May 2017

FORT MCMURRAY RIVER HAZARD STUDY

OPEN WATER HYDROLOGY ASSESSMENT REPORT

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REPORT

Golder Associates

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EXECUTIVE SUMMARY

Alberta Environment and Parks (AEP) retained Golder Associates Ltd. (Golder), in collaboration with SG1 Water Consulting Ltd. (SG1) and Hatch Ltd. (Hatch), in September 2016 to conduct the Fort McMurray River Hazard Study. The purpose of the study is to assess and identify river and flood hazards along the Athabasca River, the Clearwater River (including the Snye), and the Hangingstone River through Fort McMurray, Alberta in the Regional Municipality of Wood Buffalo (RMWB). The study is part of the provincial Flood Hazard Identification Program (FHIP), the goals of which include enhancement of public safety and reduction of future flood damages through the identification of river and flood hazards. Project stakeholders include the Government of Alberta, the RMWB, and the general public.

The Fort McMurray River Hazard Study comprises multiple components and deliverables. This report documents the methodology and results of the open water hydrology assessment that will support the hydraulic modelling and open water flood mapping. Tasks associated with this hydrology assessment component include the following:

- compile available peak flow information for gauged locations and prepare flood flow data series;
- compile calculated/estimated peak flow information for ungauged locations based on available data at gauged locations and prepare flood flow data series;
- carry out frequency analyses to estimate flood flows for return periods ranging from 2 to 1,000 years using the recorded and derived flood peak data for the available periods of record up to 2016; and
- provide comments and insight into how climate change processes may impact flood peaks and the flood frequency estimates.

The flood frequency estimates obtained in this study are the most up-to-date for the various locations along the Athabasca, Clearwater and Hangingstone rivers. These estimates provide the updated flood hydrology information as input to the Fort McMurray River Hazard Study under the FHIP.

This study includes the use of preliminary estimates provided by Water Survey of Canada (WSC) of the annual peak flows in 2014, 2015 and 2016 for the Athabasca River at Athabasca, and the preliminary estimates in 2016 for the Athabasca River below Fort McMurray, Clearwater River at Draper, and Hangingstone River at Fort McMurray. Including these provisional data increases the sample sizes for the flood frequency analyses and reliability of the resulting flood frequency estimates.

Table E1 provides a summary of the recommended estimates of the flood peak discharges and the 95% upper and lower confidence intervals for the various return periods.

Table E1: Flood Frequency Estimates and 95% Confidence Intervals

WSC Station ID / Node ID	WSC Station Name or Location of Interest	Gross Drainage Area (km²)	Effective Drainage Area (km²)	Distribution / Method	Computed Maximum Instantaneous Flood Discharges with 95% Confidence Bounds (m³/s)																																			
					1000-yr			750-yr			500-yr			350-yr			200-yr			100-yr			75-yr			50-yr			35-yr			20-yr			10-yr			5-yr			2-yr		
ATHABASCA RIVER																																								
Node 1	Athabasca River above Clearwater River Confluence	100,722	98,719	EV2	8200	10500	5840	7820	9910	5680	7310	9110	5450	6870	8410	5240	6230	7420	4900	5480	6350	4470	5190	5950	4320	4790	5430	4060	4460	4990	3820	3950	4380	3460	3360	3700	3010	2800	3080	2550	2030	2220	1890
07DA001 / Node 2	Athabasca River below Fort McMurray, extended	132,588	130,457	EV2	8680	11400	6220	8300	10700	6040	7780	9780	5800	7340	9070	5580	6680	8040	5260	5920	6930	4840	5620	6500	4660	5210	5940	4430	4860	5470	4200	4330	4820	3800	3710	4070	3350	3110	3410	2850	2290	2480	2130
CLEARWATER RIVER and TRIBUTARIES																																								
07CD001 / Node 3	Clearwater River at Draper	30,799	30,771	EV3	1170	1510	848	1140	1440	835	1090	1350	818	1050	1270	800	983	1160	771	900	1040	728	864	985	709	814	915	682	770	859	654	699	777	605	609	675	536	513	571	456	366	415	328
07CD004 / Node 4	Hangingstone River at Fort McMurray	962	962	EV2	434	699	170	397	624	163	349	533	154	312	463	144	260	372	131	206	285	115	187	255	108	162	217	100	143	188	92.6	116	149	80.7	87.4	111	65.6	63.5	79.9	50.4	35.8	44.5	29.6
Node 5	Clearwater River at the Mouth	31,879	31,851	EV3	1240	1660	820	1200	1580	809	1150	1480	794	1110	1390	780	1040	1270	756	949	1130	724	911	1070	708	859	998	685	812	933	661	737	836	617	641	722	554	540	607	477	385	435	344

ACKNOWLEDGEMENTS

The technical lead for the open water hydrology assessment component for the Fort McMurray River Hazard Study was Dr. Getu Biftu. Dr. Wolf Ploeger provided overall management for this study component. The hydrology assessment was completed by Dr. Shouhong Wu and Ms. Nancy Guo. Additional review of the draft report was provided by Mr. Dave Andres (affiliated with SG1 Water Consulting Ltd.), Mr. Darren Shepherd of SG1, and Dr. Dejiang Long.

The authors thank Samantha Hussey from Environment and Climate Change Canada (Water Survey of Canada) for providing preliminary flow data for the gauges in the study area.

The authors express their special thanks to Mr. Abdullah Mamun, project manager for Alberta Environment and Parks (AEP), who provided overall study direction, background data, and technical guidance; and Mr. Adam Minke from AEP for providing his review comments.

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1.0 INTRODUCTION

1.1 General

Alberta Environment and Parks (AEP) retained Golder Associates Ltd. (Golder), in collaboration with SG1 Water Consulting Ltd. (SG1) and Hatch Ltd. (Hatch), in September 2016 to conduct the Fort McMurray River Hazard Study. The purpose of the study is to assess and identify river and flood hazards along the Athabasca River, the Clearwater River (including the Snye), and the Hangingstone River through the City of Fort McMurray (Fort McMurray), Alberta in the Regional Municipality of Wood Buffalo (RMWB). The study is part of the provincial Flood Hazard Identification Program (FHIP), the goals of which include enhancement of public safety and reduction of future flood damages through the identification of river and flood hazards. Project stakeholders include the Government of Alberta, the RMWB, and the general public.

The Fort McMurray River Hazard Study comprises multiple components and deliverables. This report documents the methodology and results of the open water hydrology assessment that supports the hydraulic modelling and open water flood mapping.

1.2 Study Objectives

The primary project objective of the Fort McMurray River Hazard Study is to identify and assess river-related hazards along approximately 15 kilometers of the Athabasca River, approximately 20 km of the Clearwater River, and approximately 5 km of the Hangingstone River. The objective of open water hydrology assessment is to generate flood peak discharge estimates for multiple locations along the Athabasca, Clearwater, and Hangingstone Rivers, including locations of hydrometric gauges, and upstream and downstream of major tributaries near the City of Fort McMurray.

This study report includes preliminary estimates of annual maximum instantaneous discharges for 2014, 2015, and 2016. The results of frequency analysis undertaken in this study includes estimates of the 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1000-year open water flood peak discharges.

It is important to note that some of the 2014, 2015, and 2016 annual maximum instantaneous discharges used in this study are provisional and preliminary and may be subject to change when reviewed and corrected by the Water Survey of Canada (WSC). Therefore, the flood frequency statistics presented in this report should be used with caution and reviewed when the finalized discharge values are available.

1.3 Study Area and Reaches

The study area and the selected study reaches (Figure 1) represent the following three major rivers along which flood hazards area of concern within Fort McMurray: the Athabasca, Clearwater and Hangingstone rivers.

The Athabasca River has its sources in the Rocky Mountains near Mount Columbia (elevation 3747 m and flows northeast for 1300 km before discharging into the Peace-Athabasca Delta and Lake Athabasca (elevation 208 m) (RAMP 2016a). The river drains an area of approximately 133,000 km² at the gauging station below Fort McMurray (i.e. Athabasca River below Fort McMurray, WSC Station 07DA001).

As a major river system, the Athabasca River is influenced by a variety of climate, terrain and landscape characteristics found within its basin (RAMP 2016b). The seasonal climate is a major factor affecting river flow conditions. The climate includes cold winters, when most of the seasonal precipitation falls as snow, followed by warm summers, when snow and glacial melt from the river’s headwaters combine with runoff from localized snowmelt and rainfall events throughout the basin. As the river flows toward Lake Athabasca, water is contributed to the river from individual sub-basins including Clearwater River.

The Clearwater River at Draper (WSC Station 07CD001) drains an area of approximately 30,800 km². Broach Lake in northwestern Saskatchewan, at an elevation of 460 m, forms the headwaters of the Clearwater River, and from there the river flows through Saskatchewan and Alberta to its confluence with the Athabasca River at Fort McMurray. High flows often occur in spring as snowmelt combined with spring rainfall results in seasonal high (peak) flows. Floods have also been recorded in the summer months due to severe rainfall events that typically occurred in the Christina River basin.

The Hangingstone River originates in the highlands southwest of Fort McMurray and flows northward to its confluence with the Clearwater River at Fort McMurray, approximately 65 km from its origin. The river basin has a total area of 1105 km². From the perspective of flood management for Fort McMurray, the basin has three main components. Saline Creek is a tributary that joins the Hangingstone one kilometre downstream of the WSC gauge, and has a basin area of approximately 137 km² above Tolen Drive near its mouth. Finally, there is a small basin area of about 2.0 km² which drains to the lower portion of the river below the WSC gauge and Saline Creek.

Due to the locations of the various river confluences, the study area comprises five main reaches for which flood flows are estimated. These reaches (i.e. two along the Athabasca River, two along the Clearwater River, and one on the Hangingstone River) are listed below.

- Athabasca River above the Clearwater River confluence (Node 1).
- Athabasca River below Fort McMurray (WSC Station 07DA001 / Node 2).
- Clearwater River at Draper (WSC Station 07CD001 / Node 3).
- Hangingstone River at Fort McMurray (WSC Station 07CD004 / Node 4).
- Clearwater River at the Mouth (Node 5).

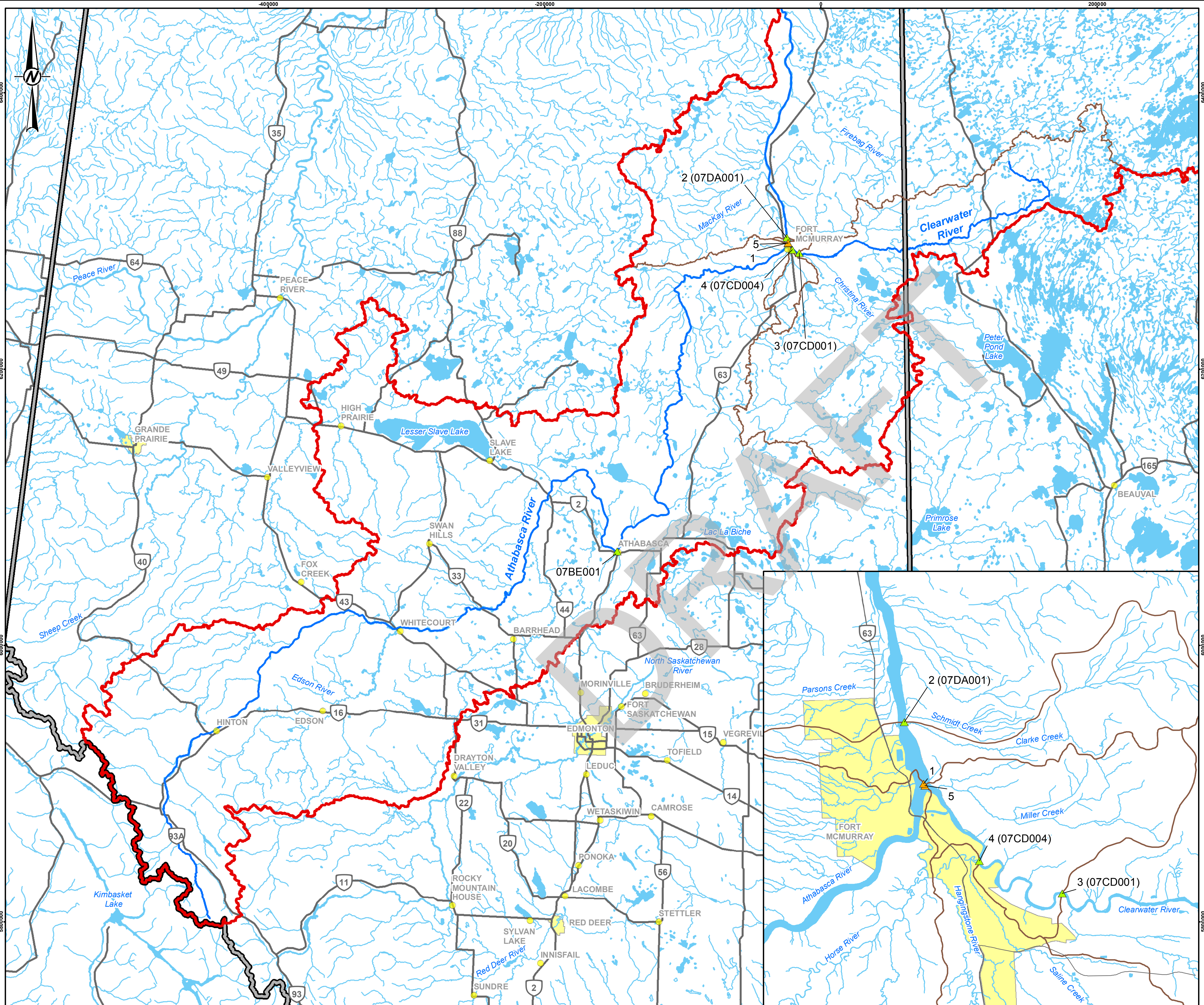
The recorded annual maximum daily discharges for the Athabasca River at Athabasca (WSC Station 07BE001) were also considered in this study to generate extended flood series for the Athabasca River below Fort McMurray and Athabasca River above Clearwater Confluence.

Available records indicate that major floods occurred on the Athabasca River in 1944, 1954, 1971, 1980, 1986, and 2011. These floods were typically associated with high rainfall or rain-on snow events during the period of June and July. Significantly large floods occurred along the Clearwater River in 1974 and 2013, and the largest recorded flood along the Hangingstone River occurred in 2013.

1.4 Scope of Work

The scope of work for the open water hydrology study is summarized below.

- Generation of annual maximum instantaneous discharge series along the Athabasca, Clearwater, and Hangingstone rivers at locations listed in Section 1.3.
- Frequency analyses of the annual maximum instantaneous discharge series along the Athabasca, Clearwater, and Hangingstone rivers using available data up to 2016.
- Commentary on the effects of potential future climate change on the flood peak estimates as well as on any recent changes observed on the seasonality of flood peak occurrences as a result of climate change.



LEGEND

- WATER SURVEY OF CANADA STATION
- NODE LOCATION
- DELINEATED SUB-BASIN
- ATHABASCA RIVER BASIN
- MAJOR RIVER
- WATERCOURSE
- WATERBODY
- PRIMARY HIGHWAY
- POPULATED PLACE
- PROVINCIAL BOUNDARY

0 100 200

1:2,800,000 KILOMETRES

NOTE(S)

SUB-BASINS WERE OBTAINED FROM HUC8 WATERSHEDS (GOVERNMENT OF ALBERTA 2015) WHERE POSSIBLE. OUTSIDE OF ALBERTA, SUB-BASINS WERE OBTAINED FROM AAFC WATERSHED DATA.

REFERENCE(S)

HYDROMETRIC STATIONS OBTAINED FROM AGRICULTURE AND AGRI-FOOD CANADA (AAFC).
BASIN AND SUB-BASIN DATA OBTAINED FROM AGRICULTURE AND AGRI-FOOD CANADA (AAFC) AND THE GOVERNMENT OF ALBERTA 2015.
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DATUM: NAD 83 CSRS PROJECTION: 3TM 111

CLIENT
ALBERTA ENVIRONMENT AND PARKS

PROJECT
FORT MCMURRAY RIVER HAZARD STUDY

TITLE
ATHABASCA AND CLEARWATER RIVER BASINS

CONSULTANT

Golder Associates

YYYY-MM-DD	2017-01-13
DESIGNED	NG
PREPARED	PT
REVIEWED	WP
APPROVED	GB

PROJECT NO.	REV.	FIGURE
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2.0 AVAILABLE FLOW DATA

2.1 Recorded Data

Recorded flow data from the WSC website are available at three locations within the study area and on the Athabasca River at Athabasca. Preliminary annual maximum instantaneous discharge data for these locations in 2014, 2015, and 2016 were also obtained from WSC. Table 1 provides a summary of the basic hydrologic information used to derive the flood frequency estimates for the study reaches. The data details are provided in Appendix A.

Table 1: Summary of Gauged Stations used for the Fort McMurray River Hydrology Assessment

WSC Station Number	WSC Station Name	Latitude	Longitude	Gross Drainage Area (km²)	Effective Drainage Area (km²)	Period of Record	Length of Record (year)
07BE001	Athabasca River at Athabasca	54° 43' 19"	113° 17' 16"	74,602	73,332	1913 – 2016	98
07DA001 / Node 2	Athabasca River below Fort McMurray	56° 46' 49"	111° 24' 07"	132,588	130,457	1957 – 2016	60
07CD001 / Node 3	Clearwater River at Draper	56° 41' 07"	111° 15' 19"	30,799	30,771	1930 – 2016	63
07CD004 / Node 4	Hangingstone River at Fort McMurray	56° 42' 32"	111° 21' 22"	962	962	1965 – 2016	52

2.2 Historic Data

There is no additional historic flow data available for the study area before systematic gauging and monitoring.

2.3 Previous Studies

This study reviewed a number of background documents, including previous hydrology and flood studies and any reports that contain historical flood information for the open water period. Several hydrology studies were completed for the Athabasca River and the Clearwater River over the last 4 decades. Most of these studies included assessments of both open water hydrology and ice jam flood condition at Fort McMurray. These studies include the following:

- Feasibility Study – Athabasca River Basins (IBI and Golder 2014).
- Hangingstone River Basin Study (Tetra Tech EBA 2015).
- Fort McMurray Flood Protection Conceptual Design (NHC 2014).
- Climate Change Assessment for Athabasca River Basin (Golder 2013).
- Hydro-Climate Model Selection and Application on the Athabasca and Beaver River Basins (Golder 2009).
- Modelling Hydrologic Responses of Athabasca River Basin to Climate Change by Modified ISBA Land Surface Scheme (Kerkhoven and Gan 2005).

The reviews were used to understand any assumptions, limitations, and to develop an understanding of hydrologic techniques applied in the past studies. The results of these past studies provide a frame of reference for comparison to the results from this study. The review helped to identify both data gaps and apparent discrepancies in the data that may affect their use in subsequent analyses.

3.0 PREPARATION OF FLOOD FLOW DATA SERIES

3.1 Introduction

There are complex factors considered in the study reaches when preparing the flood flow series, including large flow changes at the confluences of the Athabasca and Clearwater rivers and the Clearwater and Hangingstone rivers, unequal and non-overlapping record lengths, and incomplete flow records. Methodologies used to compile the flood flow series and to address the data gaps are documented in the following sections.

Annual peak flow data are not available at two locations (i.e., the Athabasca River above the Clearwater River confluence and the Clearwater River at the Mouth) where flood estimates are required for the study reach. Hence, there are some uncertainties associated with generation of flood flows based on recorded data at other location on the Athabasca River and Clearwater River.

3.2 Flood Flow Series for Gauged Locations

Results from the sensitivity analysis comparing flood flows computed for the Athabasca River below Fort McMurray based on three flood series are presented in Section 4.2.

The flood frequency estimates for gauged locations, the Athabasca River below Fort McMurray (WSC Station 07DA001 / Node 2), the Clearwater River at Draper (WSC Station 07CD001 / Node 3), and the Hangingstone River at Fort McMurray (WSC Station 07CD004 / Node 4), were derived based on recorded annual maximum instantaneous discharge series, and where necessary, the annual maximum daily discharges factored to instantaneous flood flows.

General steps used for the development of natural flow series at these locations are as follows:

- Annual maximum daily discharge series were developed using either recorded flows or an extended data series based on flows at other locations. Data series were extended either by prorating flood peaks on the basis of the ratio of the effective drainage areas at two locations, or by establishing a relationship between recorded annual maximum daily discharges at the two locations for concurrent flood events.
- Annual maximum instantaneous discharge series were developed from recorded annual maximum instantaneous discharges or by establishing a relationship between event-based recorded annual maximum daily and recorded annual maximum instantaneous discharges in the record. If the reported annual maximum daily and annual maximum instantaneous discharges for the same year are not coincident (i.e., from the same flood event), the former values are replaced by the daily flow values for the events corresponding to the annual maximum instantaneous discharges.

Annual maximum instantaneous flood series for Athabasca River below Fort McMurray (WSC Station 07DA001) was extended for the period 1913 to 1957 based on a relationship established with the recorded annual maximum daily discharge series for Athabasca River at Athabasca (WSC Station 07BE001) for the same events. Even though the drainage area of the Athabasca River at Athabasca represents 56 percent of the drainage area of the Athabasca River below Fort McMurray, on average, more than 80 percent of the flood discharges below Fort McMurray are generated by the drainage area upstream of Athabasca. Hence, there is a strong correlation of flood discharges at the two locations as shown in Figure 2.

In consideration of the strong correlation in the recorded flood flows between these two locations, the flood series for Athabasca River below Fort McMurray was extended based on the relationship between the annual maximum daily discharges at the two locations. This increases the record length of the Athabasca River below Fort McMurray by 38 years and helps to reduce uncertainties associated with using a shorter period of record to generate flood estimates for large return periods. In addition, the extended flood data capture the two largest floods recorded in 1944 and 1954 on the Athabasca River at Athabasca as shown in Figure 3.

Sensitivity of the flood estimates to the record length were assessed by comparing the flood frequency estimates derived from the following three annual maximum instantaneous discharge series:

- Recorded annual maximum instantaneous discharge series and generated annual maximum instantaneous discharges series based on recorded annual maximum daily discharge series at the Athabasca River below Fort McMurray (WSC 07DA001) (from 1958 to 2016).
- Combined recorded and generated annual maximum instantaneous discharge series at the Athabasca River below Fort McMurray (WSC 07DA001) with extended annual maximum instantaneous discharge series (from 1913 to 1957) based on best-fit relationship shown in Figure 2.
- Combined recorded and generated annual maximum instantaneous discharge series at the Athabasca River below Fort McMurray (WSC 07DA001) with extended annual maximum instantaneous discharge series (from 1913 to 1957) based on the 50^{th} percentile upper-bound line shown in Figure 2. The 50^{th} percentile upper bound confidence interval was found adequate to assess the sensitivity of the flood estimates in this study as it provides a cut-off to exclude a meaningful number of outliers.

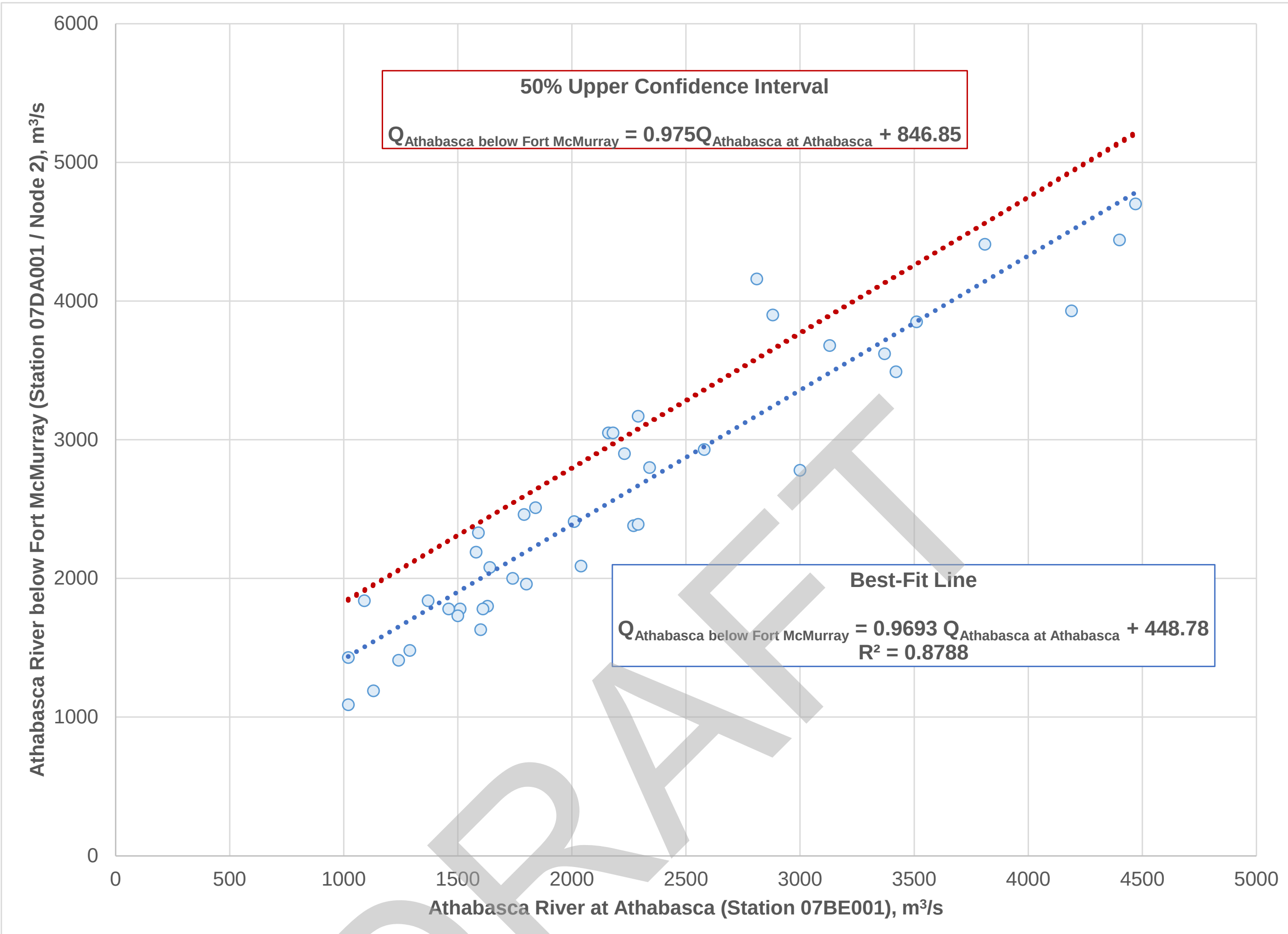

Figure 2: Annual Daily Maximum Discharges Relationship between Athabasca River at Athabasca (WSC Station 07BE001) and Athabasca River below Fort McMurray (WSC Station 07DA001 / Node 2)

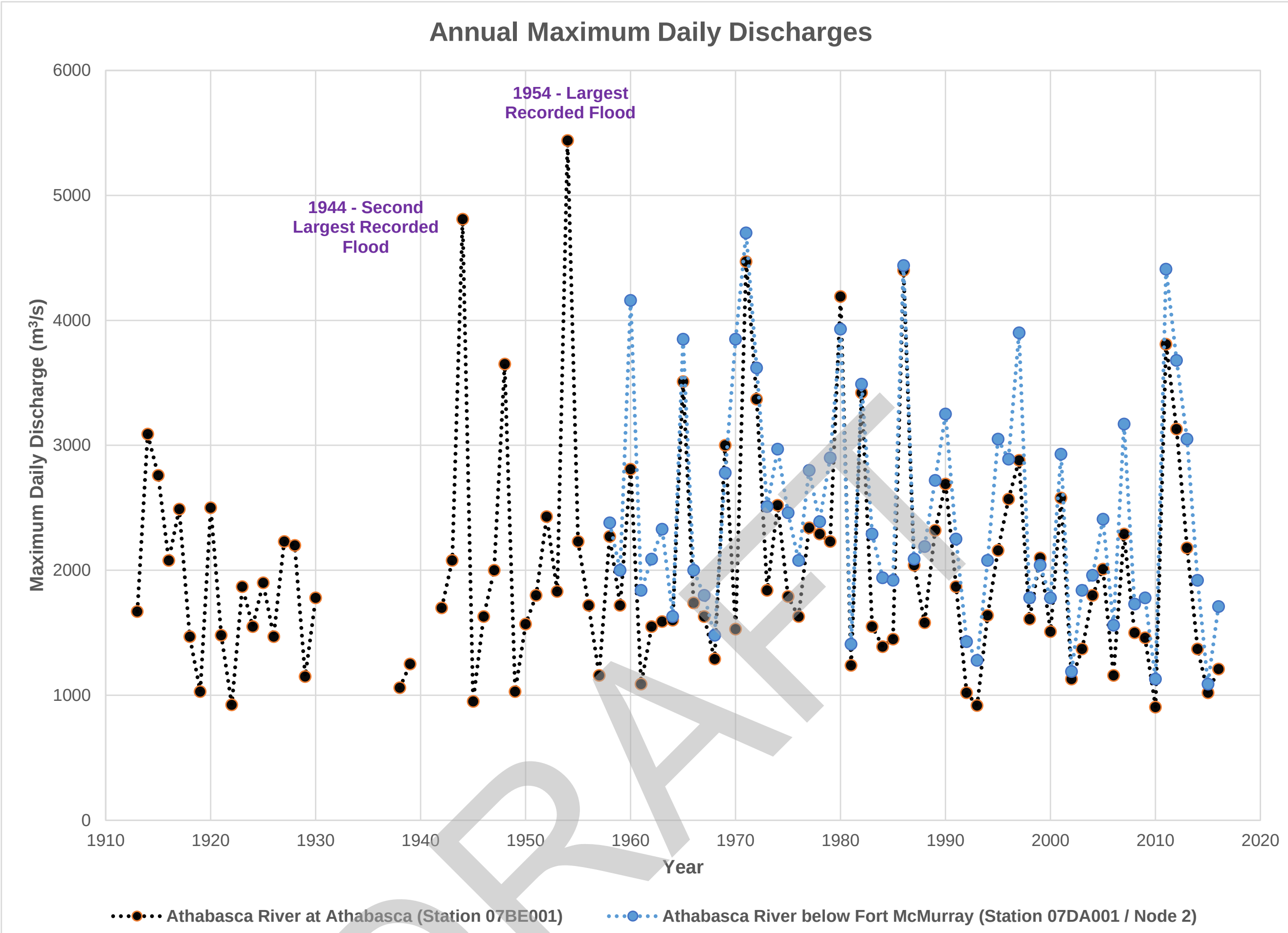

Figure 3: Recorded Annual Daily Maximum Discharges on Athabasca River at Athabasca (WSC Station 07BE001) and below Fort McMurray (WSC Station 07DA001)

3.3 Flood Flow Series for Ungauged Locations

3.3.1 Clearwater River at the Mouth

The annual maximum instantaneous synthetic discharge series for the Clearwater River at the Mouth were generated based on recorded discharge data for the Clearwater River at Draper (WSC Station 07CD001) and the Hangingstone River at Fort McMurray (WSC Station 07CD004) for the concurrent recorded period as described below.

- **Coincident Peaks, Clearwater River Dominated**: Add reported Clearwater River annual maximum instantaneous discharge to the corresponding Hangingstone River daily discharges (observed on the same day) factored to daily instantaneous discharge using the relationship developed for the Hangingstone River (Figure A-5 in Appendix A). Additional discharges from the local tributary watershed, Saline Creek, are included using recorded flows at Hangingstone River adjusted by an area-based factor (i.e., ratio between drainage area at Saline Creek and Hangingstone River).

- **Coincident Peaks, Hangingstone River Dominated**: Add reported Hangingstone River annual instantaneous flood flows to the corresponding Clearwater River daily discharges (observed on the same day) factored to daily instantaneous discharges using the relationship developed for the Clearwater River (Figure A-4 in Appendix A). Additional discharges from the local tributary watershed, Saline Creek, are included using recorded flows at Hangingstone River adjusted by an area-based factor (i.e., ratio between drainage area at Saline Creek and Hangingstone River).
- **Coincident Peaks, neither Dominated**: Sum of reported Clearwater River and Hangingstone River annual maximum instantaneous discharges for the same events. Additional discharges from the local tributary watershed, Saline Creek, are included using recorded flows at Hangingstone River adjusted by an area-based factor (i.e., ratio between drainage area at Saline Creek and Hangingstone River).

The maximum flood values calculated by the three methods described above were used as the annual maximum instantaneous discharge series for Clearwater River at the Mouth for each year.

Annual maximum instantaneous discharge series generated for the Clearwater River at the Mouth has 52 years of data (i.e., 1965 to 2016) as it is governed by the length of available record data of the Hangingstone River at Fort McMurray (WSC Station 07CD004).

3.3.2 Athabasca River above the Clearwater River Confluence

On average, the Clearwater River contributes about 10 percent of the flood discharge for the Athabasca River below Fort McMurray, based on recorded data. Hence, the Athabasca River above the Clearwater River confluence contributes about 90 percent of the flood discharge for the Athabasca River below Fort McMurray, or about two percent more than the flood flows of the Athabasca River at Athabasca (see Figure A-2 in Appendix A).

For the study reach of the Athabasca River above the Clearwater River Confluence, the annual maximum instantaneous synthetic discharge series was generated from the annual maximum instantaneous discharge series below Fort McMurray by subtracting the recorded daily discharges (observed on the same day) for the Clearwater River at Draper and the Hangingstone River at Fort McMurray and factored to daily instantaneous discharges. Additional discharges from the local tributary watershed of Saline Creek are included using flows recorded on the Hangingstone River adjusted by an area-based factor (i.e., ratio between drainage area at Saline Creek and Hangingstone River).

The extended annual maximum instantaneous discharge series for the Athabasca River below Fort McMurray (from 1913 to 1964) was also used to extend annual maximum instantaneous discharge series for the Athabasca River above the Clearwater River confluence that covers the period from 1913 to 1964 as shown in Figure A-2 (45 years in total). Therefore, the annual maximum instantaneous discharge series generated for the Athabasca River above the Clearwater confluence also has 98 years of data (i.e., 1913 to 2016).

The annual maximum instantaneous discharge series recorded for Athabasca River at Athabasca (WSC Station 07BE001) were also used to extend annual maximum instantaneous discharge series for the Athabasca River above the Clearwater River confluence (1913 to 1964). Comparison of the extended series generated by using either Athabasca River at Athabasca or Athabasca River below Fort McMurray indicates that the two series are very comparable as shown in Figure 4.

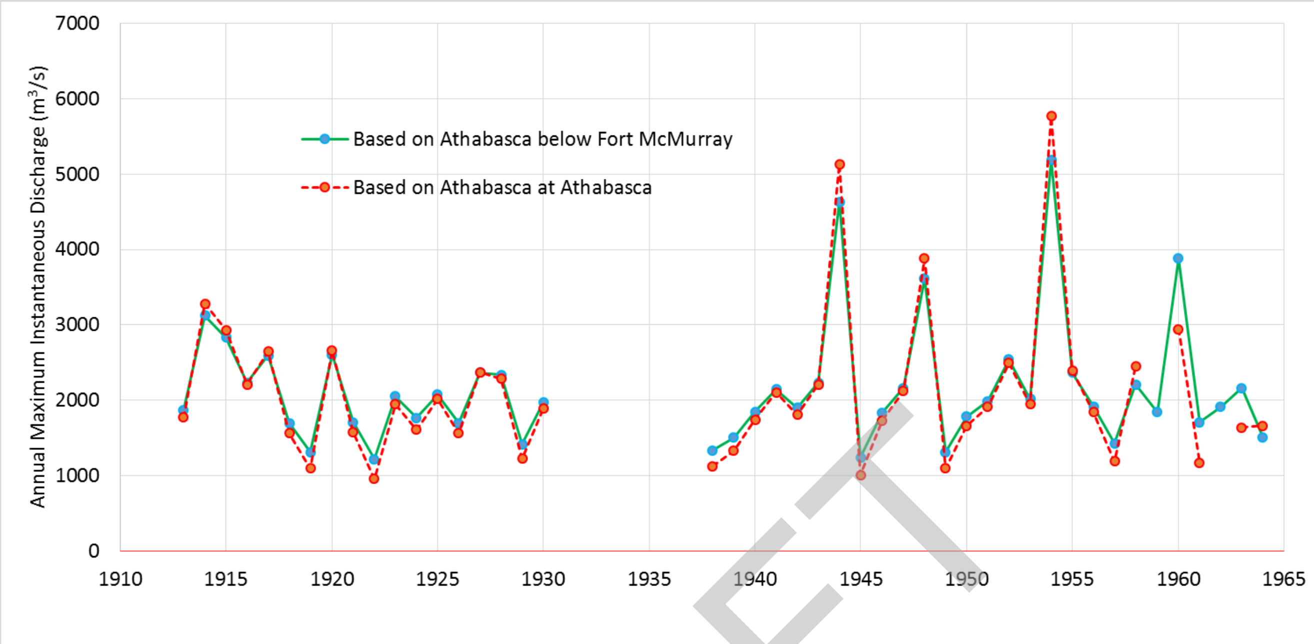

Figure 4: Extended Annual Maximum Instantaneous Discharges for Athabasca River above Clearwater River Confluence

Table 2 shows the summary of the seven annual maximum instantaneous discharge series compiled and generated based on approaches outlined in Sections 3.2 and 3.3. Appendix A presents the relationships established between annual maximum daily and annual maximum instantaneous discharges for the Athabasca, Clearwater, and Hangingstone rivers. Appendix A also presents plots showing the annual maximum instantaneous discharge series of both the recorded and estimated values.

Table 2: Summary of Compiled and Generated Flood Flow Series

WSC Station No. / Node ID	WSC Station Name or Name of Location of Interest	Period of Data	Methodology Used
Node 1	Athabasca River above Clearwater River Confluence	1913 – 2016	■ 1965 to 2016: Generated using annual maximum instantaneous discharge series for Athabasca River below Fort McMurray and subtracting discharge from tributaries (Clearwater and Hangingstone rivers), ■ 1913 to 1964: Generated using the relationship established with derived annual maximum instantaneous discharge series for Athabasca River below Fort McMurray, and ■ 1913 to 1964: Generated using the relationship established with derived annual maximum instantaneous discharge series for Athabasca River at Athabasca.
07DA001 / Node 2	Athabasca River below Fort McMurray, recorded	1958 – 2016	■ Based on recorded annual maximum instantaneous discharge series and a relationship established with annual maximum daily discharge series.
	Athabasca River below Fort McMurray, extended	1913 – 2016	■ Recorded annual maximum instantaneous discharges and annual maximum daily discharges factored to instantaneous, and ■ Extended by factoring recorded annual maximum daily discharges for Athabasca River at Athabasca based on best-fit relationship established with Athabasca River below Fort McMurray.
	Athabasca River below Fort McMurray, upper bound	1913 – 2016	■ Recorded annual maximum instantaneous discharges and recorded annual maximum daily discharges factored to instantaneous, and ■ Extended by factoring recorded annual maximum daily discharges for Athabasca River at Athabasca based on the upper-bound 50th percentile line.
07CD001 / Node 3	Clearwater River at Draper	1957 – 2016	■ Recorded annual maximum instantaneous discharges and annual maximum daily discharges factored to instantaneous.
07CD004 / Node 4	Hangingstone River at Fort McMurray	1965 – 2016	■ Recorded annual maximum instantaneous discharges and annual maximum daily discharges factored to instantaneous.
Node 5	Clearwater River at the Mouth, below Hangingstone River Confluence	1965 – 2016	■ The maximum of the annual instantaneous discharges generated through 1) coincident peaks - Clearwater River dominated; 2) coincident peaks - Hangingstone River dominated; and 3) peak of coincident annual maximum instantaneous discharges for Clearwater and Hangingstone Rivers.

4.0 FLOOD FREQUENCY ANALYSIS

4.1 Statistical Tests

4.1.1 Methodology

Prior to fitting the appropriate frequency distribution to the flood flow data, a number of statistical tests were performed to determine the quality of the developed annual maximum instantaneous discharge series. Software developed by Golder that is similar to Environment Canada's Consolidated Frequency Analysis (CFA), but with enhanced methodology, was used for: flood frequency analyses and statistical tests for independence (not serially correlated), (ii) trend, randomness, and homogeneity. Golder's software includes modern boot-strapping method and estimation of confidence intervals.

The following probability distributions were analyzed with select parameter estimation methods (i.e., method of moments [Moment], maximum likelihood estimation [MLH], and Method of L-moments [MLM]):

- Three-parameter Log Normal distribution (3P, Moment and MLH).
- Generalized Extreme Value distribution, which includes Extreme Value 1, 2, and 3 distributions (EV, MLM).
- Log-Pearson Type III distribution (LP3, Moment, and MLH).
- Weibull distribution (Moment).

Numerical goodness-of-fit tests were performed using the non-parametric Anderson-Darling test (Stephens, 1974).

4.1.2 Results

Table 3 provides the results of statistical tests for recorded or generated flood flow series at various locations along the Athabasca, Clearwater, and Hangingstone Rivers. The results show that most of the annual maximum instantaneous flood flow series are independent, random, homogeneous, and do not display any significant trends. The results are highlighted and discussed below:

- The annual maximum instantaneous discharge series for the Athabasca River below Fort McMurray generated by extending the data based on using 50-percentile upper-bound relationship, displays a trend at the 5% level of significance but not at 1% level of significance. The trend does not appear to be due to any large-scale climate change. The estimates for the two large flood discharges in 1944 and 1954 become significantly higher than any of the flood flows recorded, and therefor they influence the downward trend when one uses the 50-percentile upper-bound relationship. Similar effects were observed for discharge series generated for Athabasca River above the Clearwater River confluence.
- The annual maximum instantaneous discharge series for the Clearwater River at Draper displays dependence, trend, and non-homogeneity at the 5% level of significance. Similar effects were observed for discharge series generated for Clearwater River at the Mouth. The dependence, trends and non-homogeneity are influenced by significantly large floods in the 1960's and 1970's but relatively lower flood magnitudes on the Clearwater River since 1980's, notwithstanding the flood of 2013.

Data dependence, trends, and non-homogeneities are caused when either changes in climate conditions (relatively long dry and wet hydrologic cycles) or anthropogenic changes such as forestry operations, flow regulation or diversions affect the observations through time.

For the Athabasca River, the observed trend at 5% level of significance is mainly related to uncertainties associated with estimated large floods in 1944 and 1954. This is obvious since the same trend was not observed if the best-fit line is used instead of the 50th percentile upper-bound line.

For the Clearwater River, the effects are more related to the fact that the data shows a wet hydrologic cycle in 1960s and 1970s and then a dry hydrology cycle after the 1980's. Hence, had a sufficiently long period of record been available for the Clearwater River, the data series might not exhibit dependence, trends, or non-homogeneity. In reality, obtaining data that is perfectly independent, free of trends, and non-homogeneous is almost impossible since factors, such as data length and record period, can affect the outcome of the statistical tests.

4.2 Flood Frequency Estimates

Flood frequency analyses of the annual maximum instantaneous discharge series (that includes the preliminary estimates of 2014, 2015, and 2016 flood flows) at five locations within the study area were conducted to estimate the discharges of various return period (i.e., 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1000-year) floods. Table 4 summarizes the flood discharge estimates and the discharges associated with the upper and lower 95% confidence intervals. The annual maximum instantaneous discharge series used in the flood frequency analyses, the various frequency distributions, and the best-fit distributions along with their 95% confidence intervals are provided in Appendix B.

Table 5 compares flood flows computed for the Athabasca River below Fort McMurray based on three flood series as described in Section 3.2. Results indicate the following:

- Using the best-fit line (Figure 2) to extend the annual maximum instantaneous discharge series based on recorded annual maximum daily discharges of the Athabasca River at Athabasca will result in a marginal decrease in flood peak estimates for return periods less than 35 years. An increase in the flood peak estimates is evident for return periods equal or greater than 35 years, with an increase of about 3.5% for the 100-year flood and about 13% for the 1000-year flood.
- Using the 50th percentile upper-bound line (Figure 2) to extend the annual maximum instantaneous discharge series will result in a marginal increase in the flood peak estimate for all return periods, with increases ranging from 2.1% (20-year flood) to 5.1% (2-year flood).
- Using extended data will increase the reliability of the flood frequency estimates (particularly for low-probability events) by capturing more extreme flood events. Hence, flood frequency estimated using extended annual maximum instantaneous discharge for Athabasca River below Fort McMurray are recommended as the final values.

Table 3: Results of Statistical Tests of Annual Maximum Instantaneous Discharges and Goodness-of-Fit of Probability Distribution Functions

WSC Station ID	Node 1	07DA001 / Node 2			07CD001 / Node 3	07CD004 / Node 4	Node 5
WSC Station Name or Location of Interest	Athabasca River above Clearwater River Confluence	Athabasca River below Fort McMurray, reported	Athabasca River below Fort McMurray, extended	Athabasca River below Fort McMurray, 50-percentile upper bound	Clearwater River at Draper	Hangingstone River at Fort McMurray	Clearwater River at the Mouth
Anderson-Darling statistic, A² = - N -S							
3 Parameter Log-normal	0.201	0.302	0.199	0.208	0.188	0.169	0.185
Extreme Value	0.206	0.325	0.184	0.191	0.184	0.145	0.182
Log-Pearson III	0.200	0.327	0.191	0.199	0.190	0.154	0.197
Weibull	0.611	0.420	0.680	1.482	0.226	0.487	0.278
Serial correlation coefficient test for independence							
S_1	0.084	0.103	0.084	0.112	0.302	0.173	0.349
t	0.814	0.777	0.814	1.095	2.394	1.228	2.607
t(α=0.05)	1.661	1.673	1.661	1.661	1.672	1.677	1.677
t(α=0.01)	2.367	2.395	2.367	2.367	2.394	2.405	2.405
Spearman rank order correlation coefficient test for no-trend							
r_s	0.039	0.211	0.032	0.232	0.314	0.178	0.295
t	0.377	1.632	0.316	2.329	2.518	1.279	2.187
t(α=0.05)	1.985	2.002	1.985	1.985	2.002	2.009	2.009
t(α=0.01)	2.629	2.665	2.629	2.629	2.663	2.678	2.678
Mann-Whitney split sample test for homogeneity							
Size of earlier sample	48	30	48	48	30	26	26
z	-0.534	-1.751	-0.660	-1.209	-2.536	-1.455	-2.251
z(α=0.05)	-1.645	-1.645	-1.645	-1.645	-1.645	-1.645	-1.645
z(α=0.01)	-2.326	-2.326	-2.326	-2.326	-2.326	-2.326	-2.326
Test of general randomness (Runs for above or below the median)							
Median	2012	2280	2245	2492	362	35.9	382
N1(for Q>=Median)	49	30	49	49	30	26	26
N2(for Q<Median)	48	29	48	48	30	26	26
Run_ab	49	28	47	40	25	24	21
z	0.101	0.655	0.509	1.938	1.562	0.840	1.681
z(a=0.05)	1.960	1.960	1.960	1.960	1.960	1.960	1.960
z(a=0.01)	2.576	2.576	2.576	2.576	2.576	2.576	2.576

Notes:

1. Selected distribution based on best statistical fit	0.475
2. Criteria for the respective statistical tests were not met	1.960

Table 4: Computed Flood Peak Discharge and their 95% Confidence Intervals

WSC Station ID / Node ID	WSC Station Name or Location of Interest	Gross Drainage Area (km^2)	Effective Drainage Area (km^2)	Distribution / Method	Computed Flood Peak Discharges with 95% Confidence Bounds (m^3/s)																																						
					1000-yr			750-yr			500-yr			350-yr			200-yr			100-yr			75-yr			50-yr			35-yr			20-yr			10-yr			5-yr			2-yr		
ATHABASCA RIVER																																											
Node 1	Athabasca River above Clearwater River Confluence	100,722	98,719	EV2	8200	10500	5840	7820	9910	5680	7310	9110	5450	6870	8410	5240	6230	7420	4900	5480	6350	4470	5190	5950	4320	4790	5430	4060	4460	4990	3820	3950	4380	3460	3360	3700	3010	2800	3080	2550	2030	2220	1890
07DA001 / Node 2	Athabasca River below Fort McMurray, reported	132,588	130,457	EV2	7690	9550	5830	7440	9090	5740	7090	8480	5580	6780	7960	5430	6310	7210	5170	5720	6350	4820	5480	6050	4670	5150	5610	4440	4850	5270	4230	4390	4780	3860	3820	4210	3370	3230	3610	2880	2360	2660	2130
	Athabasca River below Fort McMurray, extended [1]			EV2	8680	11400	6220	8300	10700	6040	7780	9780	5800	7340	9070	5580	6680	8040	5260	5920	6930	4840	5620	6500	4660	5210	5940	4430	4860	5470	4200	4330	4820	3800	3710	4070	3350	3110	3410	2850	2290	2480	2130
	Athabasca River below Fort McMurray, 50-percentile upper bound			EV2	7990	11000	5680	7710	10400	5580	7330	9590	5430	6990	8940	5300	6480	8040	5080	5860	7020	4780	5610	6640	4640	5260	6110	4450	4950	5650	4280	4480	5000	3960	3900	4260	3540	3320	3600	3060	2480	2680	2310
CLEARWATER RIVER and TRIBUTARIES																																											
07CD001 / Node 3	Clearwater River at Draper	30,799	30,771	EV3	1170	1510	848	1140	1440	835	1090	1350	818	1050	1270	800	983	1160	771	900	1040	728	864	985	709	814	915	682	770	859	654	699	777	605	609	675	536	513	571	456	366	415	328
07CD004 / Node 4	Hangingstone River at Fort McMurray	962	962	EV2	434	699	170	397	624	163	349	533	154	312	463	144	260	372	131	206	285	115	187	255	108	162	217	100	143	188	92.6	116	149	80.7	87.4	111	65.6	63.5	79.9	50.4	35.8	44.5	29.6
Node 5	Clearwater River at the Mouth	31,879	31,851	EV3	1240	1660	820	1200	1580	809	1150	1480	794	1110	1390	780	1040	1270	756	949	1130	724	911	1070	708	859	998	685	812	933	661	737	836	617	641	722	554	540	607	477	385	435	344

[1] *Flood frequency estimates using extended annual maximum instantaneous discharge for Athabasca River below Fort McMurray are recommended as the final values*

Table 5: Comparison of Flood Peak Discharge Estimates at the Athabasca River below Fort McMurray based on Three Flow Series

Return Period (years)	Athabasca River below Fort McMurray, reported	Athabasca River below Fort McMurray, extended	Percent Difference[1] (i.e., Best-Fit line and Reported)	Athabasca River below Fort McMurray, 50th percentile upper bound	Percent Difference[1] (i.e., 50th percentile Upper Bound line and Reported)
1000	7690	8680	13%	7990	3.9%
750	7440	8300	12%	7710	3.6%
500	7090	7780	9.7%	7330	3.4%
350	6780	7340	8.3%	6990	3.1%
200	6310	6680	5.9%	6480	2.7%
100	5720	5920	3.5%	5860	2.4%
75	5480	5620	2.6%	5610	2.4%
50	5150	5210	1.2%	5260	2.1%
35	4850	4860	0.2%	4950	2.1%
20	4390	4330	-1.4%	4480	2.1%
10	3820	3710	-2.9%	3900	2.1%
5	3230	3110	-3.7%	3320	2.8%
2	2360	2290	-3.0%	2480	5.1%

[1] The percent differences are calculated between the computed instantaneous flow estimates of the extended Athabasca River below Fort McMurray flood flow series using the best-fit and 50th percentile upper bound lines and the reported Athabasca River below Fort McMurray flood flow series.

4.3 Comparison to Previous Studies

Table 6 presents a comparison of the flood frequency estimates obtained in this study for the Clearwater River at Draper, the Hangingstone River at Fort McMurray, and the Athabasca River below Fort McMurray with studies previously conducted by Golder (2014), Tetra Tech EBA (2015), and NHC (2014).

Table 6: Comparison of the Flood Frequency Estimates with Previous Studies

Return Period	WSC Station 07CD001 Clearwater River at Draper			WSC Station 07CD004 Hangingstone River at Fort McMurray				WSC Station 07DA001 Athabasca River below Fort McMurray		
(years)	Golder (2014)	NHC (2014)	This Study	Golder (2014)	NHC (2014)	TETRA TECH EBA (2015)	This Study	Golder (2014)	NHC (2014)	This Study
Distribution / Method	LP3 (MOM)	LP3	EV3	3P (MLH)	LP3	LP3 (MOM)	EV2	3P (MLH)	LP3	EV2
1000	-	-	1170	-	-	279	434	-	-	8680
500	1085	-	1090	405	-	249	349	7244	-	7780
100	893	866	900	242	186	184	206	5809	5240	5920
50	811	795	814	189	159	156	162	5223	4830	5210
20	700	696	699	131	123	121	116	4454	4260	4330
10	613	615	609	96	96.0	95	87.4	3875	3800	3710
5	520	-	513	66	-	69.9	63.5	3279	-	3110
2	375	379	366	34	35.8	37	35.8	2403	2440	2290

Notes:
1. The Golder (2014) report uses recorded data from 1958 to 2013 for Clearwater River at Draper, 1970 to 2013 for Hangingstone River at Fort McMurray, and 1958 to 2013 for Athabasca River at Fort McMurray.
2. The NHC (2014) report uses recorded data from 1958 to 2013 for Clearwater River at Draper, 1965 to 2013 for Hangingstone River at Fort McMurray, and 1958 to 2011 for Athabasca River at Fort McMurray.
3. The Tetra Tech EBA (2015) report uses recorded data from 1965 to 2013 for Hangingstone River at Fort McMurray.

The flood frequency estimates for previous studies were based on recorded data up to 2013, with provisional flow data from WSC for the 2012 and 2013 events. The current study uses the updated estimates of the 2013 maximum instantaneous discharges, published flow data from 2013 to 2015, and provisional flow data for 2016 from WSC. In addition, this study includes analyses to update the relationship between annual maximum daily and annual maximum instantaneous discharges at all study locations.

The resulting flood frequency estimates for this study are comparable to the results of previous studies, but with minor difference due to the length of recorded data used for the flood frequency analysis and the different frequency curve distribution that was adopted herein.

5.0 POTENTIAL EFFECTS OF CLIMATE CHANGE ON FLOOD PEAK DISCHARGES AND FLOOD FREQUENCY ESTIMATES

Recent study on the effect of climate change (e.g., Martz et al. 2007) indicate that climate change could result in increased air temperature, more frequent drought and water shortages, increased precipitation in some areas, and increased flooding. As a result of the expected change in both the systematic climate and its variability, many regions of Canada, including the Prairies, could experience warmer air temperatures and changes in stream flow magnitude and timing (e.g., higher winter stream flows and lower summer stream flows).

Assessment of future climate scenarios depends on the climate model used for the prediction. Regardless, precipitation is projected to increase in Alberta, with less precipitation falling as snow and more rainfall-on-snow precipitation events (Valeo et al. 2007). Hence, it is anticipated that such changes in precipitation patterns could increase the frequency and intensity of extreme events (i.e., flood, drought, hail, and windstorms). It is also predicted that the flood events for the Fort McMurray River watershed could occur earlier in the spring than in the past if rain-on-snow events occur more frequently and the snowpack begins to melt earlier.

The effects of potential climate change on flows in watersheds in Alberta, including the Athabasca River Basin (ARB), are discussed by Kerhoven and Gan (2005). Two sources of meteorological data were used in their study. The first is a set of archived forecasts from the Meteorological Survey of Canada's Global Environmental Multiscale Model (GEM), and the second is the ERA-40 historical re-analysis data developed by the European Centre for Mid-range Weather Forecasts (ECMWF).

The modified Interactions Soil–Biosphere–Atmosphere hydrological modelling of the Athabasca River basin with ERA-40 data was used to simulate a number of climate scenarios for the Athabasca River basin. The predicted changes to mean monthly temperature and precipitation from seven GCM models (CCSRNIES, CGCM2, CSIROMk2b, ECHAM4, GFDLR30, HadCM3, and NCARPCM) for four emission scenarios (A1FI, A21, B11, B21) over the 1961–1990 base period were used to adjust the ERA-40 temperature and precipitation for ARB, over three 30-year time periods: 2010-2039 (early-21st century), 2040-2069 (mid-21st century), and 2070-2099 (late-21st century).

Most of the models predict continuing decreases in average, maximum, and minimum flows over the next 100 years. This is mainly due to the decrease in the volume of spring runoff caused by a decreased snow pack. The high flow season also becomes much shorter.

Golder (2009) also completed analysis of the potential effects of climate change on water yield in the Lower Athabasca Regional Plan Area (LARP), which includes the downstream portion of the Athabasca River Basin. The calibrated and validated HSPF model, was used to simulate the hydrologic effects of forecasted future climate scenarios.

The following five climate scenarios provided by Alberta Environment were used to simulate flows along the Athabasca River:

- CCSRNIES_A1F1 (warmer and drier than median conditions).
- CGCM2_B23 (cooler and drier than median conditions).
- HADCM3_A2A (warmer and wetter than median conditions).
- HADCM3_B2B (median conditions).
- NCARPPCM_A1B (cooler and wetter than median conditions).

Predicted flood flow statistics (2-yr, 10-yr, and 25-yr recurrence intervals) for the 2050s climate scenarios indicate that the flood flows are predicted to decrease by 3% to 5% for median conditions, as shown in Table 7.

As part of the Frontier Oil Sands Project Environment Impact Assessment Application, Golder (2013) completed an assessment using five selected representative GCMs and scenarios outputs from the IPCC Fourth Assessment Report (AR4) (IPCC 2007) for the Athabasca River basin. The five selected scenarios represent climate conditions that were cooler and drier (BCM2.0 SR-B1), cooler and wetter (INMCM3.0 SR-A2), warmer and wetter (MIROC3.2 hires SR-A1B), and warmer and drier (CNRMCM3 SR-A2) than median conditions (CGCM3T47 SR-B1).

The forecast of climate change relative to the 1961 to 1990 baseline period (see Table 7) represents the forecasted total climate change between the modelled baseline period (1961 to 1990) as represented by its 30-year average and the modelled future period (i.e., 2051 to 2080, called the 2060s) as represented by its 30-year average. The results indicate that changes in flood peaks for the Athabasca River below Fort McMurray will vary from -4.3% for the 2-year flood to 6.1% for the 100-year flood for median conditions.

Table 7: Hydrologic Effects of Forecasted Climate Change on Athabasca River Flows below Fort McMurray

Return Period (years)	Golder (2009)		Golder (2013)	
	Range of Change in Flow Magnitude (%)	Median Condition (%)	Range of Change in Flow Magnitude (%)	Median Condition (%)
2	-1 to -20	-5	-24.1 to 27.7	-4.3
10	2 to -15	-4	-21.0 to 43.3	0.4
25	3 to -11	-3	-19.6 to 50.4	2.7
100	n/a	n/a	-17.8 to 60.4	6.1

The analysis of the effect of future climate change projections indicates that changes in flood peaks for the Athabasca River are expected to be small for median climate change projections. However, the flood peaks can either decrease or increase depending on the climate change scenario that might prevail in the future. The uncertainty associated with the analysis of climate change projections lies within these changes of peak flow magnitudes.

The 1954 flood in the Athabasca River basin has been the largest flood since 1913, as illustrated in Figure 5. Based on the recorded flow data for the past 104 years (i.e., 1913 to 2016), the annual peak flows for the Athabasca River do not appear to be trending upward. Any upward trend shown in Figure 5 is not statistically significant.

The trend in flood magnitudes on the Clearwater River and the Hangingstone River appears to be a decreasing one (Figure 5), likely due to the hydrological cycle (i.e., wet-cycle during the 1960s and 1970s and dry-cycle since 1980s).

About 76 percent of the recorded annual peak discharges in the Athabasca River occurred between the beginning of June and end of July (see Table 8 and Figure 6). About 66% percent of the recorded annual peak discharges in the Clearwater River occurred between the mid-April and end of June (see Table 8 and Figure 7). The frequency of annual peak discharges occurring outside these time window (earlier or later) does not appear to be changing with time. The recent patterns in the timing of these peak discharges are similar to what were observed at the beginning of the century. There is no clear evidence that the patterns in magnitude or timing of annual peak discharges have changed significantly over the past hundred years.

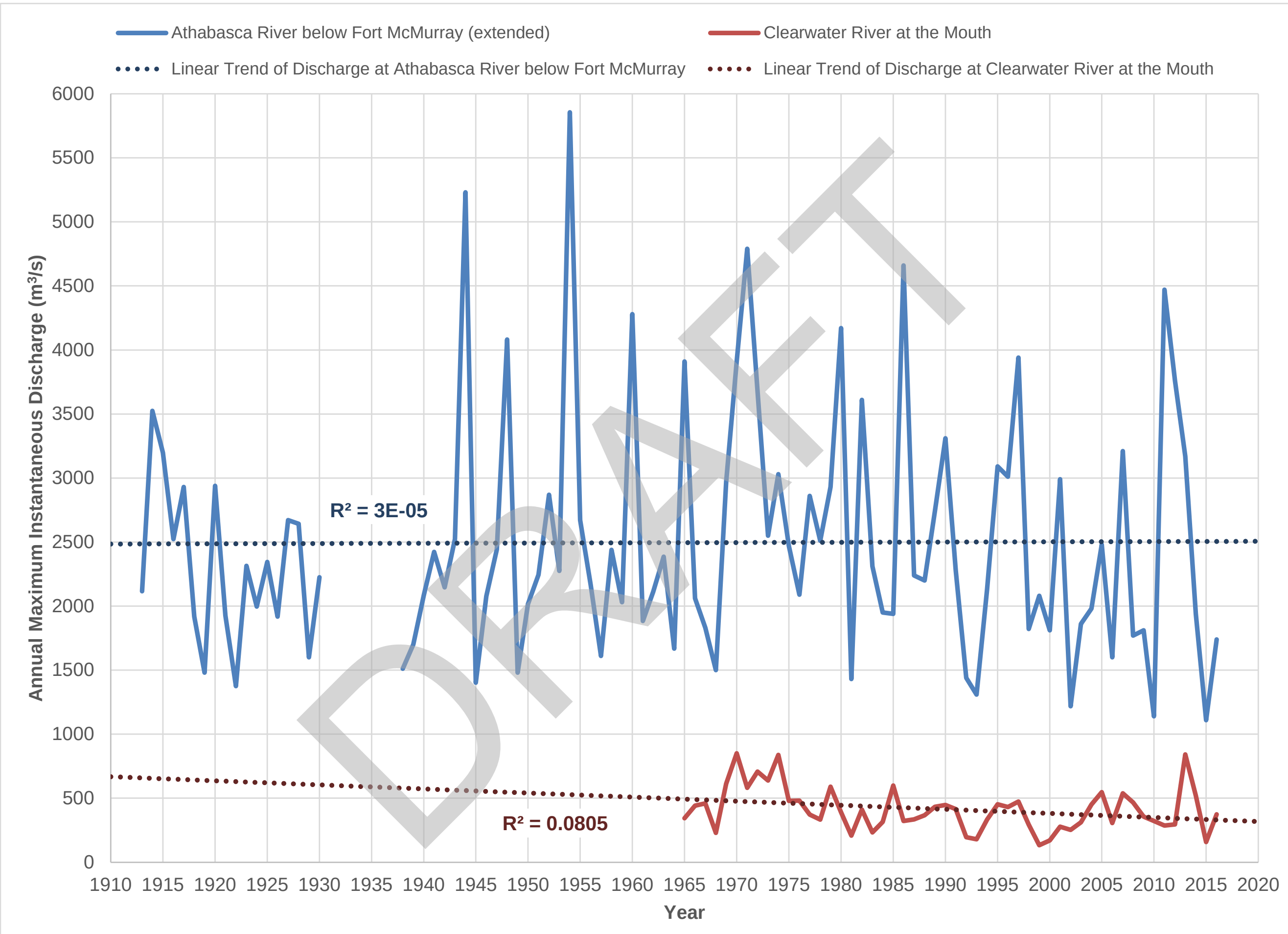

Figure 5: Annual Flood Peak Flows in the Athabasca River below McMurray and the Clearwater River at the Mouth

Table 8: Timings of Annual Maximum Daily Flows in the Athabasca River below McMurray and the Clearwater River at the Mouth

Month	Athabasca River - Occurrences of Annual Maximum Daily Flows Since 1913		Clearwater River - Occurrences of Annual Maximum Daily Flows Since 1965	
	Number	%	Number	%
April	0	0	13	25
May	10	10	15	29
June	45	46	6	12
July	29	30	8	15
August	10	10	5	10
September	3	3	5	10

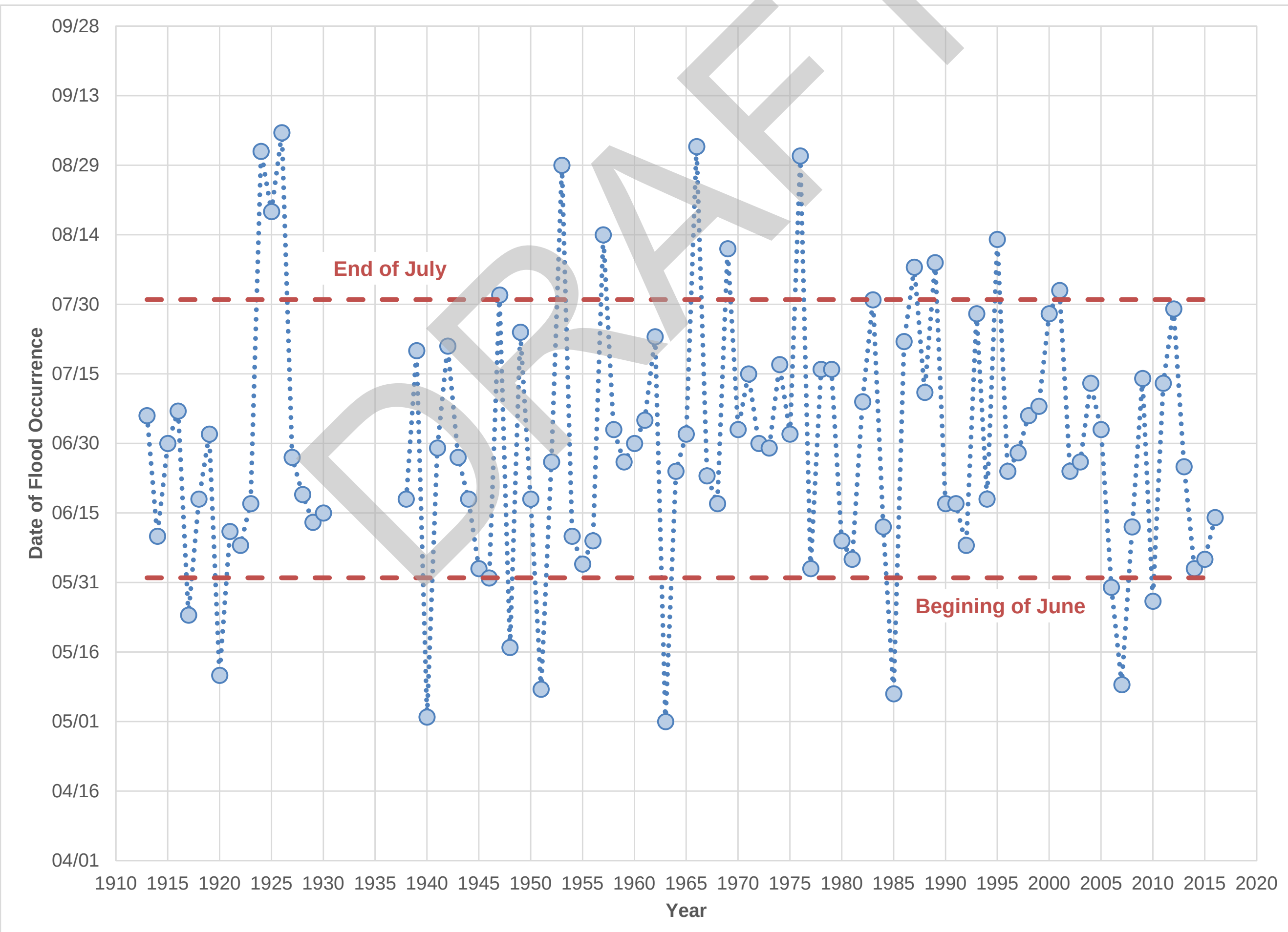

Figure 6: Timings of Past Annual Peak Flows in the Athabasca River below McMurray

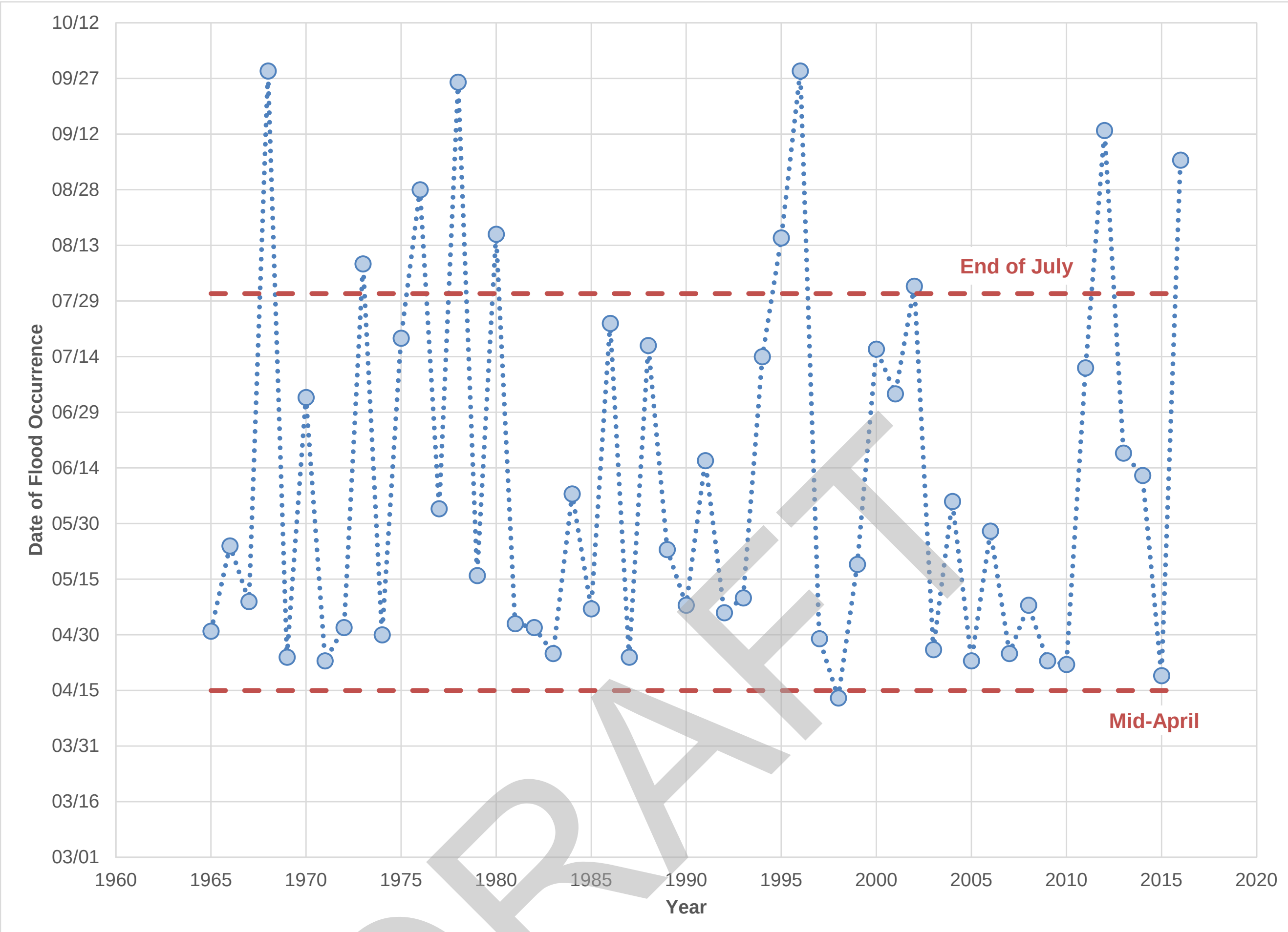

Figure 7: Timings of Past Annual Peak Flows in the Clearwater River at the Mouth

6.0 CONCLUSIONS

The results of this study support the following conclusions:

- The flood frequency estimates obtained in this study are the most up-to-date for the various locations along the Athabasca, Clearwater, and Hangingstone rivers. These estimates provide the updated flood hydrology information as input to the Fort McMurray River Hazard Study being conducted under the Provincial Flood Hazard Identification Program, as well as flood mitigation and other projects. Table 4 summarize the estimates of flood peak discharges for return periods ranging from 2 to 1,000 years, and the 95% upper and lower confidence intervals.
- This study includes preliminary estimates of the annual maximum instantaneous discharges in 2014, 2015, and 2016. Inclusion of the additional discharge information increases the sample sizes for the flood frequency analyses and reliability of the resulting flood frequency estimates.
- The lengths of periods of the recorded flood flow data available and used in the flood frequency analyses for the Clearwater and Hangingstone rivers are less than 60 years. Therefore, there are large uncertainties (i.e. the confidence intervals are very large) with flood frequency estimates for return periods greater than 100 years.

Report Signature Page

This report is prepared and reviewed by the undersigned. If you have any questions or require additional details, please contact the undersigned.

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THIRD PARTY DISCLAIMER

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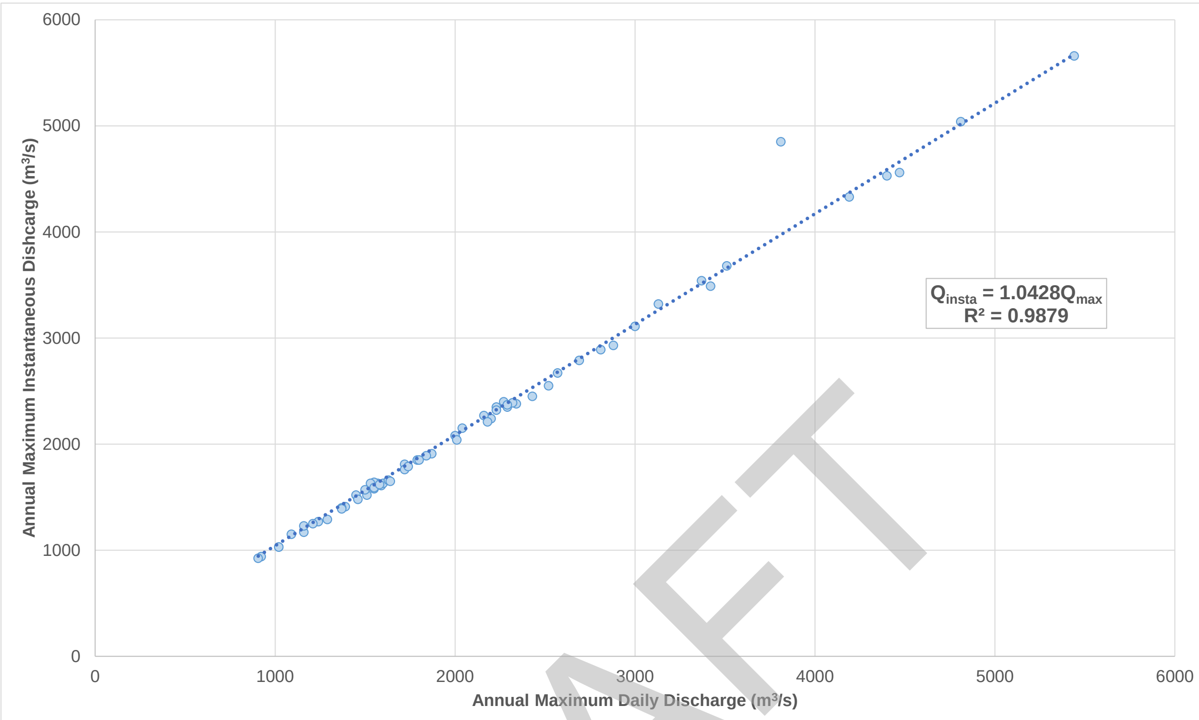
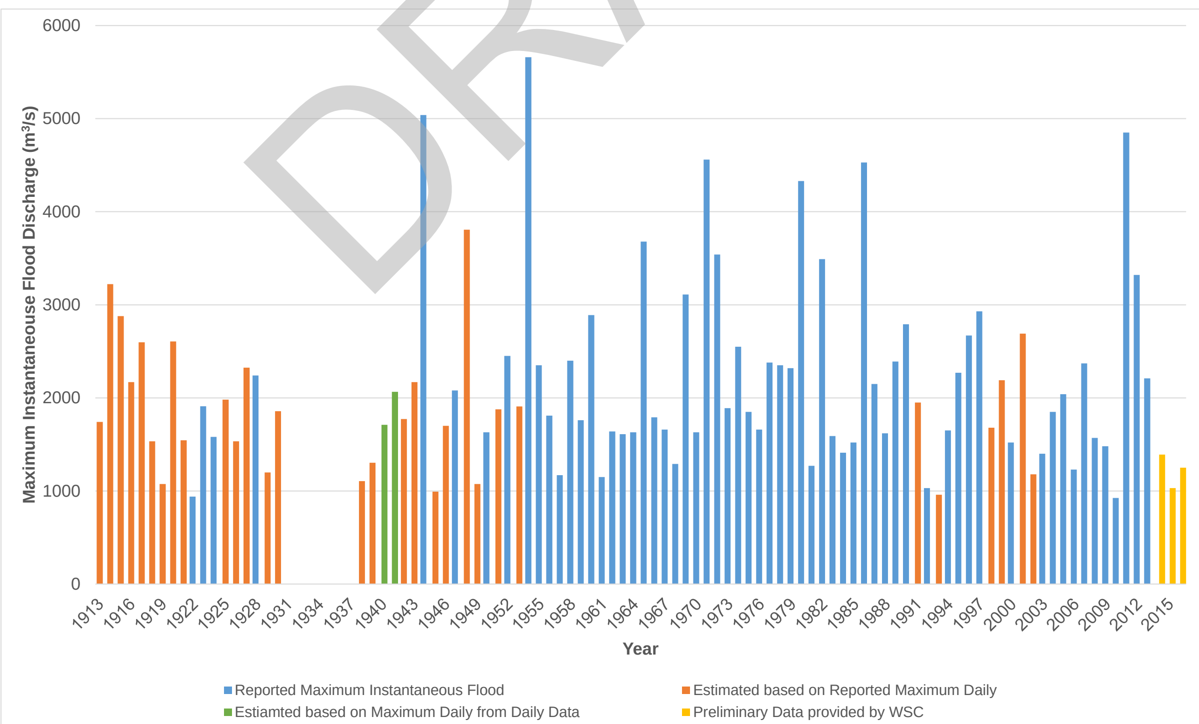
APPENDIX A

Graphical Summaries of Flood Flow Series at Gauged Stations and Locations of Interest

Figure A-1: WSC No. 07BE001, Athabasca River at Athabasca

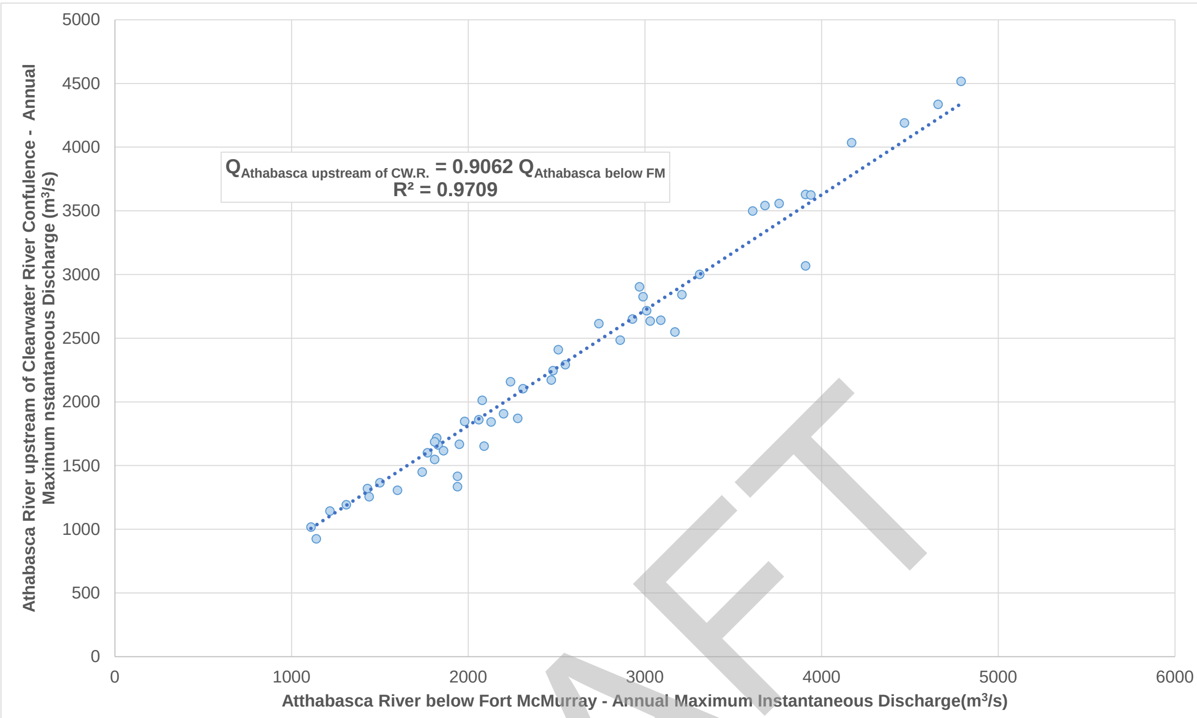


Relationship between Annual Maximum Daily and Annual Maximum Instantaneous Discharges at Athabasca River at Athabasca (WSC No. 07BE001)

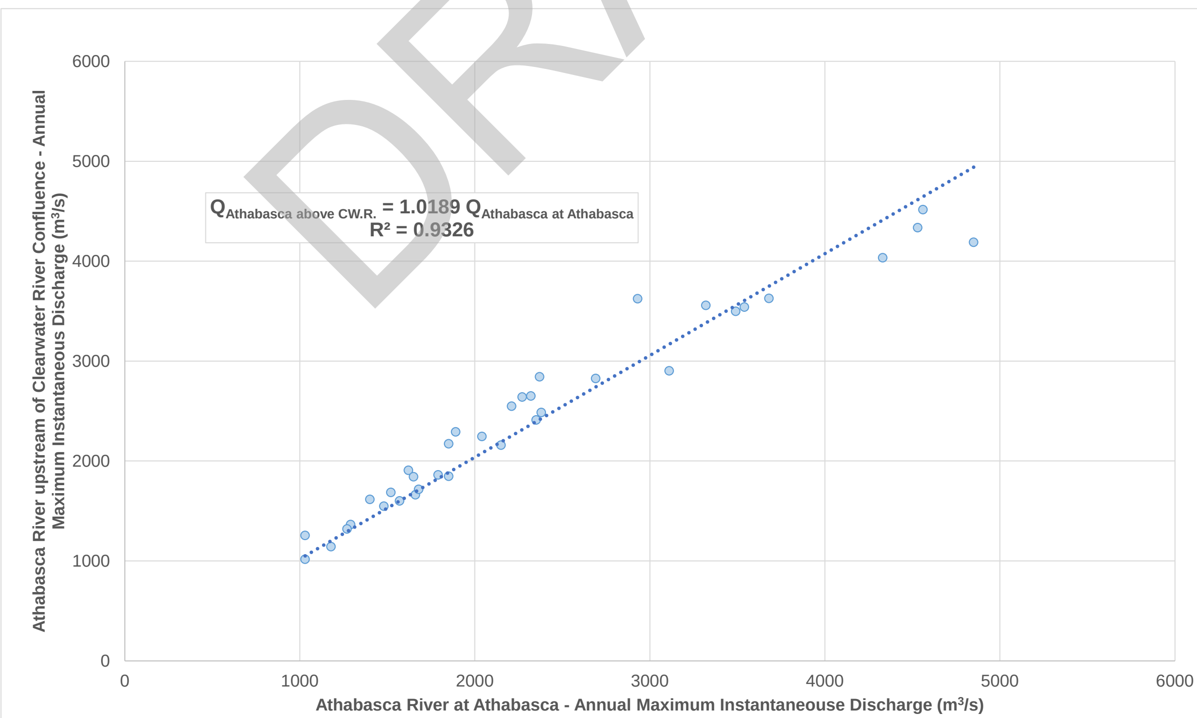


Maximum Instantaneous Flood Flow Series at Athabasca River at Athabasca (WSC No. 07BE001)

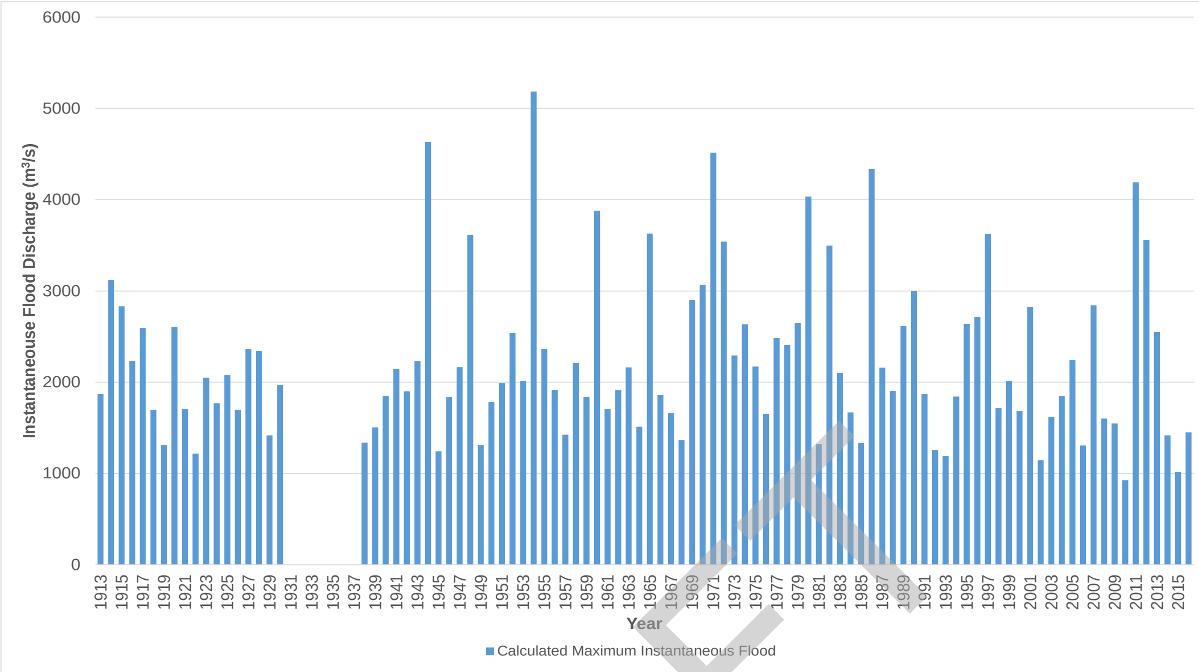
Figure A-2: Node 1, Athabasca River above Clearwater River Confluence



Relationship between Athabasca River below Fort McMurray and above Clearwater River Confluence – based on recorded and derived date from 1965 to 2016.

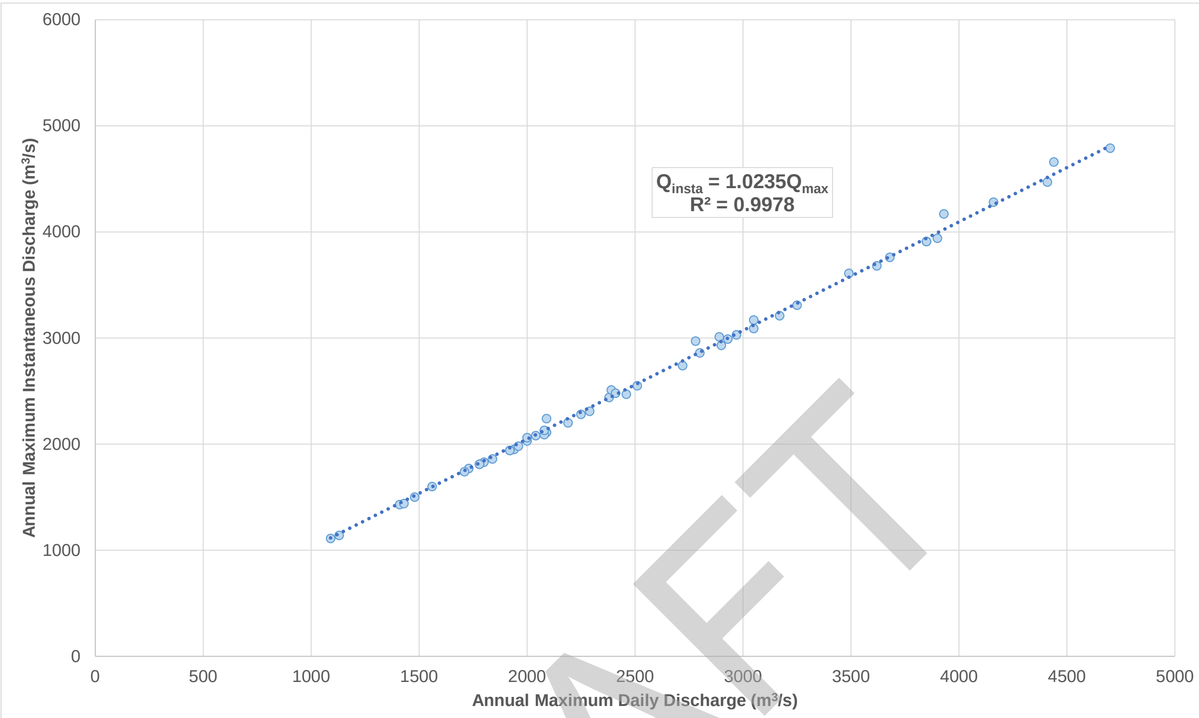


Relationship between Athabasca River above Clearwater River Confluence and at Athabasca – based on recorded and derived date from 1965 to 2016.

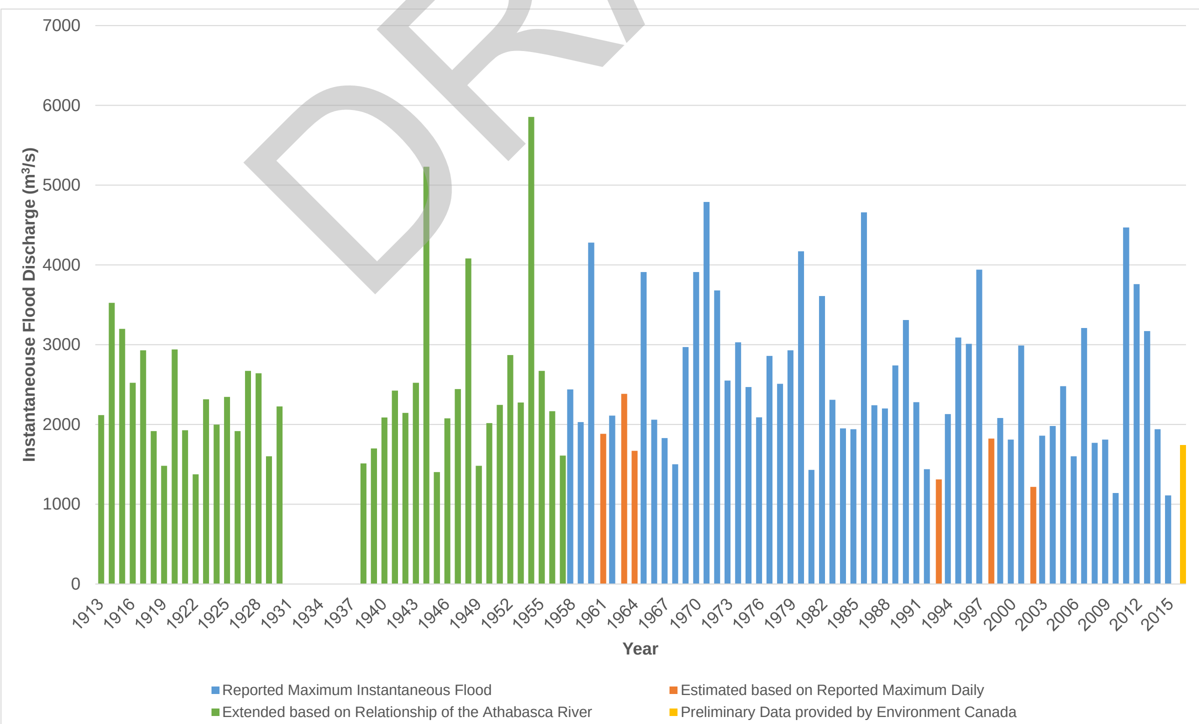


Derived Maximum Instantaneous Flood Flow Series at Athabasca River above Clearwater River Confluence (Node 1)

Figure A-3: WSC No. 07DA001 / Node 2, Athabasca River below Fort McMurray

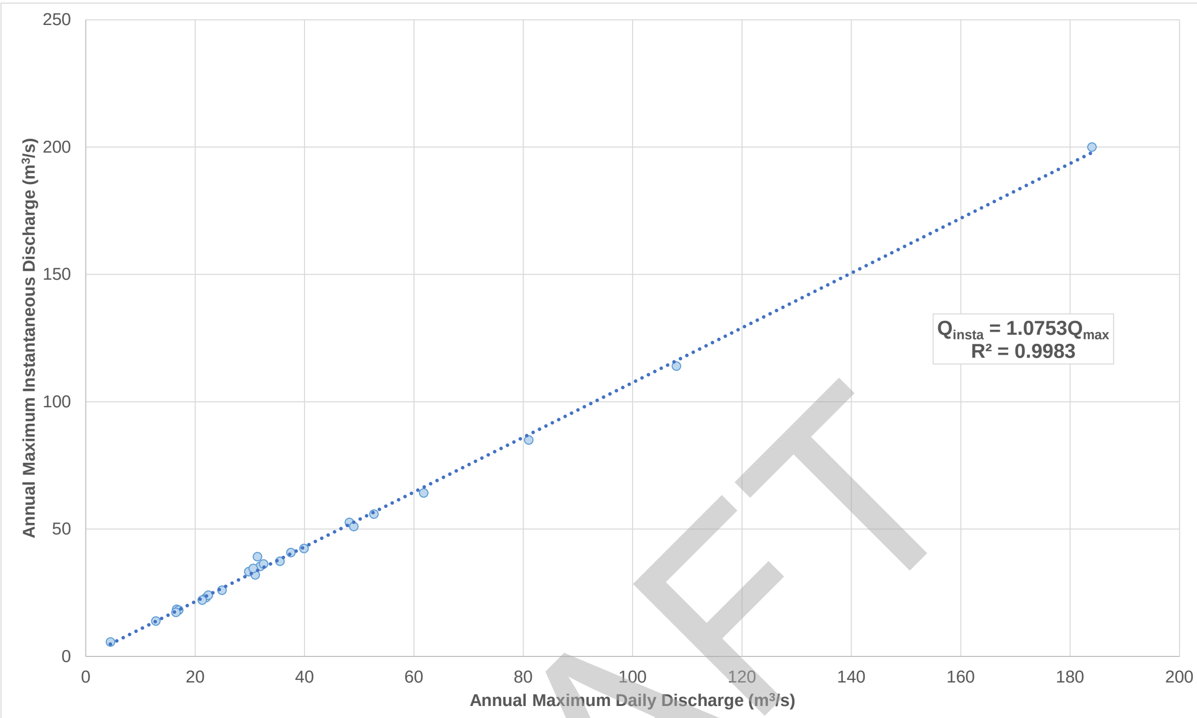


Relationship between Annual Maximum Daily and Annual Maximum Instantaneous Discharges at Athabasca River below Fort McMurray (WSC No. 07DA001 / Node 2)

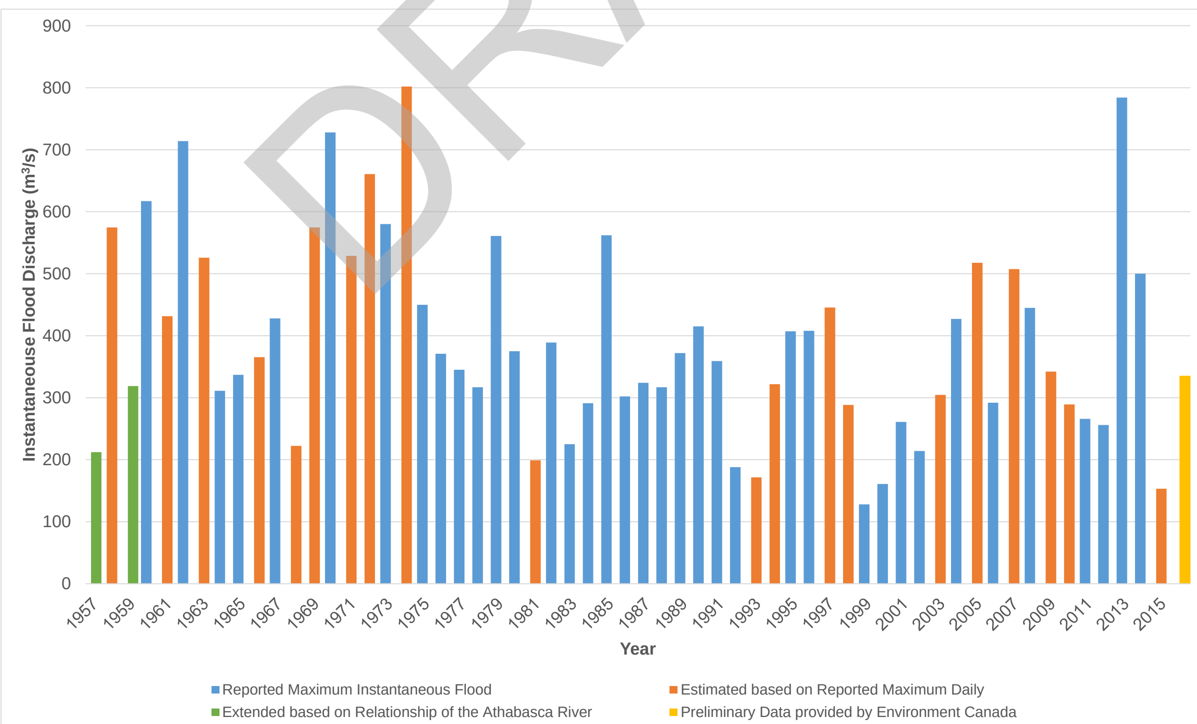


Maximum Instantaneous Flood Flow Series at Athabasca River below Fort McMurray (WSC No. 07DA001 / Node 2)

Figure A-4: WSC No. 07CD001 / Node 3, Clearwater River at Draper

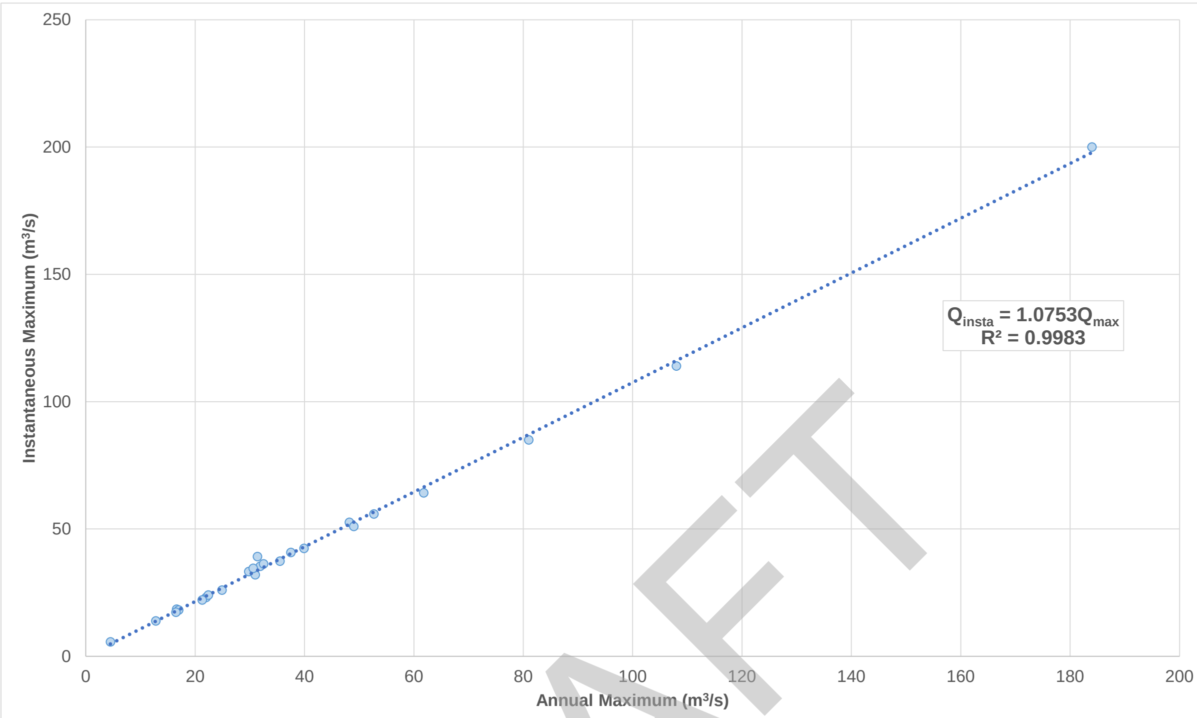


Relationship between Annual Maximum Daily and Annual Maximum Instantaneous Discharges at Clearwater River at Draper (WSC No. 07CD001 / Node 3)

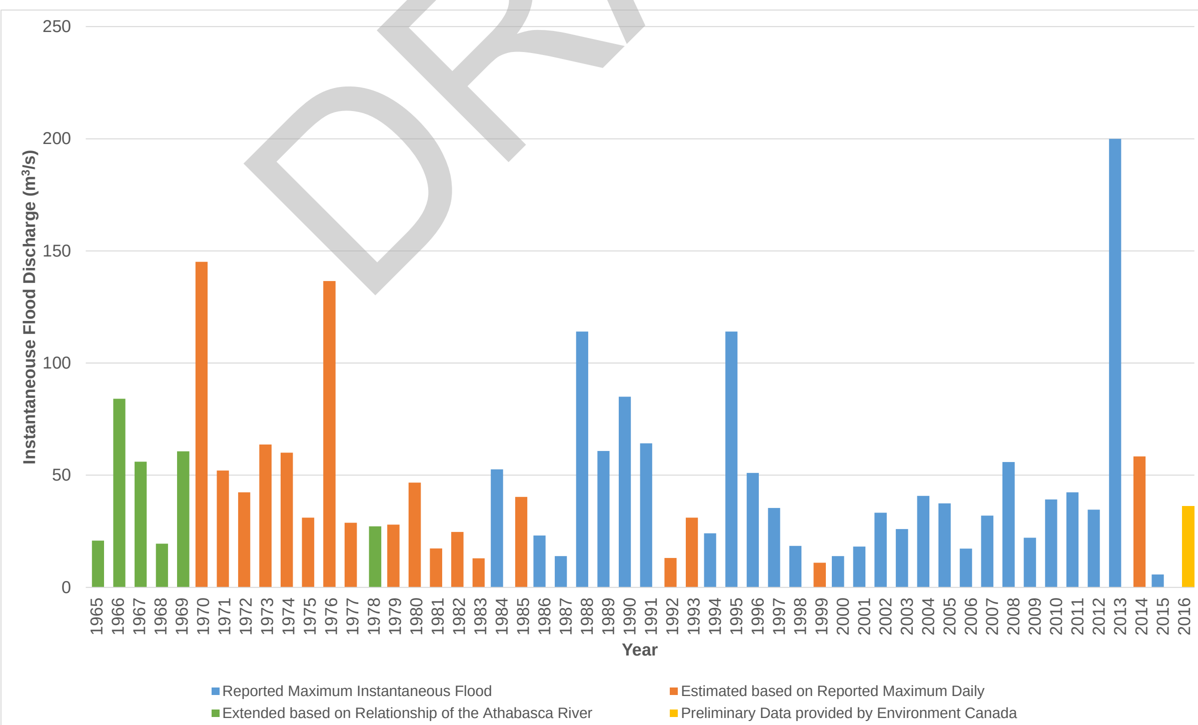


Maximum Instantaneous Flood Flow Series at Clearwater River at Draper (WSC No. 07CD001 / Node 3)

Figure A-5: WSC No. 07CD004 / Node 4, Hangingstone River at Fort McMurray

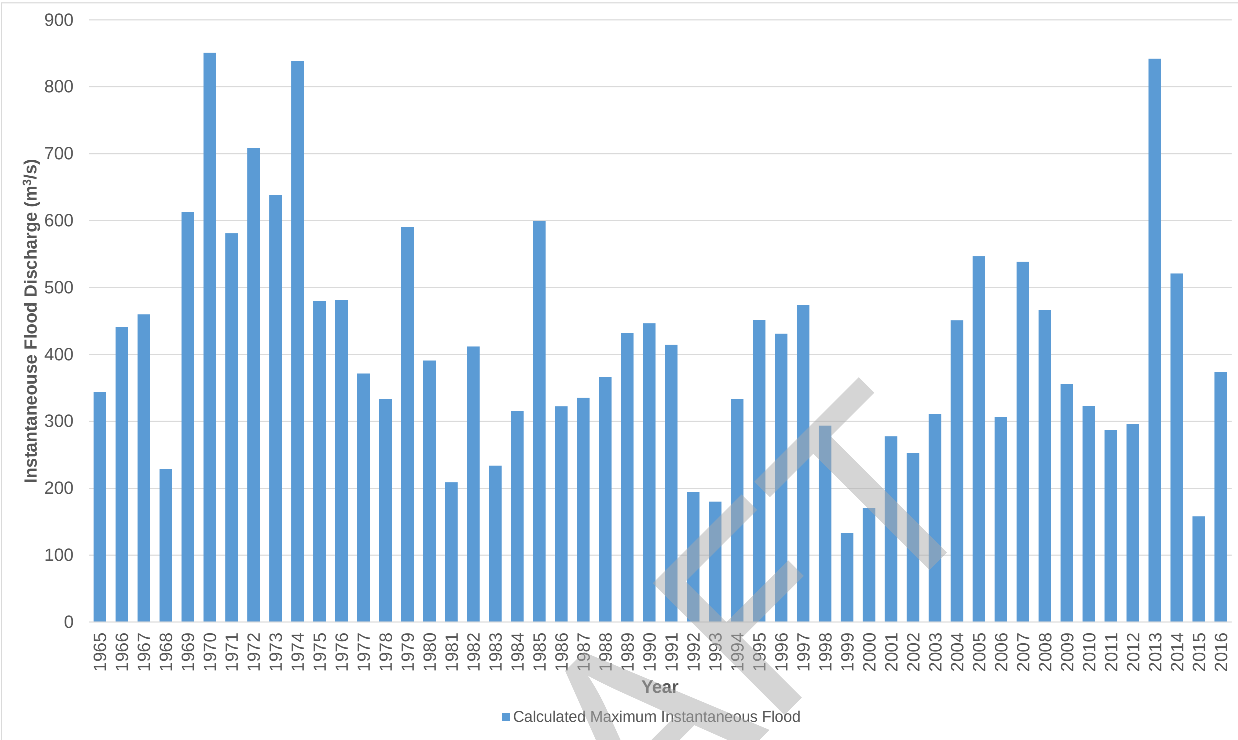


Relationship between Annual Maximum Daily and Annual Maximum Instantaneous Discharges at Hangingstone River at Fort McMurray (WSC No. 07CD004 / Node 4)



Maximum Instantaneous Flood Flow Series at Hangingstone River at Fort McMurray (WSC No. 07CD004 / Node 4)

Figure A-6: Node 5, Clearwater River at the Mouth



Derived Maximum Instantaneous Flood Flow Series at Clearwater River at the Mouth (Node 5)

Table A-1: Data used for Flood Frequency Analysis

Year	07BE001, Athabasca River at Athabasca	Athabasca River above Clearwater River Confluence	07DA001, Athabasca River below Fort McMurray		07CE001, Clearwater River	07CD004, Hangingstone River	Clearwater River below Hangingstone River
		Deriver using Athabasca River below Fort McMurray- Best-Fit Relationship	Using Best-Fit Relationship	Using Upper Bound, 50% Relationship			
1913	1741	1874	2116	2532	-	-	-
1914	3222	3121	3525	3941	-	-	-
1915	2878	2831	3197	3613	-	-	-
1916	2169	2234	2523	2939	-	-	-
1917	2597	2594	2930	3345	-	-	-
1918	1533	1698	1918	2334	-	-	-
1919	1074	1311	1481	1897	-	-	-
1920	2607	2603	2940	3355	-	-	-
1921	1543	1707	1928	2344	-	-	-
1922	940	1217	1375	1791	-	-	-
1923	1910	2049	2315	2730	-	-	-
1924	1580	1768	1997	2413	-	-	-
1925	1981	2076	2344	2760	-	-	-
1926	1533	1698	1918	2334	-	-	-
1927	2325	2365	2672	3087	-	-	-
1928	2240	2339	2642	3058	-	-	-
1929	1199	1417	1600	2016	-	-	-
1930	1856	1970	2225	2641	-	-	-
1931	-	-	-	-	-	-	-
1932	-	-	-	-	-	-	-
1933	-	-	-	-	-	-	-
1934	-	-	-	-	-	-	-
1935	-	-	-	-	-	-	-
1936	-	-	-	-	-	-	-
1937	-	-	-	-	-	-	-
1938	1105	1338	1511	1927	-	-	-
1939	1304	1505	1699	2115	-	-	-
1940	1710	1847	2086	2502	-	-	-

Table A-1: Data used for Flood Frequency Analysis

Year	07BE001, Athabasca River at Athabasca	Athabasca River above Clearwater River Confluence	07DA001, Athabasca River below Fort McMurray		07CE001, Clearwater River	07CD004, Hangingstone River	Clearwater River below Hangingstone River
		Deriver using Athabasca River below Fort McMurray-Best-Fit Relationship	Using Best-Fit Relationship	Using Upper Bound, 50% Relationship			
1941	2065	2146	2424	2839	-	-	-
1942	1773	1900	2146	2562	-	-	-
1943	2169	2234	2523	2939	-	-	-
1944	5040	4632	5231	5648	-	-	-
1945	992	1242	1403	1819	-	-	-
1946	1700	1838	2076	2492	-	-	-
1947	2080	2163	2443	2859	-	-	-
1948	3806	3613	4080	4497	-	-	-
1949	1074	1311	1481	1897	-	-	-
1950	1630	1786	2017	2433	-	-	-
1951	1877	1988	2245	2661	-	-	-
1952	2450	2541	2870	3286	-	-	-
1953	1908	2014	2275	2691	-	-	-
1954	5660	5185	5856	6273	-	-	-
1955	2350	2365	2672	3087	-	-	-
1956	1810	1917	2166	2582	-	-	-
1957	1170	1426	1610	2026	212	-	-
1958	2400	2211	2440	2440	574	-	-
1959	1760	1840	2030	2030	319	-	-
1960	2890	3879	4280	4280	617	-	-
1961	1150	1707	1883	1883	431	-	-
1962	1640	1912	2110	2110	714	-	-
1963	1610	2161	2385	2385	526	-	-
1964	1630	1512	1668	1668	311	-	-
1965	3680	3629	3910	3910	337	21	344
1966	1790	1860	2060	2060	365	84	441
1967	1660	1662	1830	1830	428	56	460
1968	1290	1365	1500	1500	222	19	229

Table A-1: Data used for Flood Frequency Analysis

Year	07BE001, Athabasca River at Athabasca	Athabasca River above Clearwater River Confluence	07DA001, Athabasca River below Fort McMurray		07CE001, Clearwater River	07CD004, Hangingstone River	Clearwater River below Hangingstone River
		Deriver using Athabasca River below Fort McMurray-Best-Fit Relationship	Using Best-Fit Relationship	Using Upper Bound, 50% Relationship			
1969	3110	2903	2970	2970	574	61	613
1970	1630	3068	3910	3910	728	145	851
1971	4560	4516	4790	4790	529	52	581
1972	3540	3542	3680	3680	661	42	708
1973	1890	2292	2550	2550	580	64	638
1974	2550	2635	3030	3030	802	60	839
1975	1850	2172	2470	2470	450	31	480
1976	1660	1653	2090	2090	371	137	481
1977	2380	2485	2860	2860	345	29	372
1978	2350	2410	2510	2510	317	27	333
1979	2320	2651	2930	2930	561	28	591
1980	4330	4035	4170	4170	375	47	391
1981	1270	1321	1430	1430	199	17	209
1982	3490	3499	3610	3610	389	25	412
1983	1590	2104	2310	2310	225	13	234
1984	1410	1668	1950	1950	291	53	315
1985	1520	1335	1940	1940	562	40	599
1986	4530	4336	4660	4660	302	23	323
1987	2150	2159	2240	2240	324	14	335
1988	1620	1907	2200	2200	317	114	366
1989	2390	2615	2740	2740	372	61	432
1990	2790	3001	3310	3310	415	85	446
1991	1950	1872	2280	2280	359	64	414
1992	1030	1256	1440	1440	188	13	195
1993	958	1193	1310	1310	172	31	180
1994	1650	1843	2130	2130	322	24	334
1995	2270	2641	3090	3090	407	114	452
1996	2670	2717	3010	3010	408	51	431

Table A-1: Data used for Flood Frequency Analysis

Year	07BE001, Athabasca River at Athabasca	Athabasca River above Clearwater River Confluence	07DA001, Athabasca River below Fort McMurray		07CE001, Clearwater River	07CD004, Hangingstone River	Clearwater River below Hangingstone River
		Deriver using Athabasca River below Fort McMurray-Best-Fit Relationship	Using Best-Fit Relationship	Using Upper Bound, 50% Relationship			
1997	2930	3625	3940	3940	446	35	474
1998	1679	1717	1822	1822	288	19	294
1999	2190	2012	2080	2080	128	11	133
2000	1520	1687	1810	1810	161	14	171
2001	2690	2826	2990	2990	261	18	278
2002	1178	1143	1218	1218	214	33	253
2003	1400	1617	1860	1860	305	26	311
2004	1850	1847	1980	1980	427	41	451
2005	2040	2246	2480	2480	518	37	547
2006	1230	1307	1600	1600	292	17	306
2007	2370	2843	3210	3210	508	32	539
2008	1570	1601	1770	1770	445	56	466
2009	1480	1548	1810	1810	342	22	356
2010	924	925	1140	1140	289	39	323
2011	4850	4190	4470	4470	266	42	287
2012	3320	3558	3760	3760	256	35	296
2013	2210	2549	3170	3170	784	200	842
2014	1390	1416	1940	1940	500	58	521
2015	1030	1017	1110	1110	153	6	158
2016	1250	1450	1740	1740	335	36	374
Maximum	5660	5185	5856	6273	802	200	851
Mean	2110	2233	2496	2658	392	47	412
Minimum	924	925	1110	1110	128	6	133
Standard Deviation	961	877	940	951	159	38	170

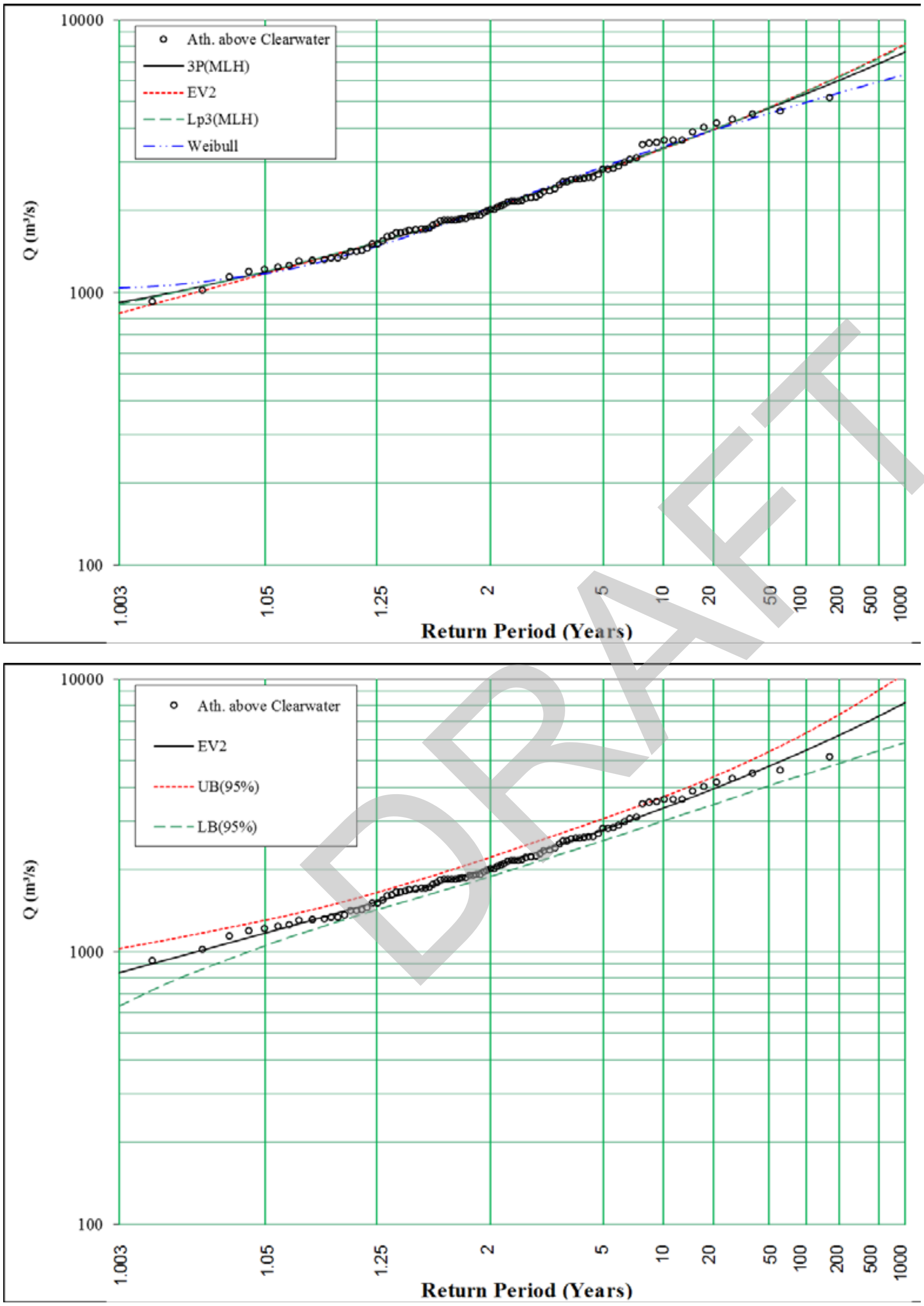
APPENDIX B

Frequency Analyses - Graphs and Tables

This document has a compilation of graphs and results from frequency analysis of the compiled/derived maximum instantaneous flood flow series at either the gauged stations or locations of interest within the study area, and each will include the follows:

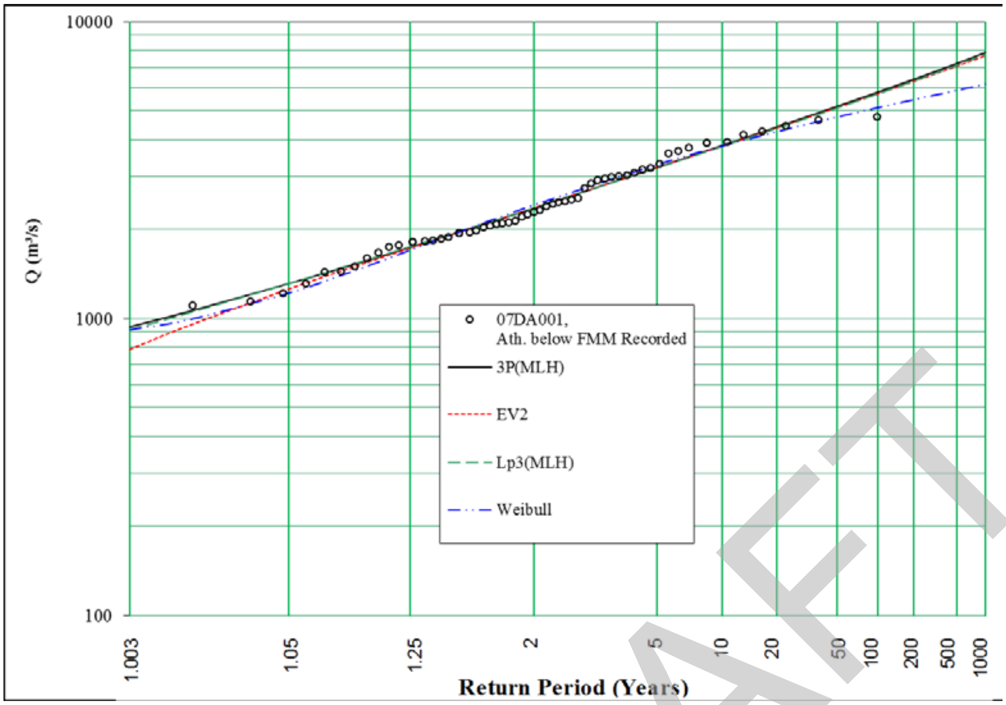
- **frequency distribution graph – all distributions;**
- **frequency distribution graph – best fit graph with confidence interval; and**
- **flood estimates – all distributions.**

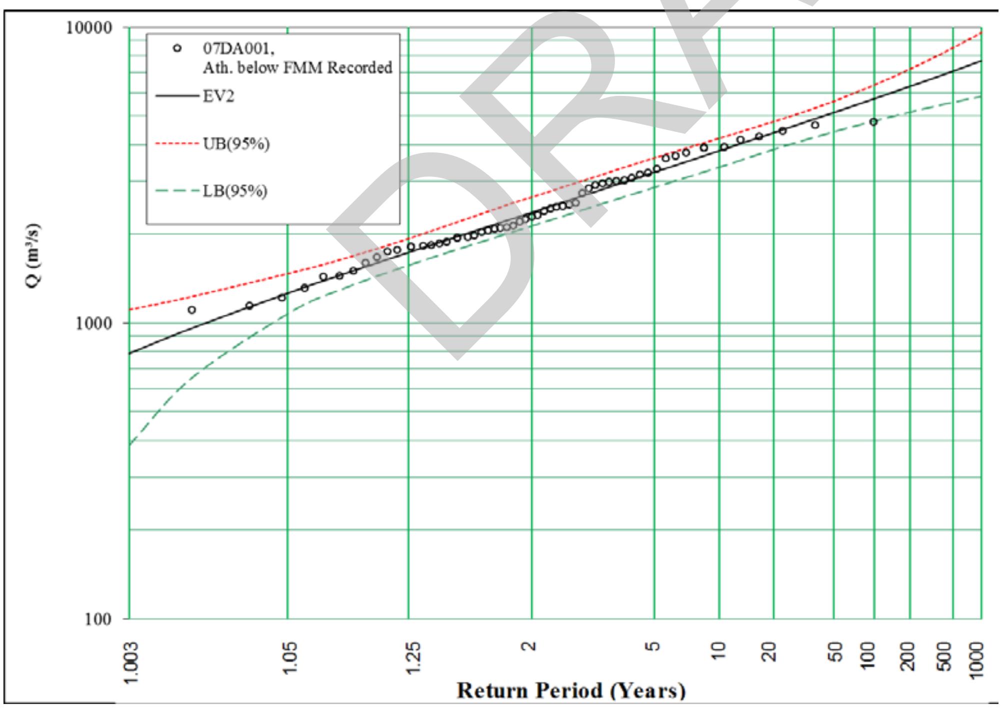
Figure B-1: Node 1, Athabasca River above Clearwater River Confluence



Return Period	3P(MLH)	EV2	Lp3(MLH)	Weibull
2	2035	2032	2032	2044
5	2822	2799	2805	2889
10	3388	3364	3370	3434
20	3960	3954	3954	3932
35	4434	4457	4449	4311
50	4743	4793	4777	4543
75	5101	5190	5164	4800
100	5362	5483	5449	4978
200	6008	6228	6170	5394
350	6551	6873	6792	5719
500	6908	7305	7209	5921
750	7324	7819	7704	6147
1000	7627	8198	8069	6305

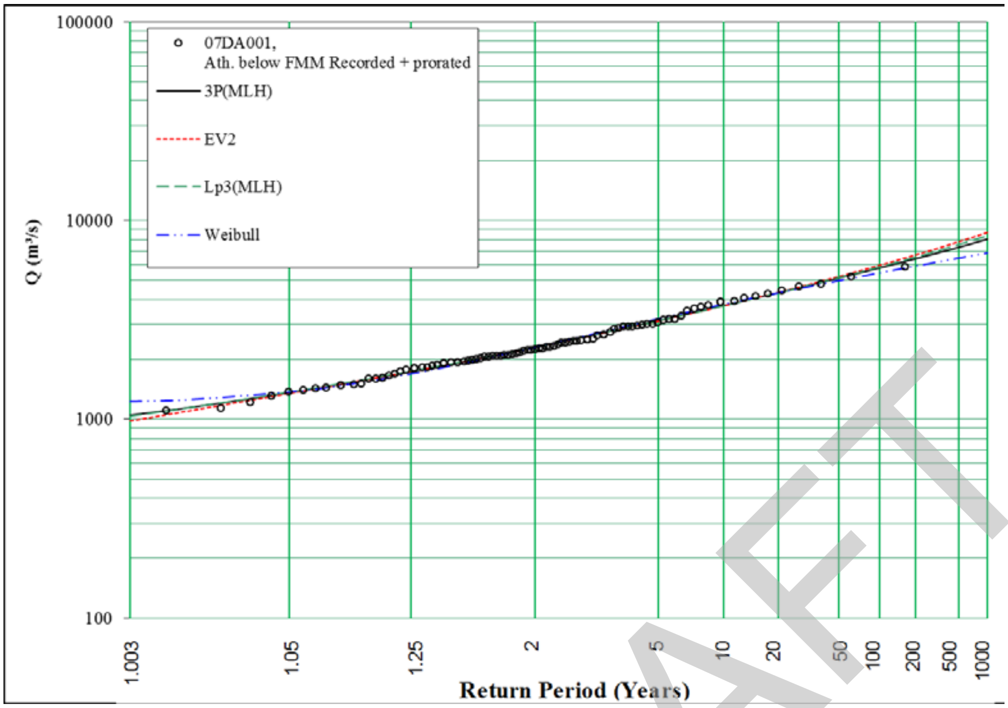
Figure B-2: WSC No.07DA001 / Node 2, Athabasca River below Fort McMurray (recorded)

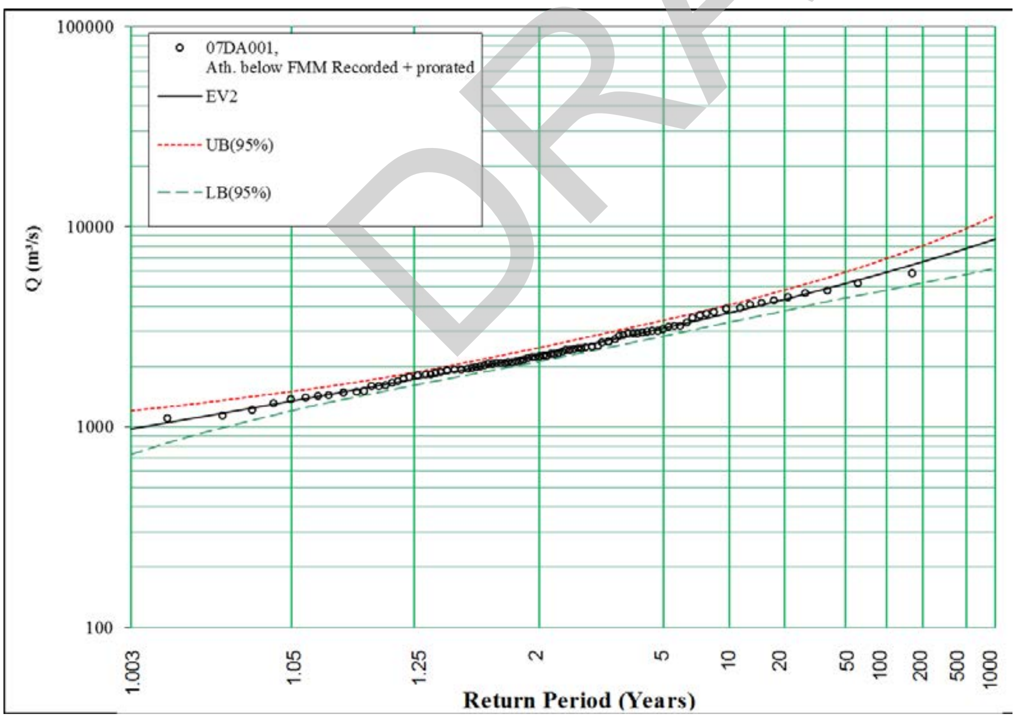




Return Period	3P(MLH)	EV2	Lp3(MLH)	Weibull
2	2352	2362	2357	2414
5	3229	3231	3218	3303
10	3828	3819	3802	3819
20	4413	4392	4373	4265
35	4886	4852	4834	4590
50	5189	5147	5130	4785
75	5536	5483	5471	4997
100	5785	5723	5715	5141
200	6394	6306	6315	5473
350	6897	6782	6812	5726
500	7223	7089	7135	5881
750	7600	7440	7510	6052
1000	7871	7691	7780	6171

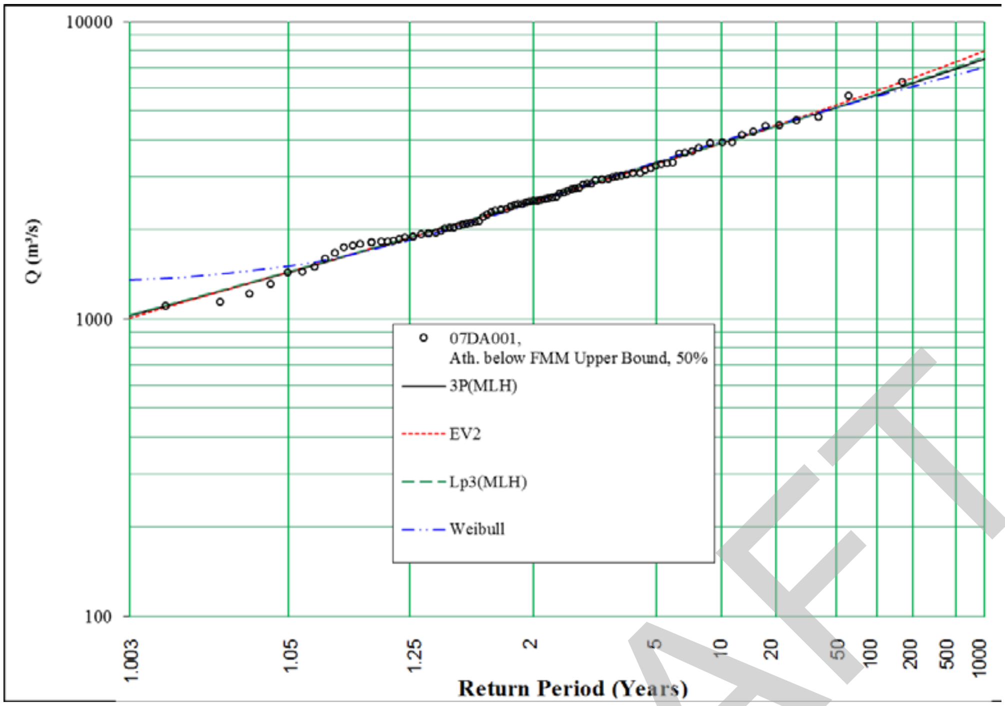
Figure B-3: Node 2, Athabasca River below Fort McMurray (extended)

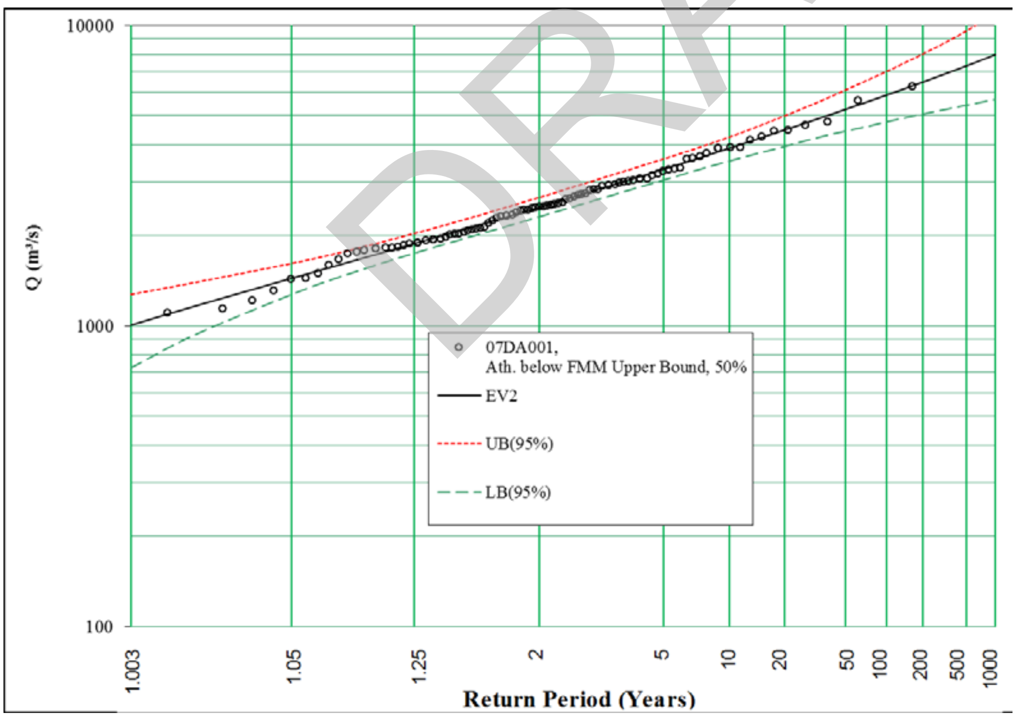




Return Period	3P(MLH)	EV2	Lp3(MLH)	Weibull
2	2294	2287	2292	2293
5	3137	3111	3120	3198
10	3732	3712	3713	3782
20	4328	4333	4316	4318
35	4817	4859	4821	4725
50	5135	5208	5153	4975
75	5502	5620	5542	5251
100	5767	5921	5826	5443
200	6422	6685	6540	5891
350	6970	7341	7150	6242
500	7328	7778	7555	6460
750	7745	8296	8033	6703
1000	8047	8676	8384	6874

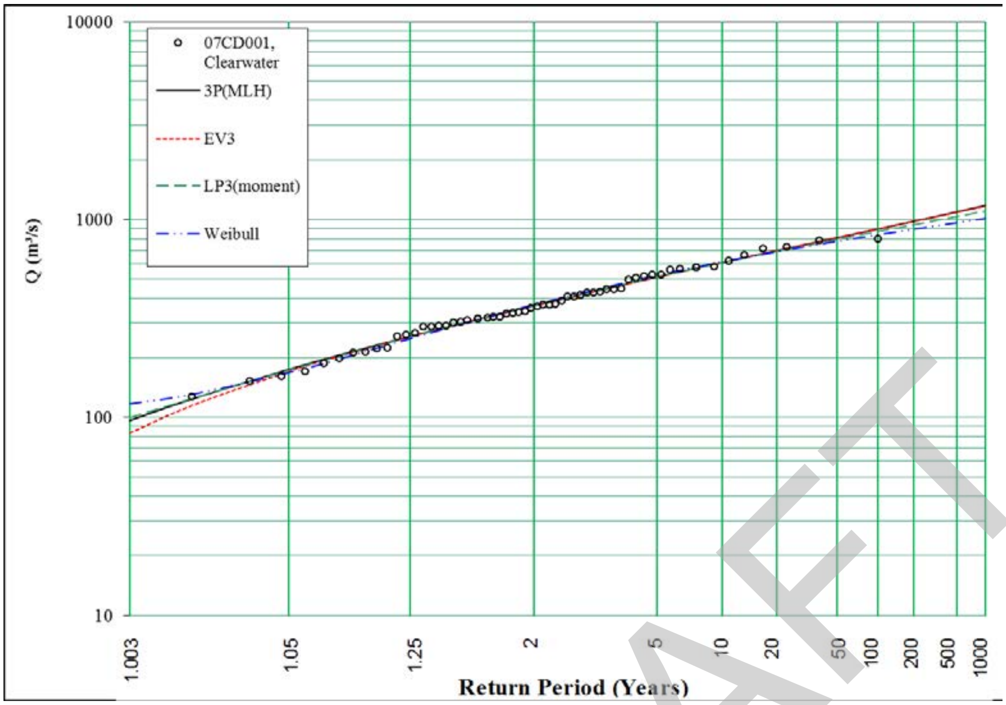
Figure B-4: Node 2, Athabasca River below Fort McMurray (50% upper confidence bound)

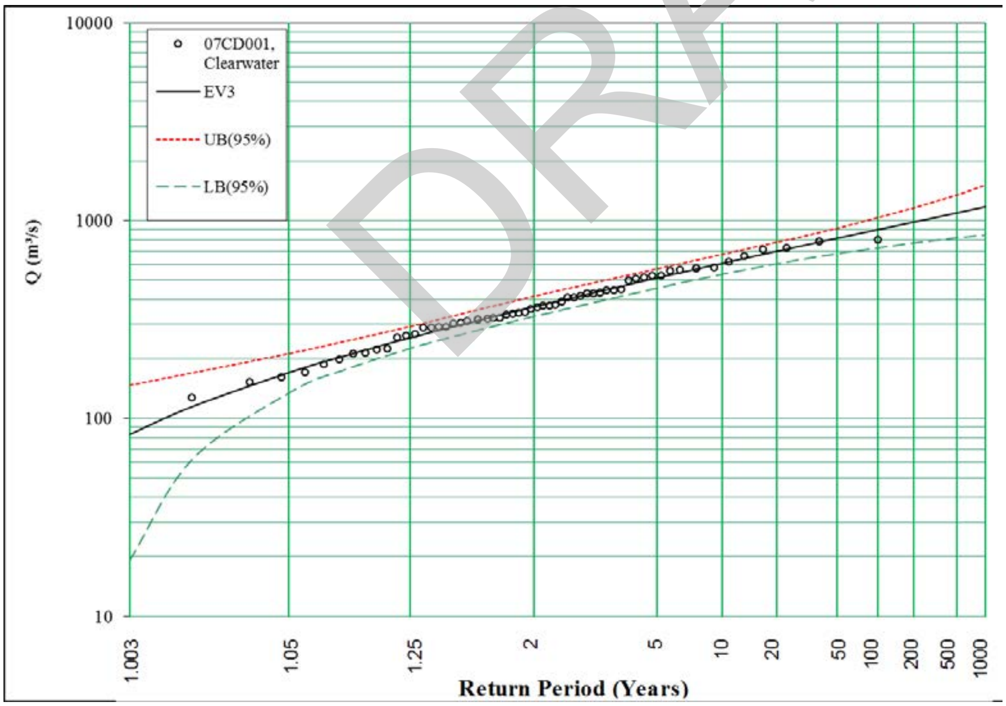




Return Period	3P(MLH)	EV2	Lp3(MLH)	Weibull
2	2494	2477	2490	2458
5	3341	3321	3331	3374
10	3903	3904	3894	3961
20	4442	4481	4438	4498
35	4871	4952	4875	4904
50	5144	5256	5155	5153
75	5454	5607	5475	5428
100	5675	5859	5703	5618
200	6211	6479	6262	6064
350	6650	6992	6723	6411
500	6932	7326	7022	6626
750	7257	7712	7367	6868
1000	7489	7990	7615	7036

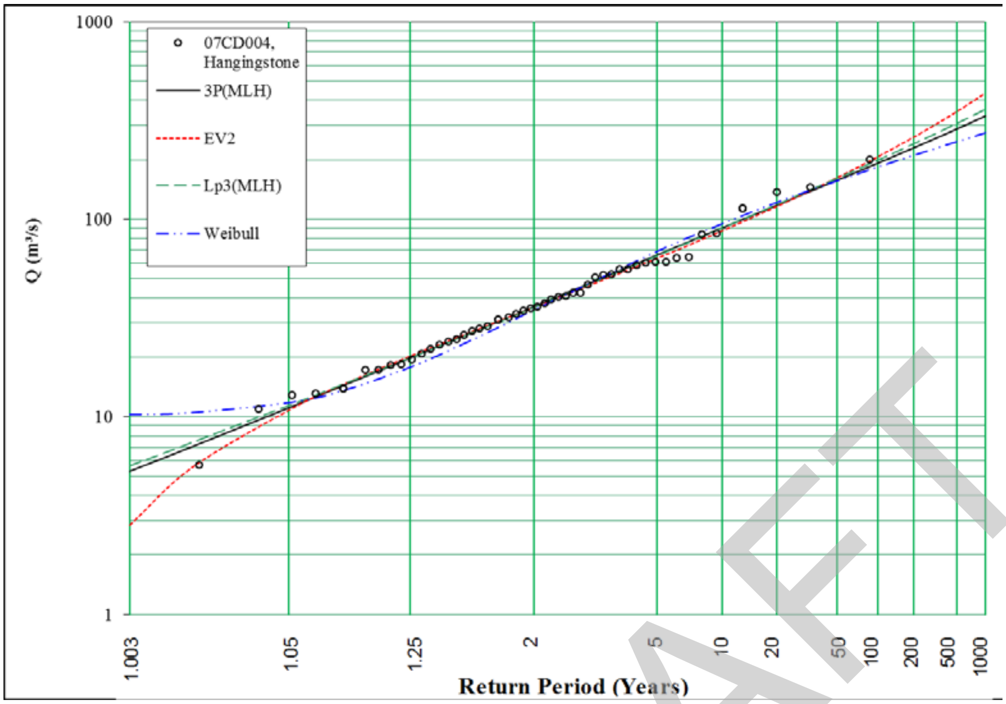
Figure B-5: WSC No.07CD001 / Node 3, Clearwater River at Draper

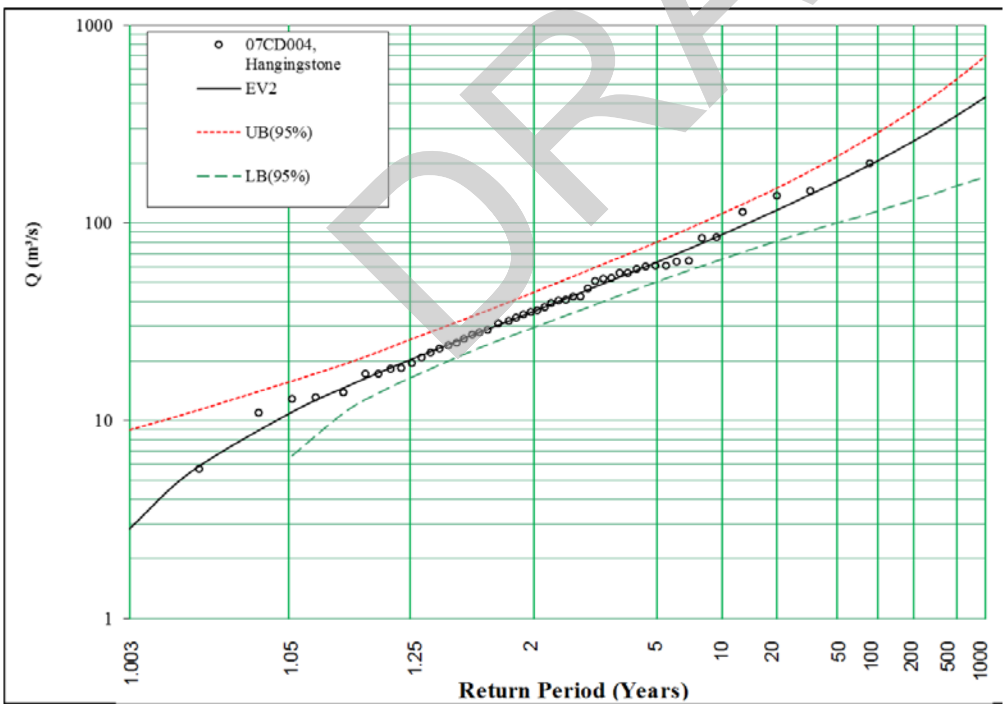




Return Period	3P(MLH)	EV3	LP3 (moment)	Weibull
2	367	366	368	371
5	513	513	515	522
10	607	609	607	610
20	696	699	692	685
35	766	770	757	741
50	810	814	796	774
75	860	864	841	810
100	895	900	872	834
200	980	983	945	890
350	1049	1050	1002	933
500	1093	1092	1038	960
750	1143	1140	1079	989
1000	1179	1174	1107	1009

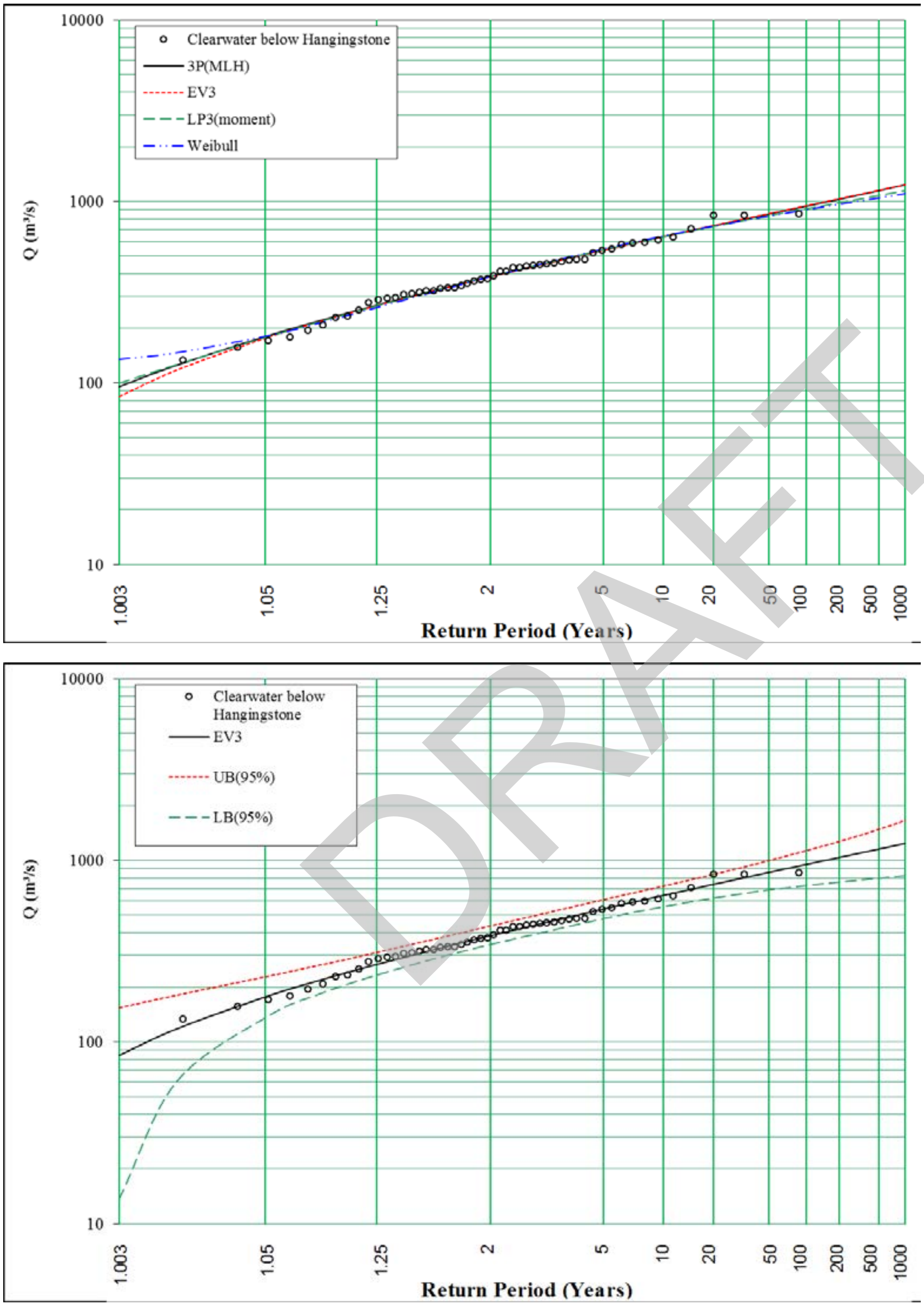
Figure B-6: WSC No.07CD004 / Node 4, Hangingstone River at Fort McMurray





Return Period	3P(MLH)	EV2	Lp3(MLH)	Weibull
2	36	36	36	35
5	66	63	65	69
10	90	87	90	95
20	118	116	118	122
35	141	143	144	143
50	158	162	161	157
75	177	187	182	173
100	192	206	198	184
200	230	260	240	211
350	263	312	278	233
500	286	349	304	247
750	313	397	336	263
1000	333	434	359	274

Figure B-7: Node 5, Clearwater River at the Mouth



Return Period	3P(MLH)	EV3	LP3 (moment)	Weibull
2	386	385	387	386
5	540	540	543	548
10	640	641	640	645
20	733	737	728	730
35	806	812	795	792
50	852	859	836	830
75	904	911	881	871
100	941	949	912	899
200	1029	1037	986	964
350	1101	1108	1044	1014
500	1147	1152	1080	1045
750	1199	1203	1120	1079
1000	1236	1238	1148	1102

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