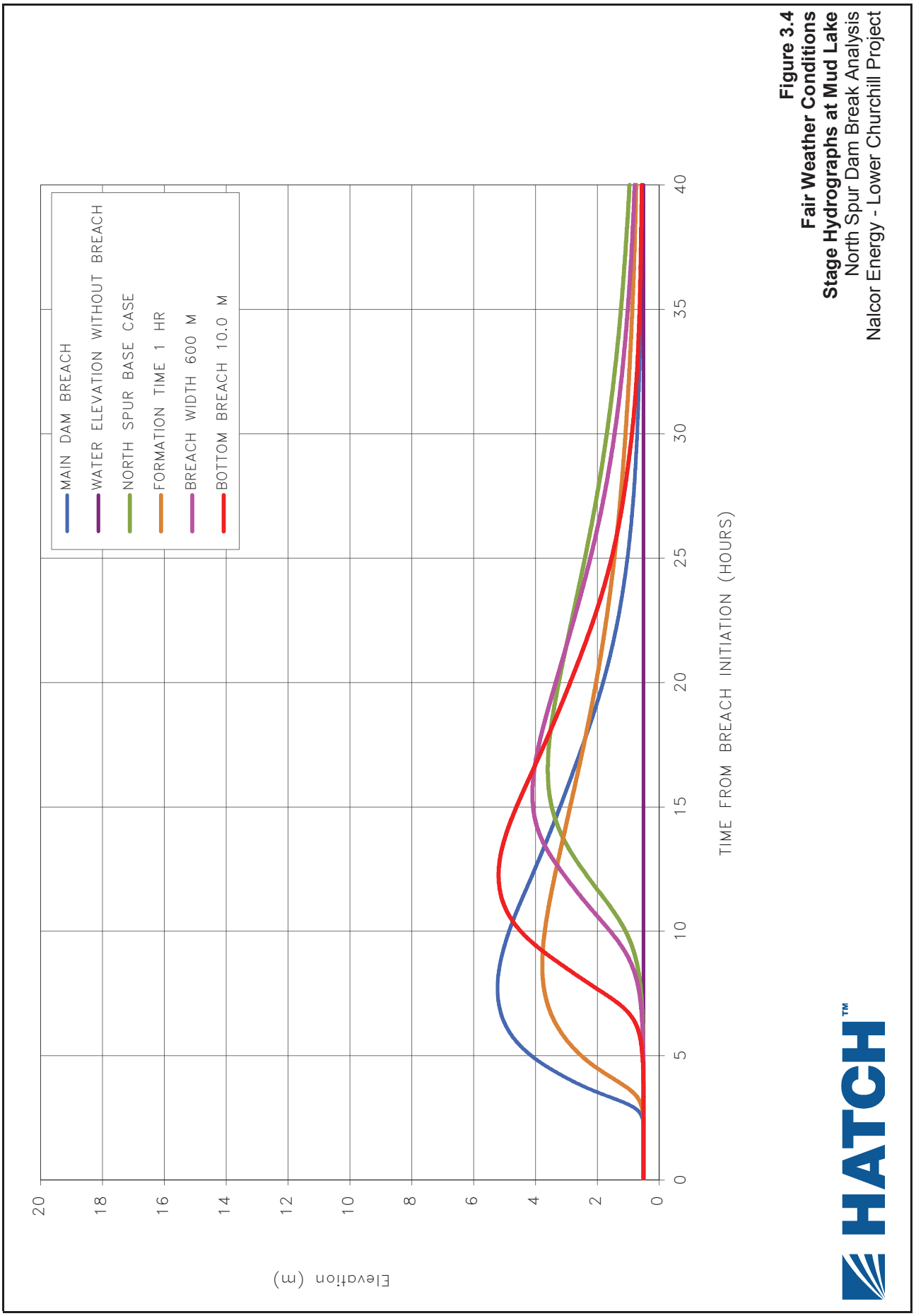

Figure 3.4
Fair Weather Conditions
Stage Hydrographs at Mud Lake
North Spur Dam Break Analysis
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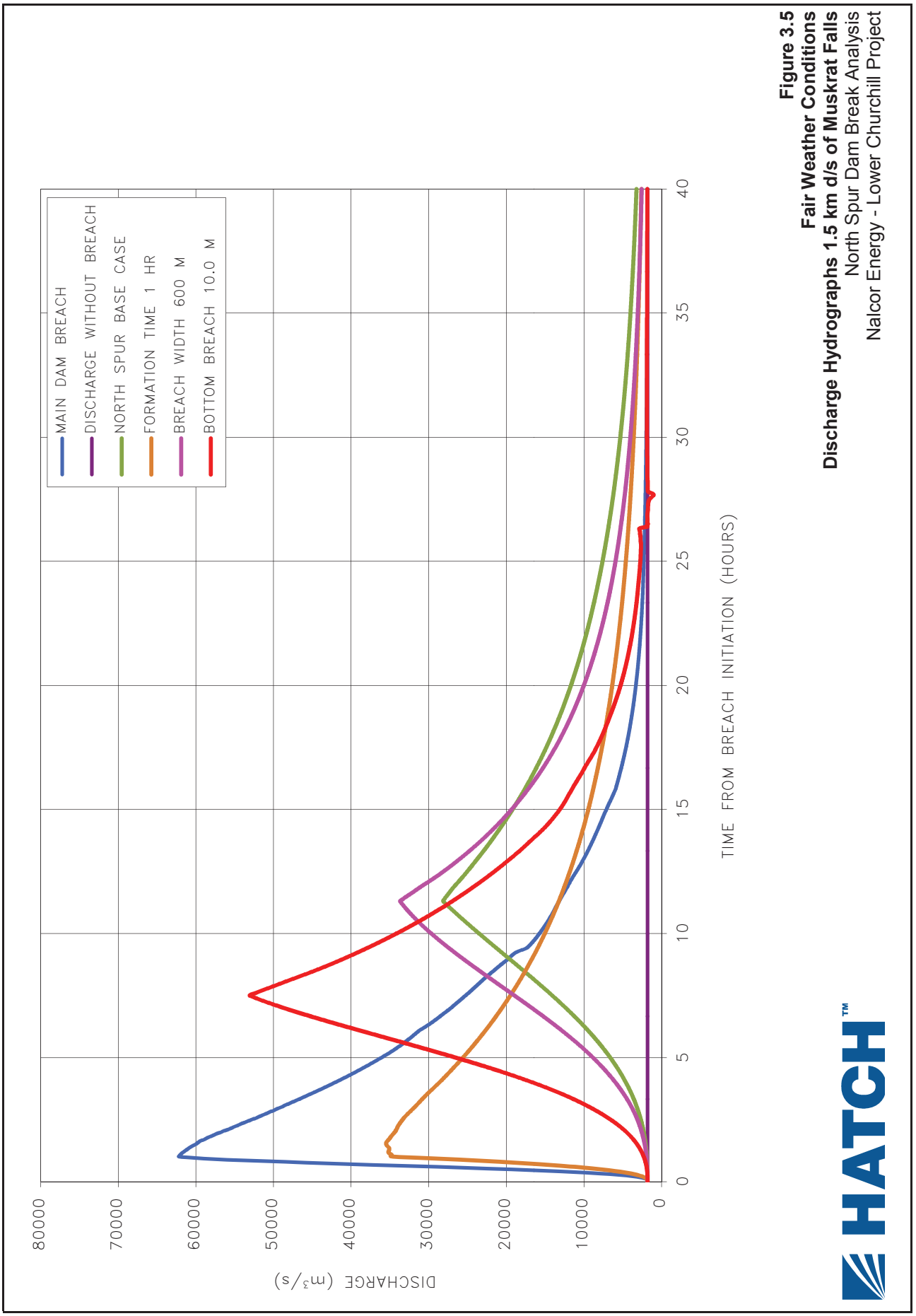

Figure 3.5
Fair Weather Conditions
Discharge Hydrographs 1.5 km d/s of Muskrat Falls
North Spur Dam Break Analysis
Nalcor Energy - Lower Churchill Project

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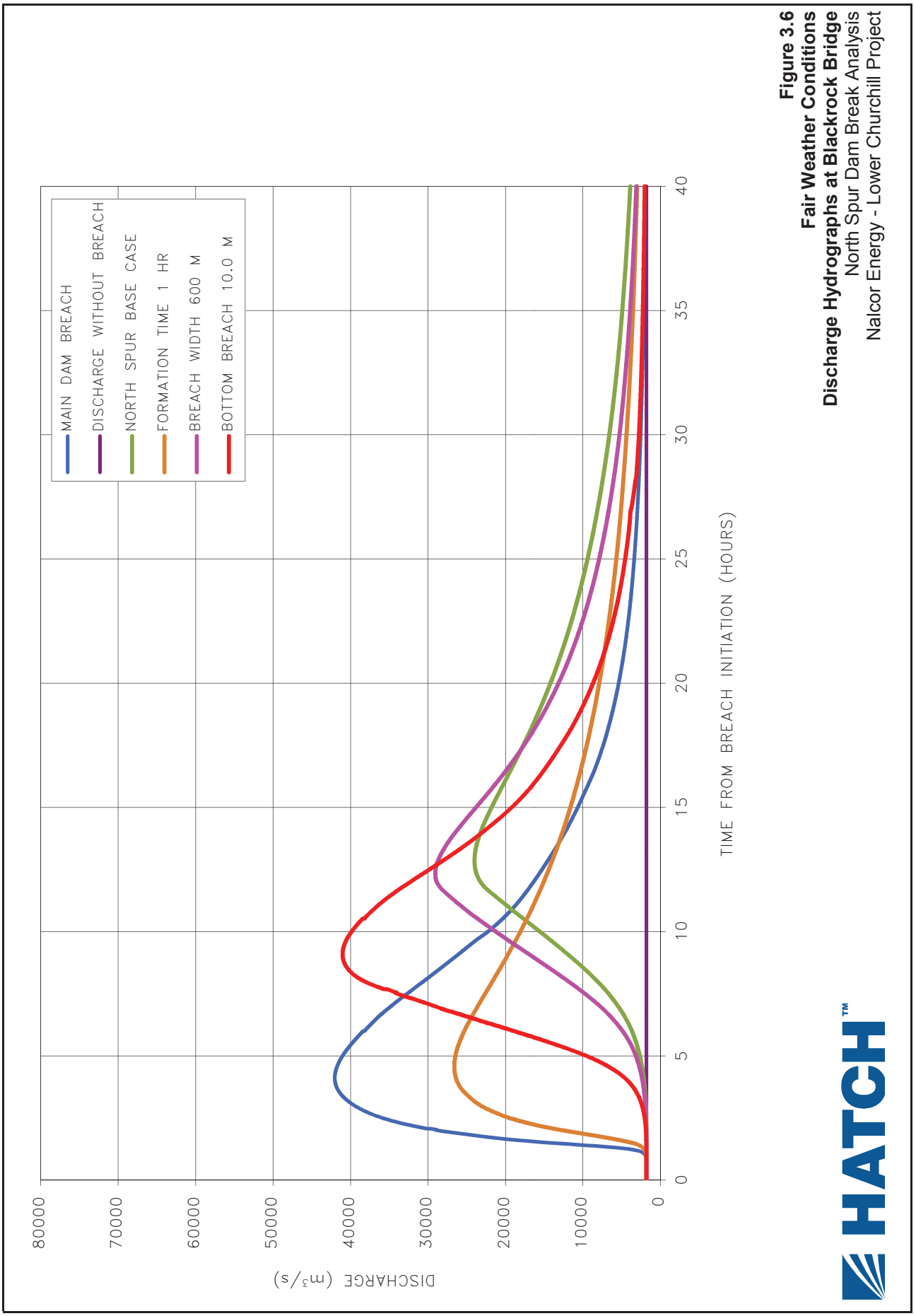

Figure 3.6
Fair Weather Conditions
Discharge Hydrographs at Blackrock Bridge
North Spur Dam Break Analysis
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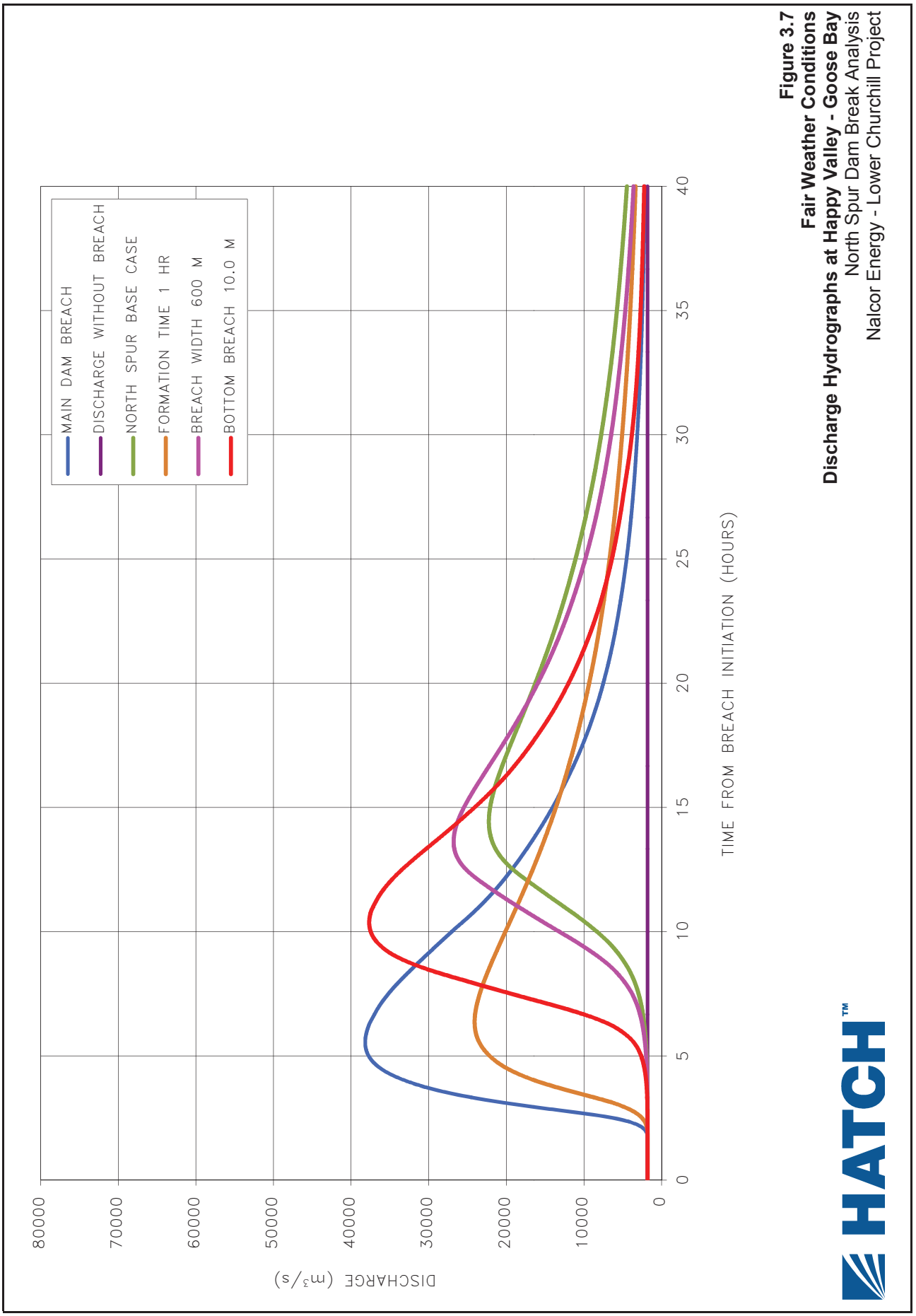

Figure 3.7
Fair Weather Conditions
Discharge Hydrographs at Happy Valley - Goose Bay
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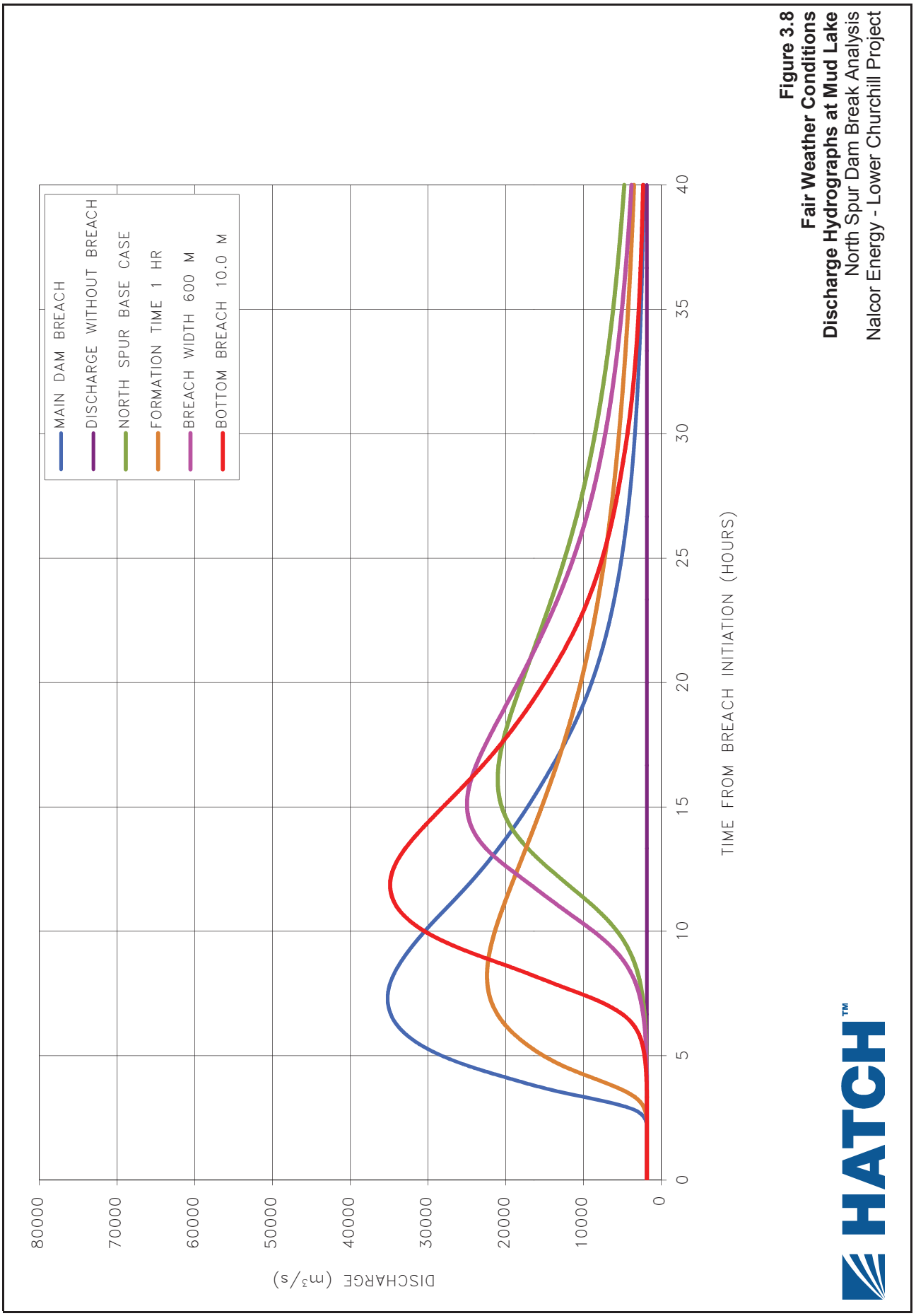

Figure 3.8
Fair Weather Conditions
Discharge Hydrographs at Mud Lake
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3.2 PMF Conditions Breach Results

Simulations were undertaken to estimate the impacts of a hypothetical breach of the North Spur on downstream water levels during PMF conditions. The analysis included simulations to test the sensitivity of the results to variations in individual parameters. Table 3-2 below summarizes the results for a number of key downstream locations. Figures 3.9 to 3.12 present the stage hydrographs for key locations, and Figures 3.13 to 3.16 present the flow hydrographs.

General observations from the simulations follow.

- The North Spur base case breach scenario resulted in peak water levels lower than those of the North Dam breach scenario.
- The differences between the peak water levels for the various sensitivities progressively diminish in the downstream direction.
- Among the sensitivity simulations, the highest peak water levels resulted from the breach bottom elevation sensitivity scenario. In that case, the peak water levels were similar to those of the North Dam breach scenario.
- Flood arrival times were generally very similar to the arrival times for a hypothetical breach of the North Dam.
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- Appendix A includes the results of additional sensitivity simulations that consider possible combinations of the breach widths, breach bottom elevations, and formation times. The most extreme combination of sensitivity parameters resulted in a peak water level at Happy Valley-Goose Bay that was 0.8 m higher and a time to peak that was 0.4 h shorter than for a hypothetical failure of the North Dam.

Table 3-2: HEC-RAS Results – PMF Conditions

Scenario	Distance Downstream of Muskrat Falls (km)	Cross Section Description	Maximum Water Level without Breach (m)	Breach Flood Summary				
				Breach Flood Arrival Time (hr)	Peak Water Level (m)	Incremental Depth of Flooding (m)	Maximum Discharge (m^3/s)	Time to Peak Water Level (hr)
North Dam (MF1330)	1.5	D/S Muskrat Falls	11.4	0.0	21.1	9.7	101,600	3.2
	18.7	U/S Blackrock Bridge	8.2	0.3	17.3	9.1	66,900	3.4
	33.6	Happy Valley - Goose Bay	5.4	0.8	8.8	3.4	62,700	5.9
	40.0	Mud Lake	4.2	1.2	7.5	3.3	60,900	6.3
Base Case	1.5	D/S Muskrat Falls	11.4	0.0	17.6	6.2	58,400	11.4
	18.7	U/S Blackrock Bridge	8.2	0.8	13.9	5.7	51,100	11.7
	33.6	Happy Valley - Goose Bay	5.4	1.6	7.8	2.4	49,200	13.8
	40.0	Mud Lake	4.2	2.1	6.5	2.3	48,500	14.3
Breach Width Sensitivity	1.5	D/S Muskrat Falls	11.4	0.0	18.7	7.3	64,300	11.2
	18.7	U/S Blackrock Bridge	8.2	0.8	15	6.8	56,100	11.3
	33.6	Happy Valley - Goose Bay	5.4	1.6	8.1	2.7	53,700	13.4
	40.0	Mud Lake	4.2	2.1	6.8	2.6	52,700	13.8
Formation Time Sensitivity	1.5	D/S Muskrat Falls	11.4	0.0	19.1	7.7	78,600	3.8
	18.7	U/S Blackrock Bridge	8.2	0.3	15.4	7.2	57,600	4.0
	33.6	Happy Valley - Goose Bay	5.4	0.8	8.2	2.8	54,500	6.7
	40.0	Mud Lake	4.2	1.2	6.9	2.7	53,400	7.1
Breach Bottom Elevation Sensitivity	1.5	D/S Muskrat Falls	11.4	0.0	21.8	10.4	87,700	8.5
	18.7	U/S Blackrock Bridge	8.2	0.3	18.0	9.8	71,200	8.7
	33.6	Happy Valley - Goose Bay	5.4	0.8	9.0	3.6	66,800	11.8
	40.0	Mud Lake	4.2	1.2	7.7	3.5	64,300	11.1

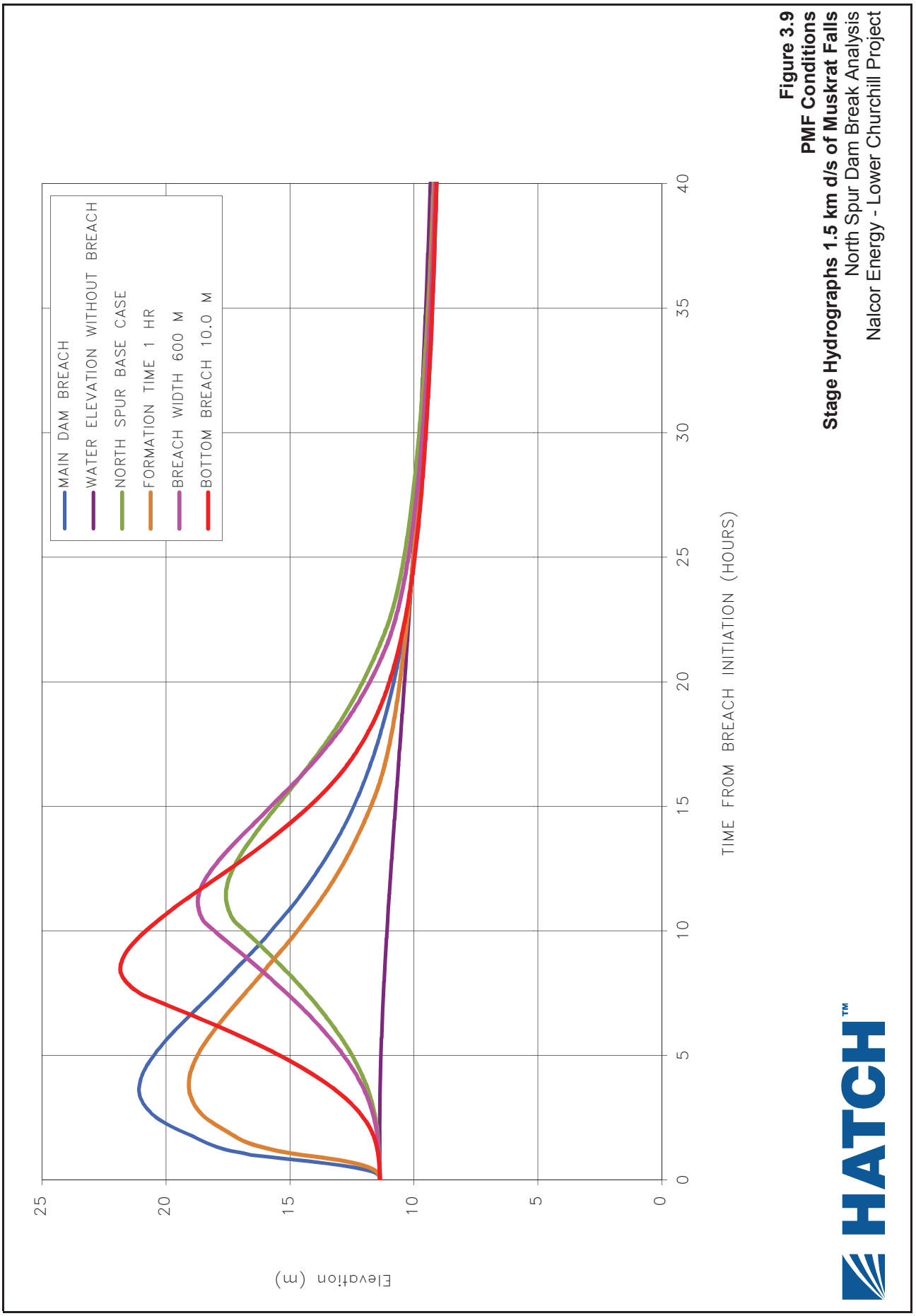

Figure 3.9
PMF Conditions
Stage Hydrographs 1.5 km d/s of Muskrat Falls
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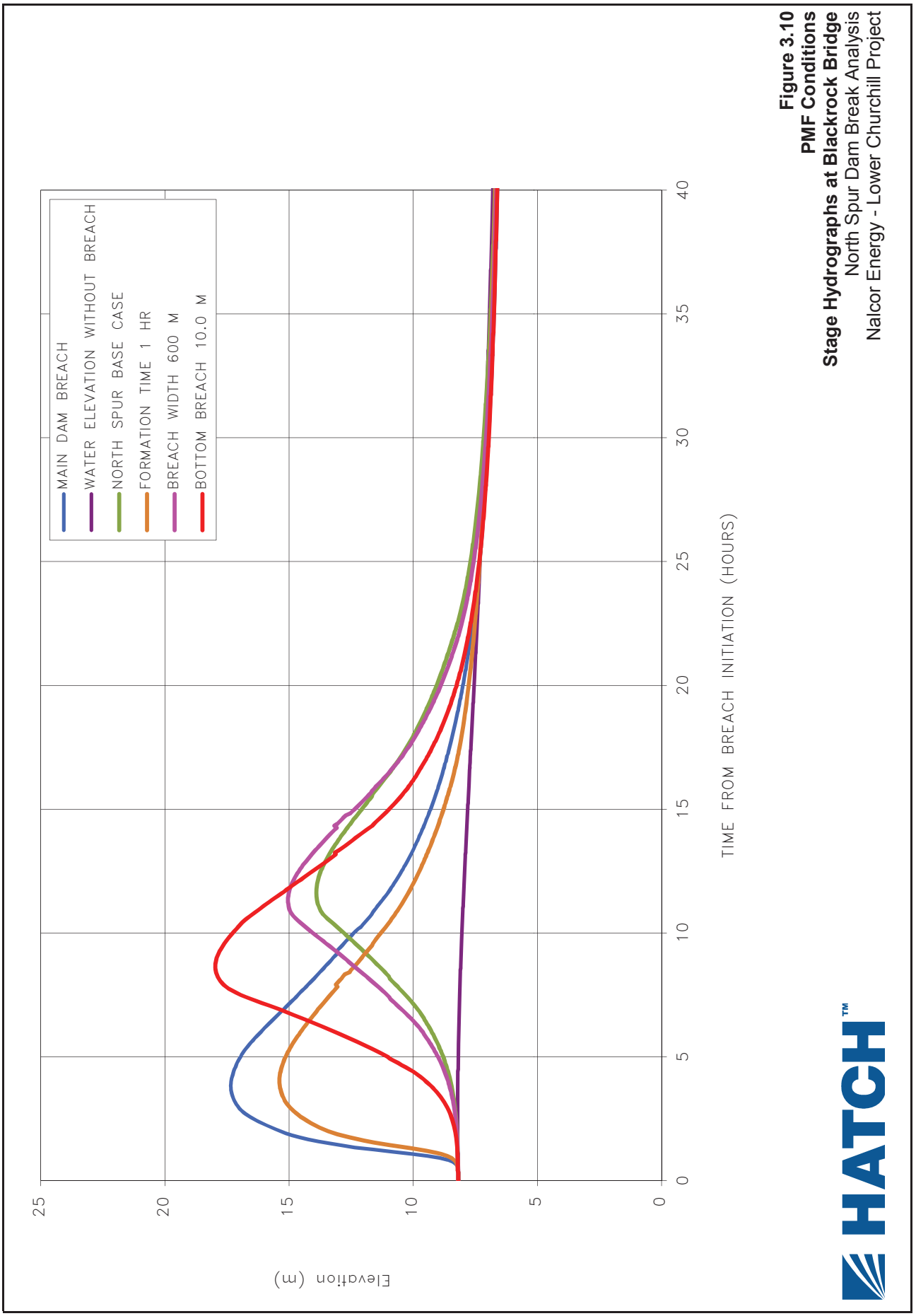

Figure 3.10
PMF Conditions
Stage Hydrographs at Blackrock Bridge
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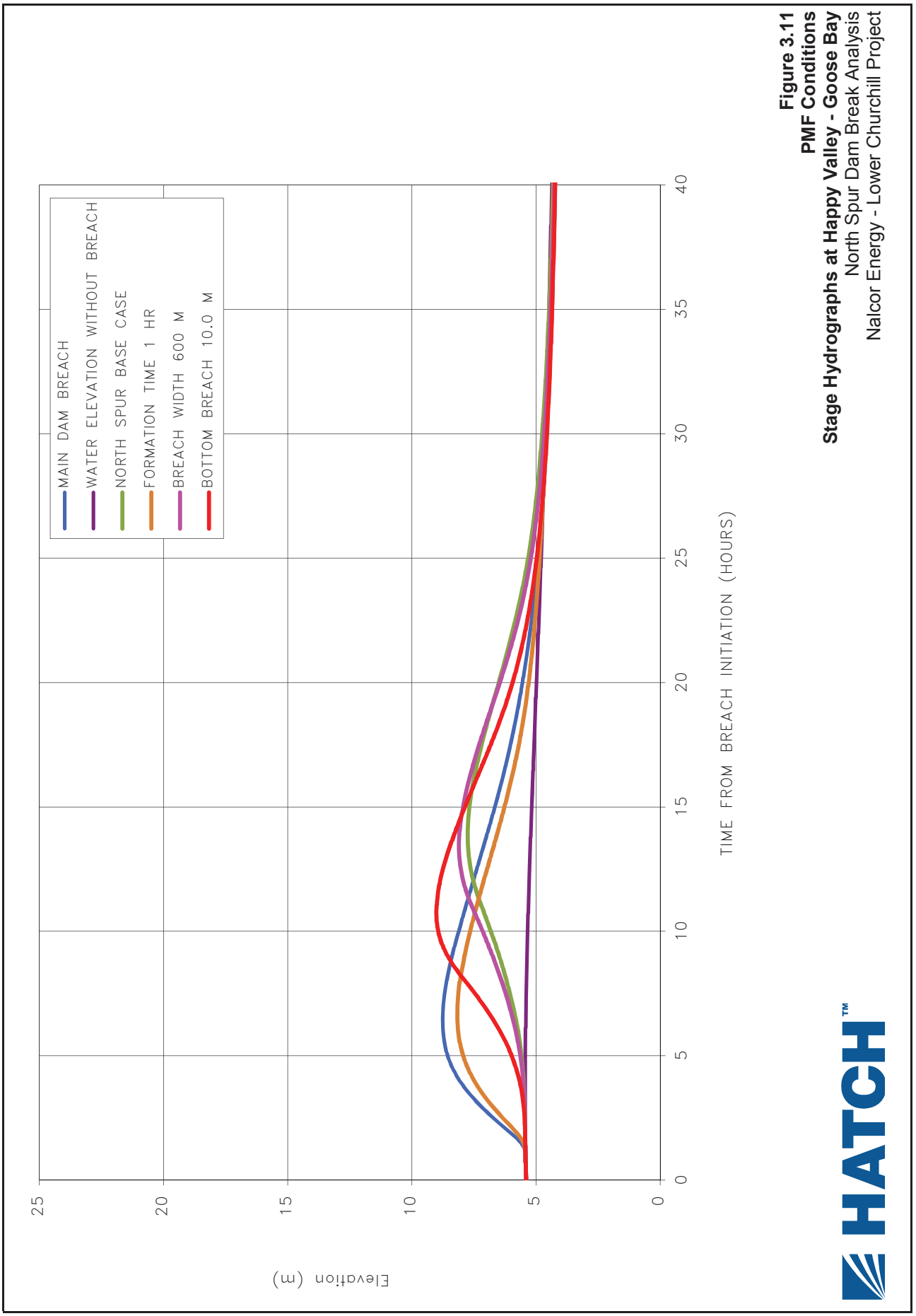

Figure 3.11
PMF Conditions
Stage Hydrographs at Happy Valley - Goose Bay
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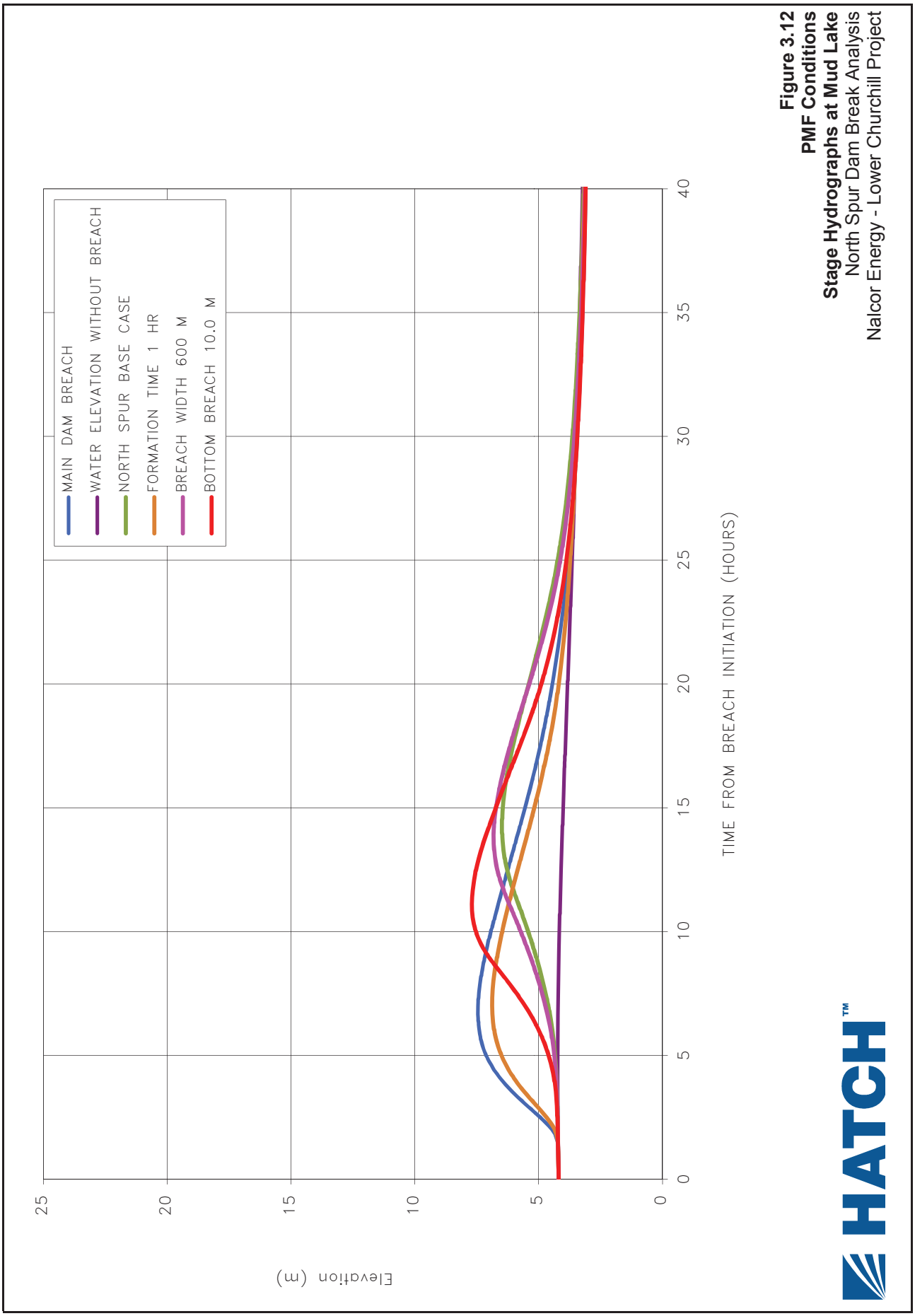

Figure 3.12
PMF Conditions
Stage Hydrographs at Mud Lake
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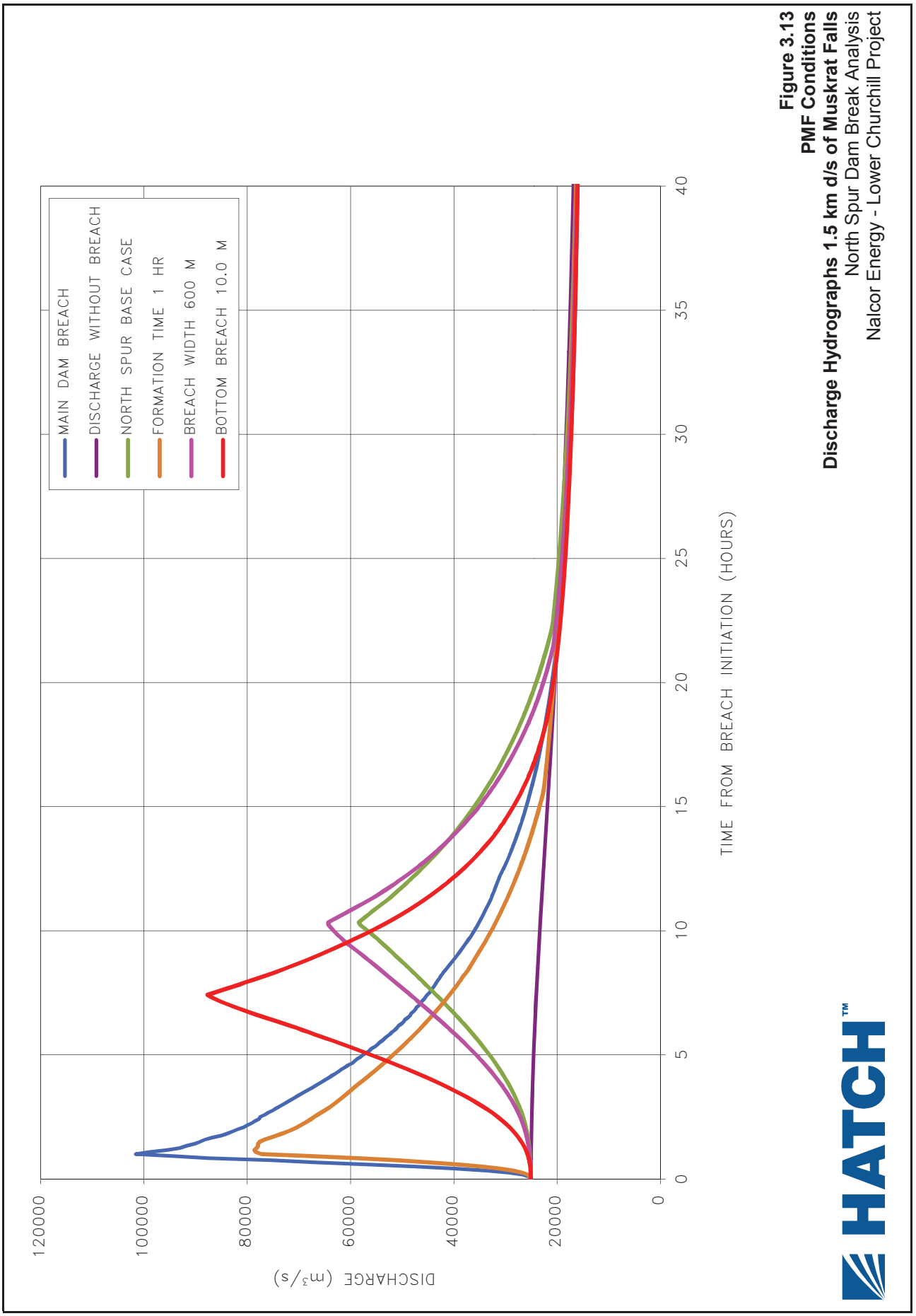

Figure 3.13
PMF Conditions
Discharge Hydrographs 1.5 km d/s of Muskrat Falls
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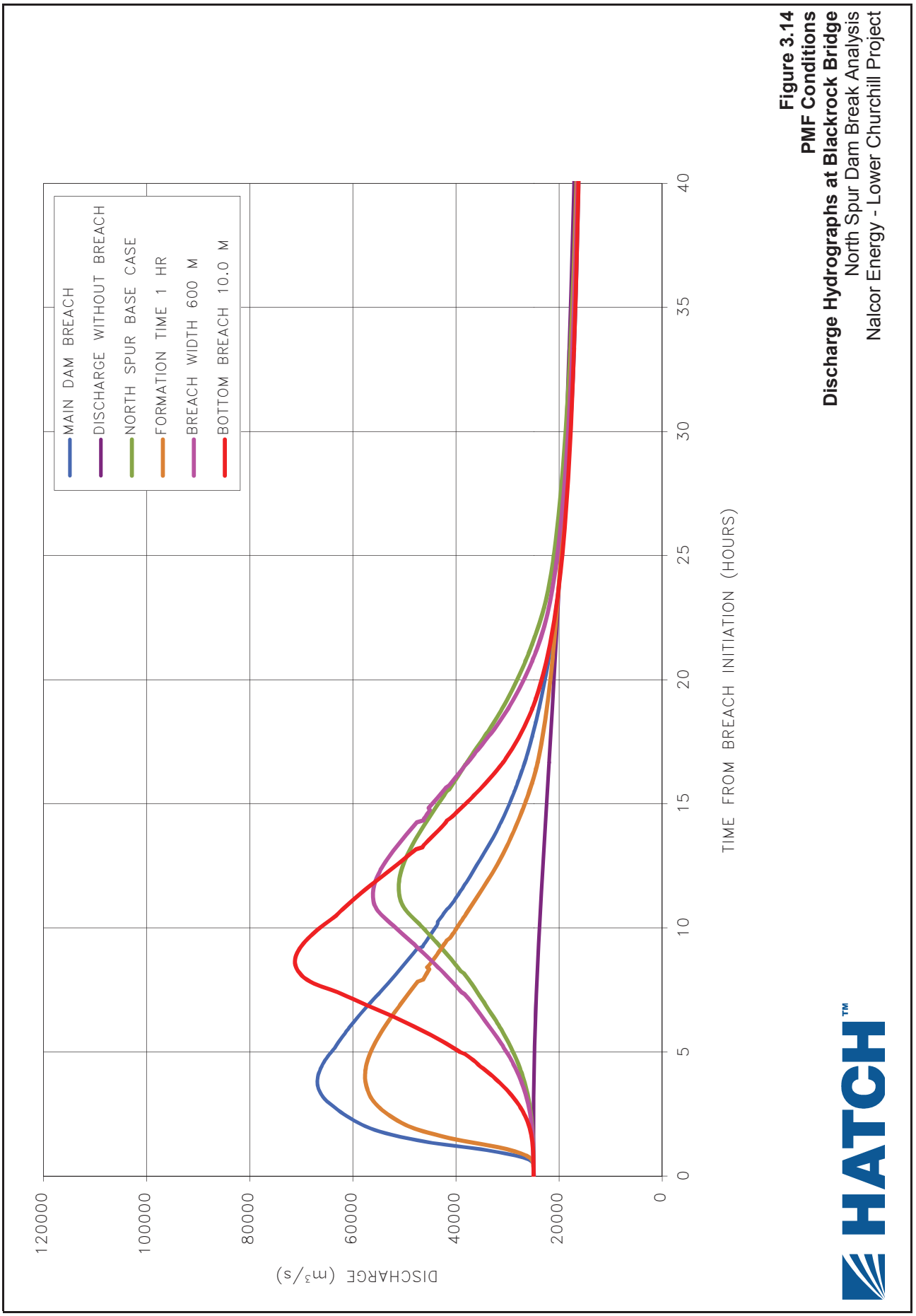

Figure 3.14
PMF Conditions
Discharge Hydrographs at Blackrock Bridge
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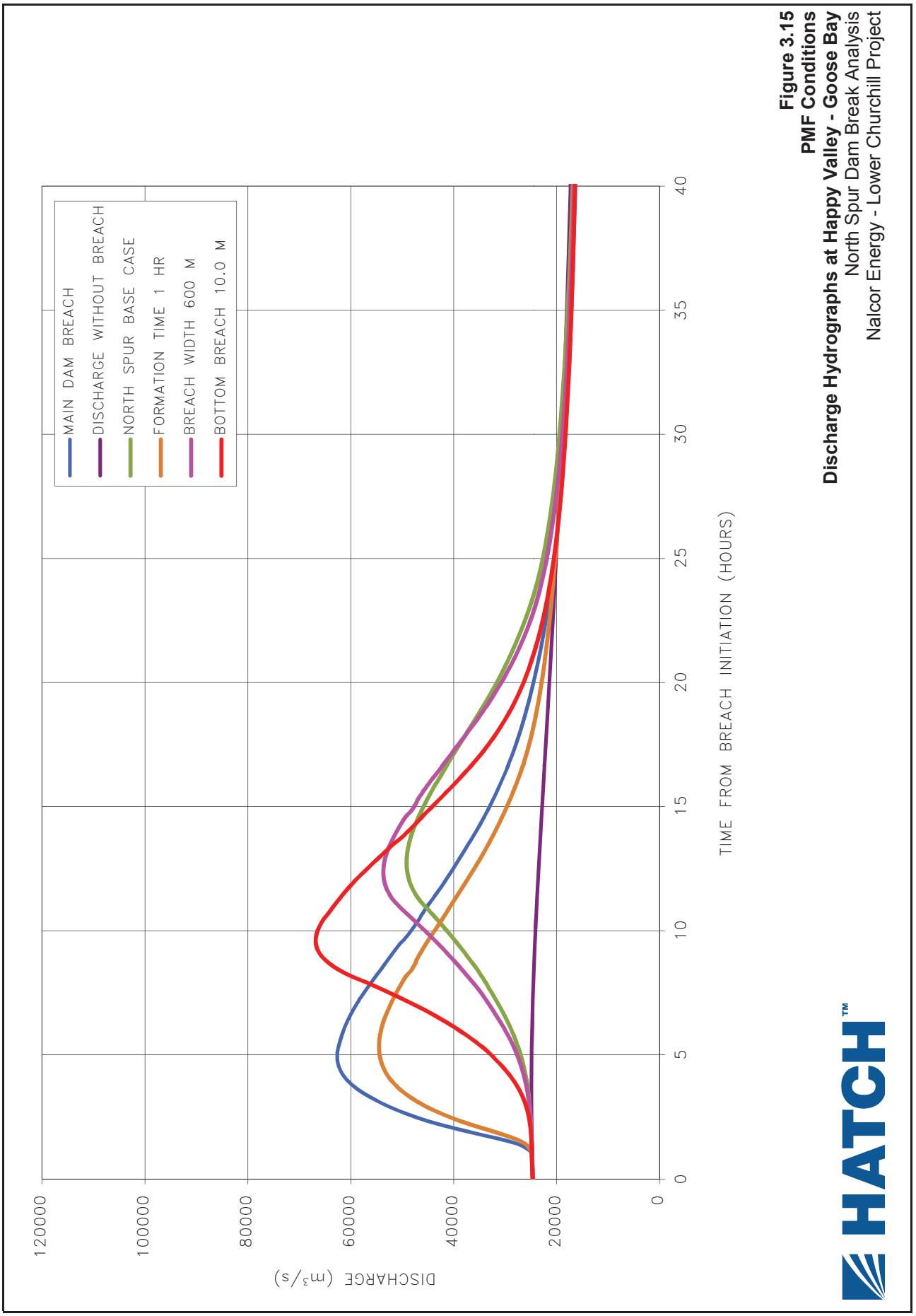

Figure 3.15
PMF Conditions
Discharge Hydrographs at Happy Valley - Goose Bay
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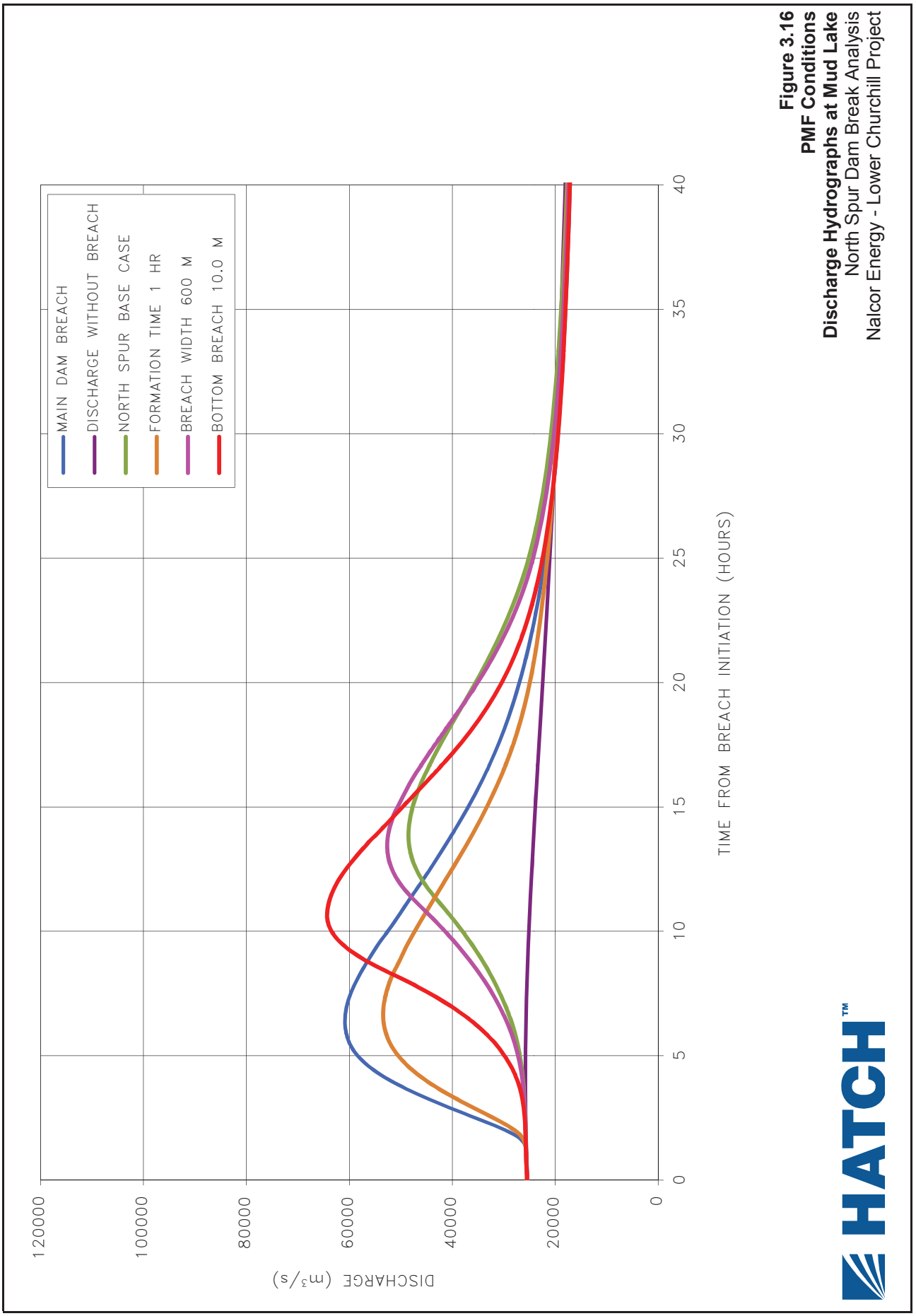

Figure 3.16
PMF Conditions
Discharge Hydrographs at Mud Lake
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4. Conclusions

1. A HEC-RAS model capable of simulating dam breach floods was updated and used to model hypothetical breaches of the North Spur under “fair weather” and PMF conditions.

2. Characteristics for a hypothetical breach of the North Spur were calculated using empirical predictive equations based on historical data. Based on these characteristics, the simulated downstream water levels were lower, and the times to peak were longer, than those for a hypothetical breach of the North Dam.

3. Sensitivity analysis of North Spur breach parameters was carried out. The differences between the peak water levels produced by varying each parameter were largest immediately below the dam, but diminished progressively in the downstream direction. The most extreme combinations of sensitivity parameters resulted in peak water levels at Happy Valley-Goose Bay that were 0.5 m (“fair weather”) to 0.8 m higher (PMF) and a time to peak that was 0.4 h shorter than for hypothetical failure of the North Dam in the same conditions.

Appendix A
Additional Sensitivity Simulations

Dam Breach Parameters

Run	Condition	Avg Breach Width (m)	Beach Bottom Elev (m)	Formation Time (hrs)	Notes/Sensitivities
1	Fair Weather	402	10.0	1.0	Breach bottom elevation, formation time
2	Fair Weather	402	10.0	7.5	Breach bottom elevation
3	Fair Weather	391	20.5	1.0	Formation time
4	Fair Weather	391	20.5	11.3	Base Case
5	Fair Weather	600	10.0	1.0	Breach width, breach bottom elevation, formation time
6	Fair Weather	600	10.0	7.5	Breach width, breach bottom elevation
7	Fair Weather	600	20.5	1.0	Breach width, formation time
8	Fair Weather	600	20.5	11.3	Breach width
9	PMF	454	10.0	1.0	Breach bottom elevation, formation time
10	PMF	454	10.0	7.4	Breach bottom elevation
11	PMF	446	20.5	1.0	Formation time
12	PMF	446	20.5	10.3	Base Case
13	PMF	600	10.0	1.0	Breach width, breach bottom elevation, formation time
14	PMF	600	10.0	7.4	Breach width, breach bottom elevation
15	PMF	600	20.5	1.0	Breach width, formation time
16	PMF	600	20.5	10.3	Breach width

Results

Run	Condition	Distance Downstream of MF Dam (km)	Maximum Water level without Breach (m)	Breach Flood Arrival Time (hr)	Peak Water Level (m)	Incremental Depth of Flooding (m)	Maximum Discharge (m^3/s)	Time to Peak Water Level (hr)
1	Fair Weather	1.5	2.6	0.0	15.8	13.2	65500	3.8
		18.7	1.6	0.6	12.1	10.5	43700	4.2
		33.6	0.7	1.3	6.5	5.8	39600	7.1
		40.0	0.5	1.7	5.3	4.8	36200	7.6
2	Fair Weather	1.5	2.6	0.0	15.2	12.6	53100	8.8
		18.7	1.6	0.7	11.5	9.9	41000	9.1
		33.6	0.7	1.5	6.4	5.7	37700	11.8
		40.0	0.5	1.8	5.2	4.7	34900	12.3
3	Fair Weather	1.5	2.6	0.0	11.6	9	35500	4.3
		18.7	1.6	0.6	8.2	6.6	26600	5.3
		33.6	0.7	1.3	5	4.3	24100	8.0
		40.0	0.5	1.7	3.8	3.3	22400	8.7
4	Fair Weather	1.5	2.6	0.0	11.1	8.5	28200	12.6
		18.7	1.6	0.8	7.8	6.2	24000	13.5
		33.6	0.7	1.6	4.8	4.1	22300	15.8
		40.0	0.5	2.1	3.6	3.1	21000	16.5
5	Fair Weather	1.5	2.6	0	17.4	14.8	87300	3.3
		18.7	1.6	0.6	13.7	12.1	50300	3.5
		33.6	0.7	1.3	6.9	6.2	44500	6.4
		40.0	0.5	1.7	5.7	5.2	39700	6.9
6	Fair Weather	1.5	2.6	0.0	16.4	13.8	59500	8.2
		18.7	1.6	0.7	12.8	11.2	46400	8.4
		33.6	0.7	1.6	6.8	6.1	42000	10.9
		40.0	0.5	1.7	5.5	5	38200	11.3
7	Fair Weather	1.5	2.6	0	13.3	10.7	48800	3.8
		18.7	1.6	0.6	9.7	8.1	33600	4.3
		33.6	0.7	1.3	5.6	4.9	30200	7.2
		40.0	0.5	1.7	4.4	3.9	27500	7.8
8	Fair Weather	1.5	2.6	0.0	12.3	9.7	33600	12
		18.7	1.6	0.8	8.7	7.1	29100	12.7
		33.6	0.7	1.6	5.3	4.6	26800	14.9
		40.0	0.5	2.1	4.1	3.6	25000	15.5
9	PMF	1.5	11.4	0	23	11.6	114300	3.4
		18.7	8.2	0.3	18.9	10.7	77600	3.6
		33.6	5.4	0.8	9.3	3.9	71700	5.9
		40.0	4.2	1.2	8	3.8	68500	6.3
10	PMF	1.5	11.4	0.0	21.8	10.4	87700	8.5
		18.7	8.2	0.3	18	9.8	71200	8.7
		33.6	5.4	0.8	9	3.6	66800	11.8
		40.0	4.2	1.2	7.7	3.5	64300	11.1
11	PMF	1.5	11.4	0	19.1	7.7	78600	3.8
		18.7	8.2	0.3	15.4	7.2	57600	4
		33.6	5.4	0.8	8.2	2.8	54500	6.7
		40.0	4.2	1.2	6.9	2.7	53400	7.1
12	PMF	1.5	11.4	0.0	17.6	6.2	58400	11.4
		18.7	8.2	0.8	13.9	5.7	51100	11.7
		33.6	5.4	1.6	7.8	2.4	49200	13.8
		40.0	4.2	2.1	6.5	2.3	48500	14.3
13	PMF	1.5	11.4	0	24.3	12.9	136600	3.1
		18.7	8.2	0.3	20.1	11.9	85700	3.2
		33.6	5.4	0.8	9.6	4.2	78000	5.5
		40.0	4.2	1.1	8.3	4.1	73300	5.8
14	PMF	1.5	11.4	0.0	22.9	11.5	94200	8.1
		18.7	8.2	0.3	18.9	10.7	77700	8.2
		33.6	5.4	0.8	9.3	3.9	72200	10.2
		40.0	4.2	1.2	8	3.8	68700	10.4
15	PMF	1.5	11.4	0	20.6	9.2	93200	3.7
		18.7	8.2	0.3	17	8.8	64200	3.8
		33.6	5.4	0.8	8.6	3.2	60100	6.4
		40.0	4.2	1.1	7.3	3.1	58500	6.8
16	PMF	1.5	11.4	0.0	18.7	7.3	64300	11.2
		18.7	8.2	0.8	15	6.8	56100	11.3
		33.6	5.4	1.6	8.1	2.7	53700	13.4
		40.0	4.2	2.1	6.8	2.6	52700	13.8

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