DRUMHELLER RIVER HAZARD STUDY

OPEN WATER HYDROLOGY ASSESSMENT REPORT

Prepared for:

Alberta

20 March 2020

NHC Ref. No. 1003877

nhc
northwest hydraulic consultants
water resource specialists

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FINAL REPORT

Prepared for:

Alberta Environment and Parks
Edmonton, Alberta

Prepared by:

Northwest Hydraulic Consultants Ltd.
Edmonton, Alberta

20 March 2020

NHC Ref No. 1003877

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EXECUTIVE SUMMARY

Alberta Environment and Parks (AEP) retained Northwest Hydraulic Consultants Ltd. (NHC) in June 2018 to complete a river hazard study for the town of Drumheller and surrounding areas of Kneehill County, Starland County, Wheatland County, and Special Areas No. 2. The river hazard study area includes 53.3 km of the Red Deer River, 7.7 km of Kneehills Creek, 5.3 km of Michichi Creek, 10.5 km of the Rosebud River, and 2.9 km of Willow Creek. The study is being conducted under the provincial Flood Hazard Identification Program, and the overall objectives are to enhance public safety and to reduce future flood damages and disaster assistance costs.

As part of this study, an open water hydrology assessment was required to provide estimates of flood frequencies for both naturalized and regulated conditions for a range of return periods up to 1000 years at the following locations:

- Red Deer River above Kneehills Creek
- Red Deer River above Michichi Creek
- Red Deer River at Drumheller (WSC Station No 05CE001)
- Red Deer River below Rosebud River
- Red Deer River below Willow Creek
- Kneehills Creek near Drumheller (WSC Station No. 05CE002)
- Michichi Creek at Drumheller (WSC Station No. 05CE020)
- Rosebud River at the mouth
- Willow Creek at the mouth

Flows in the Red Deer River have been regulated since 1983 by Dickson Dam, which impounds Gleniffer Reservoir located about 50 km upstream of the city of Red Deer. Flow naturalization to remove the effects due to operations at Dickson Dam was completed in 2018 as part of the Upper Red Deer and Red Deer River Hazard study. AEP provided naturalized and regulated flow data series for the 1912-2016 period for various locations along the Red Deer River between Dickson Dam and the Highway 11 bridge crossing downstream of the city. In this study, routing analyses were performed for the Red Deer River from Red Deer to Drumheller using both the data provided by AEP and available streamflow gauge data from the Water Survey of Canada. The results were then used to develop flood frequency estimates through flood frequency analysis for the study sites along the Red Deer River for both the naturalized and regulated flow conditions.

AEP also provided a set of regulated synthetic flood hydrographs for Red Deer River at Highway 11 for a range of return periods. These hydrographs were developed through routing of synthetic inflow design floods for Gleniffer Reservoir under a set of reservoir operating rules. In this study, the synthetic flood hydrographs were also routed from Highway 11 to Drumheller to develop a second set of flood frequency estimates for Red Deer River at Drumheller under the regulated flow condition. This second set of estimates was compared with the flood frequency analysis results for both naturalized and regulated flow conditions. Based on the comparison, it was recommended that, for the regulated flow scenario, the flood frequency curve for regulated flows be used to estimate flood peaks at Drumheller for return periods up to 20 years; the synthetic hydrograph routing results be used for return periods between 20 and 1000 years; and the 1000-year peak discharge be assumed to be equal to the estimate for the naturalized flow condition.

Based on comparisons of estimated annual peak discharges for the ungauged sites on the Red Deer River against those for WSC Station 05CE001 (Red Deer River at Drumheller), it is recommended that the flood frequency estimates for WSC Station 05CE001 be used for all the ungauged sites, including Red Deer River above Kneehills Creek, above Michichi Creek, below Rosebud River and below Willow Creek.

Flood frequency estimates for the study sites on Kneehills Creek, Michichi Creek and the Rosebud River were based on measured peak discharges on these streams, while regional analysis was performed to develop flood frequency estimates for Willow Creek at the mouth.

This hydrology assessment is based on the up-to-date available data. The resulting flood frequency estimates, as summarized in the tables below, are intended to support hydraulic modelling and flood inundation mapping of the Drumheller River Hazard Study.

Table E-1: Recommended flood frequency estimates for Red Deer River Sites near Drumheller (1)

Return Period (Years)	Annual Probability of Exceedance (%)	Naturalized Peak Instantaneous Discharge (m^3/s)		Regulated Peak Instantaneous Discharge (m^3/s)
		Value	Upper 95% Limit Lower 95% Limit	
1000	0.10	3,820	5,150 2,990	3,820 (2)
750	0.13	3,600	4,820 2,830	3,580 (3)
500	0.20	3,300	4,380 2,620	3,170 (3)
350	0.29	3,050	4,020 2,440	2,900 (3)
200	0.50	2,680	3,480 2,170	2,450 (3)
100	1.0	2,260	2,870 1,850	1,850 (3)
75	1.3	2,090	2,640 1,730	1,670 (3)
50	2.0	1,870	2,330 1,560	1,430 (3)
35	2.9	1,690	2,080 1,420	1,240 (3)
20	5.0	1,410	1,710 1,200	869 (4)
10	10	1,100	1,290 951	702 (4)
5	20	807	929 712	542 (4)
2	50	448	502 400	330 (4)

Notes:

1. The estimates are applicable for Red Deer River at Drumheller (WSC Station 05CE001), above Kneehills Creek, above Michichi Creek, below Rosebud River and below Willow Creek.
2. The 1000-year naturalized peak discharge has been adopted as the estimate for the regulated flow condition.
3. The adopted value is from the synthetic flood hydrograph routing.
4. The adopted value is from the flood frequency curve for the regulated peak discharges of Red Deer River at Drumheller.

Table E-2: Recommended flood frequency estimates for Kneehills Creek, Michichi Creek, Rosebud River and Willow Creek

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)						
		Kneehills Creek near Drumheller		Michichi Creek at Drumheller		Rosebud River at the Mouth		Willow Creek at the Mouth
		Value	Upper 95% Limit Lower 95% Limit	Value	Upper 95% Limit Lower 95% Limit	Value	Upper 95% Limit Lower 95% Limit	Value (1)
1000	0.10	286	327 255	103	125 89	641	1,260 388	66
750	0.13	274	313 244	99	119 85	586	1,140 359	62
500	0.20	256	292 228	93	112 80	515	975 321	58
350	0.29	241	275 215	87	105 75	458	848 289	54
200	0.50	216	246 193	79	95 68	377	675 244	49
100	1.0	186	211 166	68	82 59	292	499 195	41
75	1.3	173	197 155	64	77 55	260	437 176	40
50	2.0	155	176 139	58	69 50	220	359 152	35
35	2.9	140	159 126	52	62 45	188	300 132	31
20	5.0	116	132 104	44	52 38	145	220 104	26
10	10	87	99 77	33	40 29	99	143 74	19
5	20	58	67 50	23	28 19	63	86 49	13
2	50	22	30 14	10	14 5	27	34 21	5

Notes:

1. Estimates were from a regional analysis, and the 95% confidence limits are not available.

CREDITS AND ACKNOWLEDGEMENTS

The work described in this report was undertaken by Northwest Hydraulic Consultants Ltd. (NHC) for Alberta Environment and Park (AEP) as part of the Drumheller River Hazard Study. This report summarizes the findings of the Open Water Hydrology Assessment.

NHC gratefully acknowledges the contributions and assistance of both Peter Bezeau, M.Sc., P.Geo. and Ms. Jane Eaket, M.Sc., P.Eng. who jointly managed the project on behalf of AEP and provided valuable support with project management, data collection, and review. Thanks are also expressed to Ms. Jennifer Nafziger and other members of AEP for providing relevant information and valuable comments throughout the course of the work.

This report was prepared by Dr. C.H. (Ken) Zhao, P.Eng., who served as NHC's lead hydrologist for the study and Mr. Makamum Mahmood, M.Eng., P.Eng., who performed modelling for flow naturalization and regulation. Technical review for the report was provided by Mr. Gary Van Der Vinne, M.Sc., P.Eng. of NHC. Mr. Robyn Andrishak, M.Sc., P.Eng. managed the project on behalf of NHC.

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1 INTRODUCTION

1.1 Study Background

The Drumheller River Hazard Study was initiated by Alberta Environment and Parks (AEP) to identify and assess river and flood hazards along the Red Deer River, Kneehills Creek, Michichi Creek, Rosebud River, and Willow Creek within the town of Drumheller and surrounding areas of Kneehill County, Starland County, Wheatland County, and Special Areas No. 2. This study was facilitated under the Flood Hazard Identification Program (FHIP) with the intent to enhance public safety and reduce future flood damages within the Province of Alberta. Results from this study are intended to inform local land use planning decisions, flood mitigation projects, and emergency response planning.

A flood hazard mapping study was previously completed for the Drumheller area by Matrix Solutions Inc. (Matrix, 2007); however, the present study covers an expanded study reach and represents a significant update to the prior work. It is comprised of seven major study components:

1) Survey and Base Data Collection
2) Open Water Hydrology Assessment
3) Hydraulic Modelling and Flood Inundation Mapping
4) Design Flood Hazard Mapping
5) Flood Risk Assessment and Inventory
6) Channel Stability Investigation

Each component includes a separate report and associated deliverables for that portion of the study. This report summarizes the work of the second component – ***Open Water Hydrology Assessment***.

1.2 Study Objectives

The objective of this component of the overall river hazard study is to provide open water flood frequency estimates under naturalized and regulated conditions at the following locations defined by the terms of reference of the Drumheller River Hazard Study:

- Red Deer River above Kneehills Creek
- Red Deer River above Michichi Creek
- Red Deer River at Drumheller (WSC Station No 05CE001)
- Red Deer River below Rosebud River

- Red Deer River below Willow Creek
- Kneehills Creek near Drumheller (WSC Station No. 05CE002)
- Michichi Creek at Drumheller (WSC Station No. 05CE020)
- Rosebud River at the mouth
- Willow Creek at the mouth

These locations are shown in **Figure 1**. The flood frequency estimates, which are supported by a brief description of the hydrologic characteristics of the Red Deer River basin, are meant to provide a framework for the hydraulic analysis that will ultimately identify flood hazards within the study area.

1.3 Scope of Report

Flows in the Red Deer River are regulated by Dickson Dam on its main stem upstream of the city of Red Deer. Some of its tributaries between Red Deer and Drumheller are also affected by smaller water management projects for various purposes including irrigation, low-flow augmentation, and water supply for industrial, municipal and domestic users. Given the effects of flow regulation on the downstream flood peaks, and because regulation may have effects on mitigating flood-related hazards, analyses of both the regulated and naturalized flood peaks are required for the Drumheller River Hazard Study.

To these ends, this report contains the following:

- a description of the hydrologic characteristics of the study area and the prevailing flood generating mechanisms,
- routing of naturalized and regulated flows from Red Deer down the main stem of the Red Deer River to the Drumheller area, and the creation of naturalized and regulated daily flow series and annual maximum daily flow series at the flood frequency estimate sites listed in Section 1.2,
- evaluating potential effects of major tributary flow regulation projects on flood peaks at the study sites,
- statistical descriptions of the naturalized and regulated flood peaks, and corresponding frequency curves, at the flood frequency estimate sites listed in Section 1.2, and
- a brief discussion of the effects of climate change on the flood regime.

1.4 Study Area and Reach

The Red Deer River originates in the Rocky Mountains in Alberta and generally flows in an eastward direction to the Alberta/Saskatchewan border. The total length of the Red Deer River is approximately 720 km, including approximately 15 km in Saskatchewan before it enters the South Saskatchewan River. Its drainage area within Alberta is approximately 46,800 km^2 according to the Water Survey of Canada (WSC). While the river hazard study area is limited to an approximately 53 km long sub-reach of the Red Deer River and its tributaries in the Drumheller area (**Figure 1**), the open water hydrologic assessment covers a larger area, which extends along the Red Deer River from the city of Red Deer to the downstream boundary of the river hazard study area (the southern boundary of SE-3-27-17-W4M). In this area, the Red Deer River generally flows in a south-easterly direction. Along this approximately 200 km long sub-reach, the drainage area of the Red Deer River increases from approximately 11,600 km^2 at Red Deer (WSC Station 05CC002) to 24,900 km^2 at Drumheller (WSC Station 05CE001). A basin map is shown in **Figure 2.**

Most of the runoff conveyed by the Red Deer River is typically derived from the mountain and foothill portions of the basin, due to spring snowmelt runoff augmented by rainfall. Annual peaks usually occur in June, while heavy rainfall in summer can also result in large flood events such as the August 1954 event.

Flows in the Red Deer River have been regulated since 1983 by Dickson Dam, which impounds Gleniffer Reservoir located about 50 km upstream of Red Deer. The drainage area upstream of the reservoir is approximately 5,590 km^2 and accounts for about 22% of the area upstream of Drumheller. **Figure 3** shows pre and post-regulation mean monthly flow volumes of the Red Deer River at Drumheller (WSC Station 05CE001). The plot based on the flow data from 1915 to 1931 and from 1959 to 1982 reflects the pre-regulation condition, while the data from 1983 to 2018 reflects the post-regulation condition. Over the 1983-2018 period, due to operations at Dickson Dam, the mean monthly flow volumes for April through August were lower than those for the pre-regulation period with the most significant reduction in May (22% smaller than in the pre-regulation period), while flows in winter months were significantly increased.

The tributary area contributing to the Red Deer River between Red Deer and Drumheller is relatively flat. It consists of many undrained lakes and wetlands that usually overflow only in extremely wet years. Small flow regulation and diversion projects exist on the tributaries in this area. The Parlby Creek-Buffalo Lake Water Management Project on Parlby and Tail creeks, and Bigelow Reservoir on Threehills Creek are the two most prominent projects (**Figure 2**). However, as discussed in Section 3.1.3, these projects do not appear to have significant effects on annual peak discharges of the Red Deer River.

Within the Drumheller area, four salient tributaries contribute to the Red Deer River at Drumheller, as shown in **Figure 1**. Kneehills Creek drains an area of about 2,430 km^2 and joins the Red Deer River about 8 km upstream of the WSC Drumheller gauge station (05CE001). Michichi Creek has a drainage area of about 1,170 km^2 and flows into the river immediately upstream of the WSC Drumheller station. The Rosebud River, with a total drainage area of about 4,290 km^2, is the largest of the four tributaries. It enters the Red Deer River about 8 km downstream of the WSC Drumheller station. At approximately 9 km further downstream, Willow Creek flows into the river and drains an area of approximately 400 km^2. These tributary areas are mostly located within the Grassland Natural Region, which is the warmest and driest region in Alberta. Annual peak flows on these tributaries can occur in spring due to snowmelt runoff with or without rainfall, or in summer due to intense rainstorm events. There are a number of relatively small dams and flow diversions in these tributary sub-basins. Most of the dams are for irrigation and are located off stream main stems.

2 DATA COLLECTION

2.1 Streamflow and Water Level Data

AEP provided flow estimates for the Red Deer River near the city of Red Deer developed by Golder (2018), including:

- naturalized and regulated daily flow timeseries (1912-2016) for the Red Deer River at eleven locations from Dickson Dam to Highway 11, and
- routed design flood hydrographs for the Red Deer River at Highway 11 for various return periods from 2 to 1000 years, under a regulated scenario.

This study has also relied on published streamflow and water level data obtained from WSC and preliminary gauge data for recent years provided by AEP. Information for the key hydrometric stations is summarized in **Table 1**. Locations of these stations are shown in **Figure 2**. Additional hydrometric stations listed in **Table 2** were used in regional hydrologic analysis to fill data gaps or validate assumptions adopted for flow naturalization.

Table 1: Key hydrometric stations describing Red Deer River flows

Type	Station No.	Station Name	Drainage Area (km^2) [1]	Period of Record
Streamflow	05CC002	Red Deer River at Red Deer	11,600	1912-1935 and 1938-2016, 2017[2]
	05CE001	Red Deer River at Drumheller	24,900	1916-1931,1959-2018
	05CE002	Kneehills Creek near Drumheller	2,430	1921-1931, 1935-1936, 1957-2014, 2015-2018[2]
	05CE020	Michichi Creek at Drumheller	1,170	1979-2014, 2015-2018[2]
	05CE005	Rosebud River at Redland	3,570	1951-2018
	05CE003	Rosebud River at Beynon	3,990	1922-1931, 1935-1936
	05CC011	Waskasoo Creek at Red Deer	487	1984-2016, 2017[2]
	05CC001	Blindman River near Blackfalds	1,800	1916-1923, 1962-2016, 2017[2]
	05CD006	Haynes Creek near Haynes	165	1978-2016
	05CE007	Threehills Creek near Carbon	1,080	1965-2016, 2017[2]
	05CG006	Fish Creek above Little Fish Lake	118	1984-2018
Water Level	05CD005	Buffalo Lake near Erskine	1,570	1965-2016, 2017[2]
	05CE901	Bigelow Reservoir near Wimborne	413	1979-2016, 2017[3]

Notes:

1. Drainage area based on information from WSC
2. Preliminary data obtained from WSC
3. Preliminary data obtained from AEP

Table 2: Additional WSC hydrometric stations for regional hydrologic analysis

Type	Station No.	Station Name	Drainage Area (km^2) [1]	Period of Record
Flow	05CD007	Parlby Creek at Alix	511	1983-2016
	05CD902	Parlby Creek near Mirror	866	1981-2017
	05CE018	Threehills Creek below Ray Creek	199	1971-2014, 2015-2017[2]
	05CE011	Renwick Creek near Three Hills	59	1967-2016
	05CE006	Rosebud River below Carstairs Creek	753	1957-2014, 2015-2018[3]
	05BM007	Parflesh Creek near Chancellor	129	1965-2014, 2015-2017[3]

Notes:

1. Drainage area is based on information from WSC
2. Preliminary data obtained from AEP
3. Preliminary data provided by WSC

2.2 Historic Flood Data

Historic floods refer to major floods that occurred prior to the period of systematic hydrometric data collection. If the magnitude of a historic flood can be estimated based on available information, the estimate could be used to improve the flood frequency estimates.

The WSC gauge station, Red Deer River at Drumheller (05CE001) was initially established in November 1915. Alberta Environment (AENV, 1975) indicates that the 1901 and 1915 events would be the two largest among the known flood events on the Red Deer River. While no definite indication of the magnitude could be found for the 1901 event, AENV (1975) estimated the 1915 peak instantaneous discharge at Drumheller based on the flood level provided by a local resident and presented in AENV (1974).

WSC Station 05CE001 was not operated between 1931 and 1959, while large open water floods were observed in 1952 and 1954. AENV (1975) provides peak discharges for these two events based on highwater mark elevations surveyed by AENV (1974).

For historic floods on Kneehills Creek, the following paragraph was cited from NHC (2008):

> *Direct discharge measurements are not available for any of the three most severe floods noted by the Village of Carbon to have occurred since the water level gauge was installed in 1921. Although it is known that the floods of June 1931, April 1948 and April 1952 caused damage to bridges and homes in Carbon, it is not clear whether flows were exceptionally large or if damage was caused as a result of inadequately designed or poorly situated infrastructure. Insight into the potential magnitude of the events cannot be gained from streamflow records for nearby streams, as no gauges were operational those years. The pre-gauge era flood of June 1902, noted to have caused the deaths of*

several Carbon area residents, also has no associated discharge estimate and cannot be used to put any more recent floods into context.

For the Rosebud River, NHC (2006) noted that the earliest recorded evidence of flooding was in the 1917-era at the town of Didsbury (located far upstream of the present study area), but neither a specific date nor an estimated discharge was available for that event.

No historic flood information is available for Michichi Creek and Willow Creek.

2.3 Previous Studies

Previous flood frequency estimates for the Red Deer River, Kneehills Creek, Michichi Creek and Rosebud River near Drumheller are presented in the following studies:

- Drumheller Flood Risk Mapping Study by Matrix (2007)
- Flood Frequency Report for Red Deer River at Drumheller by Alberta Environmental Protection (1996)
- Drumheller Floodplain Study by Alberta Environment (AENV, 1984)
- Carbon Flood Hazard Mapping Study – Kneehills Creek by NHC (2008)
- Town of Didsbury Flood Risk Mapping Study by NHC (2006)

2.4 Additional Information

AEP provided tables/relationships of flow travel time versus discharge along the Red Deer River which were used for routing of naturalized and regulated flows. AEP also provided relevant information for Bigelow Dam including the reservoir elevation – surface area – storage curves, and operation manual. Project information and operations plan for the Parlby Creek – Buffalo Lake Water Management Project were obtained from the open government portal of Alberta (https://www.alberta.ca/open-government-program.aspx).

3 FLOW NATURALIZATION AND REGULATION

3.1 Flow Naturalization

3.1.1 General

Flow naturalization is a process by which anthropogenic effects, such as regulation due to storage or diversion of flow, are removed to re-create the natural flow that would have occurred in the absence of these interventions. Red Deer River flows have been regulated by Dickson Dam, located upstream of the city of Red Deer, since 1983. Flows are also affected by diversions and operations of smaller dams on its tributaries within the basin, although these operations would have lower impacts on annual peak flows in the main-stem river.

Flow naturalization to remove effects of Dickson Dam operations on Red Deer River flows was completed as part of the Upper Red Deer and Red Deer River Hazard Study by Golder (2018). The study developed naturalized and regulated daily flow timeseries for the 1912-2016 period at eleven locations on the Red Deer River from Dickson Dam through the city of Red Deer. These results were provided by AEP and used as inputs for the present study. Flow naturalization for the Red Deer River in this study focused on estimating flows in the Drumheller area by routing the naturalized flows from the city of Red Deer to Drumheller, together with tributary inflows entering this sub-reach.

The Red Deer River flow naturalization by Golder (2018) was performed using the Project Depletion Method, which involved routing both gauged and naturalized outflows from the dam to the study sites, and adjustments (or corrections) were made at gauged sites based on the differences between the routed flows and the gauge data. The same concept was applied in the present study. The flow naturalization process includes the following primary components:

- Gauged daily flows for WSC Station 05CC002 – Red Deer River at Red Deer were routed, together with available gauged downstream tributary inflows, to Drumheller (WSC Station 05CE001). The routed flows were compared with the gauge data for the Red Deer River at Drumheller and the differences were taken as ungauged tributary inflows (or flow corrections).

- The naturalized flows for the Red Deer River at Red Deer, gauged tributary inflows and ungauged tributary inflow estimates or flow corrections were routed to Drumheller.

- For missing periods of data at Drumheller when the gauge flow correction cannot be performed, naturalized flood peaks were estimated through correlation of peak discharges at Red Deer and at Drumheller.

Details of the adopted methodology are described in the following sections. Locations of the hydrometric stations referenced in this chapter are shown in **Figure 2.**

3.1.2 Naturalized Flows for Red Deer River at Drumheller

The ultimate objective of the flow naturalization process in this study is to develop a data series of naturalized annual peak discharges for Red Deer River at Drumheller. To this end, the daily naturalized flows for the Red Deer River at Red Deer from Golder (2018) were routed through the river to Drumheller, while adding estimated tributary inflows along the river reaches.

Hydrologic Routing Model

The flow routing analysis was performed using HEC-ResSim (version 3.1). HEC-ResSim is public-domain software developed by the US Army Corps of Engineers (USACE) to model reservoir operations and channel routing. It can simulate complicated operations of a reservoir or reservoir networks and flow diversion. It is widely used for simulation of operations for flood management, low flow augmentation and water supply for planning studies, system optimization and for real-time decision support. HEC-ResSim is unique among reservoir simulation models because it attempts to reproduce the decision-making process that human reservoir operators must use to set releases.

HEC-ResSim currently supports eight hydrologic channel routing methods. In this study, the Streamflow Synthesis and Reservoir Regulation (SSARR) method was used. This method was developed by USACE and has been widely used across Alberta by AEP for water supply studies, flood forecasting and other studies. It uses a Muskingum-type of channel routing method to simulate channel storage effects based on reach-specific discharge-travel time relationships that are provided as input. The relationship can be defined by a table of discharge vs. travel time, or by the following formula:

$$T_S = \frac{KTS}{Q^n} \qquad \textbf{(Equation 1)}$$

where T_s is travel time (or time of storage); Q is discharge; and KTS and n are coefficients that need to be input to the model. The KTS and n values or the discharge vs. travel time table are usually determined by calibration against observed hydrographs or from average flow velocity estimates based on channel geometry data.

The routing model developed for this study is illustrated by the schematic in **Figure 4**. It includes the Red Deer River from Red Deer (WSC Station 05CC002) to Drumheller (WSC Station 05CE001). The SSARR routing parameter values used by AEP for flood forecasting were provided by AEP via an email on 18 July 2018. The AEP values were tested in the HEC-ResSim model using published hourly and daily flow data. Minor adjustments were then made to better fit the published data for historical flood events. **Figure 5** shows comparisons of routed and reported hourly flow hydrographs for the 2005 and 2013 annual peak events at Drumheller, based on the original AEP and adjusted routing parameters. The adopted SSARR routing parameters are summarized in **Table 3**. Final routing analyses for flow naturalization of this study were performed at a daily time step in HEC-ResSim.

Table 3: SSARR routing parameters for Red Deer River from Red Deer to Drumheller

	Number of Routing Phases (N)	*KTS*	*n*
AEP Value	18	5.29	0.13
Adopted Value	12	5.29	0.13

Estimation of Flow Corrections at Drumheller

Gauged Red Deer River daily flows at Red Deer (WSC Station 05CC002) were routed to Drumheller, together with available gauged tributary inflows. The routed flows at Drumheller were compared with the gauge data for WSC Station 05CE001, and daily differences were taken as the gauge correction flows (which represent lumped ungauged tributary inflow discharges) for each day over the simulation period. This process resulted in flow correction time series for the periods from November 1915 to May 1931 and from March 1959 to October 2016. The flow correction time series were then assigned to the node representing WSC Station 05CE001 in the model and used when performing routing for flow naturalization.

Flow Naturalization for Drumheller from 1983 to 2016

The naturalized daily flows for Red Deer River at Red Deer from Golder (2018) were routed to Drumheller, together with all tributary inflows (including gauged and correction flows). This resulted in naturalized daily flows for Drumheller for the regulated period.

Figure 6 shows the naturalized daily flow time series for Red Deer River at Drumheller (WSC Station 05CE001) compared with the recorded data for the period from 1983 to 2016. Annual maximum daily discharges from the two data sets are compared in **Figure 7**. The figure shows that the naturalized peaks are higher than the recorded for all the years except 1985, 1987 and 2004. The ratios of the naturalized peak vs. recorded peak are generally between 1.0 and 1.5 with the exception of the higher ratios for a couple of years that had relatively low peaks. Nevertheless, all the peak discharges could be fitted to a linear relationship with a slope of 1.19.

The naturalized vs. recorded peak ratios for 1985, 1987 and 2004 are 0.97, 0.99 and 0.96 respectively. The recorded annual peak daily discharges of these events are 278 m^3/s (15 September 1985), 170 m^3/s (10 April 1987) and 194 m^3/s (08 July 2004). These discharges are relatively small. The slightly higher regulated peaks (in comparison with the naturalized peaks) were likely due to drawdowns of Gleniffer Reservoir during those events (i.e. reservoir outflows were greater than natural inflows).

Naturalized Peak Flows at Drumheller for Missing Periods

Flow data for Red Deer River at Drumheller (WSC Station 05CE001) are not available between 1912 and November 1915, and between May 1931 and March 1959. The record also misses the September 1926 peak event, which was measured at Red Deer (WSC Station 05CC002). For those years, the annual peak daily discharges at Drumheller were estimated from the peak discharges at Red Deer based on the relationship derived from the gauge data for the pre-regulation periods (1916-1930 and 1959-1982), as shown in **Figure 8**.

The naturalized daily flow series from Golder (2018) do not include the data for 2017 and 2018. The gauged annual peak daily discharges for these two years from WSC were used to estimate the corresponding naturalized discharges based on the linear relationship between the 1983-2016 naturalized and measured peak daily discharges at the WSC Drumheller station, as shown in **Figure 7**.

3.1.3 Assessment of Tributary Flow Regulation

Flow diversions and smaller reservoirs exist within the local tributary area of the Red Deer River between Red Deer and Drumheller. The Parlby Creek-Buffalo Lake Water Management Project on Parlby Creek and Tail Creek and Bigelow Reservoir on Threehills Creek are the two most prominent projects. Their effects on flows in the Red Deer River are discussed in this section. Due to the lack of project information and hydrometric data, it is impossible to perform flow naturalization for other tributaries in this area. However, their regulated catchment areas are smaller and it is believed that they do not have significant effects on flood peaks for Red Deer River at Drumheller.

Parlby Creek-Buffalo Lake Water Management Project (1985-Present)

The Parlby Creek-Buffalo Lake Water Management Project is located in Central Alberta, approximately 70 km east of Red Deer. Project information, including the operations plan discussed in this section, is from the AEP Buffalo Lake Management Team (www.blmt.ca). The Project is an initiative of AEP to stabilize the water levels in Buffalo Lake, enhance fish and wildlife habitat, provide agricultural flood control and support local wetland projects. The construction of this multiphase project started in 1985 and finished in 2000-2001. As shown in **Figure 9**, this water management system includes: a pumphouse to withdraw water from the Red Deer River with a maximum rate of 1.42 m^3/s, a pipeline and conduit system which carries the pumped water to Alix Lake, a 20 km long Parlby Creek channel which flows from Alix Lake to Buffalo Lake, and a sheet pile weir with a fixed crest elevation of 780.85 m which regulates water levels in Buffalo Lake and allows the lake to overflow to the Red Deer River via Tail Creek.

Pumping for flow diversion from the Red Deer River typically occurs during the open water season between May 1 and October 31. It typically starts when the Buffalo Lake level drops to El. 780.60 m and stops when the lake level reaches El. 780.85 m (the overflow weir crest elevation). The flow diversion is too small to have detectable effects on annual peak discharges in the Red Deer River.

Buffalo Lake is a relatively large, shallow lake. The drainage area of the lake is about 1,570 km^2. WSC operates a gauge on the lake (WSC Station 05CD005 – Buffalo Lake near Erskine) and provides seasonal lake levels from 1965 to 2016 as shown in **Figure 10**. The plotted water level variation does not show any trends indicating any significant effects of the flow regulation. Moreover, as the operations plan of the water management system is intended to maintain the lake level at the overflow weir crest elevation with diverted water from the Red Deer River, there would be minimal effects on high natural runoff flowing through the lake. Therefore, it is believed that the Parlby Creek-Buffalo Lake Water Management Project would have negligible effects on annual peak discharges in the Red Deer River.

Bigelow Reservoir (1971-Present)

Bigelow Reservoir is located on upper Threehills Creek, about 18 km northwest of Trochu. It was formed by the construction of Bigelow Dam in 1971 to improve regulation of low flows in the creek and to provide waterfowl habitat and recreational opportunities. The drainage area upstream of the dam is about 413 km^2.

According to AEP (2018), the reservoir has a storage capacity of 6,167 dam^3. Bigelow Dam discharges into Threehills Creek via a low level outlet and a drop inlet spillway with capacities of about 1.6 m^3/s and 40 m^3/s respectively. The dam has an uncontrolled auxiliary spillway which can be overtopped at El. 883.13 m and provides a maximum discharge capacity of 160 m^3/s.

Downstream of the dam, Threehills Creek flows in a southeastern direction for about 90 km before entering the Red Deer River. The total drainage area of Threehills Creek is about 2,200 km^2.

The regulated drainage area upstream of Bigelow Dam accounts for only about 19% of the total drainage area of Threehills Creek and less than 2% of the Red Deer River drainage area upstream of Drumheller.

WSC Station 05CE901 provides seasonal water level records for Bigelow Reservoir since 1979; but it often misses high flow events. Outflow discharges from the reservoir are not gauged. As such, it is not possible to perform a full, detailed flow naturalization/regulation analysis for this project. Due to its relatively small drainage area, it is expected that operations of Bigelow Dam would have negligible effects on flood frequency estimates for the Red Deer River study sites. Nevertheless, a rough flow naturalization analysis was performed to validate this assumption as follows:

1) Daily flow data for WSC Station 05CE018 (Threehills Creek below Ray Creek with a drainage area of 199 km^2) were prorated by the drainage area ratio to estimate natural inflows to Bigelow Reservoir for the 1971-2016 period. Note that this gauge station is located approximately 15 km upstream of the reservoir.
2) Daily discharges of Bigelow Dam outflows were computed from available reservoir level data for WSC Station 05CE901 based on the rating curves for the reservoir outlet facilities.
3) Estimated peak daily inflow and outflow discharges were compared for the years in which peak reservoir levels could be identified from the gauge records – a total of 12 events were identified.
4) The differences between the peak daily inflow and outflow discharges for those 12 years were added to the peak discharges of corresponding events measured by WSC Station 05CE007 (Threehills Creek near Carbon), which has a drainage area of 1,080 km^2 and provides flow data from 1965 to 2017. The 12 adjusted peak discharges are compared with the gauge data in **Figure 11**.

5) The relationship shown in **Figure 11** was used to adjust the 1983-2016 daily flow data for Threehills Creek near Carbon. The adjusted data were then used in the flow naturalization process for Red Deer River at Drumheller. The naturalized annual daily peak discharges for Drumheller were then compared in **Figure 12**.

Figure 12 illustrates that regulation at Bigelow Dam has no detectable effects on peak discharges of Red Deer River at Drumheller. Therefore, operations of this project were ignored in the flow naturalization and regulation processes of this study.

3.2 Flow Regulation

While the Hydrologic and Hydraulic Guidelines for Flood Hazard Area Delineation by AENV (2008) require that the design flood for a river hazard study be based on naturalized flows, the scope of the present study requires the development of a regulated data series in consideration of current flow management operations, and estimates of the regulated flood frequencies. The purpose of this exercise is to gain an understanding of potential effects of current flow management operations on the flood magnitude and risk at the sites of interest.

In this flow regulation process, the regulated daily flow time series for Red Deer River at Red Deer estimated by Golder (2018) were routed to Drumheller, while adding tributary inflows (gauge corrections) assembled from the flow routing process as described in Section 3.1.2. This routing analysis was conducted at a daily time step using the HEC-ResSim model described above. As shown in **Figure 13**, the results of the analysis include regulated daily flow series for Drumheller for the periods from November 1915 to May 1931 and from March 1959 to October 2016, when the tributary flow estimation (gauge corrections) could be estimated based on the available gauge data. The regulated annual maximum daily discharges are compared with the recorded values for the post-regulation period in **Figure 14**.

For 1926 (when the annual peak event is missing) and the missing period from May 1931 to March 1959, only annual maximum daily discharges were estimated for the Drumheller station with the regulated peak discharges at Red Deer being multiplied by 1.13, which is based on the relationship of the 1916-1930 and 1959-2016 regulated peak discharges for the two stations, as shown in in **Figure 15**.

The regulated daily flow series from Golder (2018) do not include the data for 2017 and 2018. The gauged annual peak daily discharges for these two years from WSC were used to estimate the corresponding regulated discharges based on the linear relationship between the 1983-2016 regulated and measured peak daily discharges at the WSC Drumheller station, as shown in **Figure 14**.

4 FLOOD FREQUENCY ANALYSIS

4.1 General

Frequency analysis was performed on annual maximum instantaneous discharges for the sites of interest listed in Section 1.2. The analysis was conducted using the USACE HEC-SSP (version 2.1) flood frequency program and a spreadsheet model developed by NHC. In accordance with the Hydrologic and Hydraulic Guidelines for Flood Hazard Area Delineation by AENV (2008) and Guidelines on Flood Frequency Analysis by Alberta Transportation (AT, 2001), various theoretical probability distributions were tested, including the normal (N), log-normal (LN), three-parameter log-normal (LN3), Pearson type III (P3), log-Pearson type III (LP3), Gumbel (G), generalized extreme value (GEV), and Weibull (W) distributions. In accordance with AT (2001), the method of moments was used in the calculation of means, variances, and skew coefficients with theoretical limits being considered. The Cunnane positioning formula was used to plot data points for visualization purposes.

The USGS "Guidelines for Determining Flood Frequency" Bulletin 17B and Bulletin 17C were also reviewed and considered for the present study. The USGS Guidelines provide a framework primarily intended to standardize the methods to account for: historic flood information, zero flows or low outliers, and high outliers; and methods to estimate population parameters. They use the LP3 as the base method for flood frequencies and recommend use of a weighted average of the station skew and a regional skew. Bulletin 17C (USGS, 2018) updates Bulletin 17B, addressing known major limitations by recommending some new and ostensibly improved methods. For example, Bulletin 17C improves on the approach for identification of low outliers by using a Multiple Grubbs-Beck Test to replace the Grubbs-Beck Test used in Bulletin 17B; uses regional skew estimates based on the Bayesian Weighted Least Squares/Bayesian Generalized Least Squares method to replace the regional skew coefficient map in Bulletin 17B; and uses the new Expected Moments Algorithm (EMA) to extends the method of moments so that it can better handle low outlier adjustments, regional skew information and historical information. The primary difficulty with the application of Bulletin 17C guidelines is that regional skew estimates are not available in Alberta. As a result, only the station skewness was used in the present study. Note that, when the station skewness is used and no outliers are detected in the population, the resulting Bulletin 17C curve is often identical to a standard LP3 curve based on the method of moment.

The goodness of fit of each of the theoretical distributions, as applied to a flood series, was compared through the Kolmogorov–Smirnov test (K-S test) and a least squares method.

The K-S test can be used to compare a sample with a reference probability distribution. It quantifies a distance between the empirical probability of the sample and the cumulative distribution function of the reference distribution. The maximum distance (referenced to as D-statistic value, D_n) can be used to describe the goodness of fit: a smaller D_n value would indicate a better fit between the empirical distribution and the theoretical one.

The least squares method (Kite, 1977) is based on the sum of squared errors (*SSE*) calculated by

$$SSE = \sqrt{\frac{1}{n-m}\sum_{i=1}^{n}(x_i - y_i)^2} \qquad \textbf{(Equation 2)}$$

where n is the number of recorded events, m is the number of parameters used by a frequency distribution, x_i is the i^{th} recorded peak discharge, and y_i is the discharge computed from the frequency distribution at the probability equal to the empirical probability of discharge x_i.

The *SSE* values of the tested probability distributions were then normalized by the mean peak discharge (Q_{pm}) to provide a dimensionless *SSE*. In this approach a lower dimensionless *SSE* would indicate a better fit between the empirical distribution and the theoretical one.

Each of these methods has their own advantages and disadvantages. The D_n value from the K-S test is defined as the maximum discrepancy between the predicted probabilities (for given flood peaks) by the frequency curve and empirical probabilities from the data sample, which would usually occur in the middle part of the frequency curve. On the other hand, the *SSE* value represents the average deviation of predicted flood peaks from the measured or estimated discharges.

In this study, the applied frequency distributions were ranked first by D_n and *SSE* values separately and the sums of the rankings were then compared to derive the final combined ranking. Note, however, that using these statistical methods tends not to provide a foolproof assessment of the goodness of fit along the tails of the distributions, which are especially important in defining the return periods of the severe floods. Therefore, the selection of the best representative distribution is based as much on judgement, visual assessment and Bayesian concept as it is on the statistical ranking result.

For each of the final selected frequency curves, 95% confidence limits were provided. The confidence limits are the upper and lower ends of a confidence interval for a selected theoretical flood frequency distribution, which reflects uncertainties due to estimating the parameters for the frequency curve (e.g. the mean, standard deviation, skew coefficient, etc.) from a sample (i.e. flood peak discharge series) of the population of floods. By this definition, the confidence limits cannot be provided for flood frequency curves developed from empirical relationships (e.g. the regional analysis for Willow Creek presented in Section 4.5) or numerical simulations (e.g. the synthetic flood routing analysis for Red Deer regulated flows at Drumheller presented in Section 4.6.4).

In the following sections of this chapter, assessments of flood characteristics and frequency analyses are presented for the study sites on the tributaries first, in the order from upstream to downstream along the Red Deer River. The analyses for the Red Deer River sites are presented subsequently as some of the assumptions and conclusions were based on the assessments for those tributaries.

4.2 Kneehills Creek

4.2.1 Flood Characteristics

Kneehills Creek originates in the Central Parkland Natural Subregion near the town of Olds, while most of the basin area lies in the Grassland Natural Region. The creek joins the Red Deer River about 8 km upstream of Drumheller. WSC Station 05CE002 (Kneehills Creek near Drumheller) is located on the creek approximately 20 km upstream of its confluence with the Red Deer River (**Figure 2**). According to WSC, the drainage area upstream of this gauge station is about 2,430 km^2. **Figure 16** and **Table 4** show the annual peak flow series for Kneehills Creek near Drumheller. While the data series span from 1921 to 2018, there are a number of years with missing data. Instantaneous peaks are not provided in many of the years, and where missing, they were calculated on the basis of the correlation between the instantaneous peaks (Q_i) and daily peaks (Q_d) for years when both were measured, as shown in **Figure 17**.

Table 4: Annual peak instantaneous and daily discharges for Kneehills Creek near Drumheller

Year	Maximum Instantaneous Discharge (m^3/s) (1)	Date	Maximum Daily Discharge (m^3/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m^3/s)
1921	**20.2**	Apr-15	17.1	Apr-15	
1922	**5.68**	Apr-2	4.81	Apr-2	
1923	24.9	Jun-1	8.10	Jun-1	
1924	6.91	Aug-14	1.70	Aug-14	
1925	72.5	Apr-7	65.4	Apr-7	
1926	**30.6**	Mar-20	25.9	Mar-20	
1927	**31.9**	Apr-8	27.0	Apr-8	
1928	**66.8**	Mar-21	56.6	Mar-21	
1929	**1.32**	May-14	1.12	May-14	
1930	**23.5**	Feb-18	19.9	Feb-18	
1936	**46.1**	Apr-14	39.1	Apr-14	
1957	**18.8**	Aug-11	15.9	Aug-11	
1959	7.82	Aug-17	2.94	Mar-16	0.974
1960	**80.8**	Mar-26	68.5	Mar-26	
1961	50.7	May-30	19.4	May-30	
1962	12.8	Jul-27	11.9	Mar-19	4.36
1963	**19.8**	Mar-24	16.8	Mar-24	
1964	**5.98**	Apr-4	5.07	Apr-4	
1965	**47.8**	Apr-12	40.5	Apr-12	
1966	120	Mar-29	87.5	Mar-29	
1967	78.2	Apr-14	38.2	Apr-15	
1968	**5.02**	Sep-22	4.25	Sep-22	

Year	Maximum Instantaneous Discharge (m³/s) (1)	Date	Maximum Daily Discharge (m³/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m³/s)
1969	**145**	Apr-5	123	Apr-5	
1970	**17.0**	Jun-16	14.4	Jun-16	
1971	133	Apr-9	110	Apr-10	
1972	23.4	Jun-12	16.0	Jun-12	
1973	28.1	Apr-4	26.2	Apr-5	
1974	124	Apr-14	85.8	Apr-15	
1975	**16.5**	Apr-22	14.0	Apr-22	
1976	21.8	Aug-16	12.2	Mar-23	2.89
1977	6.37	Apr-8	4.42	Apr-9	
1978	21.3	Mar-27	13.0	Mar-29	
1979	9.53	Mar-7	8.86	Mar-7	
1980	14.0	Apr-9	9.63	Apr-9	
1981	8.77	May-9	7.31	May-9	
1982	14.4	Apr-16	12.7	Apr-16	
1983	**4.39**	Apr-3	3.72	Apr-3	
1984	2.12	Sep-6	1.12	Sep-21	0.497
1985	**11.9**	Mar-16	10.1	Mar-16	
1986	**7.08**	Mar-6	6.00	Mar-6	
1987	**15.0**	Apr-4	12.7	Apr-4	
1988	9.13	Aug-20	1.54	Aug-1	1.5
1989	**5.85**	Mar-31	4.96	Mar-31	
1990	15.6	Jun-15	15.1	Jun-15	
1991	10.4	May-13	5.03	Apr-5	4.01
1992	30.0	Jul-7	6.33	Jun-18	1.51
1993	**27.3**	Apr-5	23.1	Apr-5	
1994	16.6	Mar-19	13.6	Mar-19	
1995	2.09	Jul-7	1.90	Jul-7	
1996 (2)	**94.4**	Apr-8	80.0	Apr-8	
1997	153	Apr-19	148	Apr-19	
1998	7.57	Jul-8	2.68	Jul-9	
1999	16.7	Jul-18	16.0	Jul-18	
2000 (2)	**1.12**	Apr-2	0.95	Apr-2	
2001	**0.43**	Apr-10	0.36	Apr-10	
2002	**0.23**	Apr-12	0.20	Apr-12	
2003	**51.0**	Mar-23	43.2	Mar-23	
2004	21.5	Jun-7	12.1	Jun-7	
2005	21.9	Mar-12	19.3	Mar-13	

Year	Maximum Instantaneous Discharge (m³/s) (1)	Date	Maximum Daily Discharge (m³/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m³/s)
2006	**<u>45.2</u>**	Apr-5	38.3	Apr-5	
2007	**<u>49.2</u>**	Mar-13	41.7	Mar-13	
2008	**<u>14.0</u>**	Jun-13	11.9	Jun-13	
2009	53.6	Apr-12	47.8	Apr-12	
2010	7.45	Jul-23	3.03	Jul-18	2.85
2011	108	Apr-12	76.5	Apr-12	
2012	17.2	Jul-15	3.90	Jul-15	
2013	29.4	Jun-23	24.7	Jun-22	
2014	109	Apr-12	103	Apr-12	
2015 (3)	30.0	Mar-11	26.8	Mar-12	
2016 (3)	3.25	Mar-13	2.99	Mar-14	
2017 (3)	48.4	Mar-19	31.2	Mar-19	
2018 (3)	158	Apr-25	152	Apr-24	

Notes:

1. The bolded and underlined values are based on Q_i=1.18Q_d.
2. Maximum daily discharge determined from WSC daily flow record.
3. Preliminary data provided by WSC.

Snowmelt with or without rain in spring dominates peak discharges in Kneehills Creek. More than 60% of the annual peak discharges occurred in March and April and most of them were greater than 30 m^3/s, while the highest summer peak discharge was only 30 m^3/s which occurred in July 1992. The largest event on the record occurred in April 2018 and had a peak discharge of 158 m^3/s. The April 1997 event is the second largest with a peak discharge of 153 m^3/s, which is nearly the same as for the 2018 event. The April 1969 and April 1971 events are the third and fourth largest events with comparable peak discharges of 149 and 133 m^3/s respectively. NHC (2008) noted that the 1952 flood event was much more severe and had an estimated peak discharge of 425 m^3/s; however, the estimate was not reliable and was affected by an ice jam and a Canadian Pacific Railway embankment failure upstream of Carbon. This event was not included in the present assessment. **Table 5** summarizes the statistical characteristics of the Kneehills Creek peak discharge data series.

Table 5: Summary of statistical parameters of annual instantaneous peak discharge series for Kneehills Creek near Drumheller

Parameter	Annual Peak Flow Series 1921-1930, 1936, 1957 and 1959-2018
Years of record	72
Mean (m^3/s)	35.5
Median (m^3/s)	20.0
Standard deviation (m^3/s)	40.2
Coefficient of variation	1.13
Skew coefficient (minimum, maximum, actual)	2.26, 2.28, 1.68

4.2.2 Flood Frequency Analysis for Kneehills Creek near Drumheller

As required by the Terms of Reference (TOR) for this study, flood frequency analyses were performed for Kneehills Creek near Drumheller (WSC Station 05CE002). Each of the frequency distributions in the adopted suite was fitted to the instantaneous peak discharges shown in **Table 4**. The goodness of fit analyses described earlier were undertaken for each distribution, and the results are shown in **Table 6**. The Bulletin 17C frequency curve produced the smallest D_n value but it had an *SSE* value higher than most of the other distributions tested. The LP3 distribution had the lowest *SSE* value and second lowest D_n value. As such it is ranked the best in the combined ranking, followed by the P3 and Weibull distributions. These three distributions are compared in **Figure 18**. The other evaluated distributions are shown graphically in **Appendix A**.

Table 6: Goodness-of-fit comparison for probability distributions for Kneehills Creek near Drumheller

Distribution	D_n	Normalized *SSE* ($Q_{pm} = 35.5\ m^3/s$)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.231	0.527	9	8	9
Log-normal(LN)	0.089	1.067	5	9	7
Three parameter log-normal (LN3)	0.159	0.295	7	4	5
Pearson III (P3)	0.081	0.229	4	2	2
Log-Pearson III (LP3)	0.072	0.225	2	1	1
Gumbel (G)	0.177	0.339	8	6	7
Generalized extreme value (GEV)	0.157	0.308	6	5	5
Weibull (W)	0.079	0.237	3	3	2
Bulletin 17C	0.050	0.432	1	7	4

As shown in **Figure 18**, the three selected frequency curves are nearly identical with relatively small differences for return periods longer than 200 years. The 1000-year estimates from the Weibull and P3 distributions are slightly more conservative but only about 8% and 4% higher than the values from the LP3 curve respectively. The Weibull distribution has found its greatest use in drought frequency analysis (Chow et al., 1988 and Haan, 1977), while the P3 distribution is more commonly used for flood frequency analysis. Therefore, the P3 distribution is recommended for this site. The adopted P3 curve with 95% confidence limits is shown in **Figure 19**.

4.3 Michichi Creek

4.3.1 Flood Characteristics

Michichi Creek originates in the Hand Hills located on the east of the Red Deer River (**Figure 2**). It enters the Red Deer River about 500 m upstream of the Highway 9 bridge in Drumheller. WSC Station 05CE020 (Michichi Creek at Drumheller) is located on the creek near the mouth. According to WSC, the drainage area upstream of this gauge station is about 1,170 km^2. The creek is composed of two main stems, one which drains the west slopes of the Hand Hills and accounts for about 30% of the total basin area, and the other which drains a larger flatter prairie area north of Drumheller.

Figure 20 and **Table 7** show the annual peak flow series for Michichi Creek at Drumheller (WSC Station 05CE020). The data series span from 1979 to 2018 with two years (1999 and 2004) missing both instantaneous and daily peak discharges. There are another 17 years with missing instantaneous peak discharges. For those years, the instantaneous values were calculated using the observed ratio of the instantaneous versus daily peaks shown in **Figure 21**. The ratio (1.20) was based on 21 data points covering a relatively broad range of maximum daily discharges up to 57.8 m^3/s. It is similar to the instantaneous to daily peak ratio for Kneehills Creek (1.18) shown in **Figure 17**.

Table 7: Annual peak instantaneous and daily discharges for Michichi Creek at Drumheller

Year	Maximum Instantaneous Discharge (m^3/s) (1)	Date	Maximum Daily Discharge (m^3/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m^3/s)
1979	**6.07**	Mar-14	5.06	Mar-14	
1980	**25.1**	Apr-14	20.9	Apr-14	
1981	8.83	Aug-1	4.20	Aug-1	
1982	7.25	Apr-13	6.07	Apr-13	
1983	3.85	Jul-7	1.25	Mar-14	0.524
1984	**1.54**	Mar-25	1.28	Mar-25	
1985	**25.0**	Apr-2	20.8	Apr-2	
1986	**2.87**	Jun-9	2.39	Jun-9	
1987	**11.5**	Apr-2	9.57	Apr-2	
1988	**3.71**	Apr-10	3.09	Apr-10	
1989	**15.0**	Apr-4	12.5	Apr-4	
1990	**4.08**	Mar-21	3.40	Mar-21	

Year	Maximum Instantaneous Discharge (m^3/s) [(1)]	Date	Maximum Daily Discharge (m^3/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m^3/s)
1991	**2.00**	Mar-22	1.67	Mar-22	
1992	**2.47**	Jun-14	2.06	Jun-14	
1993	**23.5**	Mar-24	19.6	Mar-24	
1994	**23.9**	Mar-17	19.9	Mar-17	
1995	**6.10**	Mar-16	5.08	Mar-16	
1996	**16.6**	Apr-8	13.8	Apr-8	
1997	**35.4**	Mar-28	29.5	Mar-28	
1998	**0.55**	Jul-7	0.461	Jul-7	
2000	4.37	Sep-8	0.811	Sep-3	0.419
2001	1.94	Jul-17	0.590	Mar-13	0.277
2002	0.15	May-14	0.033	Aug-12	0.016
2003	5.70	Mar-22	4.37	May-9	4.03
2005	2.51	Aug-24	0.858	Aug-24	
2006	42.0	Apr-3	36.2	Apr-3	
2007	20.5	Mar-13	15.5	Mar-13	
2008	4.14	Jun-13	2.81	Jun-13	
2009	2.57	Jul-13	1.10	Aug-15	0.379
2010	18.3	Jun-11	14.8	Jun-11	
2011	66.8	Apr-12	57.8	Apr-12	
2012	6.39	Jun-27	3.52	Jun-27	
2013	48.2	Jun-23	37.9	Jun-24	
2014	17.0	Apr-11	15.4	Apr-11	
2015 [(2)]	17.9	Mar-11	17.2	Mar-11	
2016 [(2)]	10.2	Jul-2	6.88	Jul-16	3.53
2017 [(2)]	18.9	Mar-18	15.9	Mar-18	
2018 [(2)]	27.3	Apr-21	20.1	Apr-21	

Notes:

1. The bolded and underlined values are based on Q_i=1.20Q_d.
2. Preliminary data provided by WSC.

Like on Kneehills Creek, spring snowmelt (with or without rain) dominates peak runoff events on Michichi Creek. Nearly 60% of the annual peak events occurred in March and April. The remaining peak events occurred in the months of May through to September. The highest summer flood on record occurred in June 2013 with an instantaneous peak discharge of 48.2 m^3/s. Overall, however, spring snowmelt events tend to produce more severe floods than those in any other season for any other reason, with nine of the ten largest events occurring in March and April. The record high annual peak discharge 66.8 m^3/s occurred in April 2011. **Table 8** summarizes the statistical characteristics of the Michichi Creek peak discharge data series.

Table 8: Summary of statistical parameters of annual instantaneous peak discharge series for Michichi Creek at Drumheller

Parameter	Annual Peak Flow Series 1979-2018
Years of record	38
Mean (m^3/s)	14.2
Median (m^3/s)	8.04
Standard deviation (m^3/s)	14.8
Coefficient of variation	1.04
Skew coefficient (minimum, maximum, actual)	2.08, 2.11, 1.74

4.3.2 Flood Frequency Analysis for Michichi Creek at Drumheller

The TOR requires flood frequency estimates for Michichi Creek at Drumheller (WSC Station 05CE020). Each of the frequency distributions in the adopted suite was fitted to the annual instantaneous peak discharges shown in **Table 7**. The goodness of fit analyses described earlier were performed and the results are shown in **Table 9**. The P3, LP3 and Weibull frequency curves produced the smallest D_n and *SSE* values. As shown in **Figure 22**, all the three curves fit the data points well, and differences between them are negligible. The 100 and 1000-year values from the LP3 distribution are only about 6% and 1.5% higher than those from the P3 distribution respectively. To be consistent with the selection for Kneehills Creek near Drumheller, the P3 frequency curve is recommended for Michichi Creek at Drumheller. The adopted frequency curve with 95% confidence limits is shown in **Figure 23**.

The other evaluated distributions are shown graphically in **Appendix A**.

Table 9: Goodness-of-fit comparison for probability distributions for Michichi Creek at Drumheller

Distribution	D_n	Normalized *SSE* ($Q_{pm} = 14.2\ m^3/s$)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.171	0.469	9	8	9
Log-normal(LN)	0.118	0.746	4	9	7
Three parameter log-normal (LN3)	0.123	0.194	6	4	4
Pearson III (P3)	0.086	0.128	1	3	1
Log-Pearson III (LP3)	0.090	0.113	3	1	1
Gumbel (G)	0.150	0.260	8	7	8
Generalized extreme value (GEV)	0.125	0.210	7	5	6
Weibull (W)	0.087	0.127	2	2	1
Bulletin 17C	0.118	0.253	5	6	5

4.4 Rosebud River

4.4.1 Flood Characteristics

The Rosebud River joins the Red Deer River at the Rosedale community located south of Drumheller. As shown in **Figure 2**, the basin lies beside the Kneehills Creek basin. Similar to Kneehills Creek, the Rosebud River originates in the Central Parkland Natural Subregion near the town of Olds, while the most of the basin area lies in the Grassland Natural Region. The total drainage area of the Rosebud River at its mouth is approximately 4,250 km^2.

WSC operates a hydrometric station on the Rosebud River at Redland (WSC Station 05CE005) since 1951. This gauge station is located approximately 37 km upstream of its confluence with the Red Deer. The drainage area upstream of this gauge station is about 3,570 km^2, representing 84% of the total basin area. The annual maximum daily and instantaneous discharges have been reported at this gauge since 1967 and 1986 respectively.

Figure 24 and **Table 10** show the annual maximum instantaneous and daily discharges on the Rosebud River at Redland as summarized from the WSC records. Missing maximum instantaneous discharges were estimated by multiplying the daily discharge with the ratio of 1.08 as observed from the data shown in **Figure 25**. The available 50 years of annual peak data indicate that spring snowmelt (with or without rain) dominates peak runoff events on the Rosebud River. About 56% of the annual peak events occurred in March and April, including the 17 largest events. The largest annual maximum daily discharge on record is 177 m^3/s which occurred on 9 April 1971. The July 1998 event is the largest summer event which had a maximum daily discharge of 26.1 m^3/s and instantaneous peak of 34.5 m^3/s.

Table 10: Annual peak instantaneous and daily discharges for Rosebud River at Redland

Year	Maximum Instantaneous Discharge (m^3/s) (1)	Date	Maximum Daily Discharge (m^3/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m^3/s)
1967	**51.9**	Apr-13	48.1	Apr-13	
1969 (2)	**175**	April	162	April	
1970	**20.0**	Jun-20	18.5	Jun-20	
1971	**191**	Apr-9	177	Apr-9	
1972	**30.6**	Mar-23	28.3	Mar-23	
1973	**35.7**	Mar-26	33.1	Mar-26	
1974	**85.6**	Apr-13	79.3	Apr-13	
1975	**13.0**	May-22	12.0	May-22	
1976	**10.5**	Mar-24	9.71	Mar-24	
1977	**4.96**	Jun-1	4.59	Jun-1	
1978	**35.2**	Mar-31	32.6	Mar-31	
1979	**8.80**	Mar-11	8.15	Mar-11	

Year	Maximum Instantaneous Discharge (m^3/s) (1)	Date	Maximum Daily Discharge (m^3/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m^3/s)
1980	**<u>39.0</u>**	Apr-12	36.1	Apr-12	
1981	**<u>7.40</u>**	May-16	6.85	May-16	
1982	**<u>12.3</u>**	Apr-14	11.4	Apr-14	
1983	**<u>4.34</u>**	Apr-1	4.02	Apr-1	
1984	**<u>6.25</u>**	Jun-11	5.79	Jun-11	
1985	**<u>25.5</u>**	Mar-18	23.6	Mar-18	
1986	17.7	Sep-27	16.0	Sep-27	
1987	10.9	Jul-7	10.7	Jul-7	
1988	25.7	Aug-21	15.5	Aug-21	
1989	14.7	Apr-3	12.5	Apr-3	
1990	17.4	Jun-6	16.5	Jun-6	
1991	6.58	Aug-17	6.45	Aug-17	
1992	12.4	Jun-16	12.0	Jun-17	
1993	**<u>23.2</u>**	Mar-5	21.5	Mar-5	
1994	16.2	Mar-5	13.6	Mar-5	
1995	8.40	Jul-5	5.43	Jul-25	5.16
1996	100	Apr-9	85.6	Apr-9	
1997	**<u>125.3</u>**	Mar-29	116	Mar-29	
1998	34.5	Jul-6	26.1	Jul-6	
1999	18.8	Jul-16	15.7	Jul-16	
2000	5.48	Jun-12	5.37	Jun-12	
2001	3.92	Jun-6	3.76	Jun-7	
2002	5.26	Aug-8	5.18	Aug-8	
2003	56.2	Mar-23	52.6	Mar-23	
2004	15.5	Mar-12	11.5	Mar-14	
2005	15.5	Sep-14	15.1	Sep-14	
2006	**<u>34.0</u>**	Mar-31	31.5	Mar-31	
2007	**<u>44.1</u>**	Mar-12	40.8	Mar-12	
2008	24.6	Jun-15	23.2	Jun-15	
2009	57.0	Apr-10	51.6	Apr-10	
2010	22.6	Apr-29	13.0	Jun-18	12.4
2011	120	Apr-12	104	Apr-12	
2012	**<u>9.8</u>**	Jun-28	9.12	Jun-28	
2013	**<u>36.1</u>**	Apr-6	33.4	Apr-6	
2014	104	Apr-10	103	Apr-10	
2015	8.93	Sep-8	8.77	Sep-8	

Year	Maximum Instantaneous Discharge (m^3/s) (1)	Date	Maximum Daily Discharge (m^3/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m^3/s)
2016	11.9	Jul-18	11.2	Jul-18	
2017	**<u>57.1</u>**	Mar-19	52.9	Mar-19	
2018	160	Apr-23	154	Apr-23	

Notes:

1. The bolded and underlined values are based on Q_i=1.08Q_d.
2. The 1969 peak discharge was estimated from the data for WSC Station 05CE006 – Rosebud River below Carstairs Creek.

WSC Station 05CE006 (Rosebud River below Carstairs Creek) is another streamflow gauge that provides long-term flow records for the Rosebud River. The gauge is located on the upper reach of the river about 20 km east of Crossfield (**Figure 2**). It has a drainage area of about 753 km^2 (about 21% of the drainage area for Rosebud River at Redland). Annual peak discharges have been reported for this gauge since 1959. As noted by Matrix (2007), while the April 1971 peak discharge observed at the downstream gauge 05CE005 (Rosebud River at Redland) is the highest of the record, the highest annual peak daily discharge for WSC Station 05CE006 occurred on 2 April 1969 (41.3 m^3/s) – greater than its April 1971 peak (36.5 m^3/s). The peak discharge for the April 1969 event is missing at the downstream Redland station (WSC Station 05CE005). However, the incomplete daily record for that month includes a measured discharge of 142 m^3/s on 4 April 1969, which is only 20% lower than the April 1971 peak and 8% lower than the April 2018 peak (the second highest of the record), but is higher than all of the other peak daily discharges on the record. The April 1969 peak discharge for WSC Station 05CE005 was estimated as follows.

The annual maximum daily discharges reported at WSC Stations 05CE005 and 05CE006 from 1967 to 2018 are compared in **Figure 26**. The figure shows that the two data sets correlate relatively well with a downstream peak to upstream peak ratio of 3.92. The lower and upper 95% confidence limits of this ratio (the regression slope) were estimated as 3.50 and 4.32 respectively. Based on this relationship, the April 1969 peak daily discharge for WSC Station 05CE005 was estimated as 162 m^3/s (147 – 177 m^3/s based on the regression slope 95% confidence limits). This estimated discharge is included in **Table 10** and used in the flood frequency analysis. It is very close to the record high 1971 peak discharge and slightly greater than the second largest measured peak daily discharge on 23 April 2018 (154 m^3/s) for the Redland station. With this estimate being included, the most recent high flow event – the April 2018 event – is ranked the third largest.

It is worth noting that, if the peak discharge ratio (3.92) for WSC Stations 05CE005 versus 05CE006 shown in **Figure 26** is related to a power of drainage area ratio as shown in **Equation 3**, it would result in a power of 0.88 (i.e. m= 0.88).

$$\frac{Q_{p,1}}{Q_{p,2}} = \left(\frac{A_1}{A_2}\right)^m \qquad \textbf{(Equation 3)}$$

Where Q_p is peak discharge (m^3/s); *A* is drainage area (km^2); and subscripts *1* and *2* denote the sites in comparison.

Table 11 summarizes the statistical characteristics of the instantaneous peak discharge data series for Rosebud River at Redland shown **Table 10**.

Table 11: Summary of statistical parameters of annual instantaneous peak discharge series for Rosebud River at Redland

Parameter	Annual Peak Flow Series 1967-2018
Years of record	51
Mean (m^3/s)	38.8
Median (m^3/s)	20.0
Standard deviation (m^3/s)	45.5
Coefficient of variation	1.17
Skew coefficient (minimum, maximum, actual)	2.35, 2.61, 1.99

4.4.2 Flood Frequency Analysis for Rosebud River at Redland

The TOR requires flood frequency estimates for Rosebud River at the mouth where flows are not gauged. As described above, WSC Station 05CE005 (Rosebud River at Redland) is located about 37 km upstream of the Rosebud River mouth and represents about 84% of the total basin area. Frequency analyses were performed for this gauge site and the results were then transferred to Rosebud River at the mouth.

Note that a discontinued WSC gauge station (05CE003 – Rosebud River at Beynon) is located between WSC Station 05CE005 and the mouth. It has a drainage area of 3,990 km^2 – 12% greater than the drainage area of WSC Station 05CE005. The gauge provided intermittent daily flow measurements between 1922 and 1936 but annual maximum discharges were not reported. The maximum daily flow reported during that period was 80.7 m^3/s (29 March 1925), which has been exceeded multiple times during the gauged period for WSC Station 05CE005. Therefore, this data was not considered in the frequency analysis.

Each of the frequency distributions in the adopted suite was fitted to the annual instantaneous peak discharges for Rosebud River at Redland shown in **Table 10**. The goodness of fit analyses described earlier were performed and the results are shown in **Table 12**. The LP3 and Bulletin 17C curves, which are identical, resulted in the smallest D_n value; however, they have a high *SSE* value. The P3 distribution has the lowest *SSE* value but its D_n value is higher than those for the LP3, LN and Weibull curves. In the combined ranking, the P3, LN and Weibull distributions are ranked the highest, followed by the LP3 (identical to the Bulletin 17C curve). These four curves are compared in **Figure 27**. The other evaluated distributions are shown graphically in **Appendix A**.

Table 12: Goodness-of-fit comparison for probability distributions for Rosebud River at Redland

Distribution	D_n	Normalized *SSE* ($Q_{pm} = 38.8\ m^3/s$)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.230	0.653	9	9	9
Log-normal(LN)	0.062	0.305	3	3	1
Three parameter log-normal (LN3)	0.203	0.325	7	4	6
Pearson III (P3)	0.159	0.225	5	1	1
Log-Pearson III (LP3)	0.055	0.449	1	7	4
Gumbel (G)	0.223	0.423	8	6	8
Generalized extreme value (GEV)	0.200	0.350	6	5	6
Weibull (W)	0.140	0.227	4	2	1
Bulletin 17C	0.055	0.449	1	7	4

As shown in **Figure 27**,the Weibull and P3 curves are very similar, resulting in nearly identical 100-year peaks of about 210 m^3/s. The LN shows a slightly higher 100-year value (249 m^3/s), while its peak discharge predictions for longer return periods are noticeably higher than the values from the Weibull and P3 curves. Among the four curves shown, the LP3 has the highest peak discharges for return periods longer than 20 years. Its 100 and 1000-year values are 322 m^3/s and 913 m^3/s respectively, which are about 29% and 67% higher than the respective values from the LN curve. These values also appear to be too high from a region-wise viewpoint based on the regional flood frequency relationships presented in Section 4.5.

From a visual inspection of **Figure 27**, the lower portions of the Weibull and P3 curves do not fit the data points very well, while the LN and LP3 curves are able to provide a reasonably good fit overall.

Based on these observations, the LN frequency curve is recommended for Rosebud River at Redland. The adopted frequency curve with 95% confidence limits is shown in **Figure 28**.

4.4.3 Flood Frequency Estimates for Rosebud River at the mouth

The total drainage area of the Rosebud River at the mouth is approximately 4,250 km^2. Based on the ratio of this drainage area against that for WSC Station 05CE005, **Equation 3** with m = 0.88 (as discussed above) resulted in a ratio of 1.17 for peak discharges at the mouth versus at 05CE005. Flood frequency estimates for Rosebud River at the mouth were then developed by applying this ratio to the adopted LN frequency curve for Rosebud River at Redland. The resulting flood frequency curve with 95% confidence limits is shown in **Figure 29**. Note that the results from this approach are conservatively higher than what could be derived from the regional relationships presented in the next section; however, they are more reliable because this approach relies 100% on the nearby gauge station representing 84% of the basin area.

4.5 Willow Creek

4.5.1 Flood Characteristics

The Willow Creek basin is located immediately south of the Michichi Creek basin and east of the Red Deer River. The creek originates in the Hand Hills (same as Michichi Creek). It joins the Red Deer River near the Willow Creek Hoodoos Trail. The total drainage area is about 400 km^2, as delineated from the AltaLIS digital elevation model (DEM) in a 1:20,000 scale. Runoff contributing to Willow Creek comes mostly from the west slopes of the Hand Hills. It also receives outflows from Little Fish Lake, which is situated on the southern edge of the Hand Hills and fed by Fish Creek. While Willow Creek flows are not gauged, WSC operates a gauge station on Little Fish Creek (05CG006 – Fish Creek above Little Fish Lake, as shown in **Figure 2**), which has a drainage area of about 118 km^2 and provides flow data from 1984 to 2018.

Given their proximity and physiographic similarity, it is believed that Willow Creek and Michichi Creek would have similar flood characteristics. Annual peak runoff events on Willow Creek would be dominated by spring snowmelt (with or without rain) before May. This assumption is supported by the flow data for Fish Creek above Little Fish Lake (WSC Station 05CG006) where more than 80% of annual peak events between 1984 and 2018 occurred before May.

4.5.2 Flood Frequency Analysis

The TOR requires flood frequency estimates for Willow Creek at the mouth. As there are no streamflow measurements on Willow Creek, a regional analysis was performed to estimate flood frequencies for this site. **Table 13** shows the WSC stations selected for the regional analysis. Their locations are shown in **Figure 2**.

Table 13: Reference stations for regional analysis for Willow Creek

Station ID	Station Name	Drainage Area (km^2)	Period of Record
05CG006	Fish Creek above Little Fish Lake	118	1985-2018
05CE006	Rosebud River below Carstairs Creek	753	1957-2018 (1)
05CE020	Michichi Creek at Drumheller	1170	1979-2018 (2)
05CE002	Kneehills Creek near Drumheller	2430	1921-1930, 1936, 1957 and 1959-2018 (2)
05CE005	Rosebud River at Redland	3570	1967-2018 (1)

Notes:

1. Including preliminary data for 2018 from WSC
2. Including preliminary data for 2015-2018 from WSC

Flood frequency curves for Michichi Creek, Kneehills Creek and Rosebud River at Redland are presented in previous sections. Additional analyses were performed on annual instantaneous peak discharges for Fish Creek above Little Fish Lake (WSC Station 05CG006) and Rosebud River below Carstairs Creek (WSC

Station 05CE006). The P3 distribution provided the best fit for the data of these two stations. The adopted frequency curves are shown in **Figure 30** and **Figure 31**.

Flood frequency estimates for all gauge stations listed in **Table 13** were plotted against drainage areas to develop a set of regional relationships, which can be described by:

$$Q_T = kA^b \qquad \textbf{(Equation 4)}$$

where Q_T is the maximum instantaneous discharge (m^3/s) for return period *T*; *A* is the drainage area (km^2); *k* and *b* are constants from the regression analysis. A reasonably good fit was found for each set of the data. Some sample plots are shown in **Figure 32**. Resulting constants *k* and *b* for **Equation 4** are summarized in **Table 14**, along with R^2 (the coefficient of determination) values. These relationships were used to develop flood frequency estimates for Willow Creek at the mouth based on its drainage area of 400 km^2.

Table 14: Constants for regional flood frequency relationships

Return Period (Years)	*k*	*b*	R^2
1000	0.58	0.79	0.91
750	0.58	0.78	0.92
500	0.58	0.77	0.92
350	0.57	0.76	0.93
200	0.55	0.75	0.94
100	0.52	0.73	0.94
75	0.50	0.73	0.95
50	0.47	0.72	0.95
35	0.44	0.71	0.95
20	0.39	0.70	0.96
10	0.30	0.69	0.96
5	0.19	0.70	0.96
2	0.05	0.76	0.97

4.6 Red Deer River

4.6.1 Flood Characteristics

As per the TOR for this study, flood frequency estimates for both naturalized and regulated flood peaks are required for the following five sites on the Red Deer River in Drumheller:

- Red Deer River above Kneehills Creek
- Red Deer River above Michichi Creek

- Red Deer River at Drumheller (WSC Station 05CE001)
- Red Deer River below Rosebud River
- Red Deer River below Willow Creek

Systematic flow records are available for Red Deer River at Drumheller (WSC Station 05CE001) since 1916 with a gap from 1931 through 1958. Annual peak events on the Red Deer River generally occur from May to August. Based on the WSC flow records, most (more than 35%) of the annual peaks occurred in June when snowmelt runoff from the mountains is augmented by rain storms in the foothills. Less than 5% of the annual peak events occurred in March. Clearly, flood peaks in the Red Deer River are governed by different hydrological processes from those driving high flows in the local tributaries, as discussed in Sections 4.2 through 4.5.

Figure 33 shows the relationship between annual instantaneous peak and maximum daily discharges for Red Deer River at Drumheller. The observed instantaneous to daily peak discharge ratios were 1.19 and 1.09 for the pre-regulation period (1916-1982) and post-regulation period (1983-2018), respectively.

4.6.2 Flood Frequency Analysis for Red Deer River at Drumheller

Natural/Naturalized Flood Peaks

Figure 34 and **Table 15** show the annual natural/naturalized peak flow series for Red Deer River at Drumheller (WSC 05CE001). The annual maximum daily discharges for the 1983-2018 period were based on the naturalized flows presented in Section 3.1. Instantaneous peak discharges were calculated by multiplying the daily values with the ratio of 1.19, based on the relationship of the pre-regulation instantaneous versus daily peaks shown in **Figure 33**. To extend the data series as far back as possible, the available gauged and estimated peak discharges for the 1912-1982 pre-regulation period (see Section 3.1) were combined with the naturalized peak flows. Missing instantaneous peak discharges for this pre-regulation period were also calculated with the daily values being multiplied by the ratio of 1.19.

Table 15: Annual peak discharges of natural/naturalized flows for Red Deer River at Drumheller

Year	Maximum Instantaneous Discharge (m^3/s)	Date	Maximum Daily Discharge (m^3/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m^3/s)
1912	**717**		***603***	Jul-10	
1913	**509**		***428***	Jun-30	
1914	**209**		***176***	Jun-15	
1915	**2,020**		***1,780***	Jun-28	
1916	**1,010**		852	Aug-21	
1917	**1,080**		906	May-18	
1918	**374**		314	Mar-25	
1919	**211**		177	May-12	

Year	Maximum Instantaneous Discharge (m³/s)	Date	Maximum Daily Discharge (m³/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m³/s)
1920	**1,330**		1,120	May-10	
1921	**289**		243	Apr-18	
1922	**169**		142	May-4	
1923	1,220	Jun-3	1,130	Jun-3	
1924	178	Jul-3	176	Jul-3	
1925	328	Apr-9	326	Apr-9	
1926	**816**		***685***	Sep-12	
1927	**870**		731	Apr-15	
1928	1,060	Jun-9	878	Jun-10	544
1929	1,010	Jun-5	818	Jun-5	
1930	**156**		131	Jun-4	
1931	**253**		***213***	Jul-7	
1932	**1,390**		***1,160***	Jun-4	
1933	-	-	-	-	-
1934	-	-	-	-	-
1935	**281**		***236***	Jul-3	
1936	**509**		***428***	Apr-19	
1937	**199**		***167***	Jun-17	
1938	**385**		***324***	Jul-4	
1939	**773**		***650***	Jun-19	
1940	**295**		***248***	Apr-18	
1941	**192**		***161***	Aug-27	
1942	**702**		***590***	Jul-14	
1943	**709**		***596***	Apr-12	
1944	**748**		***628***	Aug-2	
1945	**305**		***256***	May-28	
1946	**400**		***336***	Jun-10	
1947	**717**		***603***	May-12	
1948	**909**		***764***	May-10	
1949	**99**		***83***	Apr-13	
1950	**309**		***260***	Jun-17	
1951	**502**		***422***	Sep-2	
1952	**1,360**		***1,200***	Jun-25	
1953	**816**		***685***	Jun-5	
1954	**1,530**		***1,360***	Aug-27	
1955	**453**		***381***	Apr-8	
1956	**381**		***320***	Apr-14	
1957	**149**		***125***	Apr-19	
1958	**339**		***284***	Apr-12	

Year	Maximum Instantaneous Discharge (m³/s)	Date	Maximum Daily Discharge (m³/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m³/s)
1959	507	Jun-29	481	Jun-29	
1960	**388**		326	Mar-28	
1961	139	May-30	133	May-30	
1962	**109**		91	Apr-17	
1963	**200**		168	Jul-28	
1964	**566**		476	May-9	
1965	742	Jun-20	671	Jun-20	
1966	**543**		456	Jul-5	
1967	680	Jun-2	595	Jun-2	
1968	**156**		131	Jun-11	
1969	**765**		643	Jul-8	
1970	883	Jun-18	801	Jun-18	
1971	**883**		742	Apr-16	
1972	648	Jun-27	614	Jun-27	
1973	436	Apr-4	286	Apr-4	
1974	773	Apr-16	677	Apr-21	450
1975	**397**		334	Apr-22	
1976	202	Apr-11	144	Aug-12	138
1977	**193**		162	Jun-1	
1978	220	Jun-10	205	Jun-8	197
1979	**146**		123	Apr-25	
1980	282	Jun-7	276	Jun-7	
1981	786	Aug-1	673	Aug-2	669
1982	500	Jul-8	465	Jul-8	
1983	**267**		*225*	Apr-28	
1984	**178**		*150*	Jun-12	
1985	**322**		*271*	Sep-15	
1986	**874**		*734*	Jul-21	
1987	**200**		*168*	Apr-7	
1988	**151**		*127*	Aug-21	
1989	**339**		*285*	Apr-15	
1990	**1,030**		*864*	Jun-4	
1991	**374**		*315*	Jul-1	
1992	**464**		*390*	Jun-17	
1993	**358**		*301*	Apr-6	
1994	**302**		*254*	Jun-9	
1995	**557**		*468*	Jun-9	
1996	**789**		*663*	Apr-11	
1997	**759**		*637*	Apr-19	

Year	Maximum Instantaneous Discharge (m³/s)	Date	Maximum Daily Discharge (m³/s)	Date	Daily Discharge on Date of Maximum Instantaneous Discharge (m³/s)
1998	**499**		*419*	Jul-7	
1999	**919**		*772*	Jul-18	
2000	**389**		*327*	Jul-14	
2001	**176**		*148*	Aug-1	
2002	**159**		*133*	Jun-19	
2003	**533**		*448*	Apr-28	
2004	**222**		*186*	Jul-8	
2005	**1,830**		*1,540*	Jun-21	
2006	**305**		*256*	Jun-19	
2007	**754**		*634*	Jun-20	
2008	**841**		*706*	Jun-14	
2009	**351**		*295*	Apr-14	
2010	**354**		*298*	Jun-13	
2011	**724**		*608*	May-30	
2012	**585**		*492*	Jun-9	
2013	**1,780**		*1,500*	Jun-23	
2014	**545**		*458*	Jun-22	
2015	**157**		*132*	Mar-17	
2016	**281**		*236*	Jul-18	
2017	**395**		*332*	Jun-14	
2018	**1,160**		*972*	Apr-24	

Notes:

1. The 1915, 1952 and 1954 instantaneous peak discharges (bolded) are historic flood peaks estimated from highwater mark elevations by Alberta Environment and summarized in Matrix (2007).
2. The bolded and italic daily values (1912-1915, 1926, and 1931-1958) were estimated from the data for Red Deer River at Red Deer (WSC Station 05CC002).
3. The 1916-1925, 1927-1930 and 1959-1982 data are from the pre-regulation records for Red Deer River at Drumheller (WSC Station 05CE001).
4. The 1983-2018 data (shown in italic) are from the results of flow naturalization.
5. The bolded and underlined values are based on Q_i=1.19Q_d.

The 1915 event with an instantaneous peak discharge of 2,020 m³/s is the largest event, which is followed by three slightly smaller events: 2005, 2013 and 1954. As noted by previous studies (e.g. Matrix 2007), the 1901 flood event was a larger event, but its magnitude is unknown. **Table 16** summarizes the statistical parameters of the natural/naturalized instantaneous peak flow data set.

Table 16: Summary of statistical parameters of natural/naturalized annual instantaneous peak flow series for Red Deer River at Drumheller

Parameter	Natural/Naturalized Flood Series 1912-2018
Years of record	105
Mean (m^3/s)	565
Median (m^3/s)	453
Standard deviation (m^3/s)	398
Coefficient of variation	0.705
Skew coefficient (minimum, maximum, actual)	1.41, 1.71, 1.37

Each of the frequency distributions in the adopted suite were fitted to the instantaneous flood peaks shown in **Table 15**. The goodness of fit analysis (K-S test and least squares method) was undertaken for each distribution and the results are summarized in **Table 17**.

Table 17: Goodness-of-fit comparison for probability distributions applied to natural/naturalized annual peaks for Red Deer River at Drumheller

Distribution	D_n	Normalized *SSE* (Q_{pm} = 565 m^3/s)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.137	0.253	9	9	9
Log-normal(LN)	0.093	0.135	8	8	8
Three parameter log-normal (LN3)	0.083	0.092	2	3	2
Pearson III (P3)	0.068	0.071	1	1	1
Log-Pearson III (LP3)	0.092	0.128	6	6	6
Gumbel (G)	0.091	0.110	5	5	5
Generalized extreme value (GEV)	0.088	0.098	3	4	4
Weibull (W)	0.090	0.085	4	2	3
Bulletin 17C	0.092	0.128	6	6	6

The P3 distribution produces the smallest D_n and *SSE* value; so it is ranked the best in the combined ranking. The LN3 distribution is ranked the second and is nearly identical to the P3. The Weibull, GEV and Gumbel curves are quite similar. Their middle parts fit the data reasonably well, but they are not as good as the P3 curve in their lower and upper tails. The LP3 and Bulletin 17C curves are identical, and they are very close to LN. The lower and middle parts of these three curves fit the data well, but they predict noticeably higher peak discharges for long return periods. Although they are ranked low, their D_n and *SSE* values are not significantly higher than P3. **Figure 35** shows a comparison of the P3, Weibull and LP3 curves for the natural/naturalized flood peaks of Red Deer River at Drumheller, while the other evaluated curves are shown graphically in **Appendix A**.

From a visual inspection of **Figure 35**, it is clear that the Weibull curve does not fit the data as well as the other two. The LP3 curve provides the best fit for the data points at the shorter return periods. Its middle part, between 2 and 20-year return periods, fits the data as well as the P3. The two curves diverge when the return period exceeds about 20 years. The 100 and 1000-year values from the LP3 curve are 2,260 and 3,810 m^3/s – about 21% and 47% higher than the values from the P3 curve respectively. While the P3 curve goes through the point for the largest event (1915), the LP3 appears to fit the other three largest events (2005, 2013 and 1954) better. Note that the 1915 peak discharge was estimated from a highwater mark elevation, and it is only 10% higher than the 2005 peak. As noted earlier, the 1901 flood event was larger than the 1915 event, although its magnitude is unknown. To be conservative, it is recommended that the LP3 be adopted for natural/naturalized flood peaks of Red Deer River at Drumheller.

The adopted LP3 curve with 95% confidence limits is shown in **Figure 36**.

Regulated Flood Peaks

Figure 37 and **Table 18** show the regulated annual peak flow series for Red Deer River at Drumheller (1912-2018). As described in Section 3.2, the 1912-2016 maximum daily discharges were based on the simulated flow regulation, while the 2017 and 2018 values were estimated from the WSC gauge data based on the relationship of regulated versus gauged data, as shown in **Figure 14**. The ratio of post-regulation instantaneous to daily discharge of 1.09 (**Figure 33**) was applied to the maximum daily discharges to estimate the maximum instantaneous discharges where needed.

Table 18: Annual peak discharges of regulated flows for Red Deer River at Drumheller

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
1912	**449**	412	Jul-11
1913	**555**	509	Jun-29
1914	**256**	235	Jul-7
1915	**1070**	982	Jun-30
1916	**686**	629	Sep-5
1917	**754**	692	May-21
1918	**308**	283	Mar-25
1919	**187**	172	May-12
1920	**858**	787	May-10
1921	**230**	211	Jun-4
1922	**182**	167	Apr-29
1923	**520**	477	Jun-3
1924	**172**	158	Sep-13
1925	**301**	276	Apr-18
1926	**447**	410	Sep-14
1927	**731**	671	Apr-15

Year	Maximum Instantaneous Discharge (m³/s)	Maximum Daily Discharge (m³/s)	Date
1928	**584**	536	Jul-1
1929	**396**	363	Jun-8
1930	**287**	263	Jun-6
1931	**173**	159	Jul-8
1932	**471**	432	Jun-5
1933	**184**	169	May-20
1934	**300**	275	Jan-0
1935	**181**	166	Jun-19
1936	**135**	124	Jul-5
1937	**242**	222	Jun-19
1938	**237**	217	Jul-5
1939	**433**	397	Jun-20
1940	**190**	174	Jul-15
1941	**428**	393	Apr-12
1942	**390**	358	Jul-15
1943	**184**	169	Jul-3
1944	**463**	425	Aug-3
1945	**213**	195	May-13
1946	**377**	346	Apr-27
1947	**233**	214	Jun-14
1948	**446**	409	May-26
1949	**112**	103	Sep-2
1950	**411**	377	Apr-9
1951	**371**	340	Sep-2
1952	**498**	457	Jul-2
1953	**465**	427	Jun-7
1954	**851**	781	Aug-29
1955	**211**	194	May-30
1956	**276**	253	Apr-14
1957	**125**	115	Jun-29
1958	**267**	245	Mar-28
1959	**337**	309	Jun-29
1960	**292**	268	Mar-30
1961	**103**	95	Jun-13
1962	**125**	115	Apr-17
1963	**147**	135	Jul-22
1964	**383**	351	Jun-22
1965	**627**	575	Apr-14
1966	**458**	420	Jul-6

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
1967	**378**	347	Jun-2
1968	**110**	101	Jul-25
1969	**550**	505	Apr-11
1970	**489**	449	Jun-18
1971	**734**	673	Apr-14
1972	**502**	461	Jun-30
1973	**330**	303	Apr-4
1974	**766**	703	Apr-21
1975	**289**	265	Apr-22
1976	**168**	154	Apr-12
1977	**177**	162	Jun-1
1978	**242**	222	Mar-30
1979	**158**	145	Apr-25
1980	**283**	260	Jun-9
1981	**608**	558	Aug-2
1982	**669**	614	Jul-8
1983	**237**	217	Jul-7
1984	**122**	112	Jun-13
1985	**286**	262	Sep-15
1986	**678**	622	Jul-21
1987	**179**	164	Apr-7
1988	**134**	123	Aug-21
1989	**318**	292	Apr-15
1990	**726**	666	Jul-6
1991	**316**	290	Jul-9
1992	**318**	292	Jun-17
1993	**330**	303	Apr-6
1994	**193**	177	Apr-2
1995	**412**	378	Jun-10
1996	**681**	625	Apr-11
1997	**677**	621	Apr-19
1998	**438**	402	Jul-7
1999	**635**	583	Jul-15
2000	**349**	320	Jul-14
2001	**150**	138	Aug-1
2002	**118**	108	Apr-26
2003	**376**	345	Apr-12
2004	**189**	173	Jul-8
2005	**1170**	1070	Jun-21

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
2006	**235**	216	Jun-20
2007	**610**	560	May-8
2008	**540**	495	Jun-13
2009	**287**	263	Apr-14
2010	**263**	241	Jun-13
2011	**572**	525	Apr-29
2012	**465**	427	Jun-14
2013	**1180**	1080	Jun-24
2014	**491**	450	Jun-22
2015	**186**	171	Mar-17
2016	**122**	112	Aug-12
2017	**253**	**232**	Jun-14
2018	**799**	**733**	Apr-24

Notes:

1. Maximum daily discharges for 1912-2016 are from modelling results for flow regulation.
2. The 2017 and 2018 maximum daily discharges (bolded) are the WSC gauged values multiplied by 0.94 based on the relationship shown in **Figure 14**.
3. The bolded and underlined values are based on Q_i=1.09Q_d.

The 1915 event under the regulated conditions becomes the third largest event with a simulated peak discharge smaller than those for the 2013 and 2005 events; however, the peak discharges of these three events are very similar. **Table 19** summarizes the statistical parameters of the regulated instantaneous peak flow data set.

Table 19: Summary of statistical parameters of regulated annual instantaneous peak flow series for Red Deer River at Drumheller

Parameter	Regulated Flood Series 1912-2018
Years of record	107
Mean (m^3/s)	391
Median (m^3/s)	330
Standard deviation (m^3/s)	232
Coefficient of variation	0.595
Skew coefficient (minimum, maximum, actual)	1.19, 1.61, 1.19

Each of the frequency distributions in the adopted suite were fitted to the instantaneous flood peaks shown in **Table 18**. The goodness-of-fit analysis results are compared in **Table 20**. Similar to the analysis for the naturalized flows, the P3 and LN3 are nearly identical and ranked the best in the combined ranking, followed by the GEV and LP3 (which is identical to the Bulletin 17C curve). While the other curves are shown in **Appendix A**, the P3, GEV and LP3 are compared in **Figure 38**.

Table 20: Goodness-of-fit comparison for probability distributions applied to regulated annual peaks for Red Deer River at Drumheller

Distribution	D_n	Normalized *SSE* (Q_{pm} = 391 m^3/s)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.109	0.188	9	9	9
Log-normal(LN)	0.061	0.096	2	8	5
Three parameter log-normal (LN3)	0.061	0.073	2	2	2
Pearson III (P3)	0.052	0.061	1	1	1
Log-Pearson III (LP3)	0.061	0.094	2	6	3
Gumbel (G)	0.064	0.077	7	4	6
Generalized extreme value (GEV)	0.062	0.076	5	3	3
Weibull (W)	0.078	0.080	8	5	8
Bulletin 17C	0.062	0.094	5	6	6

As shown in **Figure 38**, the P3 and GEV curves are very similar, while the LP3 provides noticeably higher flood peak estimates for return periods longer than 20 years. The LP3 curve fits the data points better at the lower tail. It also fits the second and third highest peaks (2005 and 1915). The other two curves fit the 2013 flood peak, which is the highest in the data series; but they would underpredict the 1915 and 2005 peaks. Note that the 2013 and 2005 peak discharges are nearly the same. To be conservative, and be consistent with the analysis for the naturalized flood peaks, the LP3 curve was selected in this study to provide flood frequency estimates for regulated flows of Red Deer River at Drumheller. The selected LP3 curve with 95% confidence limits is shown in **Figure 39**.

4.6.3 Flood Frequency Analysis for Other Sites on Red Deer River

Table 21 summarizes all of the sites on the Red Deer River where flood frequency estimates are required by the TOR of this study. The table includes the locations of the ungauged sites relative to WSC Station 05CE001 (Red Deer River at Drumheller), total drainage areas and tributary areas between each of the sites and the Drumheller station. Note that the drainage area for WSC Station 05CE001 is 24,900 km^2.

Table 21: Summary of relative locations and drainage areas of flood frequency estimate sites on Red Deer River

Site on Red Deer River	Location Relative to WSC Station 05CE001 (km) (1)	Drainage Area (km^2)	Tributary Area between Site and 05CE001 (km^2)		
			Total Area	Gauged Area	Ungauged Area
above Kneehills Creek	-10	21,100	3,800	3,600 (2)	200
above Michichi Creek	-0.6	23,700	1,200	1,170 (3)	30
at Drumheller (05CE001)	0	24,900	0	0	0
below Rosebud River	8	29,200	4,300	3,570 (4)	730
below Willow Creek	17	29,630	4,730	3,570 (4)	1,160

Notes:

1. Negative and positive signs indicating sites located upstream and downstream of WSC Station 05CE001, respectively.
2. WSC Station 05CE002 (Kneehills Creek near Drumheller) plus 05CE020 (Michichi Creek at Drumheller)
3. WSC Station 05CE020 (Michichi Creek at Drumheller)
4. WSC Station 05CE005 (Rosebud River at Redland)

Regulated daily flows for Red Deer River above Kneehills Creek were estimated from the regulated flows at Drumheller (WSC Station 05CE001) by subtracting gauged flows from Kneehills Creek (WSC Station 05CE002) and Michichi Creek (WSC Station 05CE020), and flows from 200 km^2 of ungauged area, which were estimated by prorating Michichi Creek flows by the drainage area ratio. Regulated annual maximum daily discharges were then derived from the daily flow estimates for the 1979-2016 period (when the flow data are available for Michichi Creek at Drumheller). These estimates are compared with the regulated maximum daily discharges for Red Deer River at Drumheller in **Figure 40**. The comparison indicates that the regulated flood peak discharges for Red Deer River above Kneehills Creek would be about 4% smaller than those at Drumheller.

Similarly, flows for Red Deer River above Michichi Creek were estimated by subtracting gauged flows for Michichi Creek at Drumheller from Red Deer River flows at Drumheller. Red Deer River flows below Rosebud River were estimated as flows at Drumheller plus Rosebud River flows at Redland (WSC Station 05CE005) multiplied by the ratio of the total area (4300 km^2) against the gauged area (3570 km^2) listed in **Table 21**. Flows below Willow Creek were estimated by further adding tributary inflows from the ungauged Willow Creek sub-basin which were estimated by prorating Michichi Creek flows by the drainage area ratio. The estimated regulated annual peak discharges for these three sites are compared with those for Red Deer River at Drumheller in **Figure 41**, **Figure 42** and **Figure 43**.

The comparisons in **Figures 39** through **42** show that the differences between regulated peak discharges for each of the ungauged sites and for 05CE001 are between -4% and +3%, which are small. The differences are summarized in **Table 22**.

The differences in naturalized peak discharges between the ungauged sites and WSC Station 05CE001 are also shown in **Table 22**. For naturalized flows, the differences are smaller because naturalized Red Deer River peak discharges upstream of these tributaries are generally greater than the regulated discharges, while tributary inflows remain the same and hence have smaller effects on the total peak discharges in the Red Deer River.

Table 22: Summary of differences between annual peak discharges for ungauged Red Deer River sites and for WSC Station 05CE001

Site on Red Deer River	Difference as Percent of WSC Station 05CE001 Value		
	Drainage Area	Regulated Annual Peak Discharge	Naturalized Annual Peak Discharge
above Kneehills Creek	-15%	-4%	-3%
above Michichi Creek	-5%	-1%	-1%
below Rosebud River	+17%	+3%	+2%
below Willow Creek	+19%	+3%	+2%

The subject tributaries (Kneehills Creek, Michichi Creek, Rosebud River and Willow Creek) have only small effects on Red Deer River peak discharges, under either regulated or naturalized conditions, because they respond to different hydrologic processes. As discussed earlier, high flows on these tributaries mostly occur in March and April while the Red Deer River generally peaks later. As these differences are negligible, it is recommended that the flood frequency estimates for Red Deer River at Drumheller (WSC Station 05CE001) be adopted for all of the four ungauged sites (Red Deer River above Kneehills Creek, above Michichi Creek, below Rosebud River and below Willow Creek).

4.6.4 Synthetic Flood Hydrograph Routing

As part of the Upper Red Deer and Red Deer River Hazard Study, Golder (2018) developed a set of synthetic hourly inflow flood hydrographs for Gleniffer Reservoir for a range of return periods. By routing the hydrographs through Gleniffer Reservoir based on specified operating rules, flood frequency estimates were developed for a number of sites on the Red Deer River from Dickson Dam through the city of Red Deer. The same approach (synthetic flood hydrograph routing) was undertaken as an alternative method to develop flood frequency estimates for Red Deer River at Drumheller under the regulated flow conditions. This method can be used to account for more realistic operations of the dam, in response to inflow floods with different magnitudes, based on a single set of operating rules; however, it has the disadvantage of having to assume corresponding downstream tributary inflows.

In the synthetic flood hydrograph routing analysis, Golder (2018) assumed that the Little Red Deer River responded to the same storm event as the upper Red Deer River (i.e. the concurrent flood on the Little Red Deer River had the same return period as the inflow flood for Gleniffer Reservoir), while downstream tributaries (e.g. the Blindman River) carried 2-year flood flows. This assumption appears to be reasonable because the Little Red Deer River basin lies in parallel with the Red Deer River basin above Gleniffer Reservoir and has similar physiographic and climate conditions, while the tributary areas downstream of Dickson Dam are affected by different hydro-climatic processes.

Routed synthetic hourly flood hydrographs for Red Deer River at Highway 11 were provided by AEP for this study. Those hydrographs were routed from Highway 11 to Red Deer River at Drumheller (WSC Station 05CE001) using an hourly time step in HEC-ResSim. For this sub-reach, the SSARR routing travel times were estimated by prorating the travel times from Red Deer to Drumheller by river lengths. As discussed in Section 4.6.3, tributary flows contributing to the Red Deer River are driven by different hydrologic processes and have insignificant effects on flood flows in the Red Deer River at Drumheller. To be consistent with Golder (2018), it was assumed that, for all the synthetic flood events, tributary areas (including the gauged Threehills, Kneehills and Michichi creek basins and ungauged areas) contributed 2-year flows to this Red Deer River sub-reach. The input and routed hydrographs are shown in **Figure 44**.

Peak discharges extracted from the routed hydrographs for Red Deer River at Drumheller are compared with peak discharges from the flood frequency analyses for natural/naturalized and regulated flows in **Figure 45**. The peak discharges from the synthetic flood routing are comparable with the estimates from the regulated flood frequency analysis for return periods shorter than 20 years, but they are noticeably higher for longer return periods. This is consistent with the observations of Golder (2018).

One of the fundamental assumptions for flood frequency analysis is that flood peaks are natural, random events that can be described by a particular probability distribution. This assumption is violated if human intervention (such as operations at a dam) imposes significant effects on flood flows. Red Deer River regulated flows at Drumheller are dominated by discharges from Dickson Dam. As described by Golder (2018), operating objectives and rules for Dickson Dam are different when the reservoir level is within different ranges (or storage zones), and the discharge capacity of the dam changes abruptly when the reservoir level changes from one storage zone to the other (e.g. when the reservoir level rises from below to above the spillway crest elevation). As such, operations of the dam tend to result in greater attenuation of flood peaks for smaller events than for extreme events. A full range of inflow flood events may result in a inhomogeneous peak outflow data series that cannot be represented by a single frequency curve. The regulated flood frequency curve for Red Deer River at Drumheller shown in **Figure 45** is based on one set of operating rules and a limited range of inflows. While the frequency curve is expected to be representative for shorter return periods, extrapolating the curve to predict peak discharges for longer return period is subject to increasing uncertainties or may not be appropriate. Under such circumstances, flood frequency estimates from routing of synthetic inflow hydrographs would be more appropriate because the inflow flood frequency estimates were developed from natural flow data and dam operations for large inflow events were simulated.

As shown in **Figure 45**, the peak discharge frequencies from the synthetic flood routing converge to the naturalized flood frequency curve at the upper part, which can be reasonably explained as attenuation of flood peaks through Gleniffer Reservoir would become less significant for larger inflow events. For very large floods (e.g. the 750 and 1000-year floods), the magnitude of regulated peak discharges could be the same as the naturalized flood peaks. The 1000-year flood peak from the synthetic flow routing is about 3% higher than that from the naturalized flood frequency curve. This relatively small difference could be attributed to many reasons, including inherent uncertainties in flow naturalization, flood frequency analysis, development of synthetic floods and routing. Particularly, as noted by Golder (2018), the synthetic flood hydrographs were developed based on some conservative assumptions that would likely produce high peak discharges downstream of Dickson Dam, including the assumption of concurrent storm events for the Little Red Deer River basin and using the historical upper limit as the starting reservoir level for the routing analysis. Nevertheless, the difference between the 1000-year flood peak estimates from the routed synthetic hydrograph and from the naturalized flood frequency curve is negligible, in comparison with those inherent uncertainties in the analyses.

Accordingly, it is recommended that, for the regulated flow condition, the regulated flood frequency curve presented in Section 4.6.2 be used to determine peak discharges for return periods up to 20 years, and the results from the synthetic flood routing be used for longer return periods, while the regulated 1000-year flood peak is assumed to be the same as the naturalized 1000-year value (**Figure 45**).

5 SUMMARY OF FLOOD FREQUENCY ESTIMATES

5.1 Recommended Flood Frequency Estimates

Tables 23 through **28** provide summaries of the recommended flood frequency estimates for the study sites as required by the TOR. The tables also show the 95% confidence limits where applicable. The flood frequency estimates are intended to support hydraulic modelling and flood inundation mapping of the Drumheller River Hazard Study.

5.1.1 Red Deer River near Drumheller

The study requires flood frequency estimates for the Red Deer River at the following five locations:

- Red Deer River above Kneehills Creek
- Red Deer River above Michichi Creek
- Red Deer River at Drumheller (WSC Station No 05CE001)
- Red Deer River below Rosebud River
- Red Deer River below Willow Creek

It is recommended that

- the log-Pearson type III distribution be adopted for Red Deer River at Drumheller (WSC Station 05CE001) for the naturalized flow condition;
- for the regulated flow condition, the log-Pearson type III curve based on the flow regulation results (Method 1) be used to estimate flood peaks at Drumheller for return periods up to 20 years; the synthetic flood routing (Method 2) results be used for return periods between 20 and 1000 years; and the 1000-year peak discharge be assumed to be the same as for the naturalized flow condition; and
- the flood frequency estimates for Red Deer River at Drumheller be also applied to the other four sites on the Red Deer River in the Drumheller area.

The recommended flood frequency estimates for the Red Deer River study sites in the Drumheller area for the naturalized flow condition are summarized in **Table 23.** The estimates for the regulated flow condition are shown in **Table 24**, including the results from the two methods (Method 1 and Method 2) and the recommended values as described above. As stated, the estimates are applicable to all the five sites of interest as effects of tributary inflows were determined to be negligible.

Table 23: Flood frequency estimates for naturalized flows of Red Deer River near Drumheller

Return Period (Years)	Annual Probability of Exceedance (%)	Naturalized Peak Instantaneous Discharge (m^3/s)	
		Value	Upper 95% Limit Lower 95% Limit
1000	0.10	3,820	5,150 2,990
750	0.13	3,600	4,820 2,830
500	0.20	3,300	4,380 2,620
350	0.29	3,050	4,020 2,440
200	0.50	2,680	3,480 2,170
100	1.0	2,260	2,870 1,850
75	1.3	2,090	2,640 1,730
50	2.0	1,870	2,330 1,560
35	2.9	1,690	2,080 1,420
20	5.0	1,410	1,710 1,200
10	10	1,100	1,290 951
5	20	807	929 712
2	50	448	502 400

Notes:

1. The estimates are applicable for Red Deer River at Drumheller (WSC Station 05CE001), above Kneehills Creek, above Michichi Creek, below Rosebud River and below Willow Creek.

Table 24: Flood frequency estimates for regulated flows of Red Deer River near Drumheller

Return Period (Years)	Annual Probability of Exceedance (%)	Regulated Peak Instantaneous Discharge (m^3/s) (1)			
		Method 1 (2)		Method 2 Value (3)	Recommended Value
		Value	Upper 95% Limit Lower 95% Limit		
1000	0.10	2,020	2,600 1,650	3,940	3,820 (4)
750	0.13	1,920	2,460 1,580	3,580	3,580 (5)
500	0.20	1,790	2,270 1,470	3,170	3,170 (5)
350	0.29	1,670	2,100 1,390	2,900	2,900 (5)
200	0.50	1,500	1,860 1,250	2,450	2,450 (5)
100	1.0	1,300	1,580 1,100	1,850	1,850 (5)
75	1.3	1,210	1,470 1,040	1,670	1,670 (5)
50	2.0	1,100	1,330 949	1,430	1,430 (5)
35	2.9	1,010	1,200 874	1,240	1,240 (5)
20	5.0	869	1,020 760	971	869 (6)
10	10	702	805 624	709	702 (6)
5	20	542	609 488	505	542 (6)
2	50	330	363 300	386	330 (6)

Notes:

1. The estimates are applicable for Red Deer River at Drumheller (WSC Station 05CE001), above Kneehills Creek, above Michichi Creek, below Rosebud River and below Willow Creek.
2. Method 1 is the frequency analysis of regulated instantaneous peak discharges for Red Deer River at Drumheller presented in Section 4.6.2.
3. Method 2 is the synthetic flood hydrograph routing from Highway 11 to Drumheller described in Section 4.6.4.
4. Equal to the 1000-year peak discharge for the naturalized flow condition.
5. Value from Method 2.
6. Value from Method 1.

5.1.2 Kneehills Creek near Drumheller

The recommended flood frequency estimates for Kneehills Creek near Drumheller (WSC Station 05CE002) are presented in **Table 25**. They are based on the Pearson Type III distribution and 72 years of gauge data between 1921 and 2018.

Table 25: Flood frequency estimates for Kneehills Creek near Drumheller

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	
		Value	Upper 95% Limit Lower 95% Limit
1000	0.10	286	327 255
750	0.13	274	313 244
500	0.20	256	292 228
350	0.29	241	275 215
200	0.50	216	246 193
100	1.0	186	211 166
75	1.3	173	197 155
50	2.0	155	176 139
35	2.9	140	159 126
20	5.0	116	132 104
10	10	87	99 77
5	20	58	67 50
2	50	22	30 14

5.1.3 Michichi Creek at Drumheller

The flood frequency estimates for Michichi Creek at Drumheller (WSC Station 05CE020) are presented in **Table 26**. They are based on the log-Pearson Type III distribution and 38 years of gauge data from 1979 to 2018.

Table 26: Flood frequency estimates for Michichi Creek at Drumheller

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	
		Value	Upper 95% Limit Lower 95% Limit
1000	0.10	103	125 89
750	0.13	99	119 85
500	0.20	93	112 80
350	0.29	87	105 75
200	0.50	79	95 68
100	1.0	68	82 59
75	1.3	64	77 55
50	2.0	58	69 50
35	2.9	52	62 45
20	5.0	44	52 38
10	10	33	40 29
5	20	23	28 19
2	50	10	14 5

5.1.4 Rosebud River at the Mouth

The flood frequency estimates for Rosebud River at the mouth presented in **Table 27** were derived from a log-Normal frequency curve for Rosebud River at Redland (WSC Station 05CE005), which was based on 51 years of flow data over the 1967-2018 period.

Table 27: Flood frequency estimates for Rosebud River at the mouth

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	
		Value	Upper 95% Limit Lower 95% Limit
1000	0.10	641	1,260 388
750	0.13	586	1,140 359
500	0.20	515	975 321
350	0.29	458	848 289
200	0.50	377	675 244
100	1.0	292	499 195
75	1.3	260	437 176
50	2.0	220	359 152
35	2.9	188	300 132
20	5.0	145	220 104
10	10	99	143 74
5	20	63	86 49
2	50	27	34 21

5.1.5 Willow Creek at the Mouth

The flood frequency estimates for Willow Creek at the mouth presented in **Table 28**. They are based on the regional flood frequency relationships.

Table 28: Flood frequency estimates for Willow Creek at the mouth

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)
1000	0.10	66
750	0.13	62
500	0.13	58
350	0.29	54
200	0.20	49
100	1.0	41
75	0.29	40
50	2.0	35
35	0.50	31
20	5	26
10	1.0	19
5	20	13
2	1.3	5

Notes:

1. The 95% confidence limits are not available as the flood frequency estimates are based on a regional analysis instead of a single theoretical distribution.

5.2 Uncertainty and Confidence

There are three main contributions to the uncertainty that is inherent in the frequency curves defined above – errors in reported flood peaks, errors in the flow naturalization, and errors associated with the application of standard statistical procedures to imperfect samples of populations.

With respect to flood peaks reported by WSC, most errors are typically expected during the highest flow events, which also are of the most interest. For the most part, however, these types of errors, unless they are systematic in one direction, tend to balance out statistically and do not necessarily contribute to unreliable estimates of the ensemble mean and variance. However, if errors are more pronounced in estimating the high flood peaks, the ensemble skewness may not be calculated properly and those statistical distributions that rely on the skewness may not properly represent the real parameters of the population. It is beyond the scope of this study to assess the reliability of each of the flood peaks reported by WSC, so the default position is to assume that all data reported by WSC are correct.

Errors in estimating flood peaks can also occur in the application of the flow naturalization procedure. Most of these errors are related to the lack of regional data and the calculation of differences between large flows that clearly contain uncertainties. In this study, the flow naturalization procedure was carried out using multiple approaches to check the simulation outcomes. While other methodologies may produce different results, it is unlikely that they would be any more defensible than those produced herein. Again, while there may be errors in individual numbers, the ensemble means and variances would still be representative of the general population.

Finally, the statistical procedures are imperfect. The number of data points in each of the flood series are quite large from a hydrologic perspective, and the mean and variance are estimated reasonably well. However, estimates of the sample skewness are necessary to properly extrapolate the frequency to longer return periods. Sample skewness at one station is usually thought to be an insufficient metric by which to define the skewness of the population, and the literature recommends that a blended skewness that reflects regional skewness values be adopted. However, the flow data series used in the present study include the longest records in the region; as such, introducing regional skewness would not improve the results. Moreover, there are no guidelines in Alberta for developing regional skew values.

The application of statistical procedures that demand year to year randomness, independence, and stationarity in the flood peaks may also be somewhat problematic. While stationarity appears not to be a problem, one could argue that no flood peaks are independent from each other due to year to year storage-related memory in large river basins and in regulated systems. Furthermore, with respect to the effects of regulation, it clearly could have an impact on year to year randomness. The difficulty is that no statistical method is sufficiently discrete to be able to differentiate statistically amenable data sets from those that are not, because of short record lengths. Therefore, while it may be difficult to demonstrate absolute year to year randomness, there is confidence that the data are sufficiently well behaved to apply the necessary statistical procedures.

The analysis presented in this report follows industry standards and is based on the best available information. The results are reasonable and adequate for the river hazard study. For return periods longer than 200 years, the estimates could be in considerable error, as shown by the confidence limits on each of the frequency plots. The estimates for the Red Deer River under the regulated condition could be subject to a higher level of uncertainty.

5.3 Comparison With Previous Studies

The present flood frequency estimates for Red Deer River at Drumheller (WSC Station No 05CE001), Kneehills Creek near Drumheller (WSC Station 05CE002), Michichi Creek at Drumheller (WSC Station 05CE020), and Rosebud River at the mouth are compared with the estimates available from previous studies in **Tables 29** through **32**. Previous estimates are not available for the other study sites.

The flood frequency estimates for Red Deer River at Drumheller are compared in **Table 29**. For the natural/naturalized flow condition, the present estimates are generally comparable with those from

Matrix (2007). The 50, 100 and 200-year values are higher than the estimates from two other earlier studies (AEP 1996 and AENV 1984), which were based on shorter periods of record. There are more variations among the estimates for the regulated flow condition as different studies were based on different assumptions. The current estimates are higher than the values from the previous studies for 100-year and longer return periods but lower for shorter return periods.

As shown in **Table 30**, the present estimates for Kneehills Creek near Drumheller are slightly higher than the previous estimates by NHC (2008), likely due to the inclusion of the record-high April 2018 event in the present analysis.

For Michichi Creek at Drumheller (**Table 31**), the current flood frequency estimates are generally consistent with the values from Matrix (2007). The values from AENV (1984) are lower. They were probably developed from a regional analysis as the gauge record for Michichi Creek were too short at that time to carry out a frequency analysis.

For Rosebud River at the mouth (**Table 32**), the current 500 and 1000-year estimates are noticeably lower than the values from Matrix (2007), which were based on a log-Pearson Type III curve for WSC Station 05CE005. As discussed in this report, using the log-Pearson Type III distribution for WSC Station 05CE005 would result in long-return-period values too high from a regional viewpoint. The estimates from AENV (1984) are also higher than the current estimates. It is not clear how the AENV estimates were developed; but they were based on shorter flow data series.

Table 29: Comparison with previous flood frequency estimates for Red Deer River at Drumheller

Return Period (Years)	Naturalized Peak Instantaneous Discharge (m^3/s)				Regulated Peak Instantaneous Discharge (m^3/s)			
	Present Study	Matrix (2007)	AEP (1996)	AENV (1984)	Present Study	Matrix (2007)	AEP (1996)	AENV (1984)
1000	3,820	3,970	-	-	3,820	3,570	-	-
750	3,600	-	-	-	3,580	-	-	-
500	3,300	3,400	-	-	3,170	3,000	-	-
350	3,050	-	-	-	2,900	-	-	-
200	2,680	-	2,070	2,288	2,450	-	1,840	1,651
100	2,260	2,290	1,840	2,033	1,850	1,189	1,640	1,472
75	2,090	-	-	-	1,670	-		
50	1,870	1,880	1,610	1,778	1,430	1,630	1,430	1,215
35	1,690	-	-		1,240	-	-	-
25	1,520	1,510	-	1,511	1,010	1,385	-	1,161
20	1,410	-	1,290	-	869	-	1,070	1,051
10	1,100	1,080	1,040	1,161	702	1,040	1,000	-
5	807	780	793	-	542	740	690	-
2	448	430	431	-	330	390	369	-

Table 30: Comparison with previous flood frequency estimates for Kneehills Creek near Drumheller

Return Period (Years)	Peak Instantaneous Discharge (m^3/s)	
	Present Study	NHC (2008)
1000	286	272
750	274	-
500	256	244
350	241	-
200	216	205
100	186	175
75	173	-
50	155	146
35	140	-
25	126	-
20	116	106
10	87	77
5	58	50
2	22	19

Table 31: Comparison with previous flood frequency estimates for Michichi Creek at Drumheller

Return Period (Years)	Peak Instantaneous Discharge (m^3/s)		
	Present Study	Matrix (2007)	AENV (1984)
1000	103	108	-
750	99	-	-
500	93	96	-
350	87	-	-
200	79	-	68
100	68	68	57
75	64	-	-
50	58	56	48
35	52	-	-
25	47	44	37
20	44	-	-
10	33	28.4	27
5	23	17.8	-
2	10	6.1	-

Table 32: Comparison with previous flood frequency estimates for Rosebud River at the mouth

Return Period (Years)	Peak Instantaneous Discharge (m^3/s)		
	Present Study	Matrix (2007)	AENV (1984)
1000	641	816	-
750	586	-	-
500	515	597	-
350	458	-	-
200	377	-	439
100	292	276	374
75	260	-	-
50	220	194	320
35	188	-	-
25	161	132	260
20	145	-	-
10	99	75	184
5	63	46	-
2	27	19.5	-

6 CLIMATE CHANGE COMMENTARY

This section provides a summary of a qualitative interpretation of climate and hydrologic projections obtained from the scientific literature that would be pertinent to evaluating future changes in flood hazards in the study area.

Current global climate models indicate that temperature will increase in the upper Red Deer River basin due to projected increases in CO_2 concentrations in the atmosphere. Increased temperatures in the winter months will likely results in smaller snow packs, earlier snowmelt runoff, higher winter flows as more winter precipitation falls as rain instead of snow, and lower summer flows due to reduced snow storage.

Martz et al. (2007) assessed effects of climate change on streamflow in the South Saskatchewan River basin, which includes the Red Deer River and other tributary sub-basins, using calibrated hydrologic models forced by selected down-scaled general circulation model (GCM) scenarios. Some of the key findings of the study are noted as follows:

- Temperature increases over the South Saskatchewan River basin could range from 1.5°C to 2.8°C for a projection period centred on 2050.
- The selected GCM models differ in their predictions of changes to annual precipitation, ranging from -3.8% (reduction) to +11.5% (increase), with the overall average of all models being a modest increase of +3.6%.
- Projected changes in annual natural streamflow volumes in the Red Deer River basin range from -32% to +13% with an average of -13%.

According to DFO (2013), annual precipitation over large basins in the Prairies is projected to generally increase; however, projections are more uncertain for the Saskatchewan River basin as both an increase and a decrease have been predicted. Higher precipitation is expected in winter compared to summer, and the type of precipitation is expected to change (e.g. more winter rain vs. snow). It is expected that there will be fewer precipitation events, but at higher intensity or more extreme weather events. During the summer months, streamflow volumes in the Saskatchewan river sub-basin could decrease by up to 50%.

Islam and Gan (2015) applied a physically based land surface scheme, the Modified Interaction Soil Biosphere Atmosphere (MISBA), to assess the future streamflow of the South Saskatchewan River basin (including the Red Deer River sub-basin) under combined impacts of climate change and El Niño Southern Oscillation (ENSO). Under climate projections alone or under the combined condition with ENSO, Red Deer River annual mean flows are projected to decrease. However, the mean spring (March to May) flows under climate projections alone are projected to increase by 2%, 9% and 9% in 2020s, 2050s and 2080s, respectively, while the mean summer (June to August) flows are projected to decrease. When climate change is combined with El Niño episodes, the spring flows are projected to decrease. On the other hand, they are projected to increase further when climate change is combined with La Niña episodes.

More recently, Gizaw (2017) assessed possible changes to extreme precipitation in the Red Deer River basin using six extreme climate indices based on two downscaled climate scenarios. The results suggest that more frequent and severe intensive storm events may impact the upper and middle Red Deer River basin, between May and August in 2050s and 2080s. While more frequent and severe intensive storm events tend to increase peak runoff discharges, it is difficult to predict their impacts on future flood risk in the Drumheller area. Higher temperature and less snowfall in winter would result in a higher snow line in the Rocky Mountains and increased snow-free area in the lower elevation bands of the Red Deer River basin, which tends to reduce the total runoff during a spring rain-on-snow event.

While temperature has been generally increasing over the last 100 years, the trend of changes in annual peak discharges of the Red Deer River appear to be different. **Figure 46** shows a downward trend for the naturalized peak discharges of Red Deer River at Drumheller (1915-2018), although the trend is statistically insignificant (a Mann-Kendall test indicated that the data have no trend). Similar observations were noted by Golder (2018) for Red Deer River at Red Deer: there is no clear evidence that the patterns in magnitude or timing of Red Deer River annual peak flows have changed significantly over the past hundred years.

Overall, there is insufficient information to be able to identify all the linkages between precipitation and runoff to make any forecasts about how climate change might affect riverine flood risks at Drumheller. This lines up with the conclusions of the Intergovernmental Panel on Climate Change – that at present there is low confidence in global climate model predictions of changes in flood magnitudes due to limited evidence (Jiménez et al., 2014). In general, increased precipitation may lead to higher flood peaks due to increased precipitation intensity but this will be mitigated by reduced snowpack and drier antecedent moisture conditions due to higher temperatures. Loss of tree cover and soil changes associated with beetle infestation, wildfires, and changing land use could also contribute to higher runoff volumes and peaks.

7 CONCLUSIONS

This report provides a summary of the available hydrometric data, as they pertain to flood peaks along the Red Deer River and its tributaries in the Drumheller area, for both natural and regulated conditions.

Naturalized and regulated flow series developed for the Red Deer River and Upper Red Deer River Hazard Studies (Golder, 2018) were routed from Red Deer to Drumheller, along with estimated tributary inflows (or gauge corrections). Naturalized and regulated annual peak flow series for Red Deer River at Drumheller between 1912 and 2018 were then derived and used to develop flood frequency estimates for the sites of interest along the Red Deer River in the Drumheller area. Routing of synthetic hourly flow hydrographs through the Red Deer River from Highway 11 to Drumheller was also performed as an alternative method to provide flood frequency estimates for the regulated condition. Based on a comparison of the routing results with the flood frequency analysis results for both naturalized and regulated flow conditions, it was recommended that, for the regulated flow scenario, the flood frequency curve for regulated flows be used to estimate flood peaks at Drumheller for return periods up to 20 years; the synthetic hydrograph routing results be used for return periods between 20 and 1000 years; and the 1000-year peak discharge be assumed to be equal to the estimate for the naturalized flow condition.

Flood frequency analyses were also performed for the sites of interest on Kneehills Creek, Michichi Creek, Rosebud River and Willow Creek.

The flood frequency analyses performed for this study were based on the most up-to-date data, and consistent with the Hydrologic and Hydraulic Guidelines for Flood Hazard Area Delineation by AENV (2008) and Guidelines on Flood Frequency Analysis by Alberta Transportation (AT, 2001). The results are reasonable when compared with the estimates available from previous studies.

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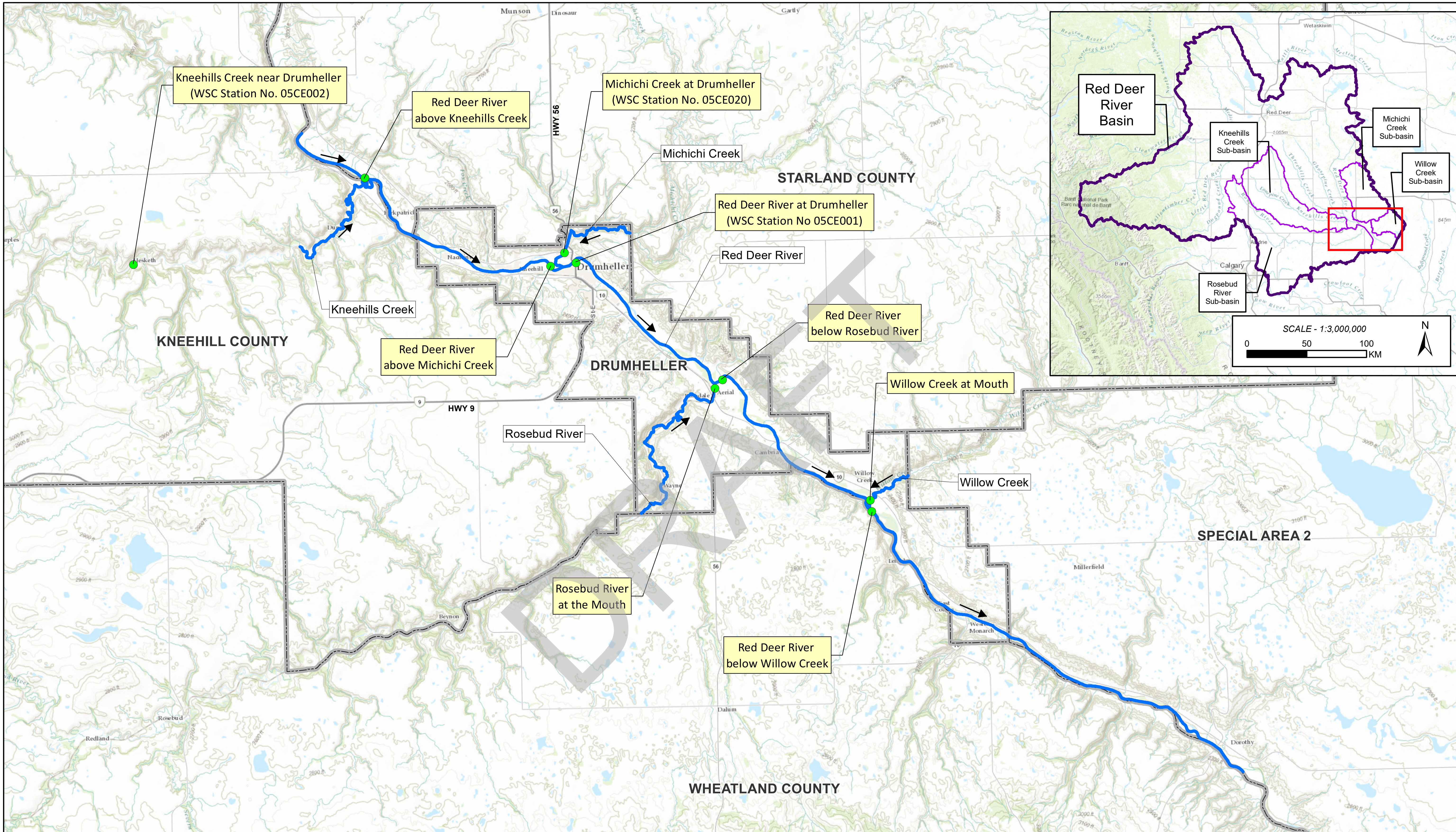
Figures



Flood Frequency Estimate Location
Study Reach
Municipal Boundary

Alberta

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DATA SOURCES: Basemap from Esri & NRCan.

SCALE - 1:150,000
0 2 4 6 KM

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES

Job: 1003877 | Date: 17-MAR-2020

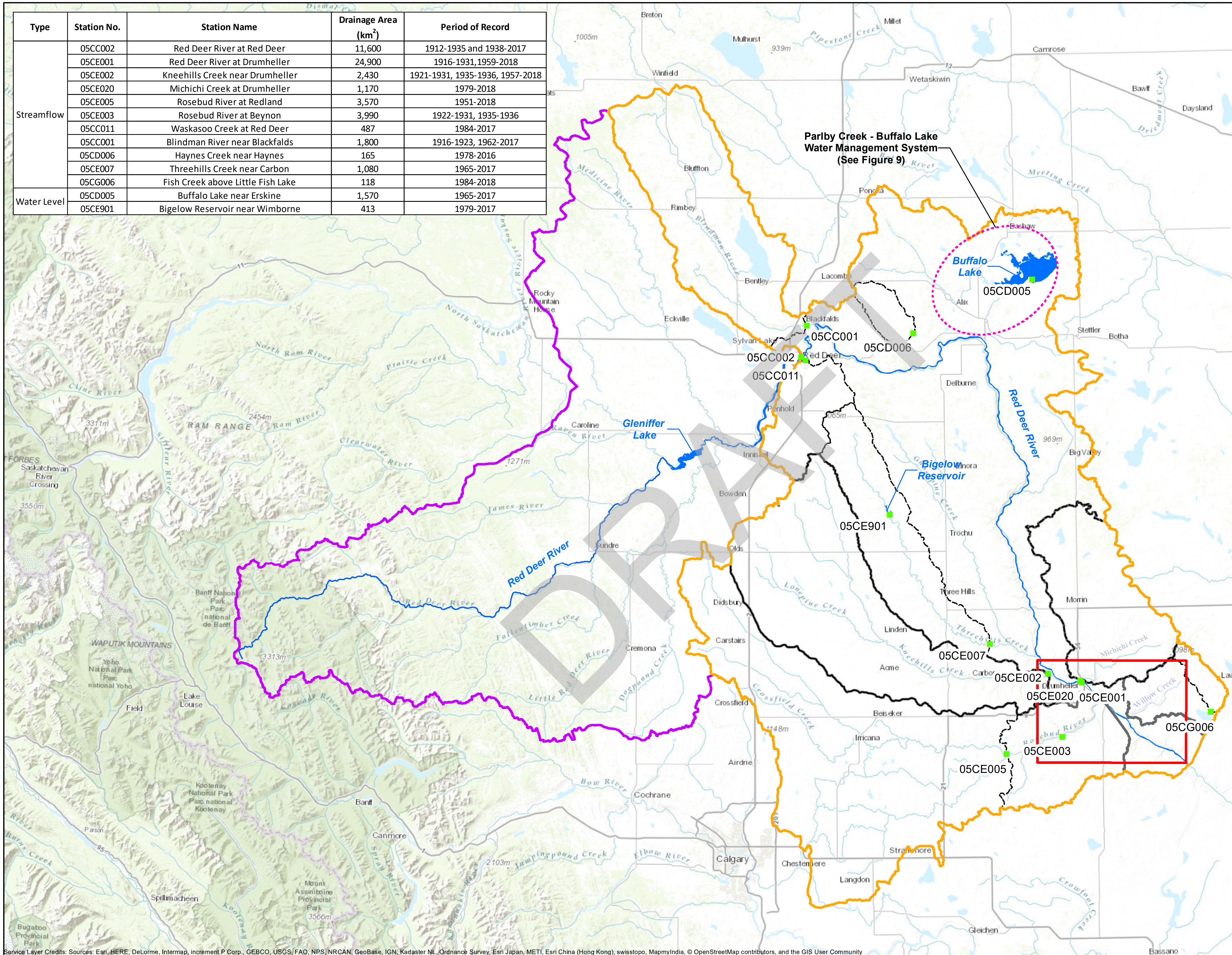
DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

RIVER HAZRD STUDY AREA AND FLOOD FREQUENCY ESTIMATE LOCATIONS

FIGURE 1

REH, P:_Projects (Active)\1003877 Drumheller River Hazard Study\03 Calculations\0200 Open Water Hydrology\GIS\Figures\MXD\1003877_T200_Fig01_StudyArea_R0.mxd

Type	Station No.	Station Name	Drainage Area (km^2)	Period of Record
Streamflow	05CC002	Red Deer River at Red Deer	11,600	1912-1935 and 1938-2017
	05CE001	Red Deer River at Drumheller	24,900	1916-1931,1959-2018
	05CE002	Kneehills Creek near Drumheller	2,430	1921-1931, 1935-1936, 1957-2018
	05CE020	Michichi Creek at Drumheller	1,170	1979-2018
	05CE005	Rosebud River at Redland	3,570	1951-2018
	05CE003	Rosebud River at Beynon	3,990	1922-1931, 1935-1936
	05CC011	Waskasoo Creek at Red Deer	487	1984-2017
	05CC001	Blindman River near Blackfalds	1,800	1916-1923, 1962-2017
	05CD006	Haynes Creek near Haynes	165	1978-2016
	05CE007	Threehills Creek near Carbon	1,080	1965-2017
	05CG006	Fish Creek above Little Fish Lake	118	1984-2018
Water Level	05CD005	Buffalo Lake near Erskine	1,570	1965-2017
	05CE901	Bigelow Reservoir near Wimborne	413	1979-2017



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Legend

- WSC Hydrometric Station
- River Hazard Study Area
- Lower Red Deer River Basin
- Upper Red Deer River Basin
- Gauged Sub-basin
- Sub-basin

DATA SOURCES: Watershed boundaries based on Canadian Water Survey of Canada data. Basemap from Esri & NRCAN.

SCALE - 1:1,000,000

0 10 20 40 Km

N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METERS

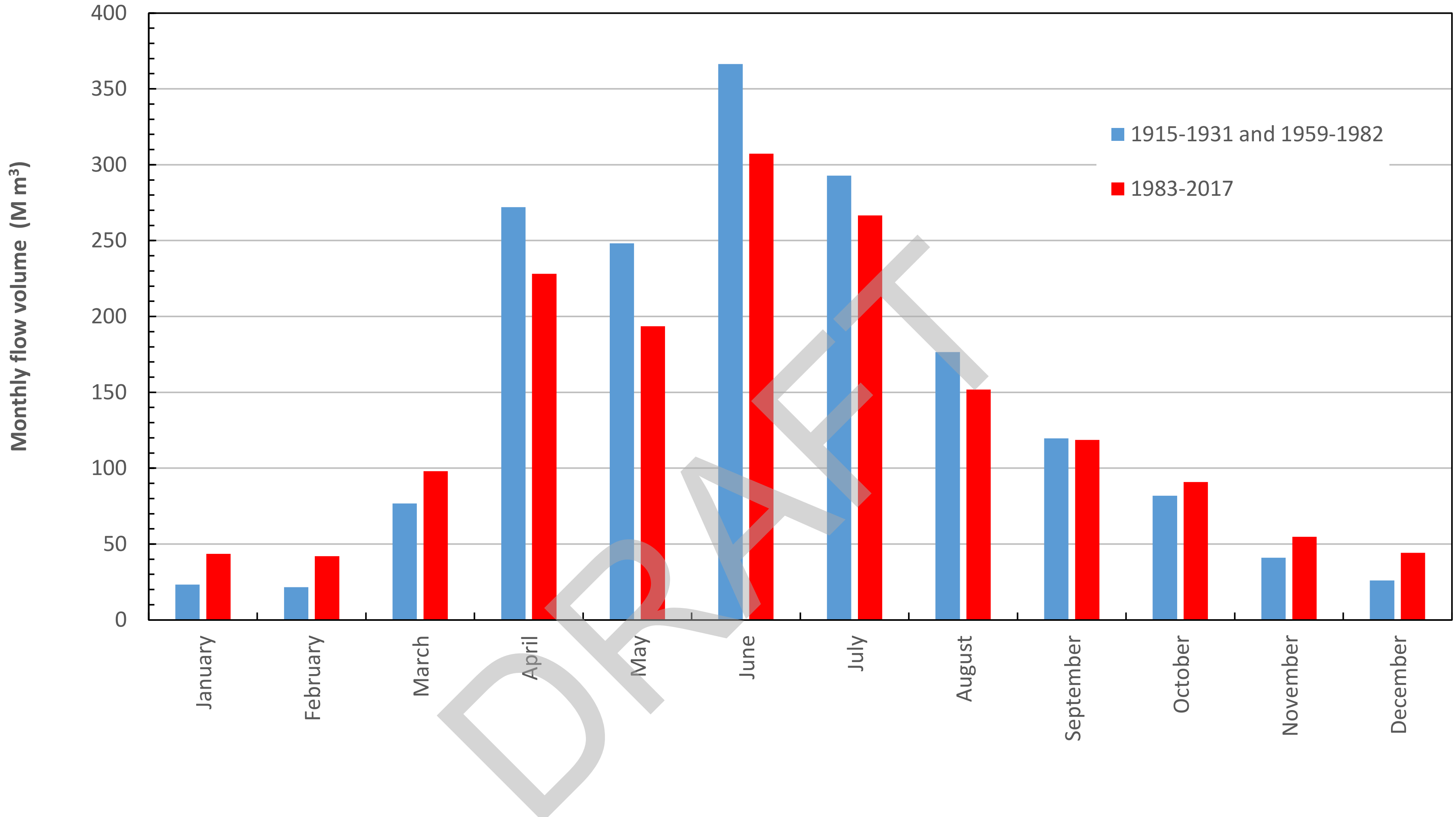
Job: 1003877 *Date: 17-MAR-2020*

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

BASIN OVERVIEW

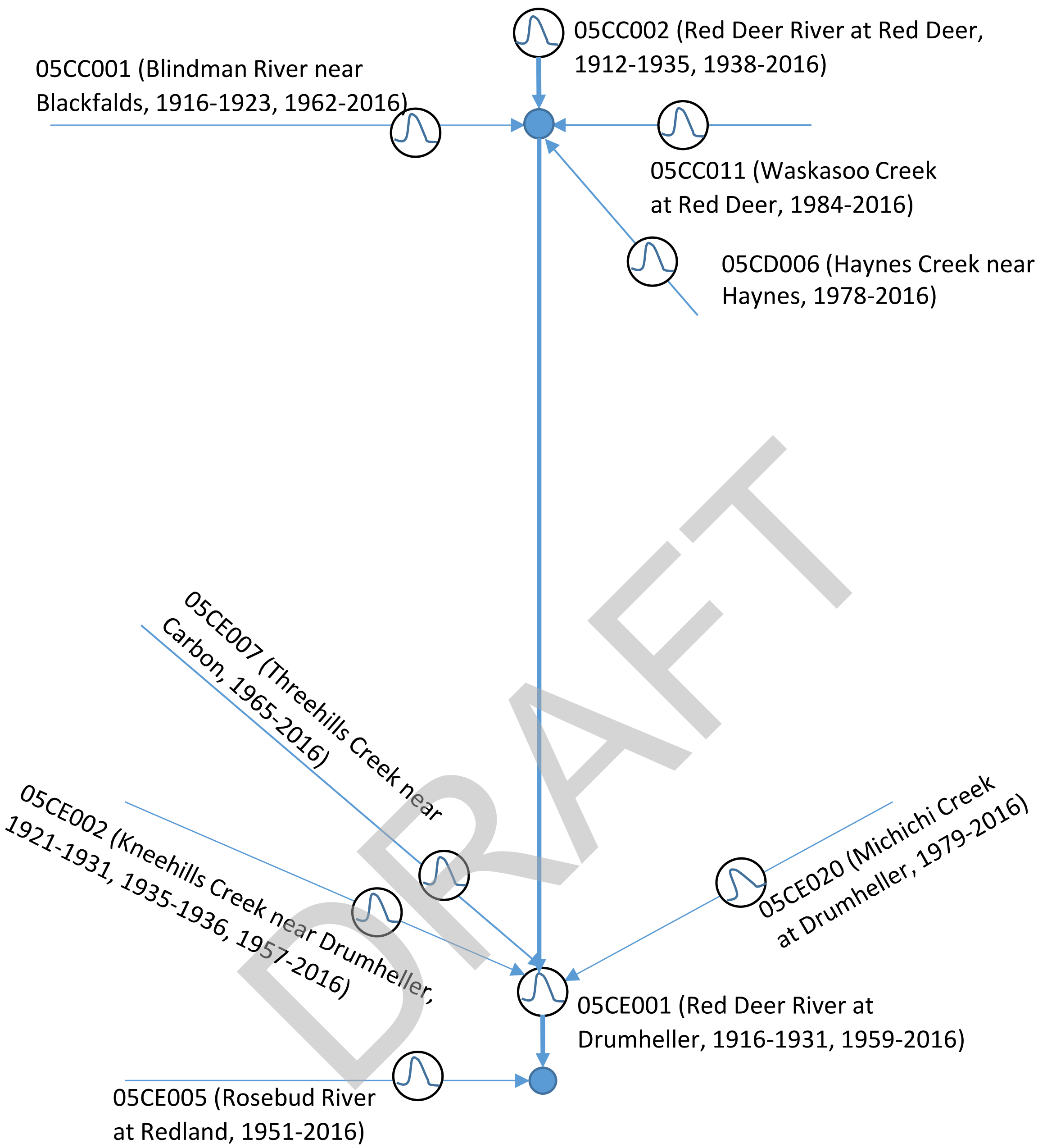
FIGURE 2

Classification: Public

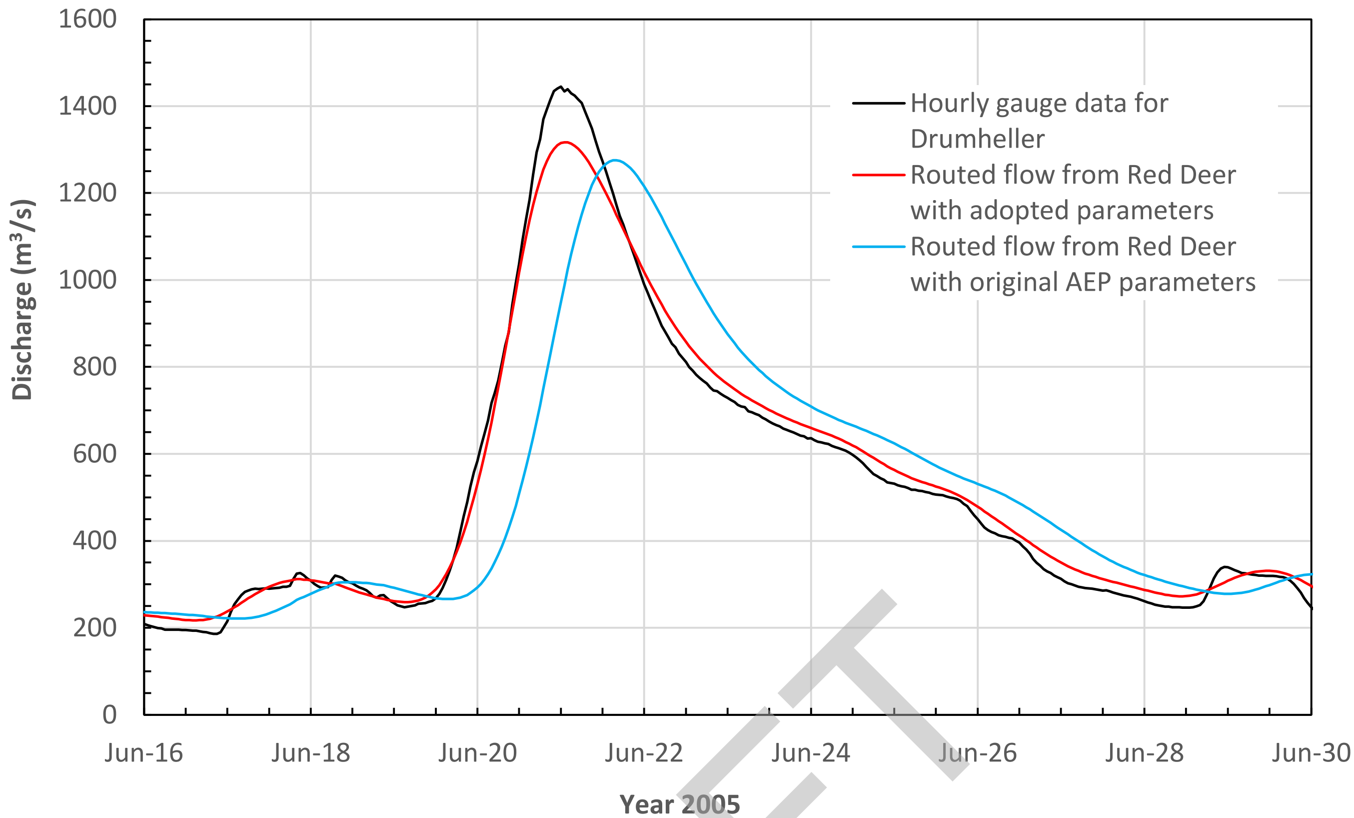


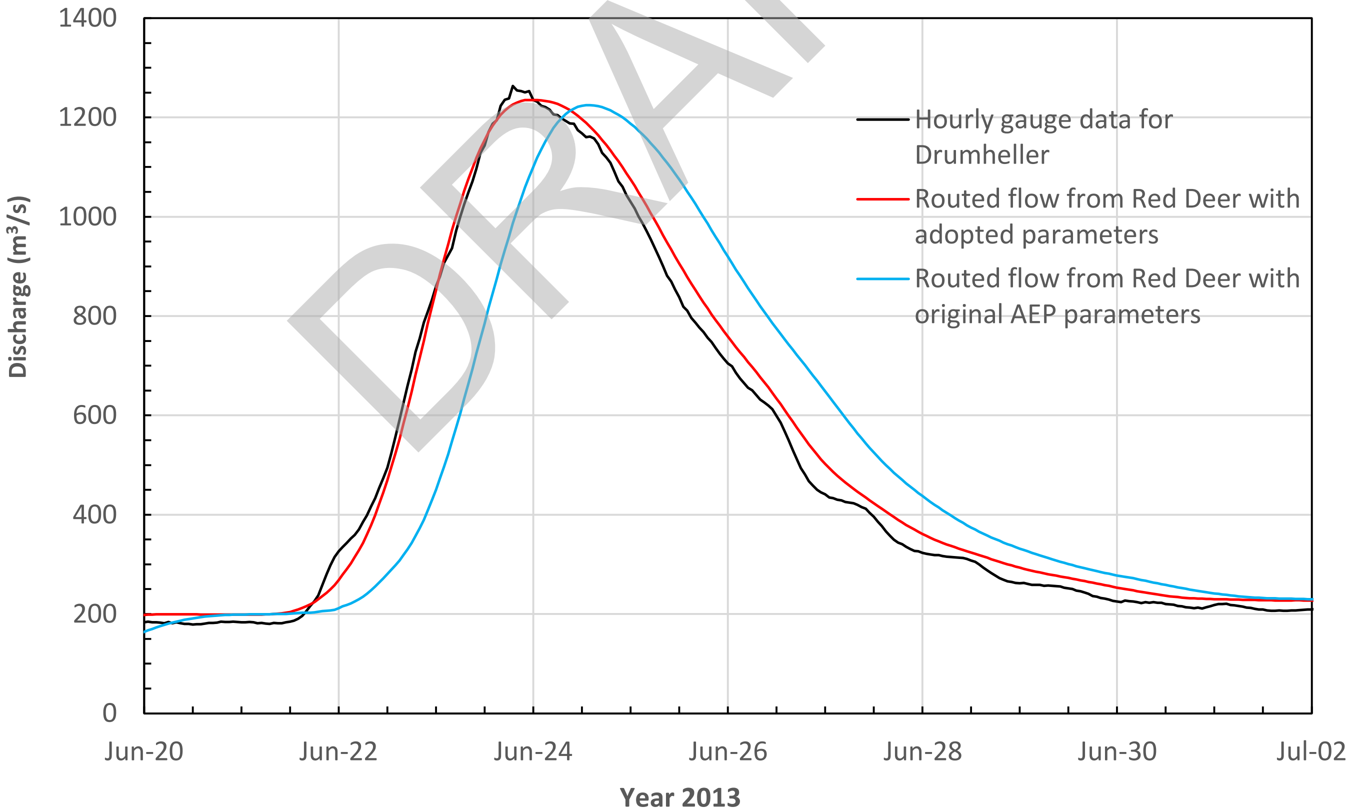
Notes: 1. 1915-1931 and 1959-1982: pre-regulation period
2. 1983-2017: regulated by the Dickson Dam

Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*MEAN MONTHLY RUNOFF FOR RED DEER RIVER AT DRUMHELLER*
	Job: 1003877 / *Date: Mar-2019*	*FIGURE 3*



Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*MODEL SCHEMATIC FOR FLOW ROUTING*
	Job: 1003877 / *Date: Mar-2019*	*FIGURE 4*





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Coordinate System:
Units: As Shown

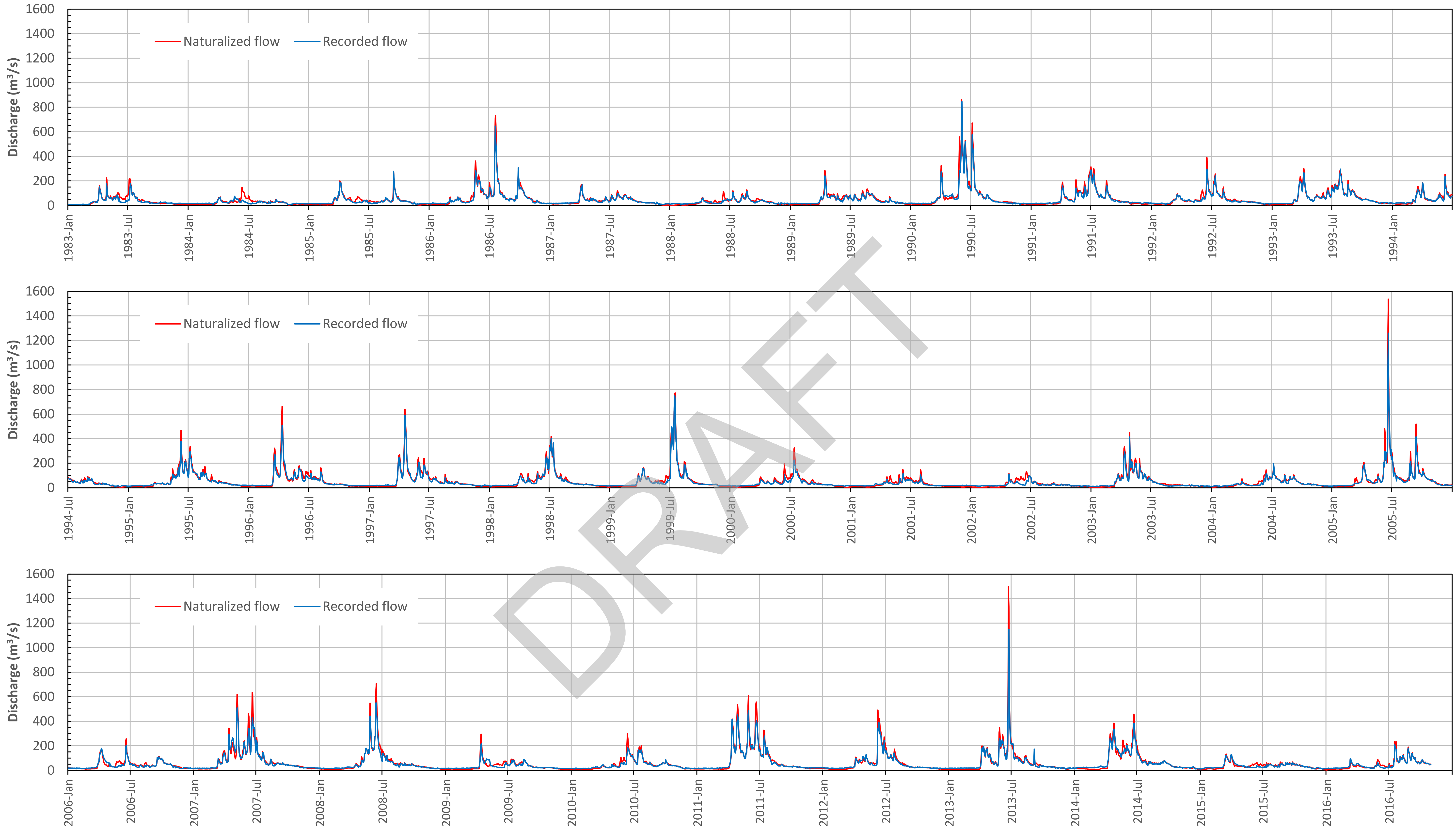
Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF ROUTED HOURLY FLOW HYDROGRAPHS FOR 2005 AND 2013 PEAK EVENTS – RED DEER RIVER AT DRUMHELLER

FIGURE 5



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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

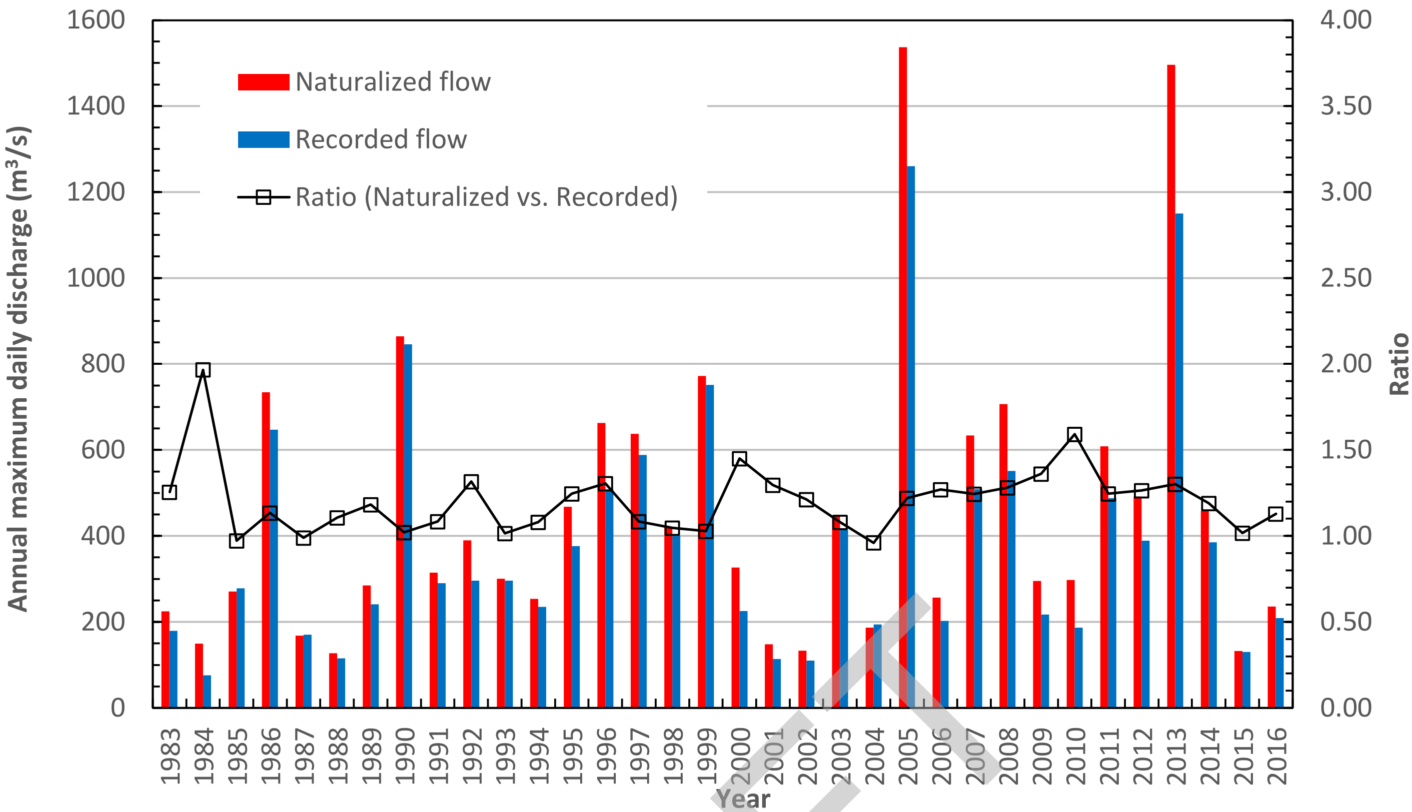
Job: 1003877

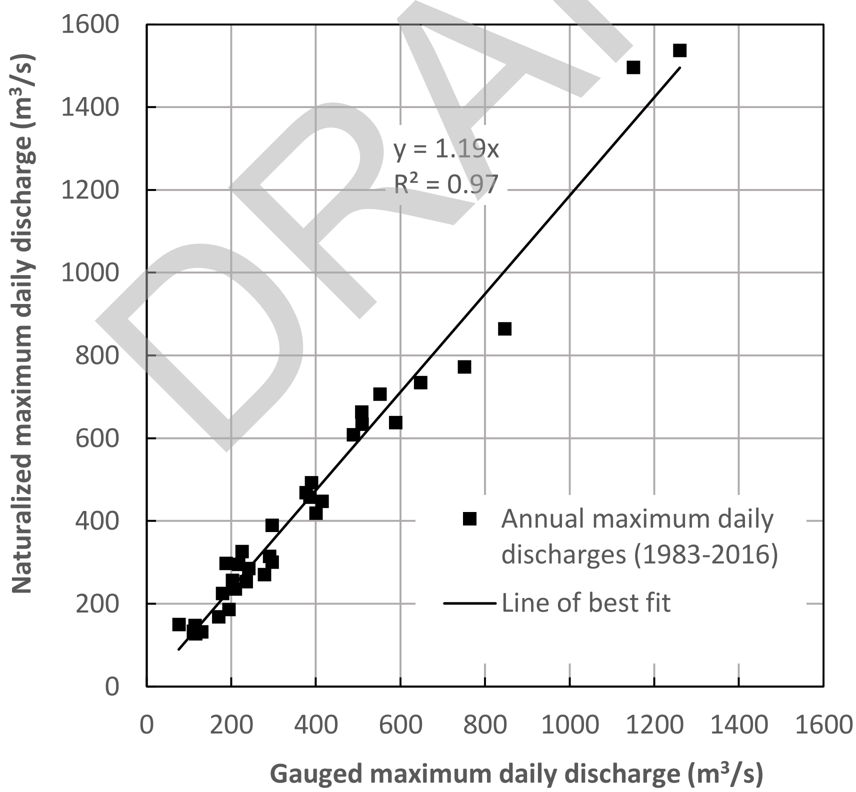
Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF NATURALIZED AND RECORDED DAILY FLOWS FOR RED DEER RIVER AT DRUMHELLER (1983-2016)

FIGURE 6





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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

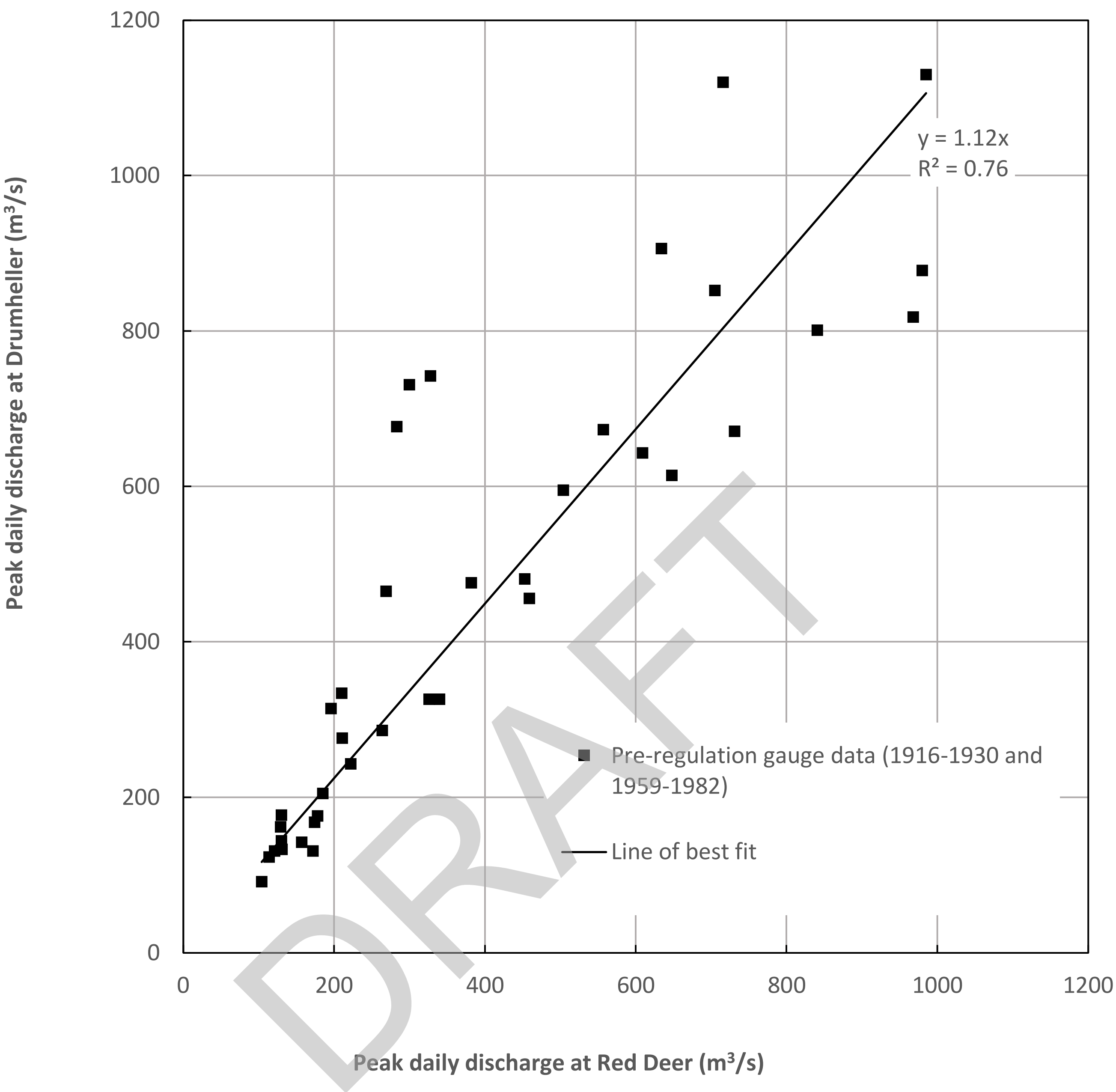
Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF NATURALIZED AND RECORDED ANNUAL PEAKS FOR RED DEER RIVER AT DRUMHELLER

FIGURE 7

Classification: Public



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SCALE – AS SHOWN

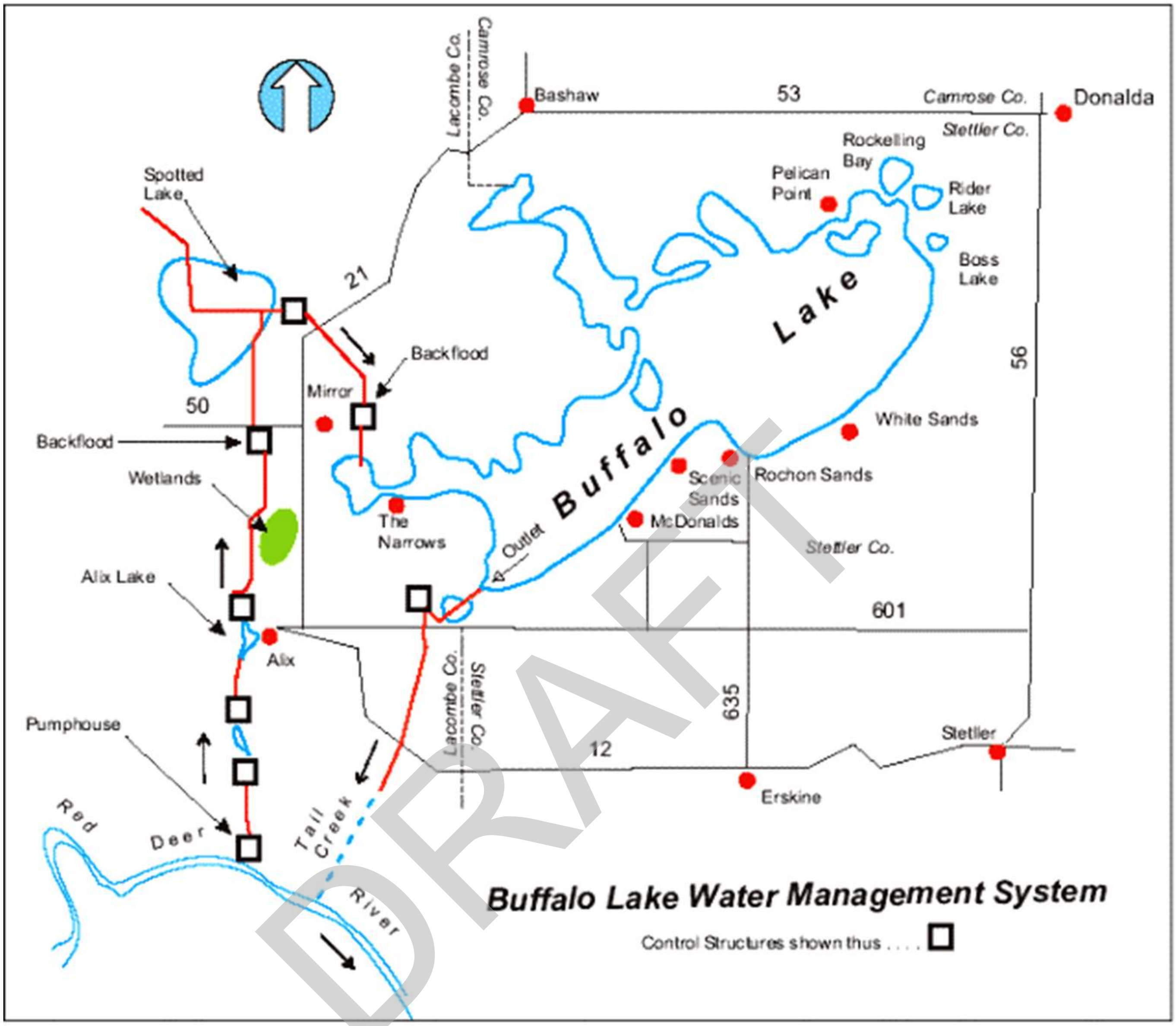
Coordinate System:
Units: As Shown

Job: 1003877

Date: Mar-2019

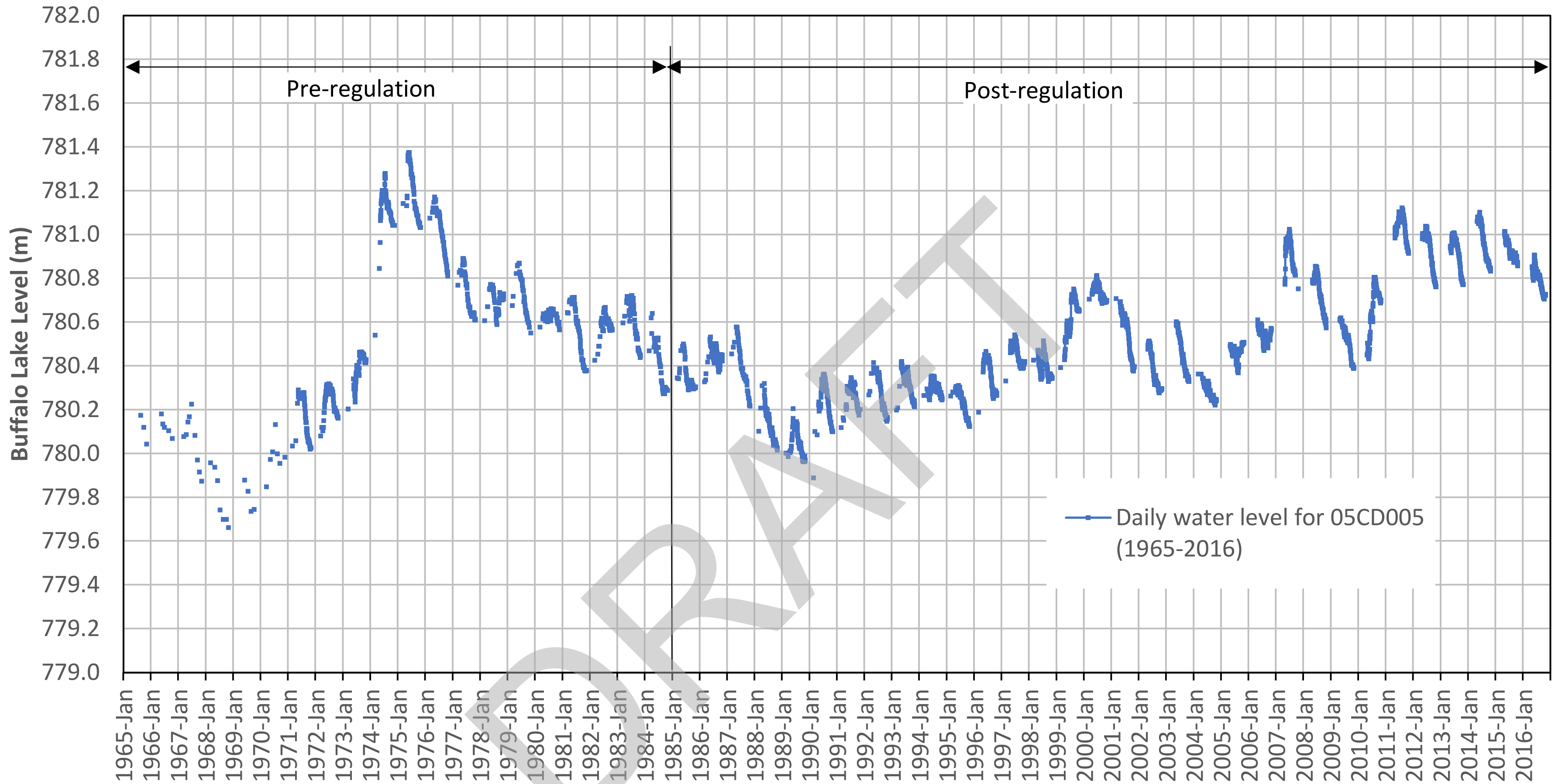
DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT
RELATIONSHIP BETWEEN ANNUAL MAXIMUM DAILY NATURAL DISCHARGES FOR RED DEER RIVER AT RED DEER AND AT DRUMHELLER

FIGURE 8

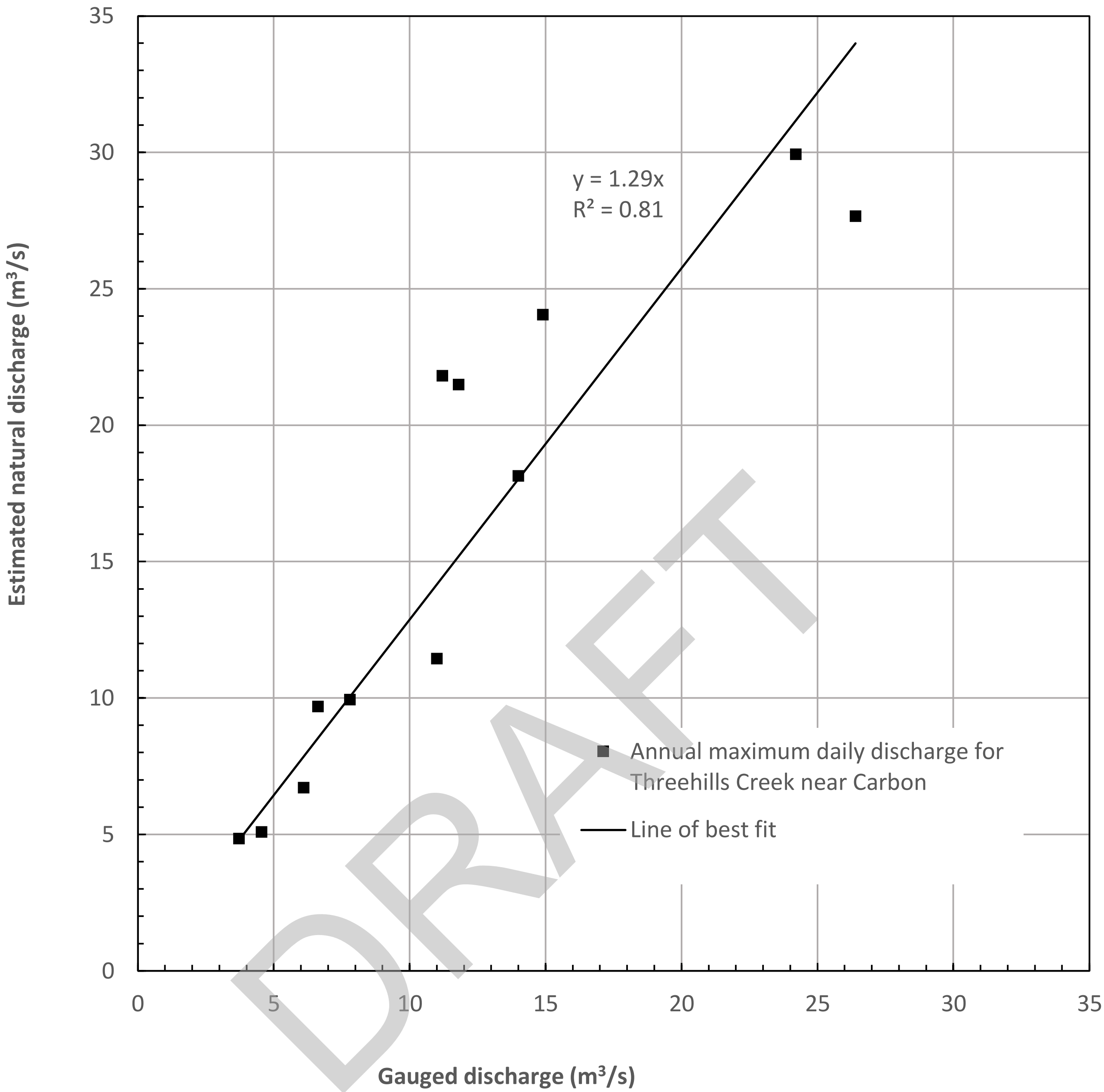


Notes: 1. The map shown is from http://www.blmt.ca.

Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*PARLBY CREEK – BUFFALO LAKE WATER MANAGEMENT SYSTEM*
	Job: 1003877 / *Date: Mar-2019*	*FIGURE 9*



Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*HISTORICAL VARIATION OF BUFFALO LAKE LEVELS*
	Job: 1003877 | *Date: Mar-2019*	*FIGURE 10*



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Coordinate System:
Units: As Shown

Job: 1003877 | *Date: Mar-2019*

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

RELATIONSHIP FOR NATURALIZED VERSUS GAUGED DISCHARGES FOR THREEHILLS CREEK NEAR CARBON

FIGURE 11

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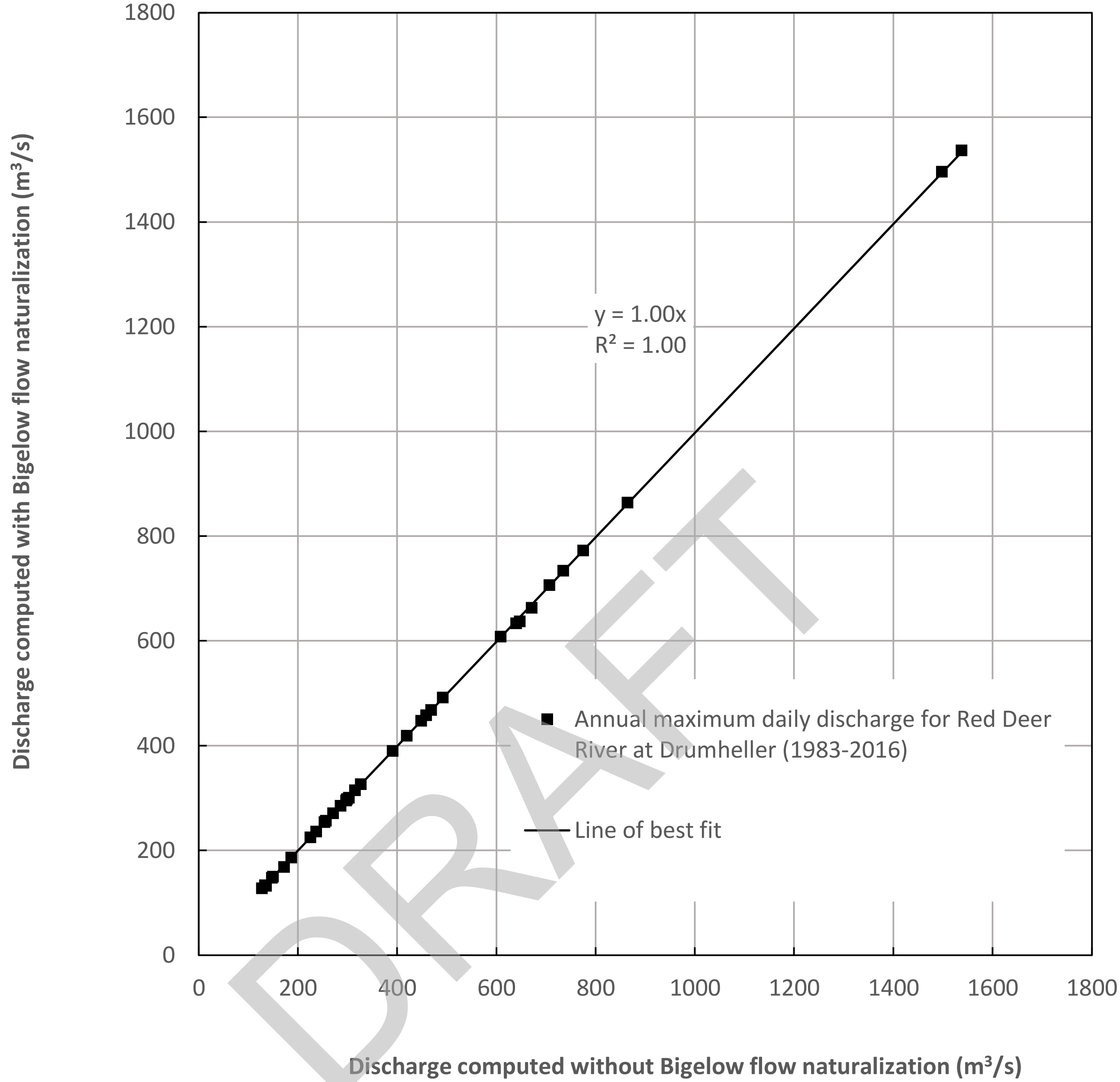
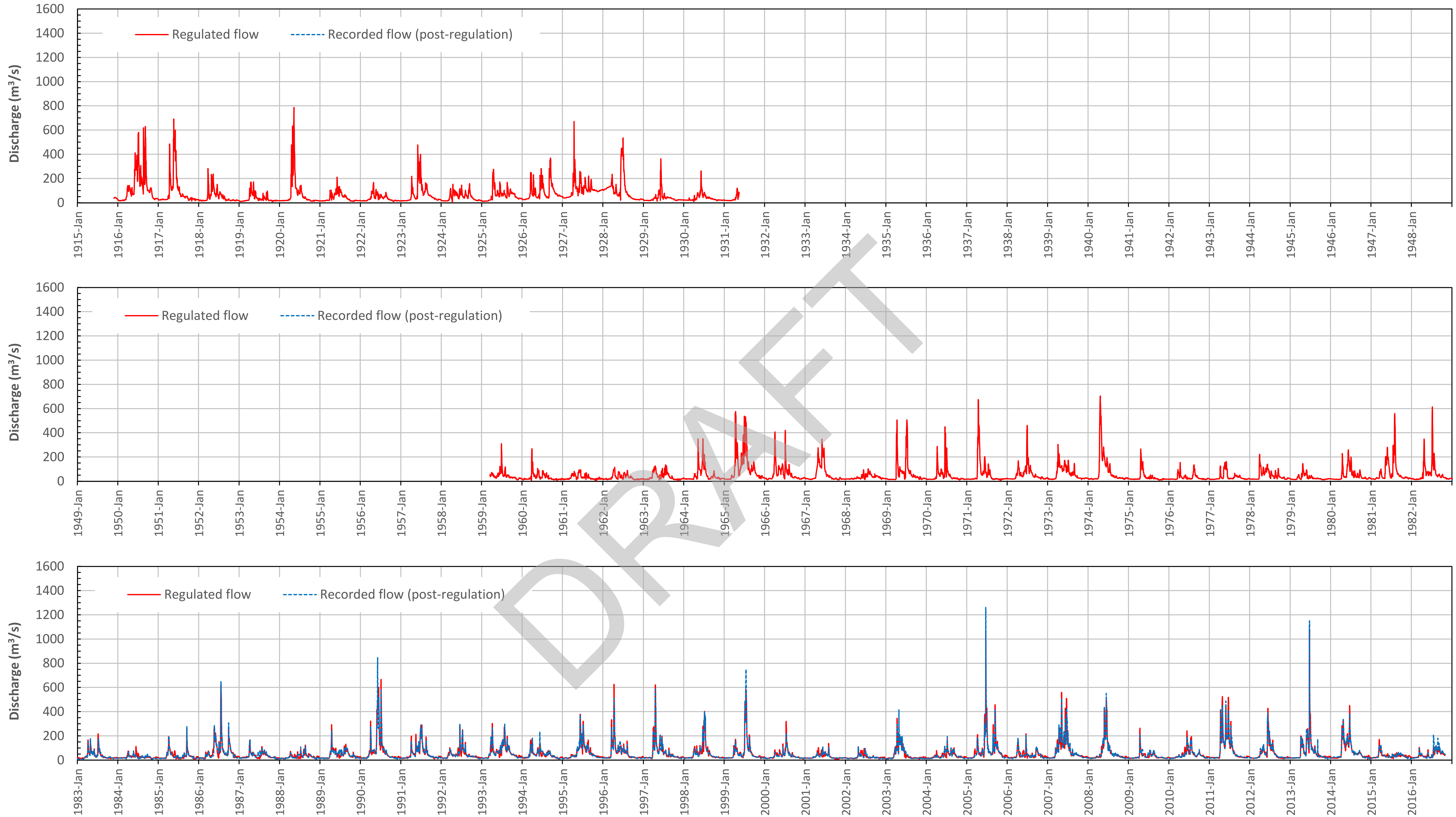


Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*EFFECTS OF BIGELOW DAM ON FLOW NATURALIZATION FOR RED DEER RIVER AT DRUMHELLER*
	Job: 1003877 / *Date: Mar-2019*	*FIGURE 12*



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

REGULATED DAILY FLOWS FOR RED DEER RIVER AT DRUMHELLER

FIGURE 13

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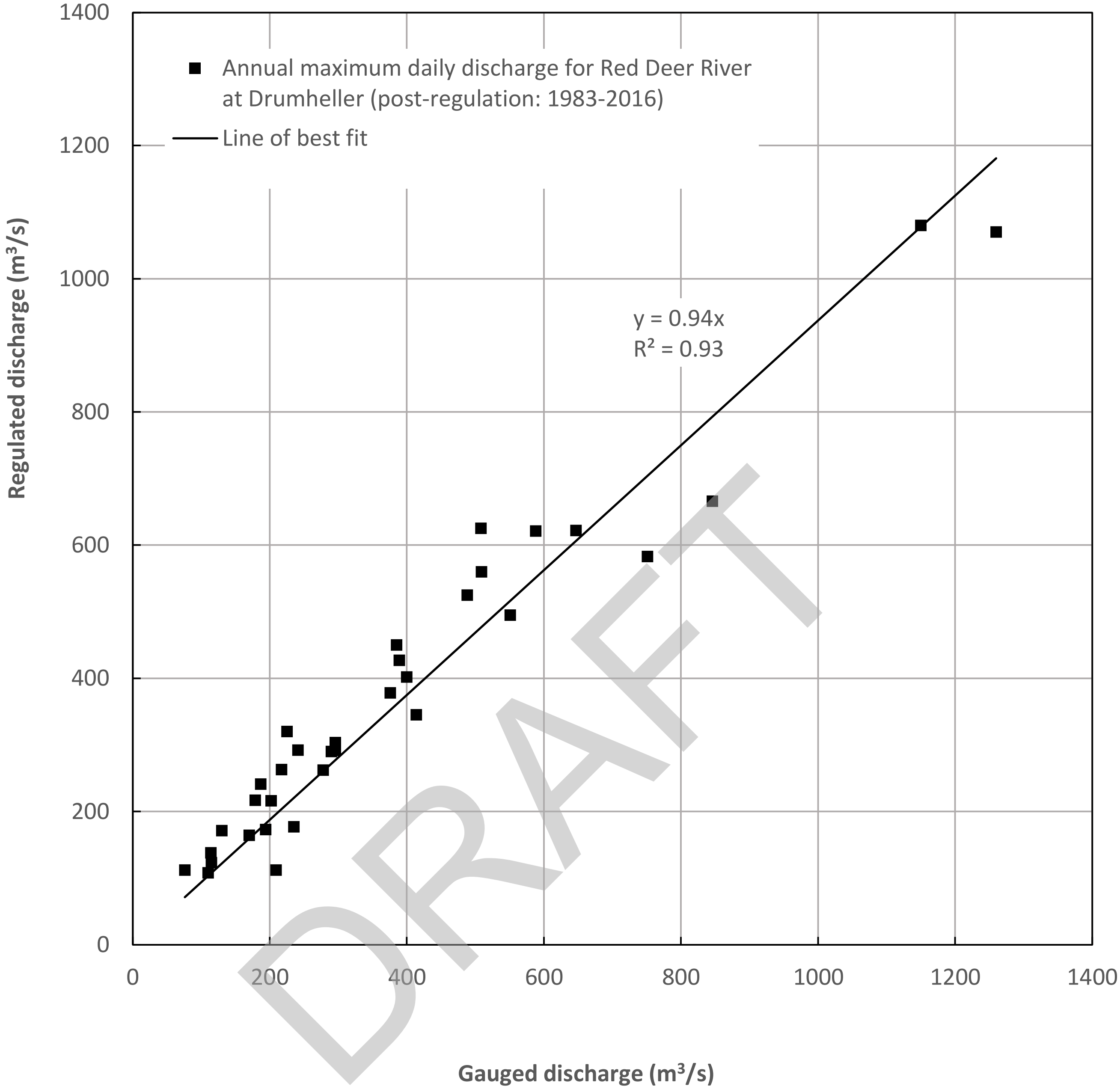
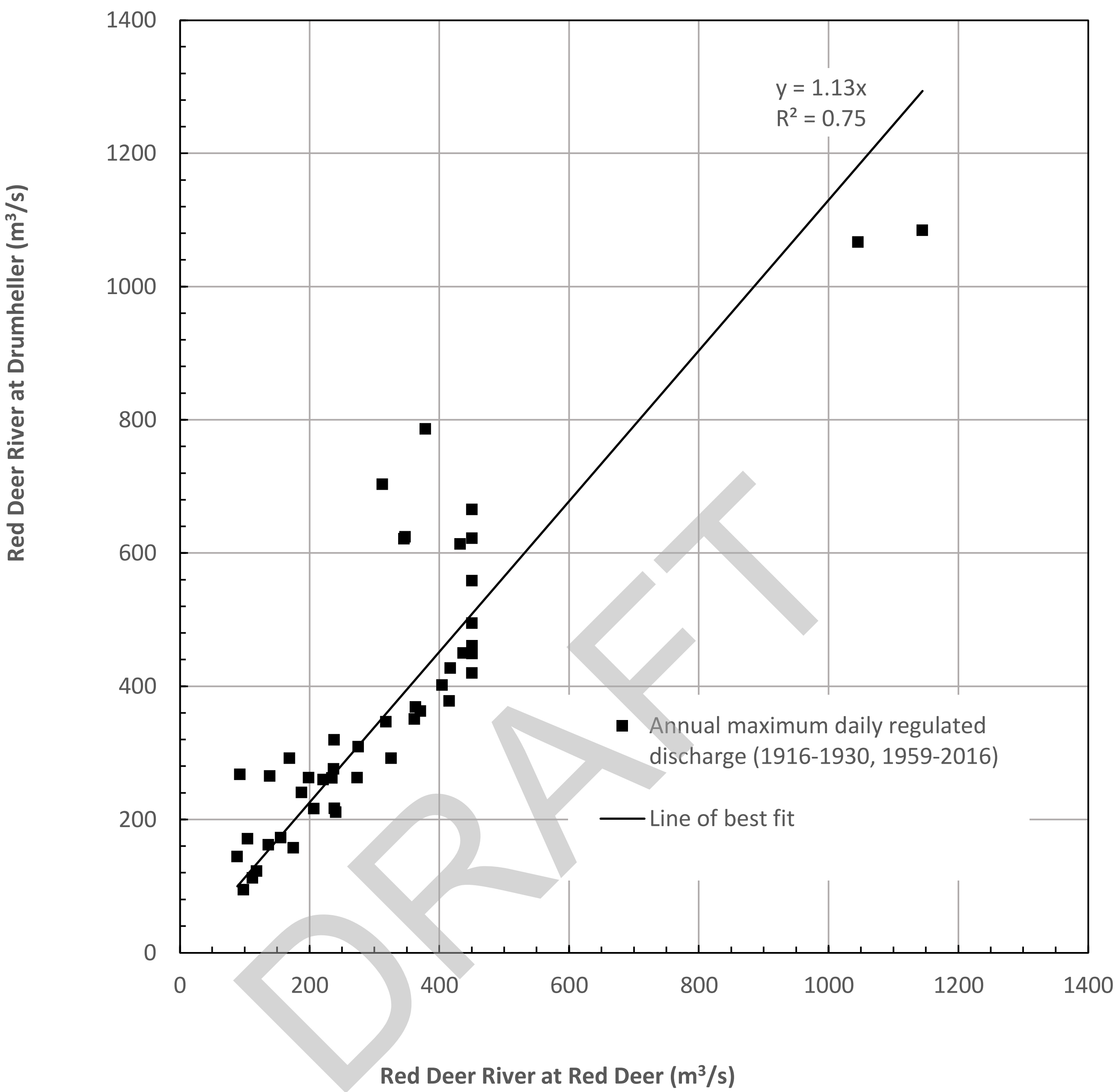


Alberta	SCALE – AS SHOWN	DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT COMPARISON OF REGULATED AND GAUGED ANNUAL MAXIMUM DAILY DISCHARGES FOR RED DEER RIVER AT DRUMHELLER
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	
	Job: 1003877 *Date: Mar-2019*	*FIGURE 14*



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877 | *Date: Mar-2019*

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT
COMPARISON OF REGULATED ANNUAL MAXIMUM DAILY DISCHARGES FOR RED DEER RIVER AT RED DEER AND AT DRUMHELLER

FIGURE 15

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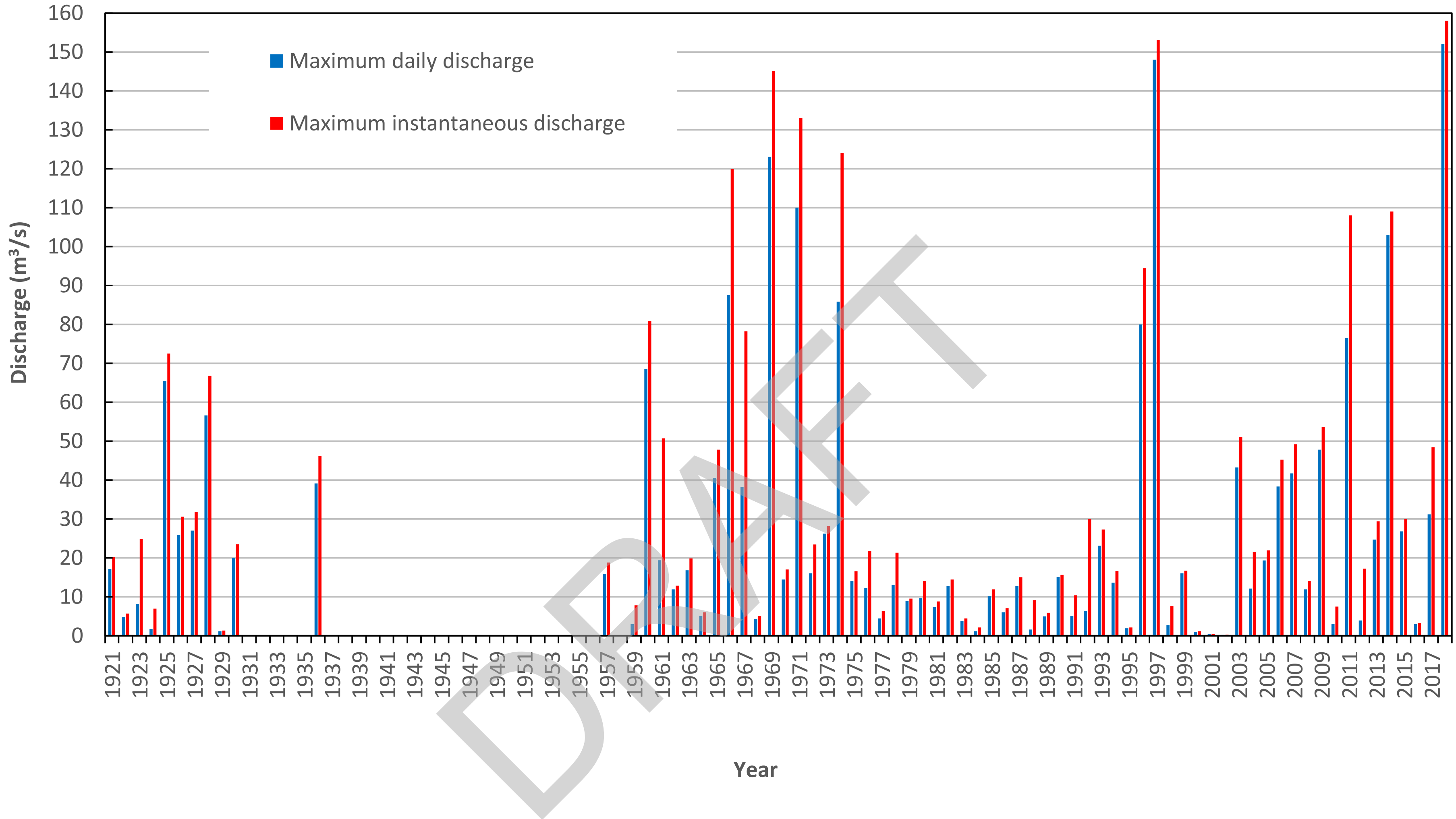

SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ANNUAL PEAK DISCHARGES FOR KNEEHILLS CREEK NEAR DRUMHELLER

FIGURE 16

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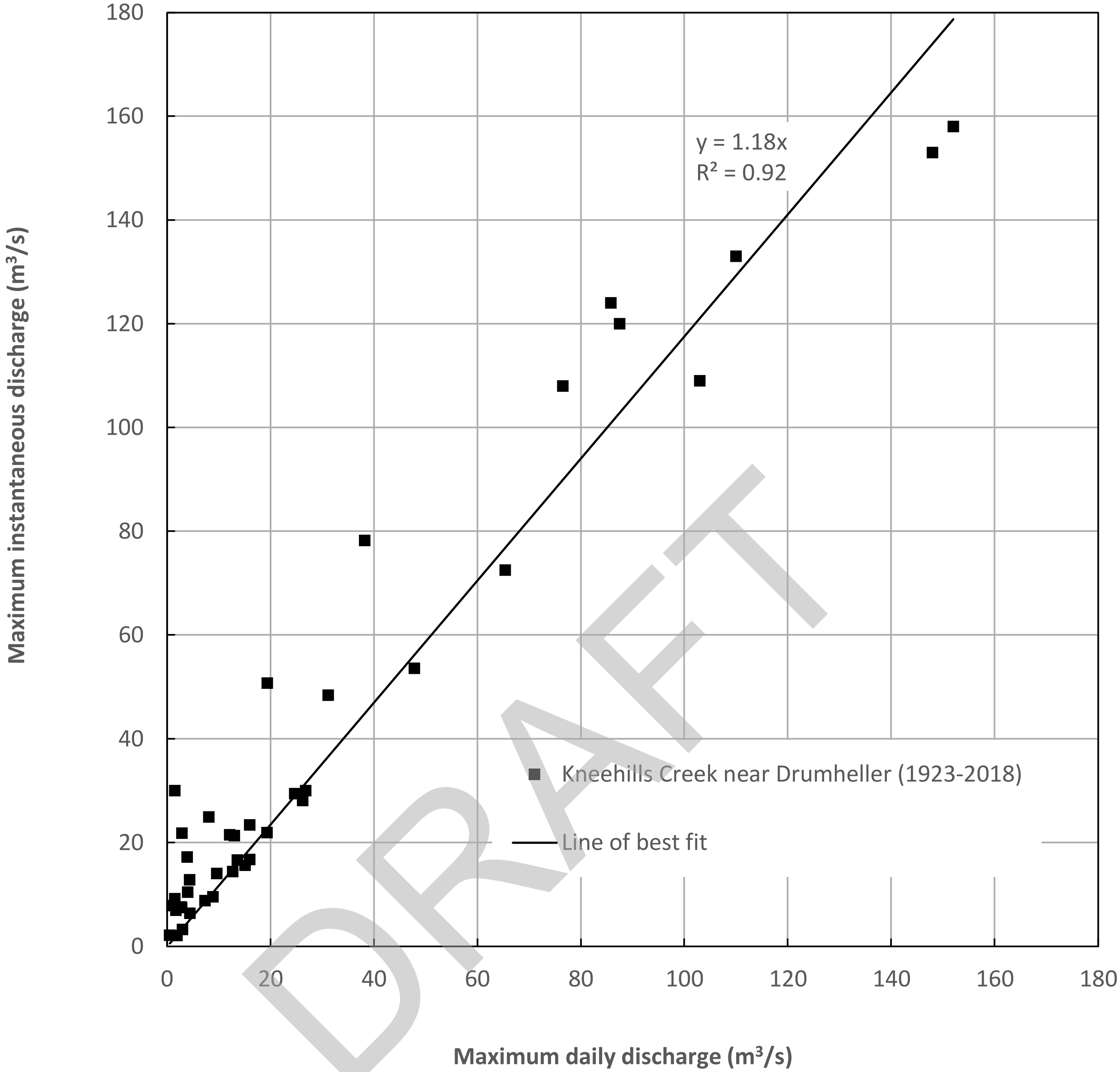
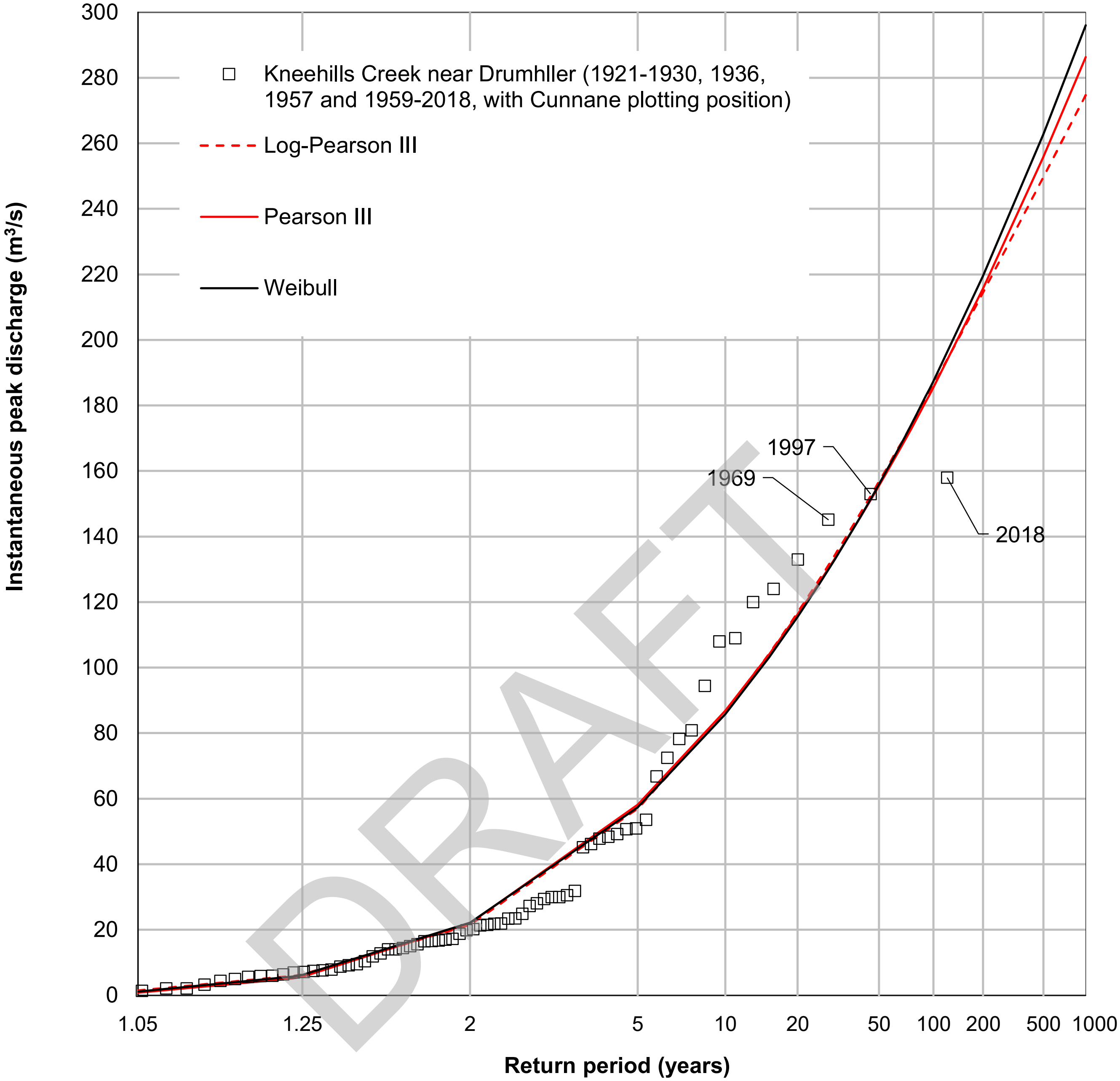


Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*KNEEHILLS CREEK NEAR DRUMHELLER MAXIMUM INSTANTANEOUS TO DAILY DISCHARGE RATIO*
	Job: 1003877 / *Date: Mar-2019*	*FIGURE 17*



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Coordinate System:
Units: As Shown

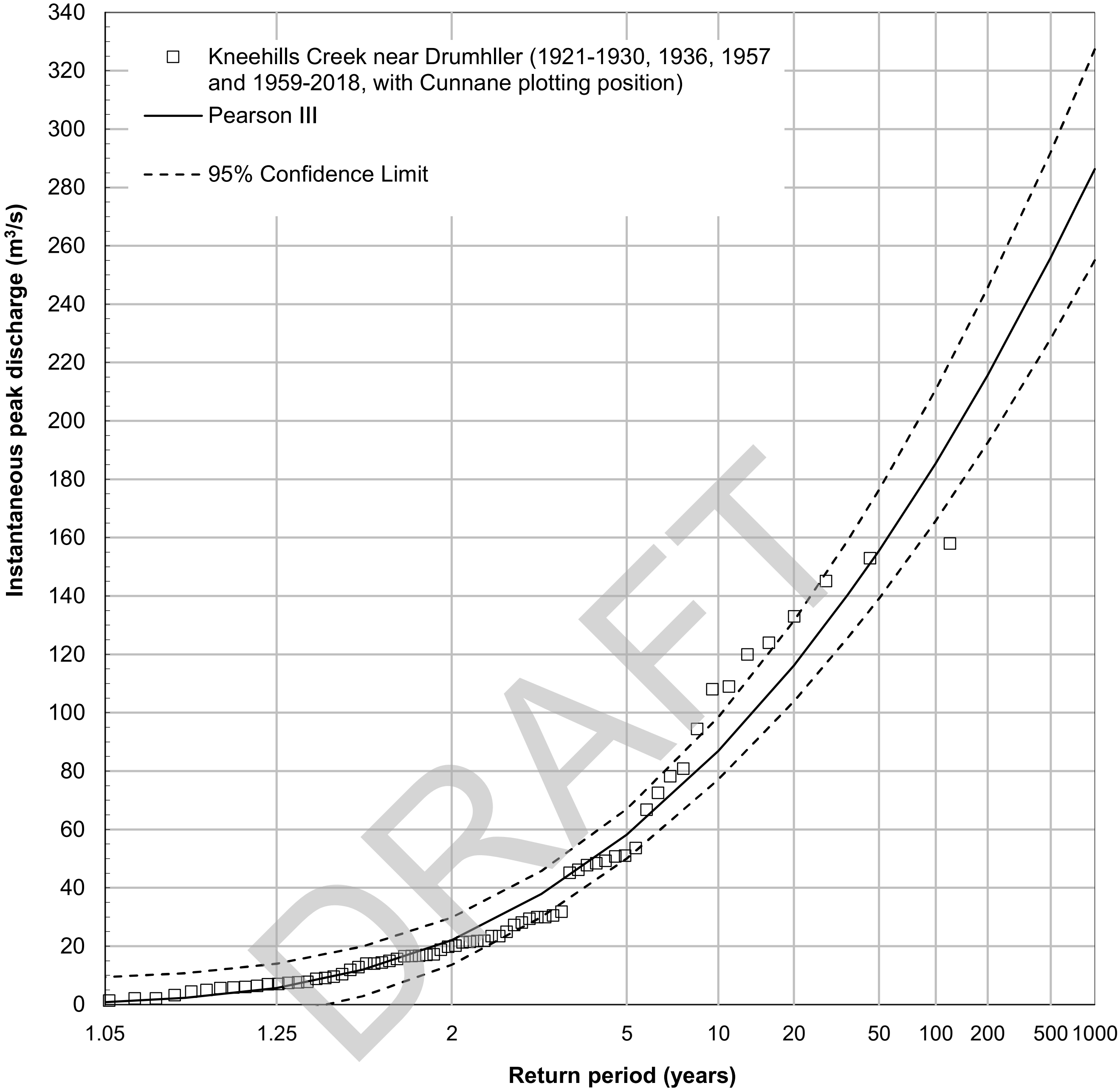
Job: 1003877

Date: Mar-2019

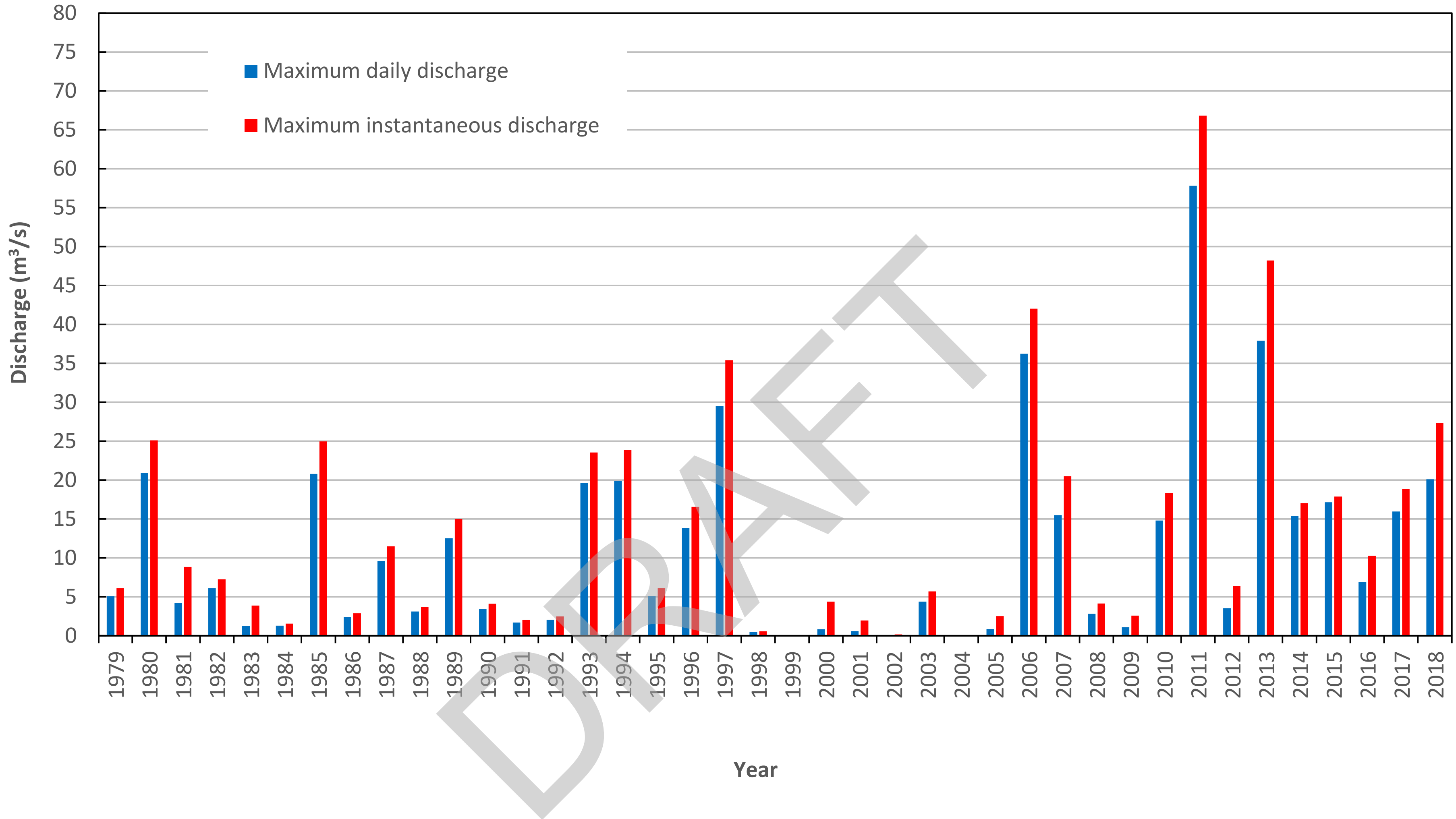
DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF FLOOD FREQUENCY CURVES FOR KNEEHILLS CREEK NEAR DRUMHELLER

FIGURE 18



Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
	Coordinate System: Units: As Shown	*ADOPTED FLOOD FREQUENCY CURVE FOR KNEEHILLS CREEK NEAR DRUMHELLER*
nhc northwest hydraulic consultants	*Job: 1003877* | *Date: Mar-2019*	*FIGURE 19*



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ANNUAL PEAK DISCHARGES FOR MICHICHI CREEK AT DRUMHELLER

FIGURE 20

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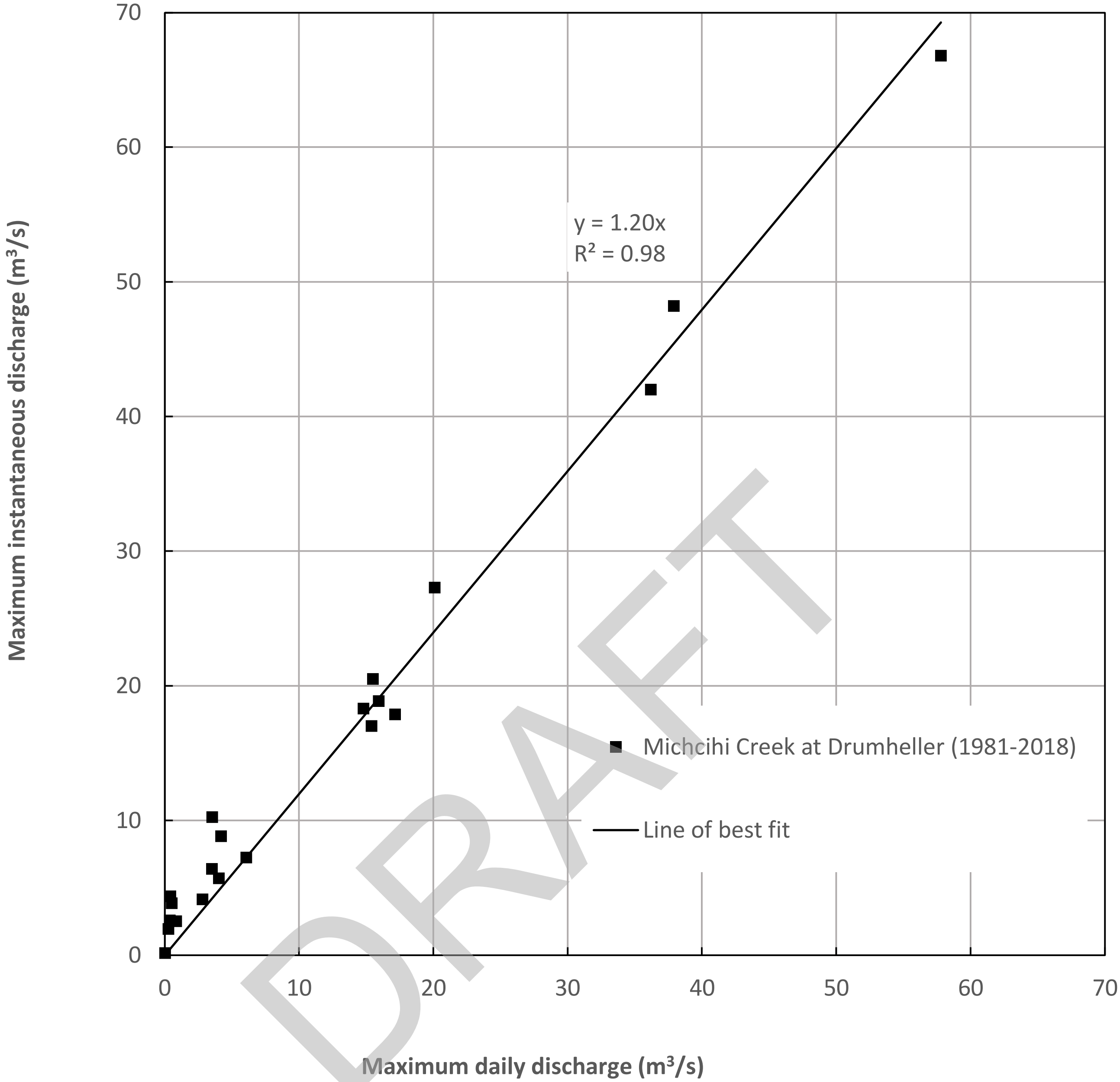

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SCALE – AS SHOWN

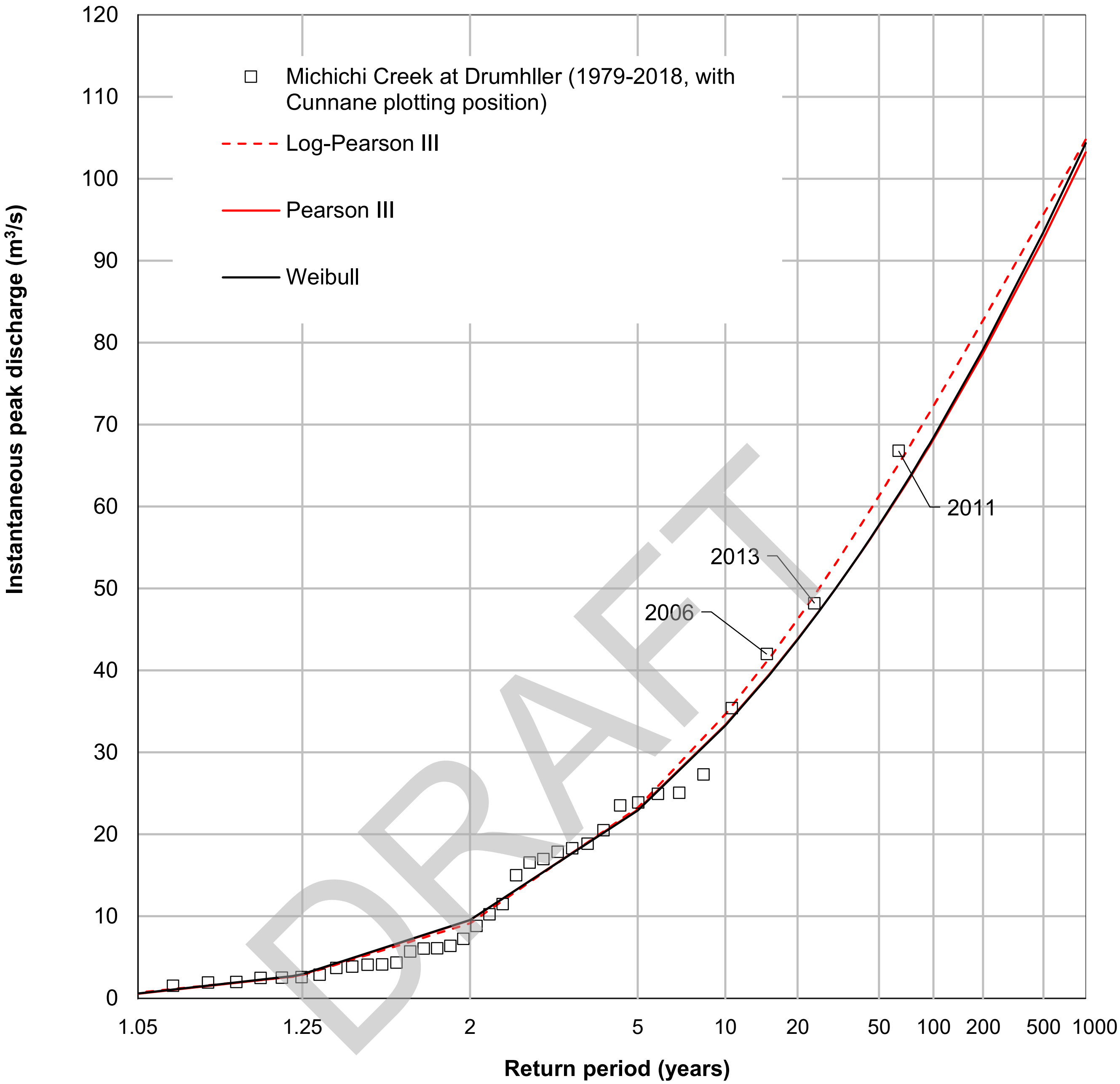
Coordinate System:
Units: As Shown

Job: 1003877 | *Date: Mar-2019*

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

MICHICHI CREEK AT DRUMHELLER
MAXIMUM INSTANTANEOUS TO DAILY
DISCHARGE RATIO

FIGURE 21



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF FLOOD FREQUENCY CURVES FOR MICHICHI CREEK AT DRUMHELLER

FIGURE 22

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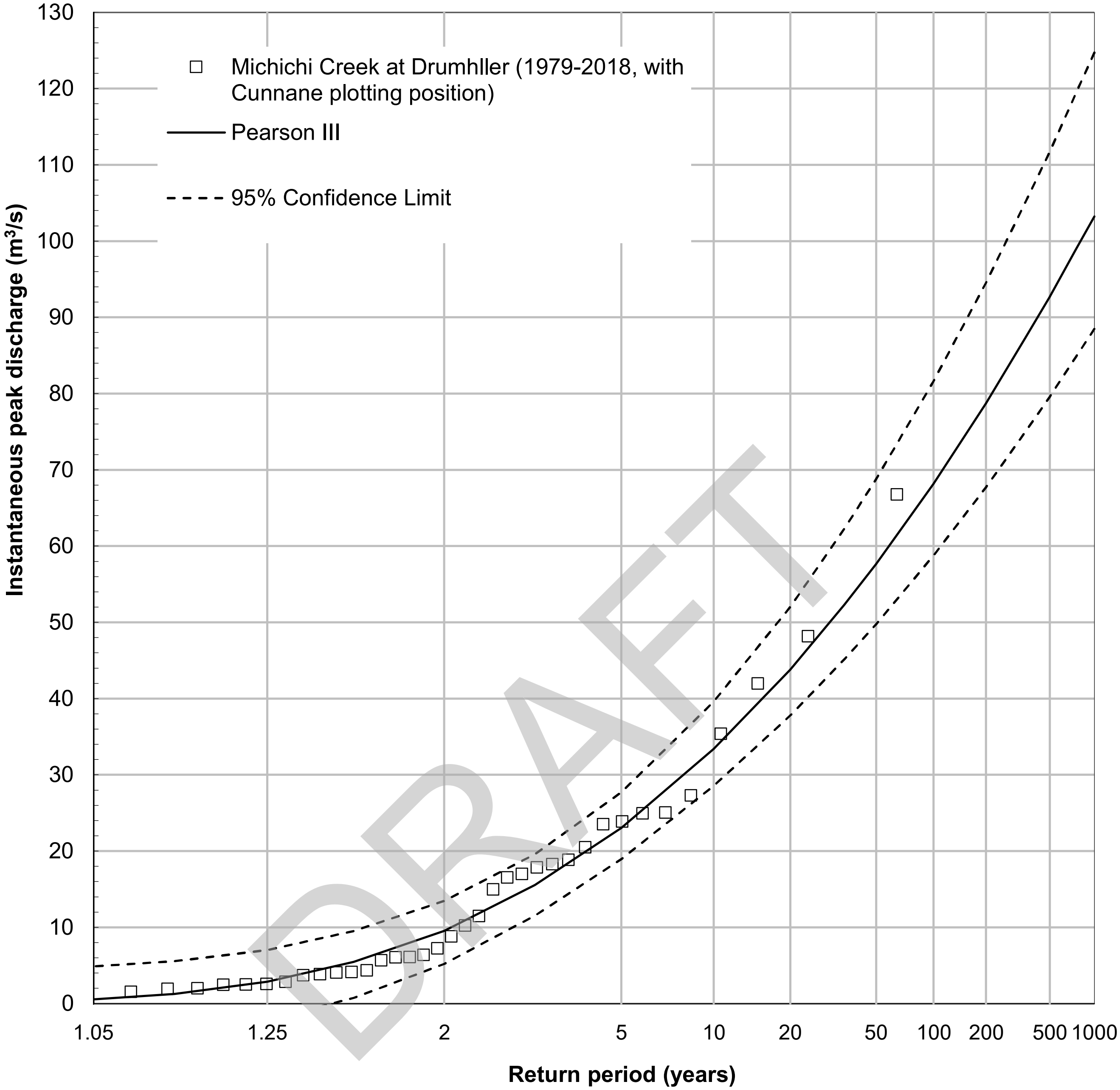

SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877 | Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ADOPTED FLOOD FREQUENCY CURVE FOR MICHICHI CREEK AT DRUMHELLER

FIGURE 23

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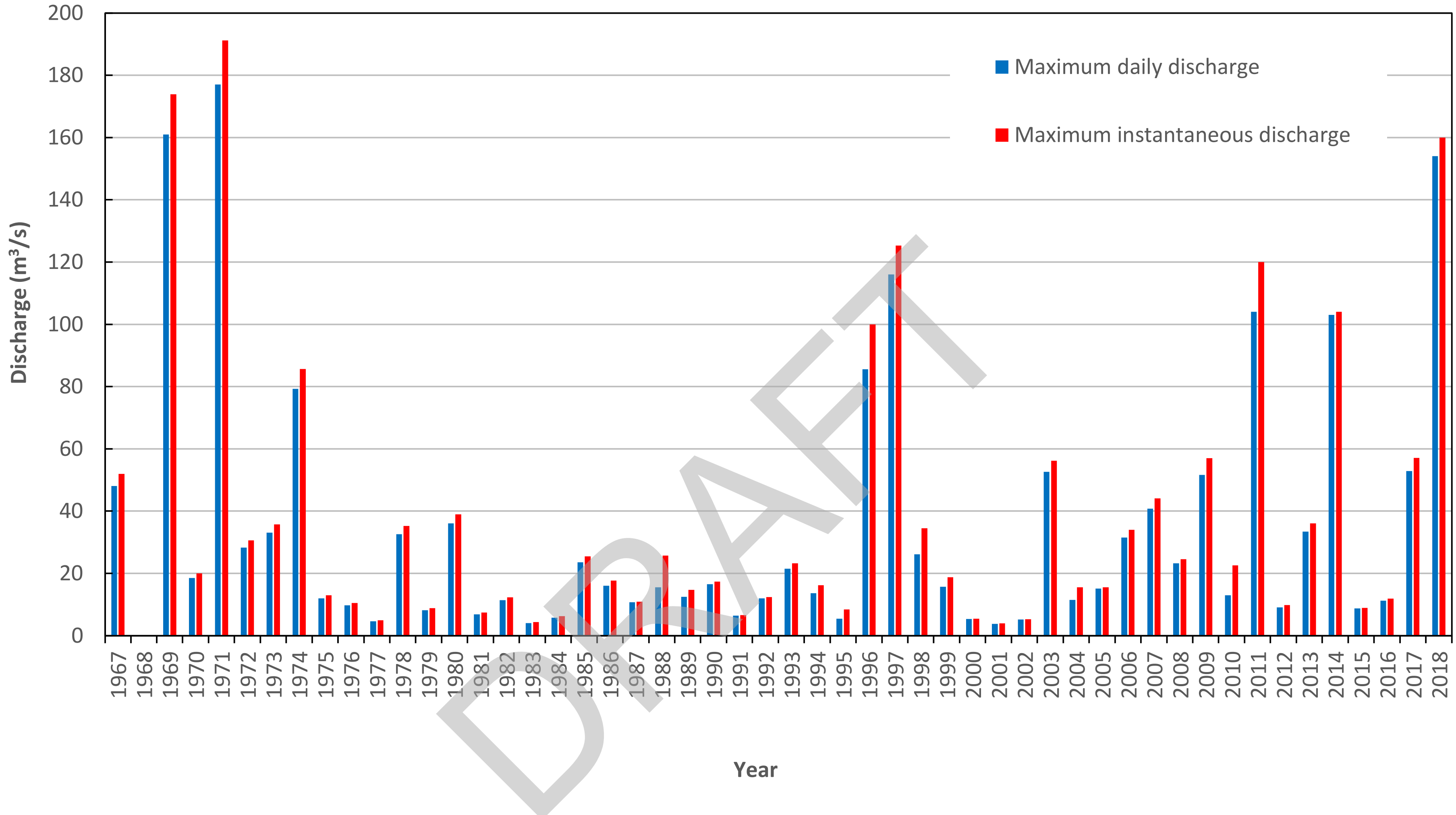

Notes: 1. The 1969 peak discharge was estimated from the data for WSC Station 05CE006 – Rosebud River below Carstairs Creek.

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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

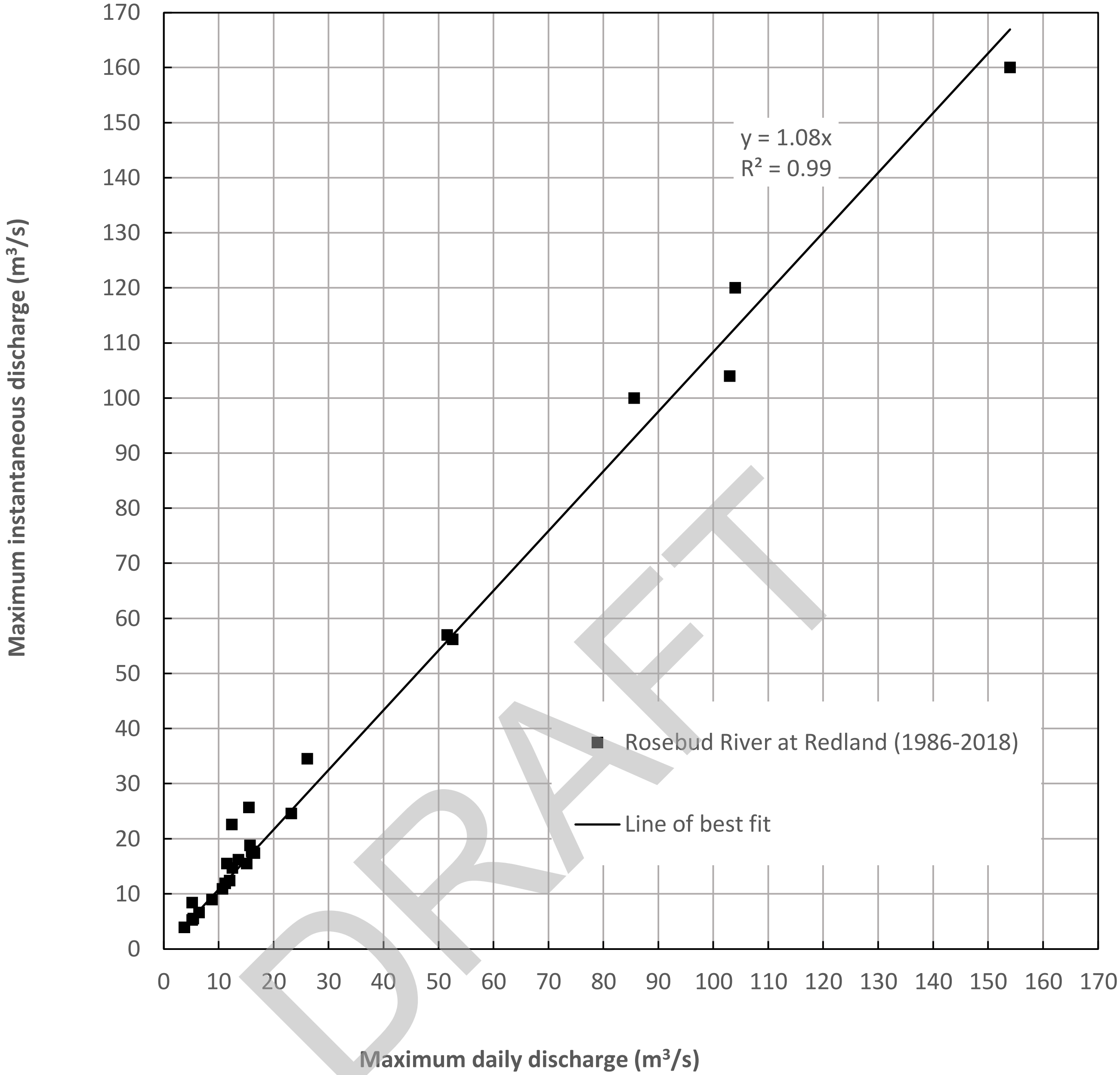
Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ANNUAL PEAK DISCHARGES FOR ROSEBUD RIVER AT REDLAND

FIGURE 24



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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

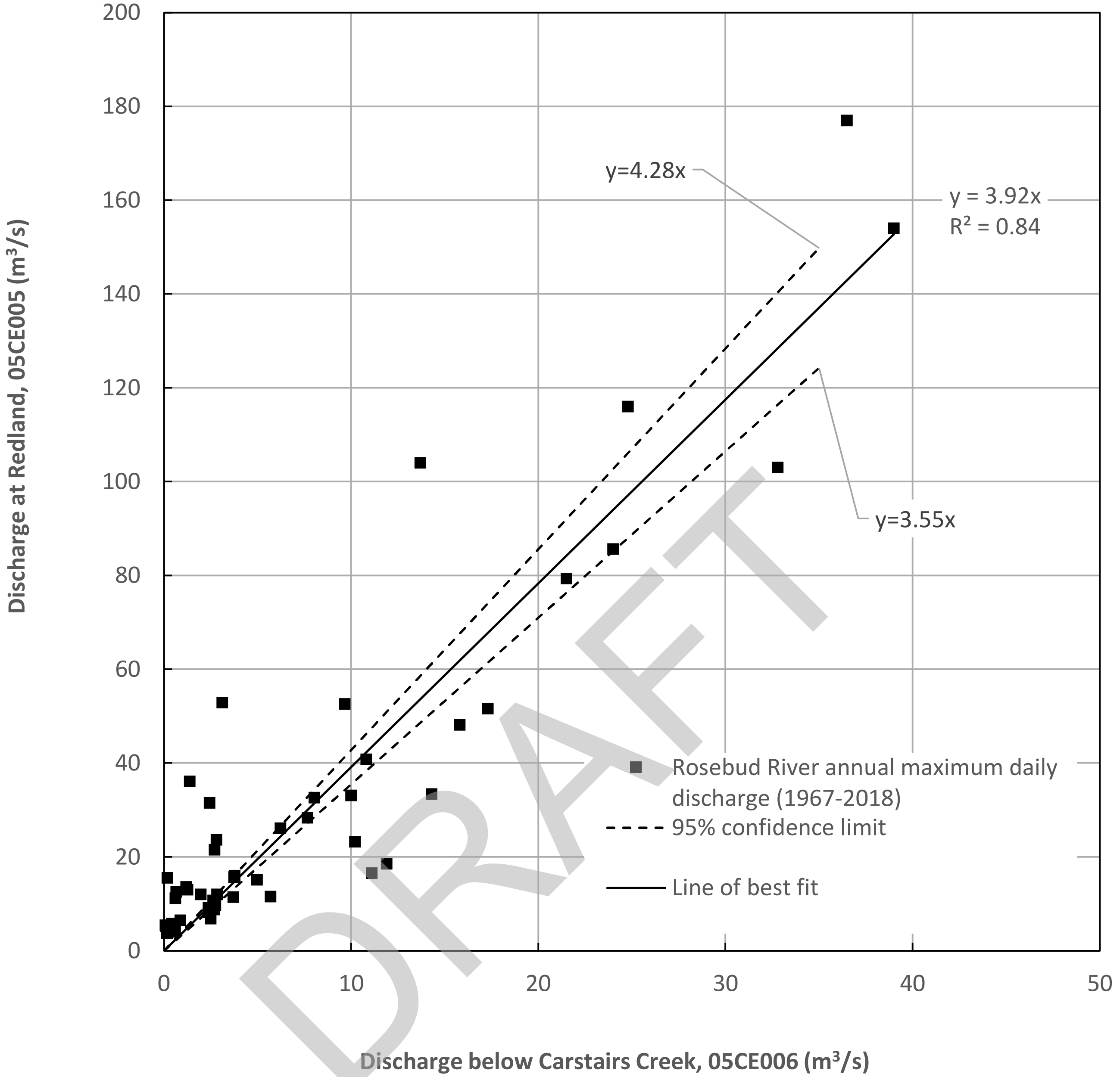
Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ROSEBUD RIVER AT REDLAND MAXIMUM INSTANTANEOUS TO DAILY DISCHARGE RATIO

FIGURE 25



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

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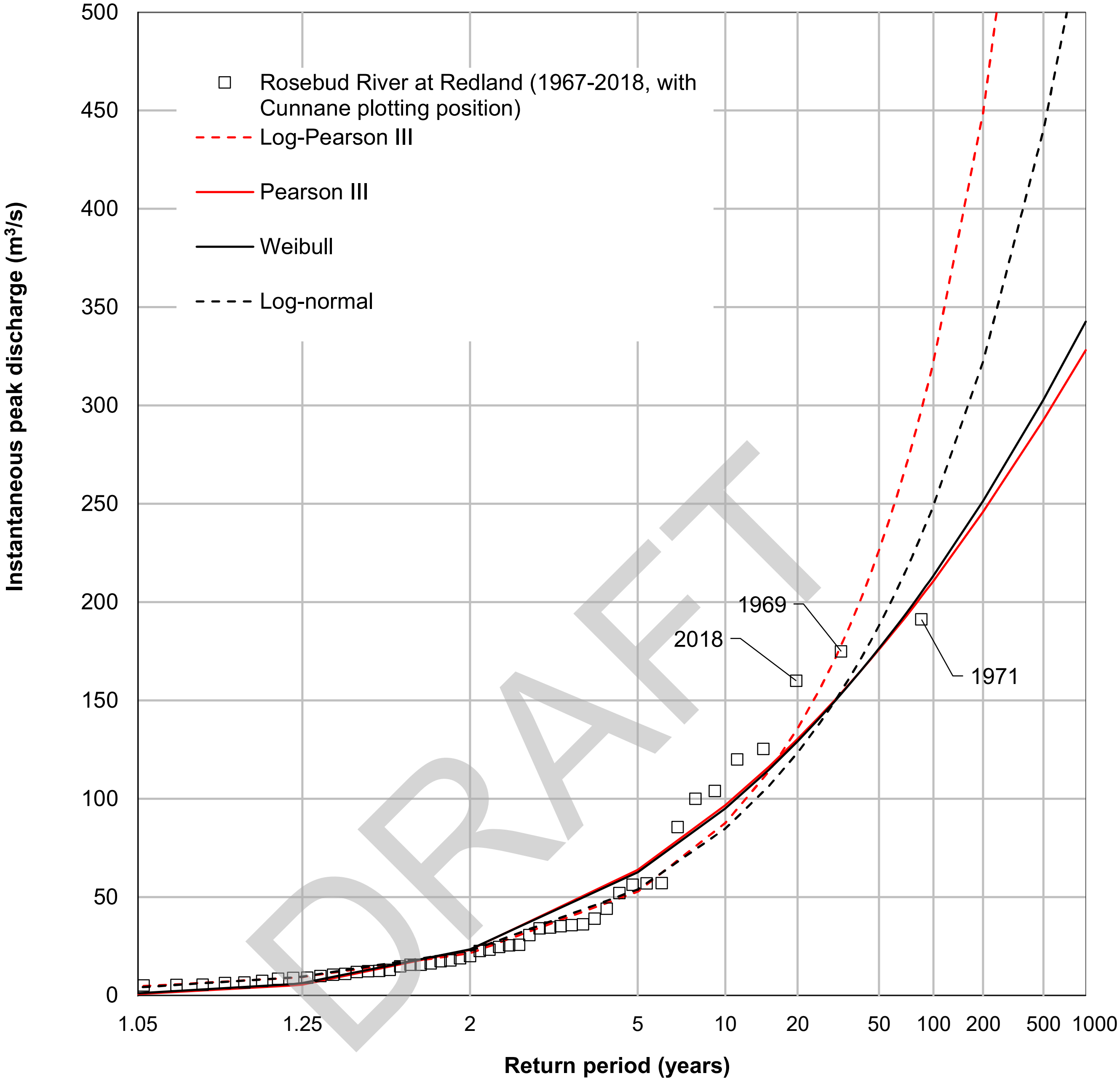
Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF ANNUAL MAXIMUM DISCHARGES OF ROSEBUD RIVER AT REDLAND AND BELOW CARSTAIRS CREEK

FIGURE 26



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF FLOOD FREQUENCY CURVES FOR ROSEBUD RIVER AT REDLAND

FIGURE 27

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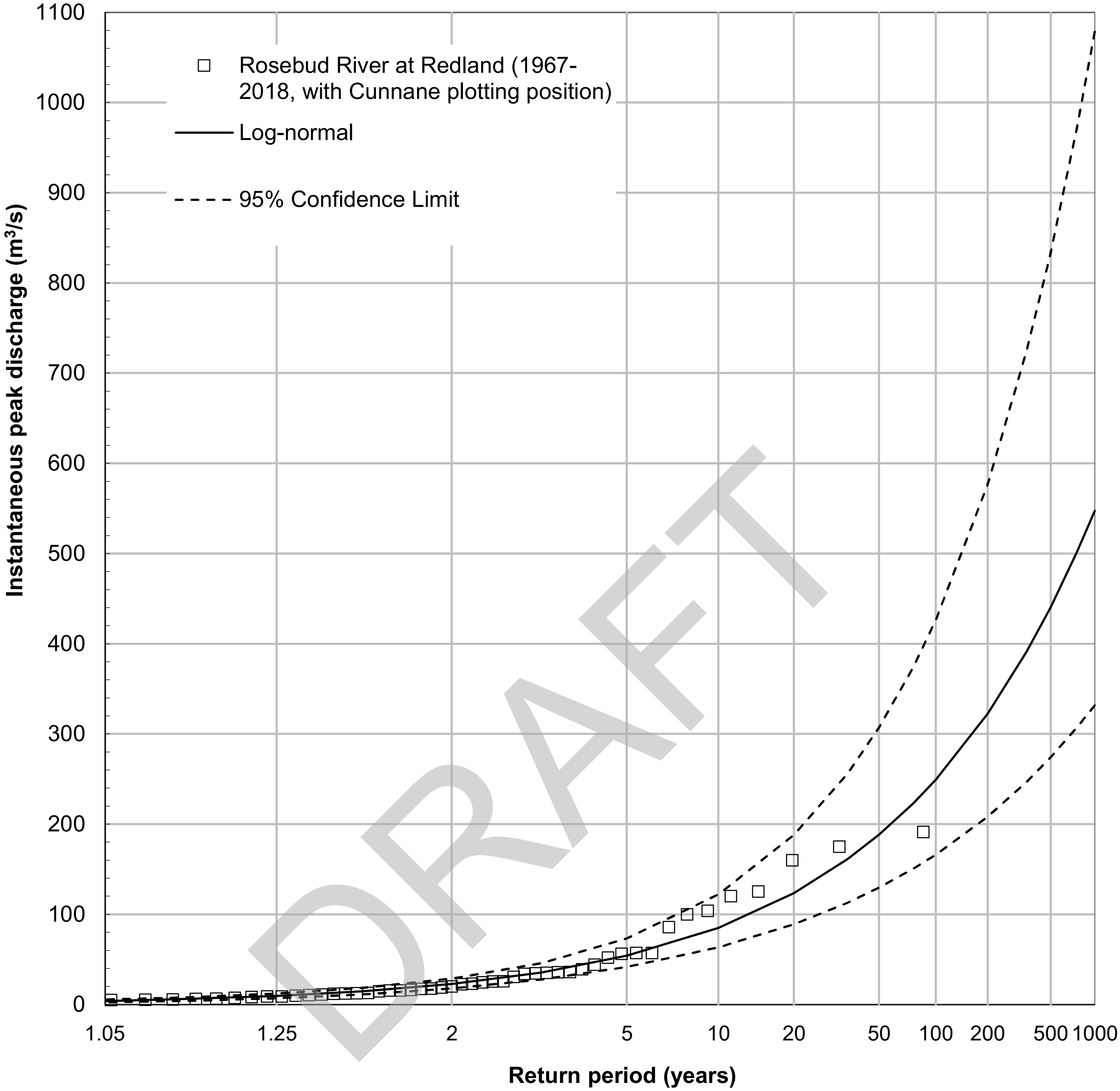

SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ADOPTED FLOOD FREQUENCY CURVE
FOR ROSEBUD RIVER AT REDLAND

FIGURE 28

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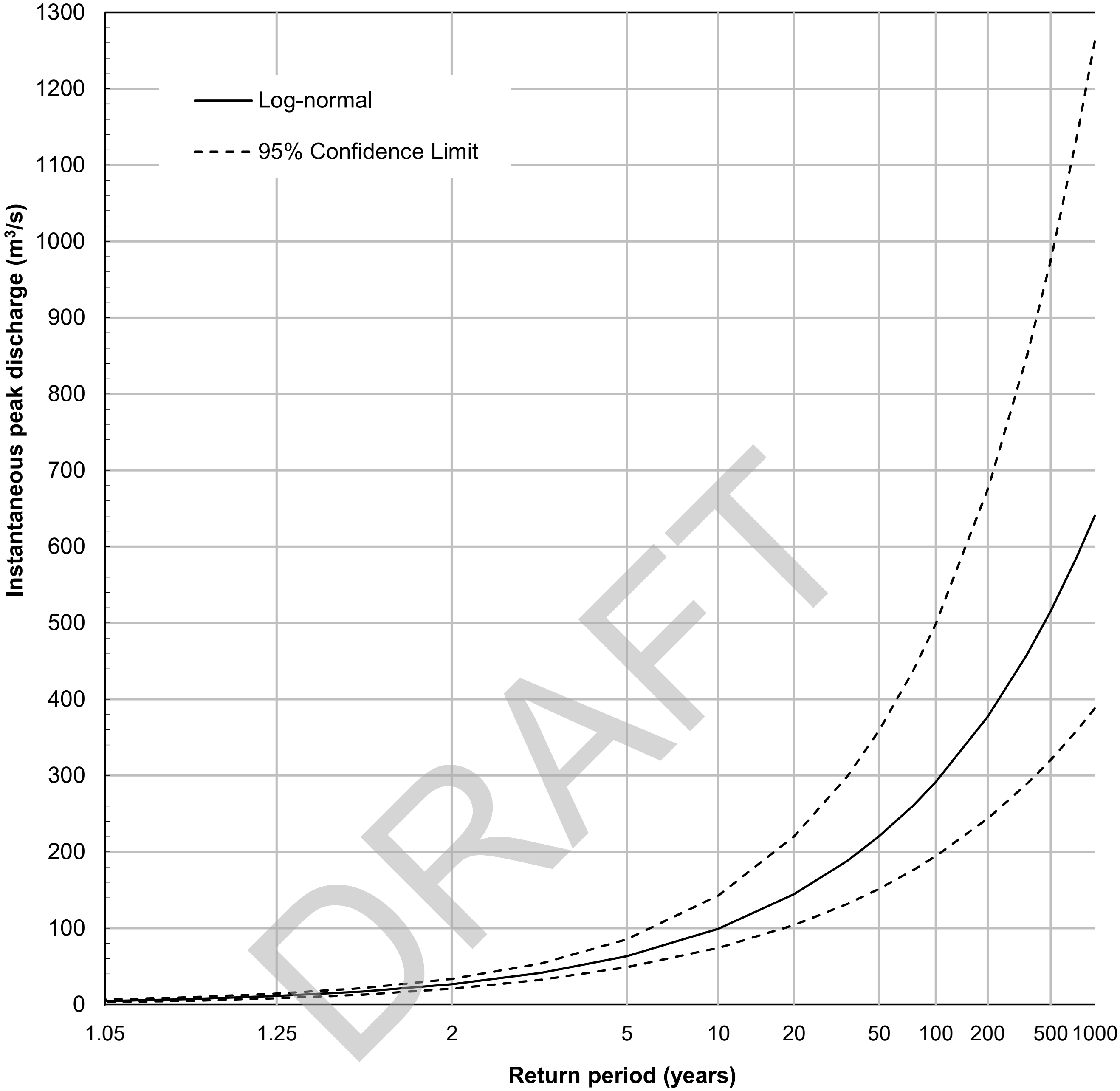

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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

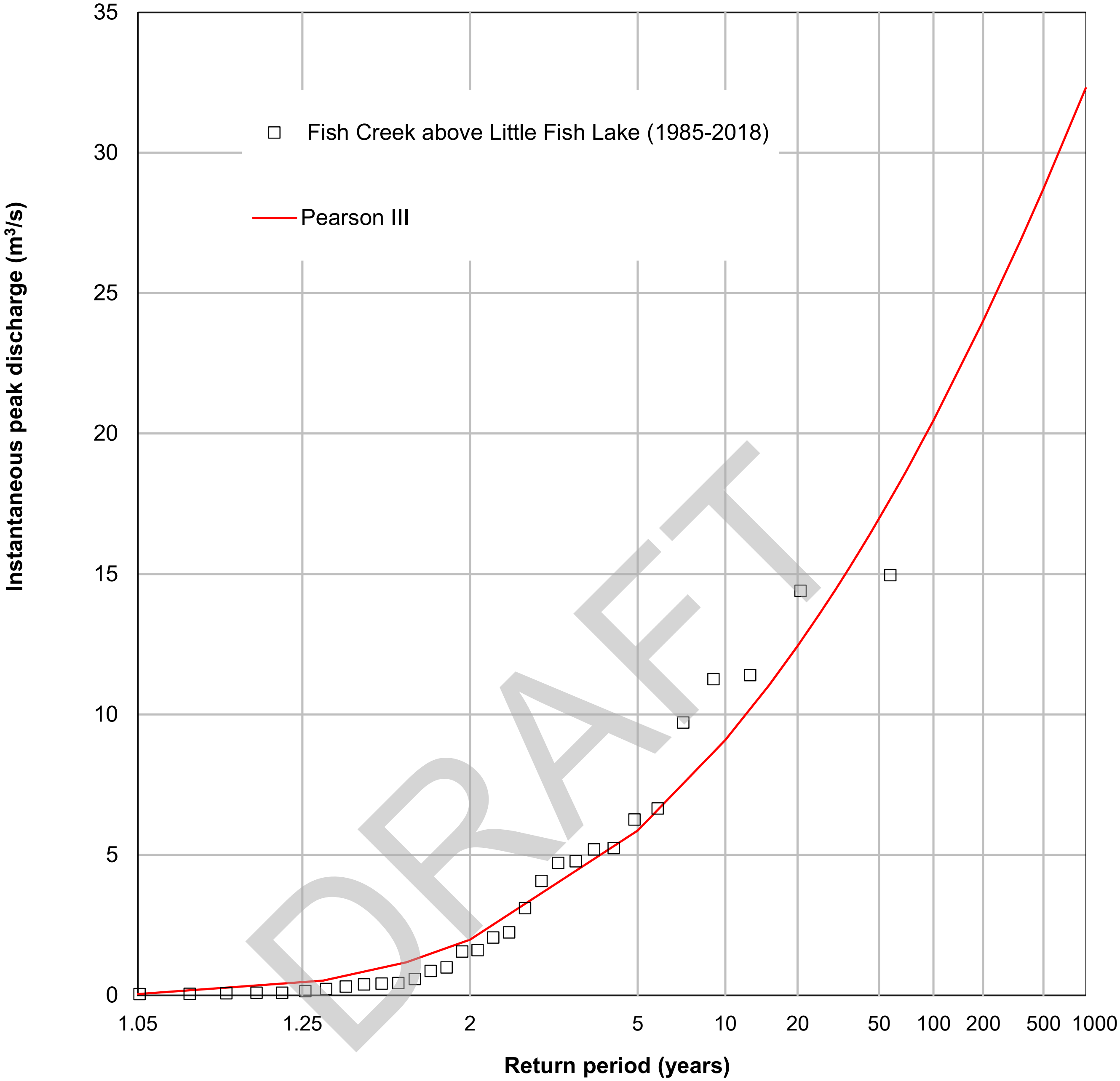
Job: 1003877

Date: Mar-2019

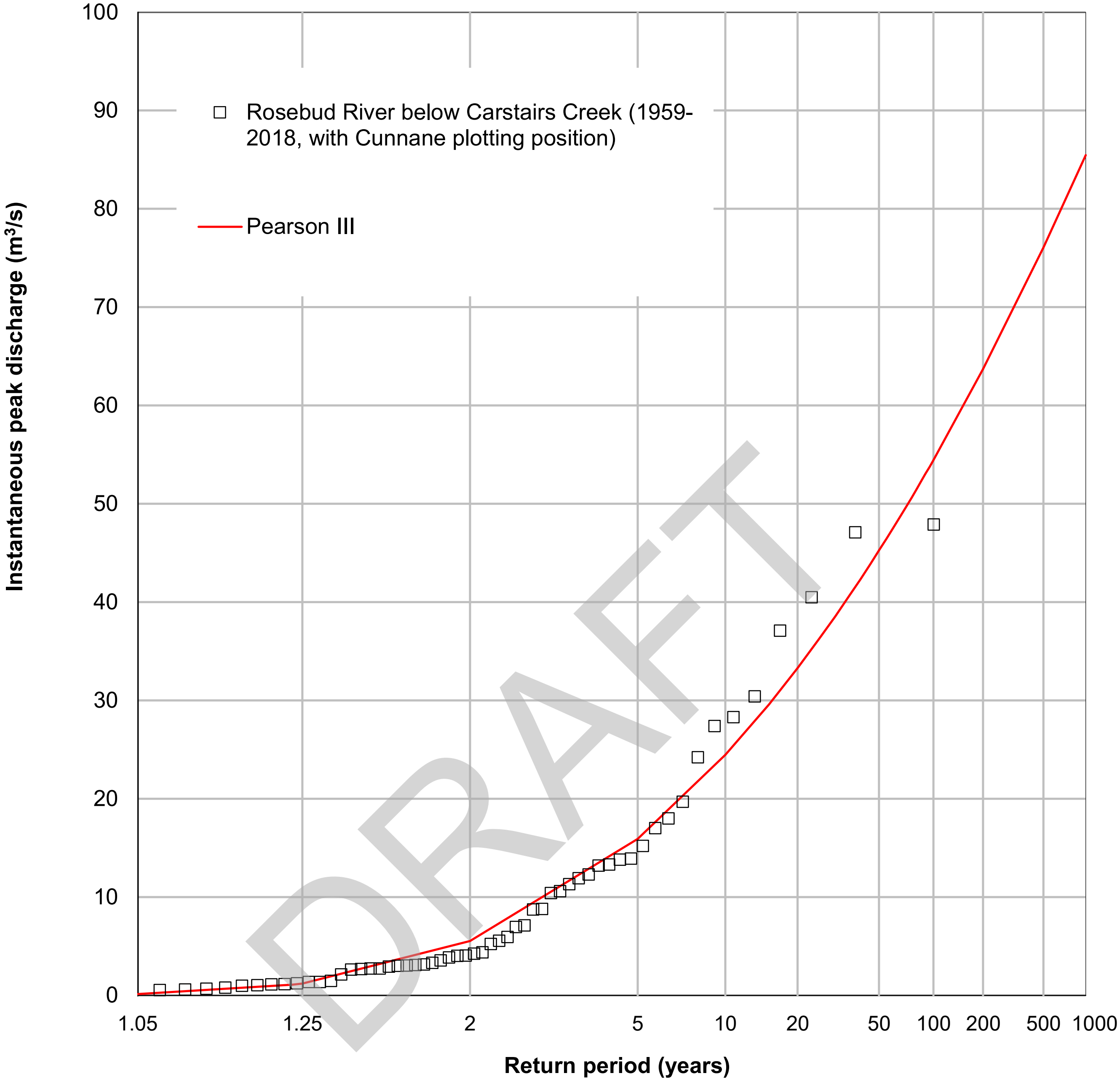
DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ADOPTED FLOOD FREQUENCY CURVE FOR ROSEBUD RIVER AT THE MOUTH

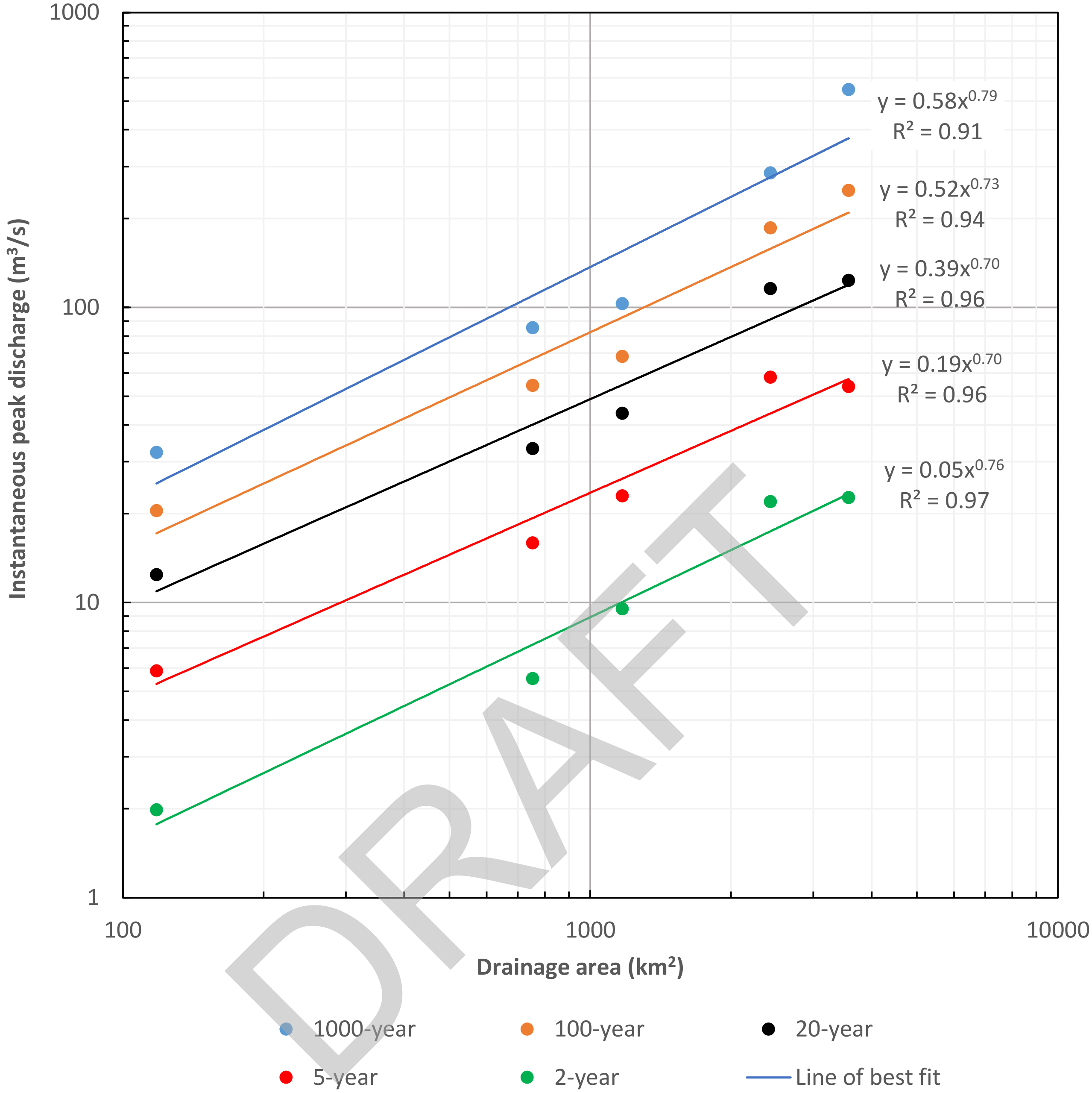
FIGURE 29



Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*ADOPTED FLOOD FREQUENCY CURVE FOR FISH CREEK ABOVE LITTLE FISH LAKE*
	Job: 1003877 / *Date: Mar-2019*	*FIGURE 30*



Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*ADOPTED FLOOD FREQUENCY CURVE FOR ROSEBUD RIVER BELOW CARSTAIRS CREEK*
	Job: 1003877 | *Date: Mar-2019*	*FIGURE 31*



Station ID	Station Name	Drainage Area (km²)	Period of Record
05CG006	Fish Creek above Little Fish Lake	118	1985-2018
05CE006	Rosebud River below Carstairs Creek	753	1957-2018
05CE020	Michichi Creek at Drumheller	1170	1979-2018
05CE002	Kneehills Creek near Drumheller	2430	1921-1930, 1936, 1957 and 1959-2018
05CE005	Rosebud River at Redland	3570	1967-2018

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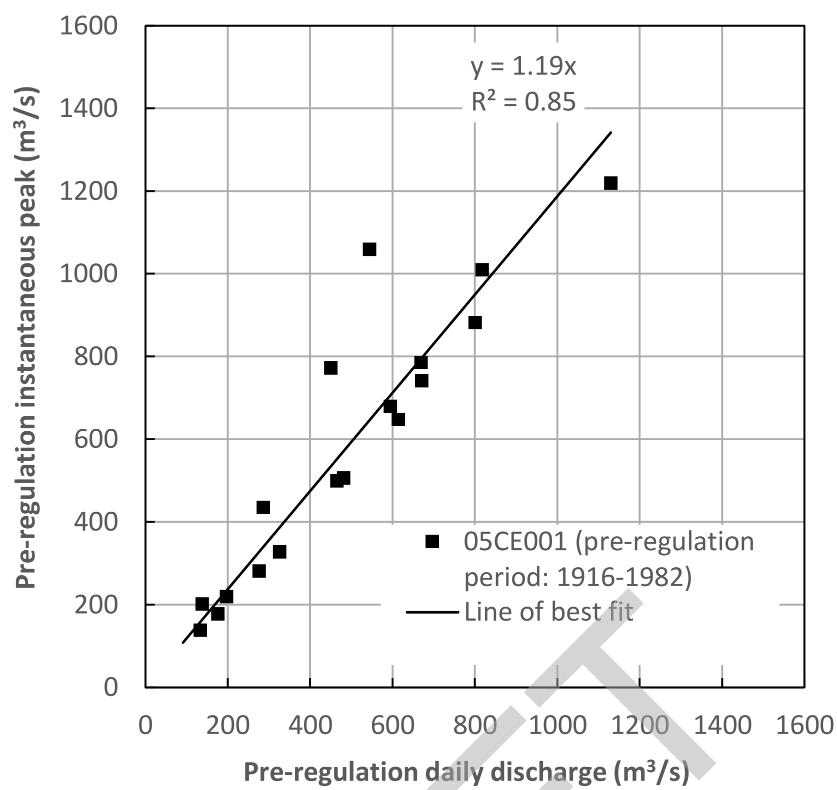
Coordinate System:
Units: As Shown

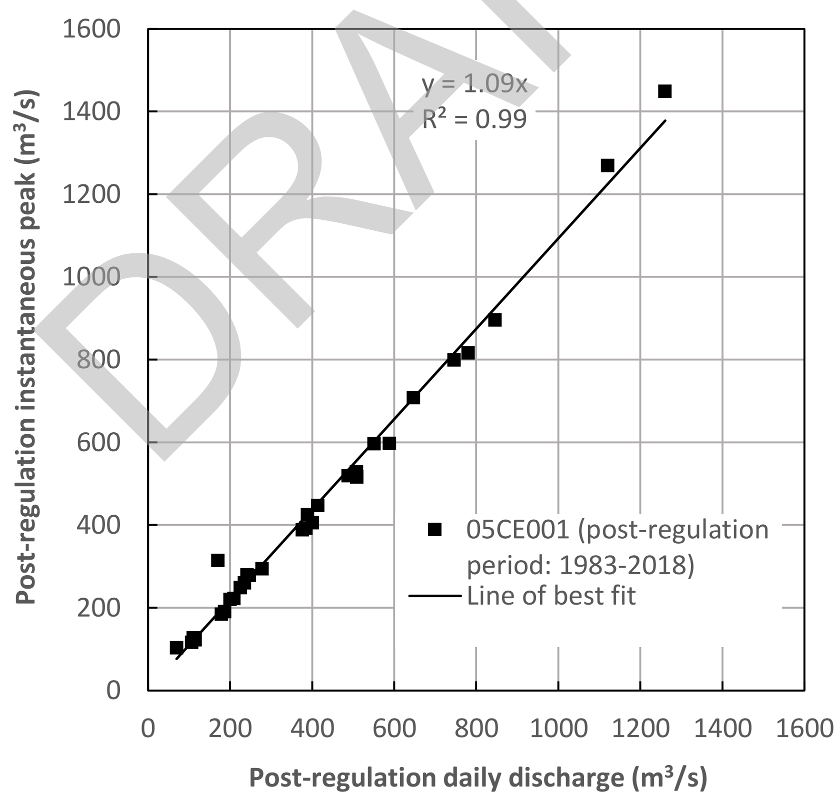
Job: 1003877 | *Date: Mar-2019*

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

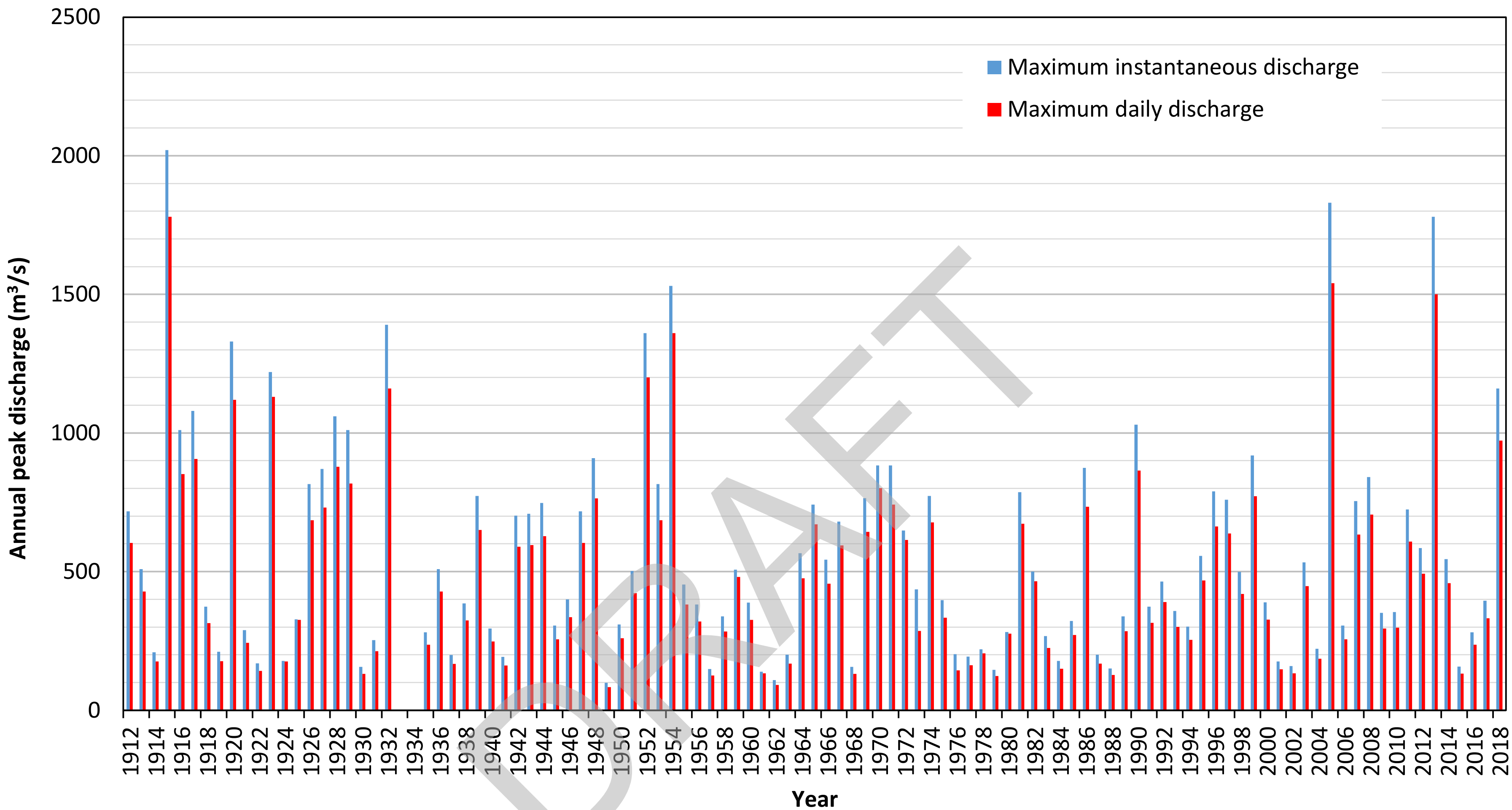
EXAMPLE REGIONAL FLOOD FREQUENCY RELATIONSHIP PLOTS

FIGURE 32





Alberta	SCALE – AS SHOWN	DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	RELATIONSHIPS BETWEEN MAXIMUM INSTANTANEOUS AND DAILY DISCHARGES FOR RED DEER RIVER AT DRUMHELLER
	Job: 1003877 / *Date: Mar-2019*	*FIGURE 33*



Notes:
1. The 1915, 1952 and 1954 data are estimated peaks from highwater mark elevations by Alberta Environment.
2. The 1912-1915, 1926, and 1931-1958 data were based on the records for Red Deer River at Red Deer (WSC Station 05CC002).
3. The 1916-1925, 1927-1930 and 1959-1982 data are from the pre-regulation flow records for Red Deer River at Drumheller (WSC Station 05CE001).
4. The 1983-2018 data are from flow naturalization.

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SCALE – AS SHOWN

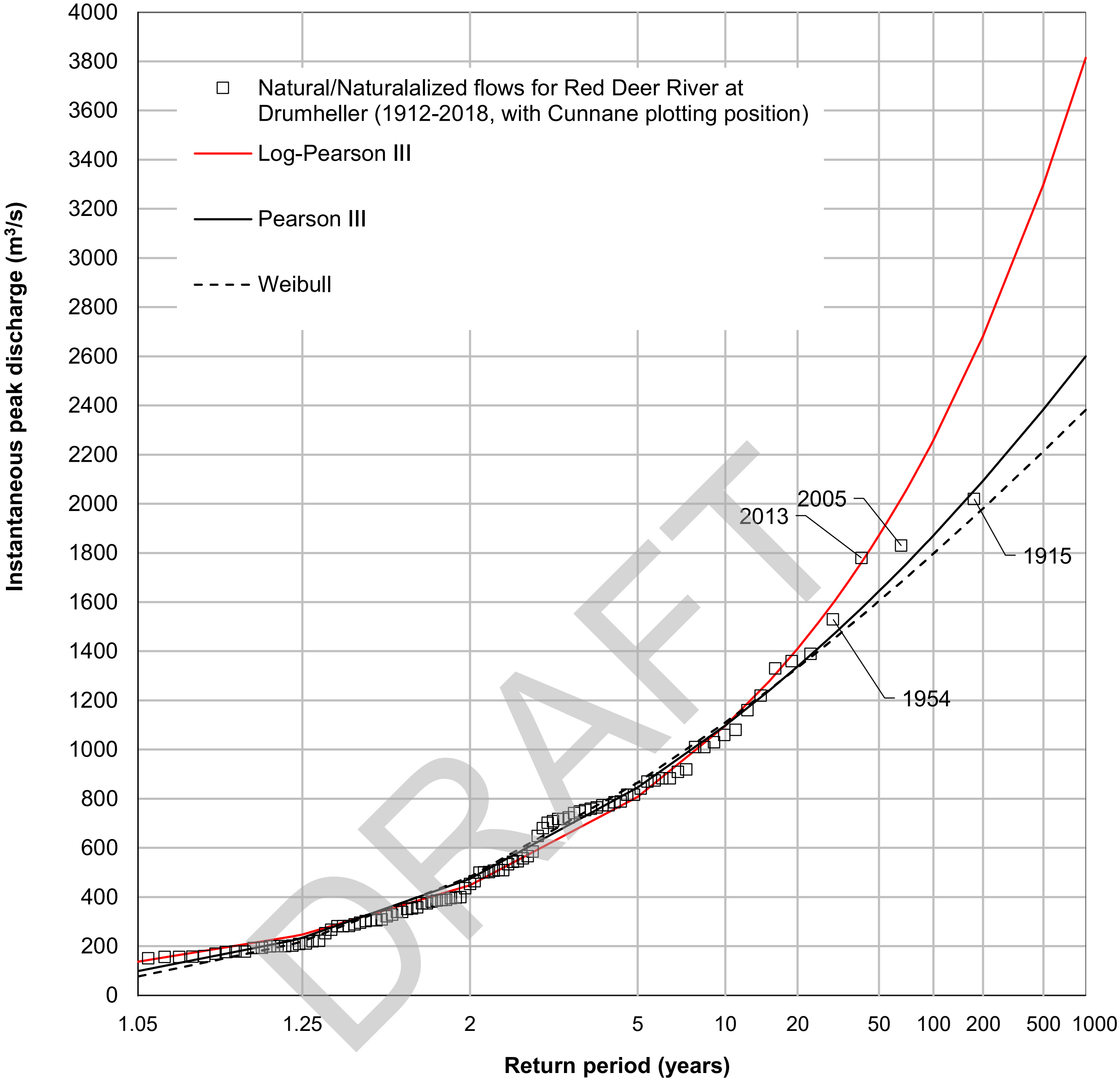
Coordinate System:
Units: As Shown

Job: 1003877

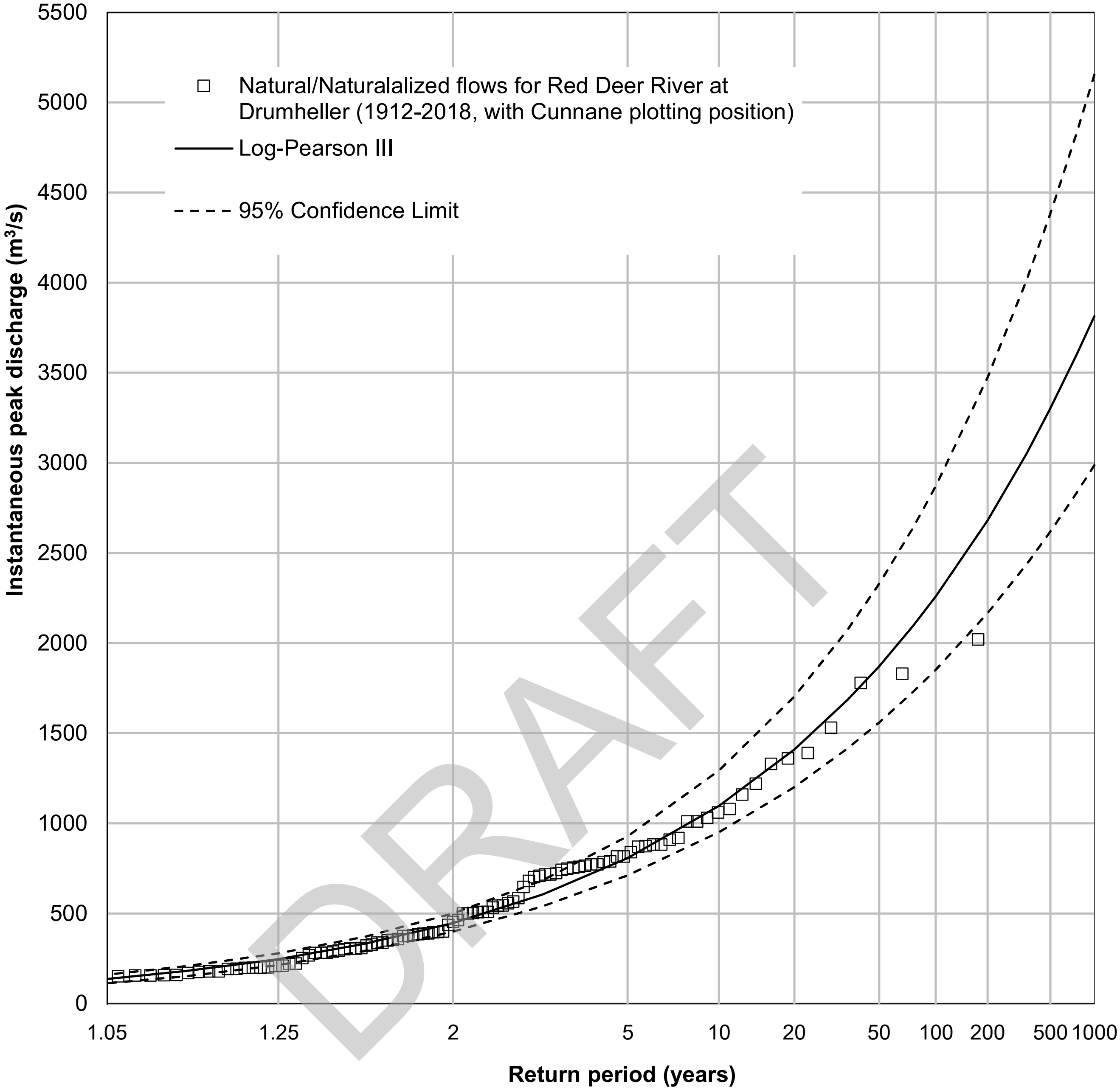
Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT
ANNUAL MAXIMUM DISCHARGES OF NATURAL/NATURALIZED FLOWS FOR RED DEER RIVER AT DRUMHELLER

FIGURE 34



Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT COMPARISON OF FLOOD FREQUENCY CURVES FOR NATURAL/NATURALIZED FLOWS OF RED DEER RIVER AT DRUMHELLER*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	
	Job: 1003877 / *Date: Mar-2019*	*FIGURE 35*



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ADOPTED FLOOD FREQUENCY CURVE FOR NATURAL/NATURALIZED FLOWS OF RED DEER RIVER AT DRUMHELLER

FIGURE 36

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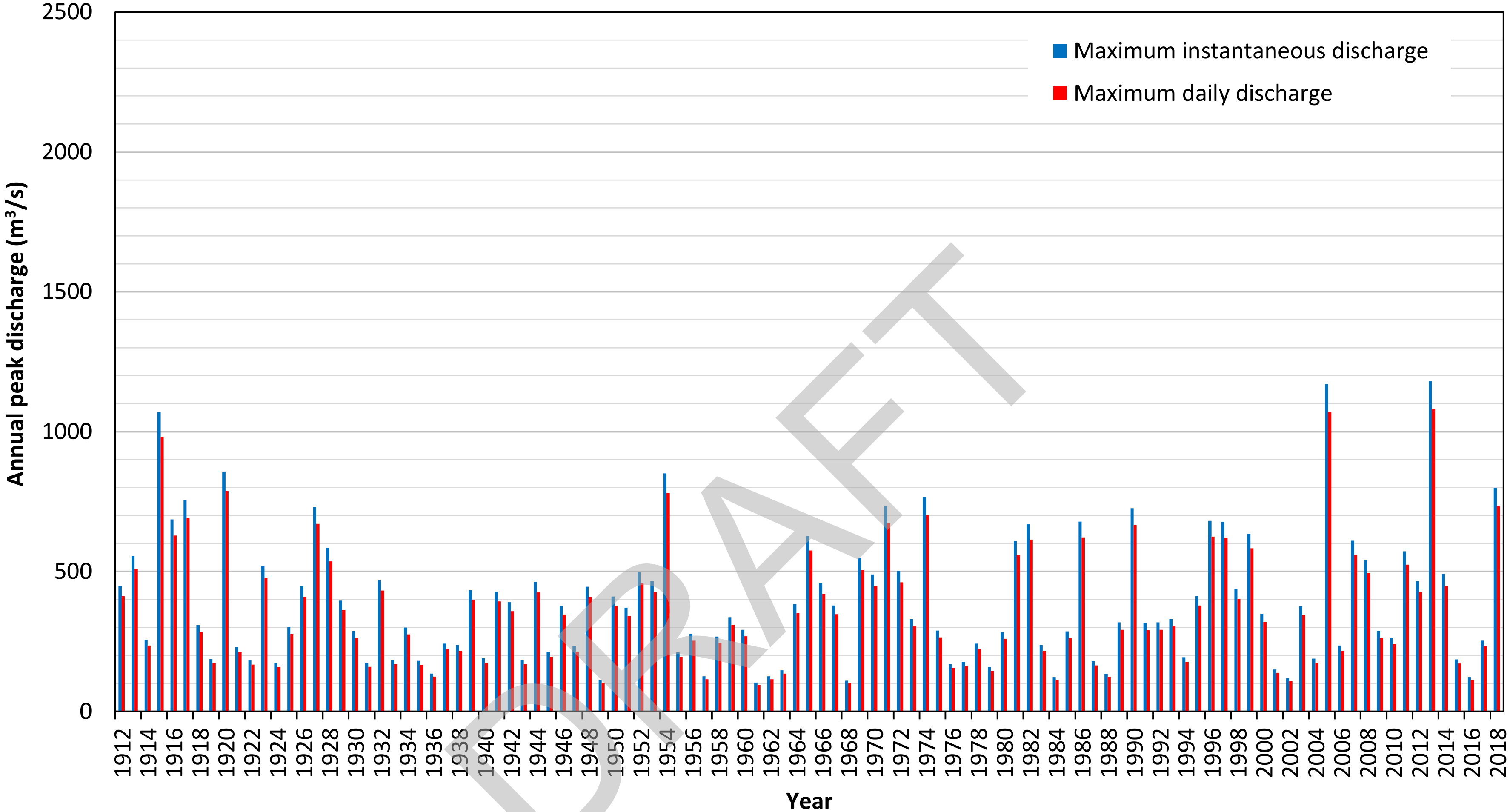
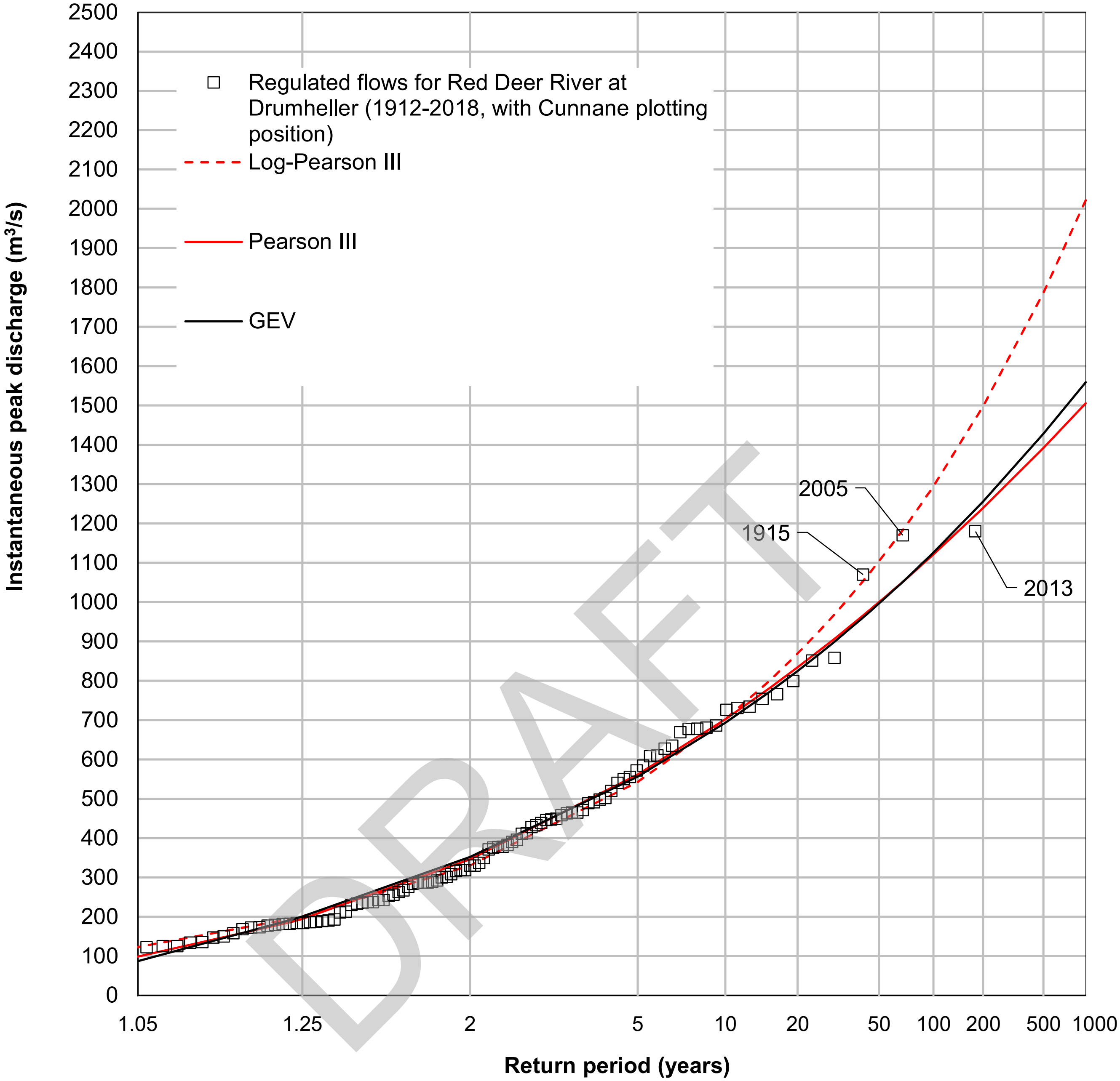


Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*ANNUAL MAXIMUM DISCHARGES OF REGULATED FLOWS FOR RED DEER RIVER AT DRUMHELLER*
	Job: 1003877 | *Date: Mar-2019*	*FIGURE 37*



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877 | *Date: Mar-2019*

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF FLOOD FREQUENCY CURVES FOR REGULATED FLOWS OF RED DEER RIVER AT DRUMHELLER

FIGURE 38

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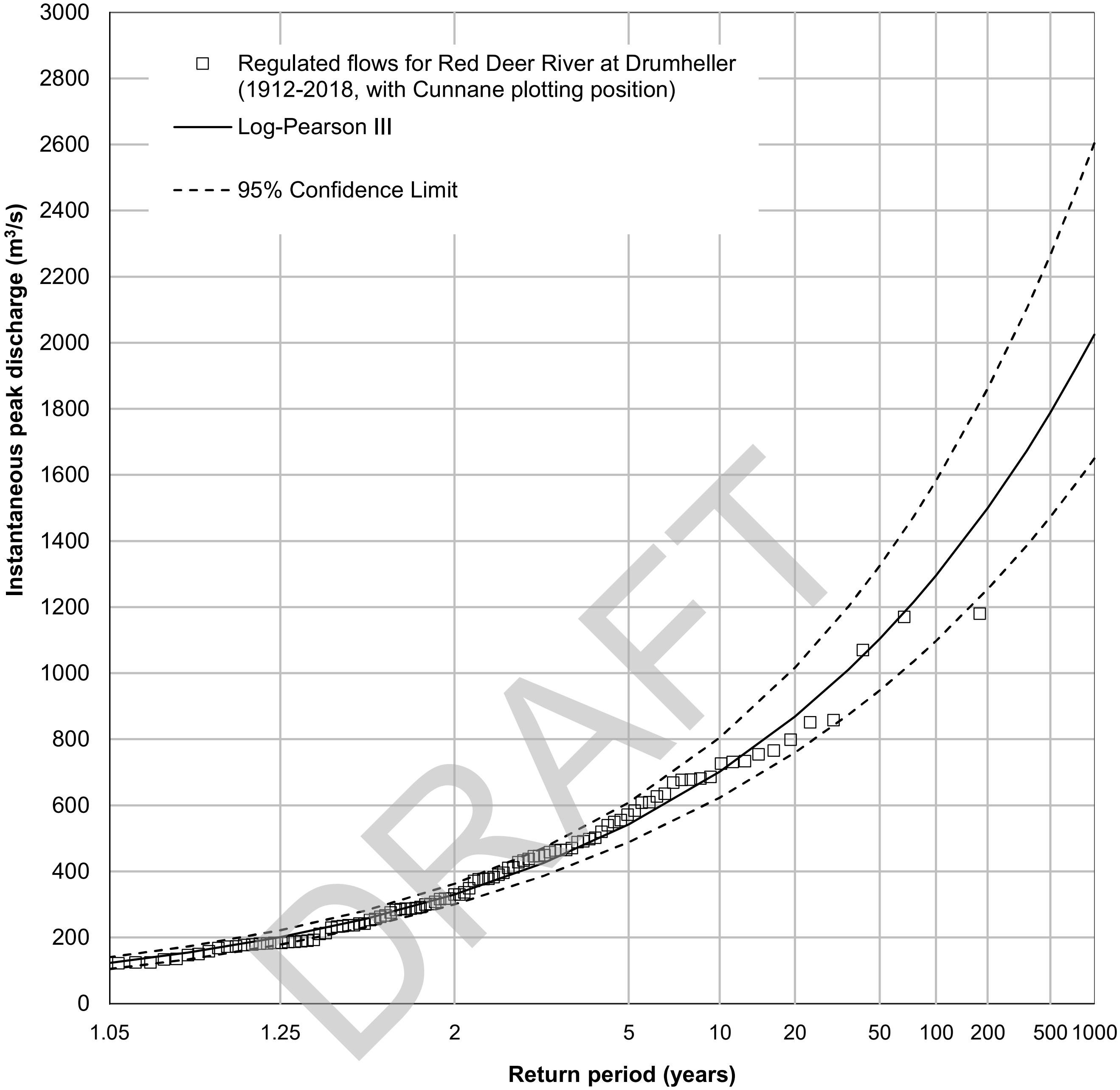
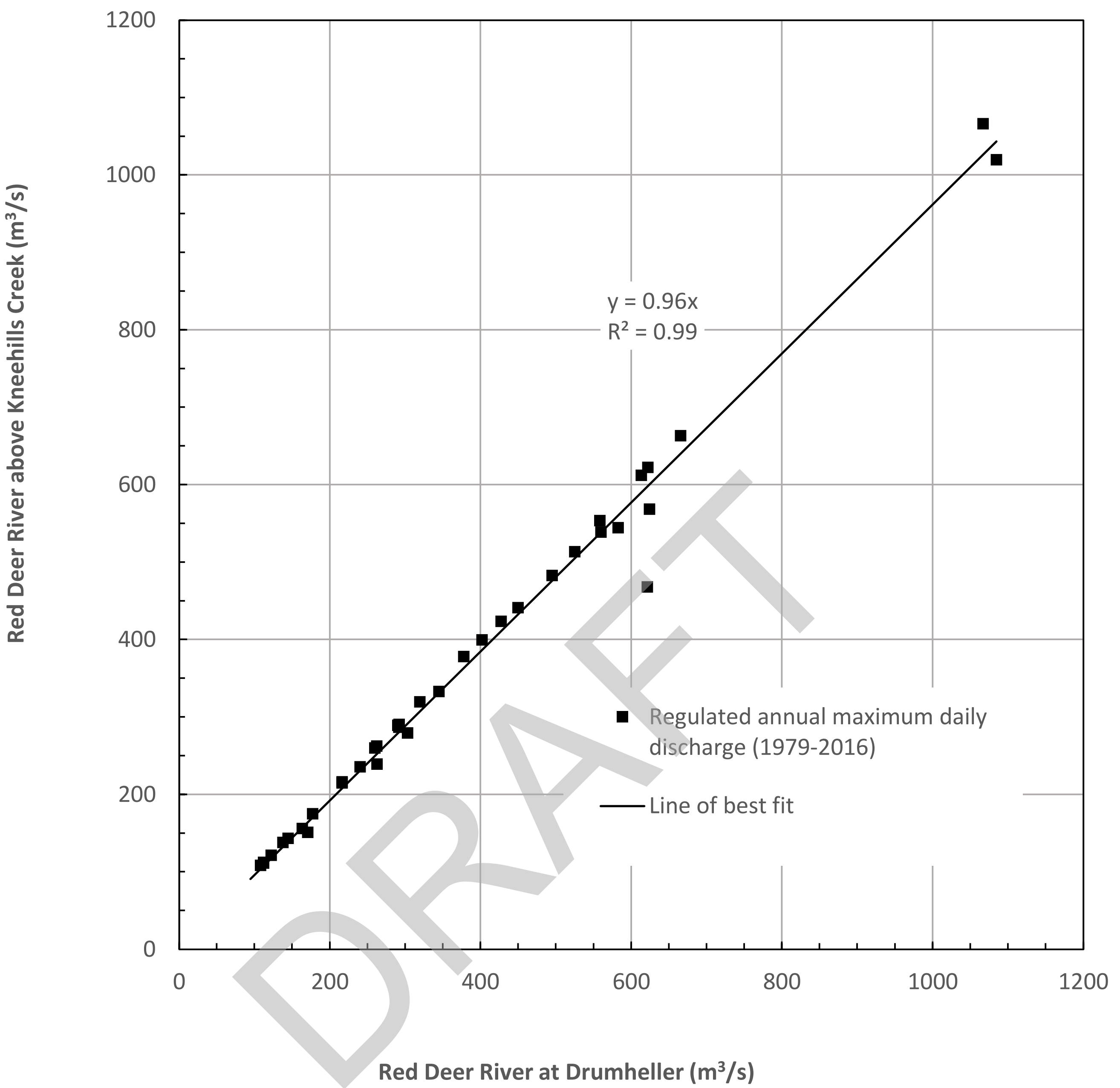
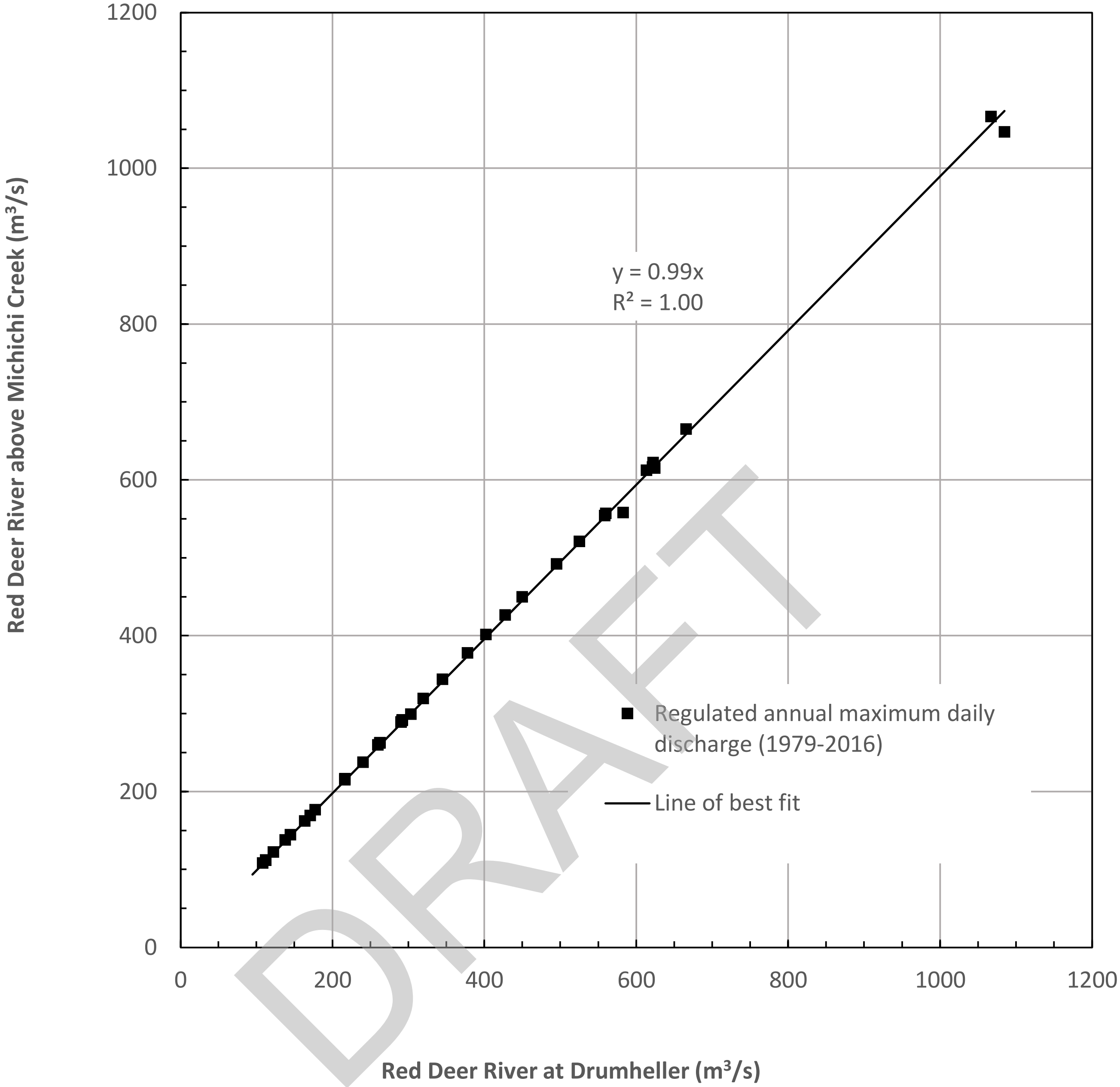


Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*SELECTED FLOOD FREQUENCY CURVE FOR REGULATED FLOWS OF RED DEER RIVER AT DRUMHELLER*
	Job: 1003877 / *Date: Mar-2019*	*FIGURE 39*



Alberta	SCALE – AS SHOWN	DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT COMPARISON OF ANNUAL PEAK DISCHARGES FOR RED DEER RIVER ABOVE KNEEHILLS CREEK AND AT DRUMHELLER
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown Job: 1003877 — Date: Mar-2019	FIGURE 40



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF ANNUAL PEAK DISCHARGES FOR RED DEER RIVER ABOVE MICHICHI CREEK AND AT DRUMHELLER

FIGURE 41

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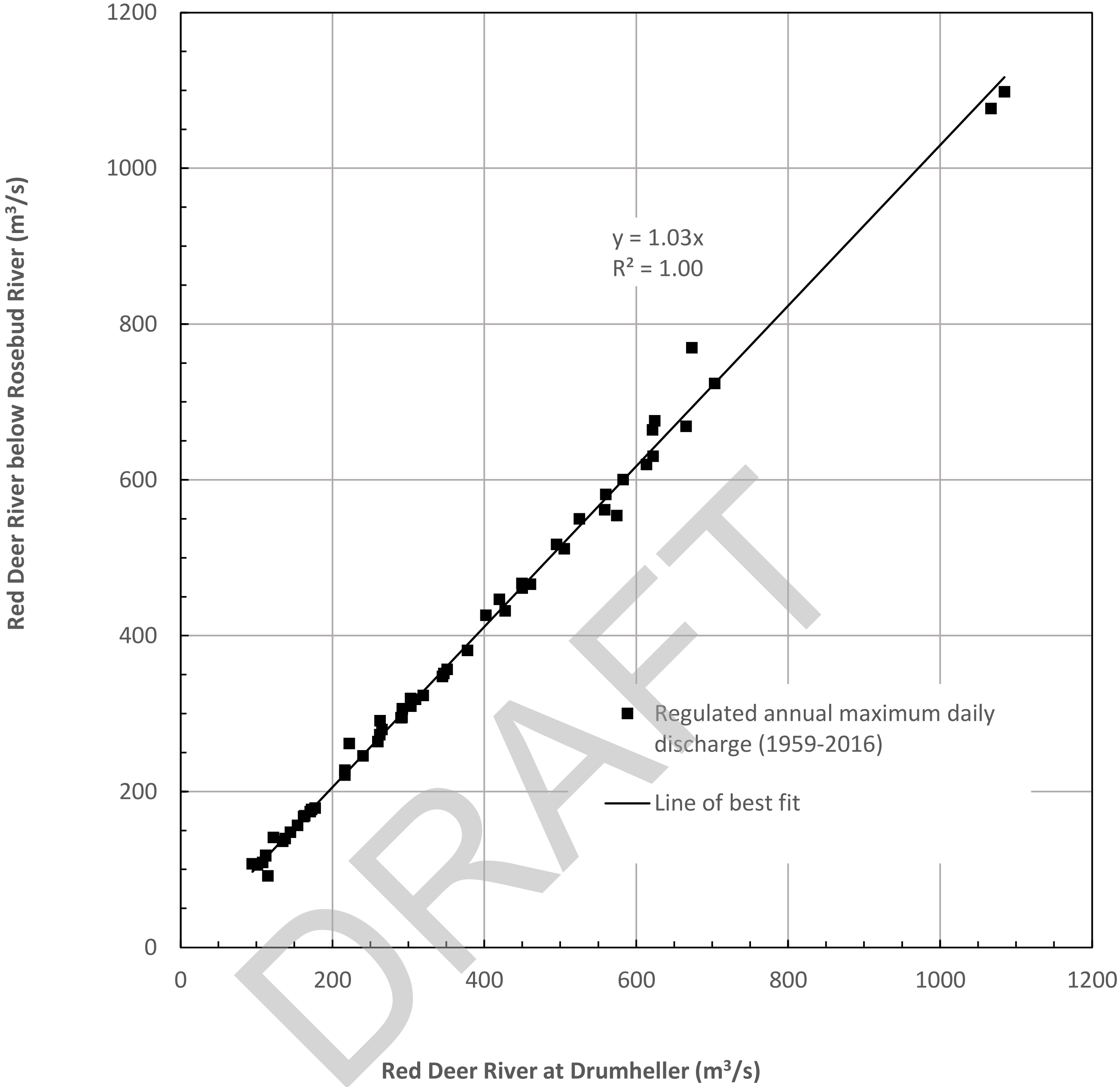
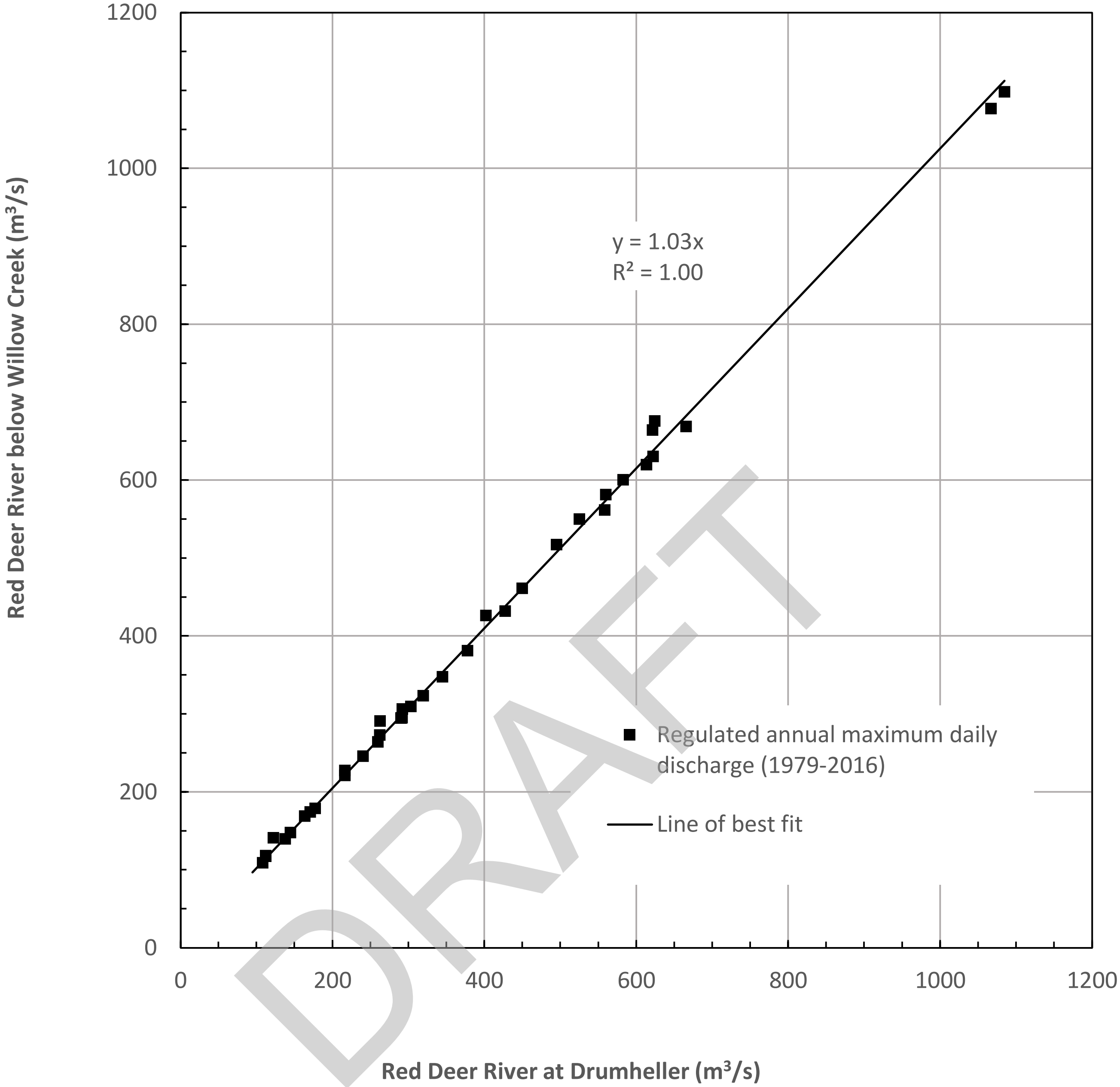


Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*COMPARISON OF ANNUAL PEAK DISCHARGES FOR RED DEER RIVER BELOW ROSEBUD RIVER AND AT DRUMHELLER*
	Job: 1003877 / *Date: Mar-2019*	*FIGURE 42*



SCALE – AS SHOWN

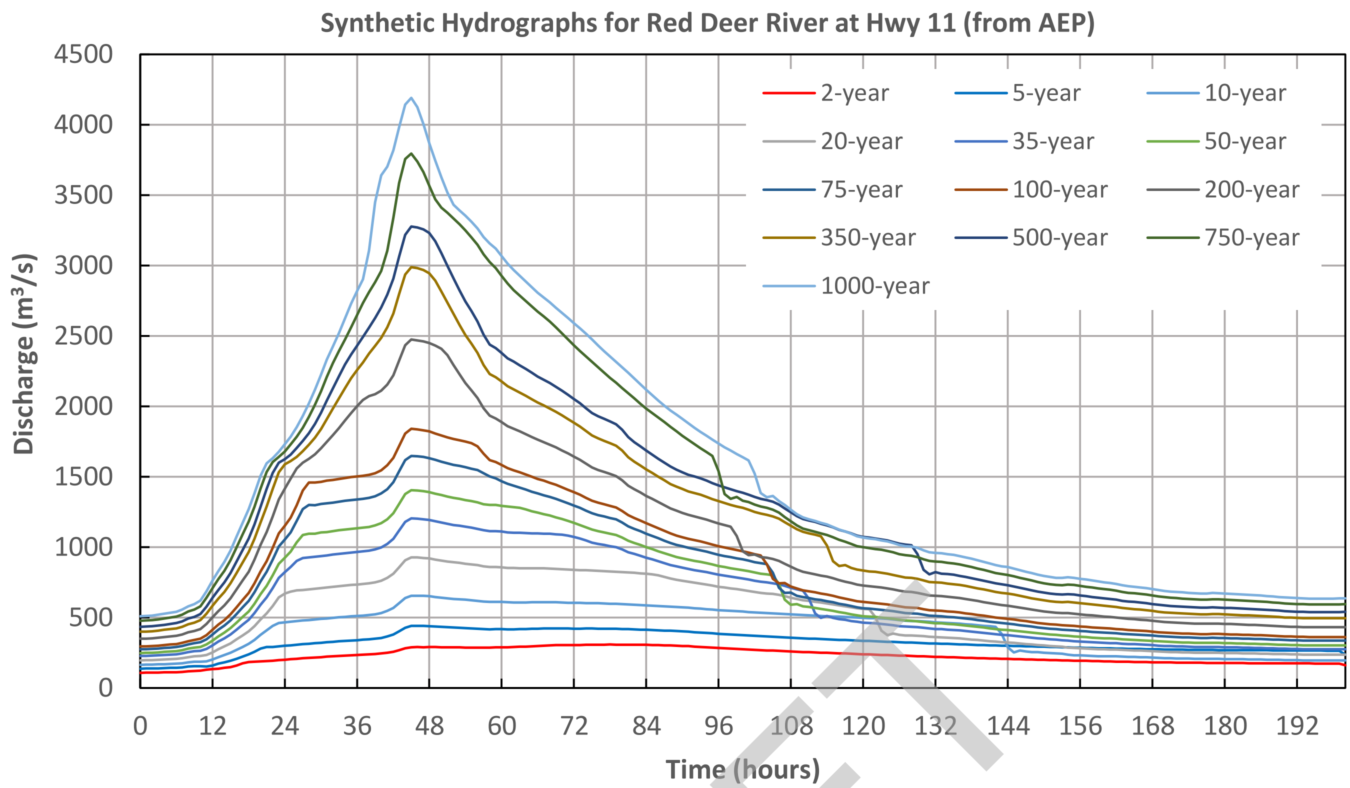
Coordinate System:
Units: As Shown

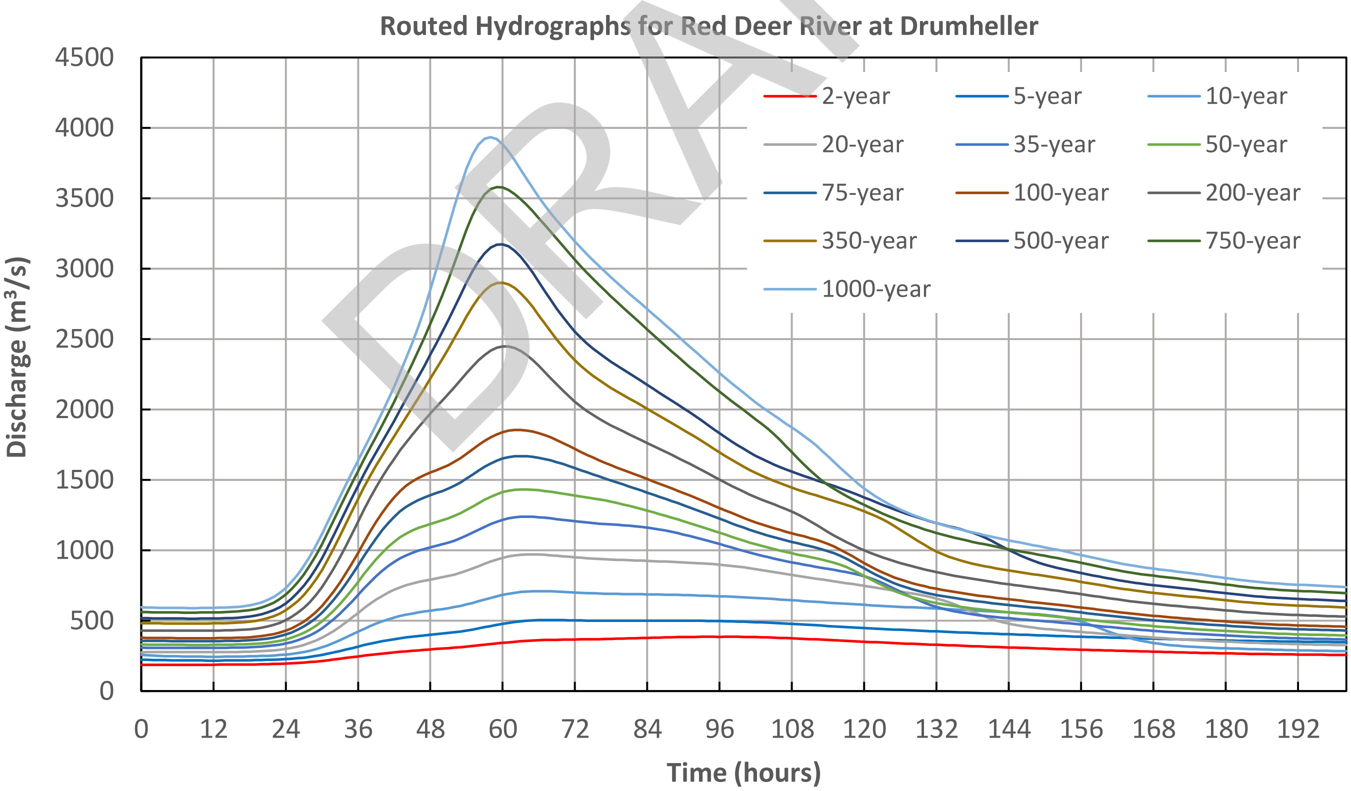
Job: 1003877 | Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF ANNUAL PEAK DISCHARGES FOR RED DEER RIVER BELOW WILLOW CREEK AND AT DRUMHELLER

FIGURE 43





Alberta

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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

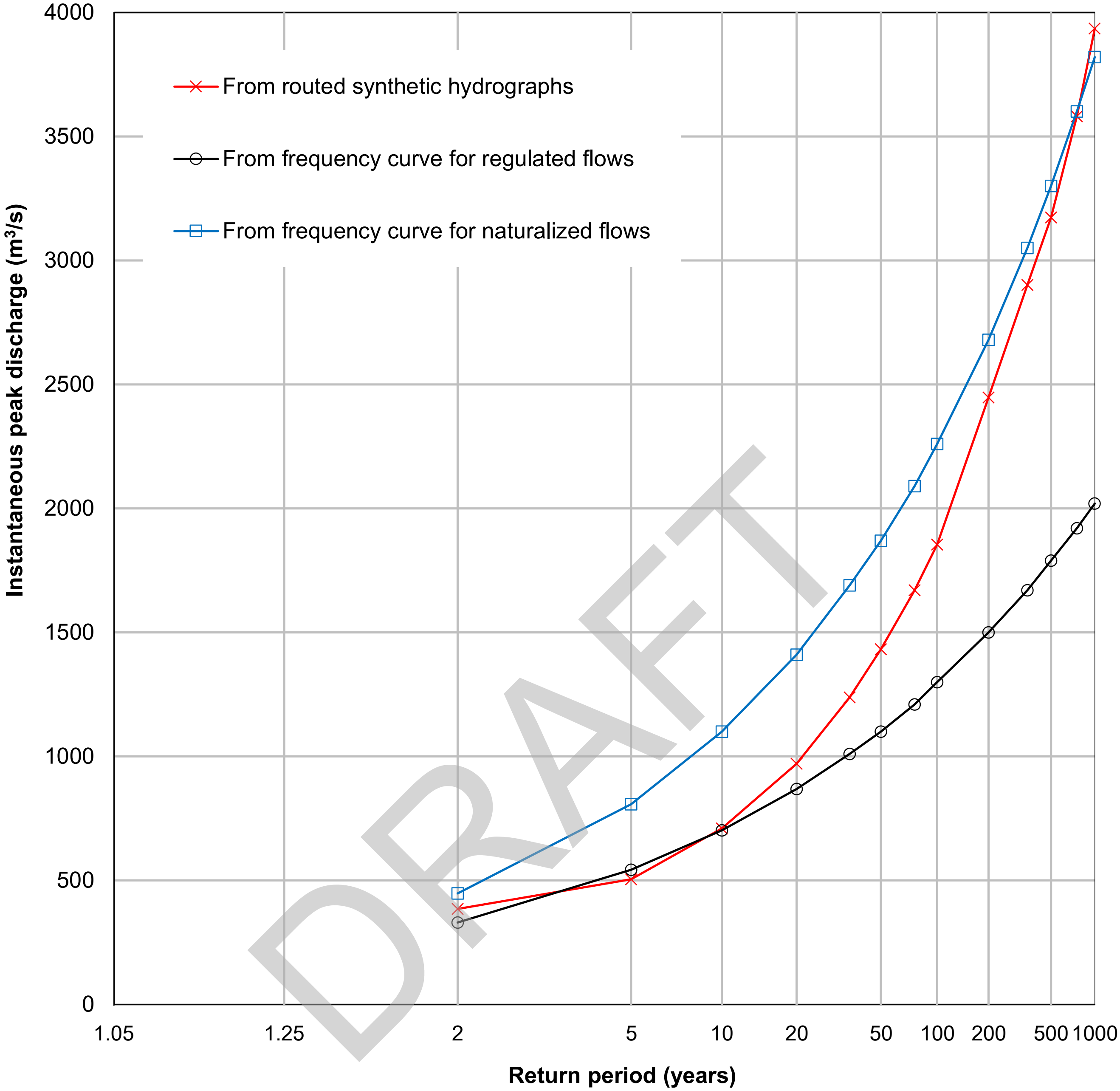
Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

SYNTHETIC FLOOD HYDROGRAPHS FOR RED DEER RIVER AT HWY 11 AND AT DRUMHELLER

FIGURE 44



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT
COMPARISON OF FLOOD FREQUENCY ESTIMATES FROM SYNTHETIC FLOOD HYDROGRAPH ROUTING AND FROM FLOOD FREQUENCY ANALYSIS

FIGURE 45

Alberta

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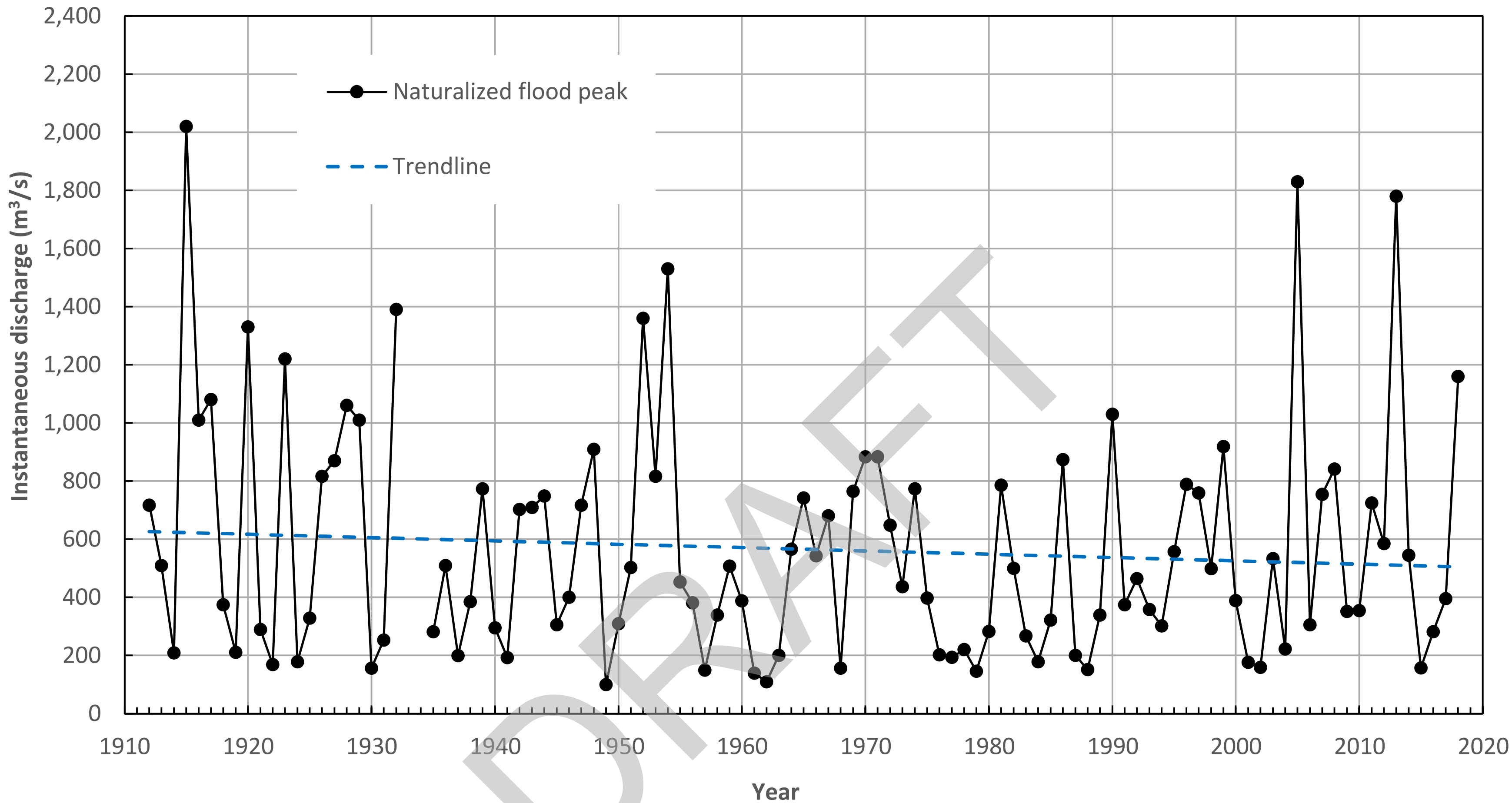

Alberta

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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

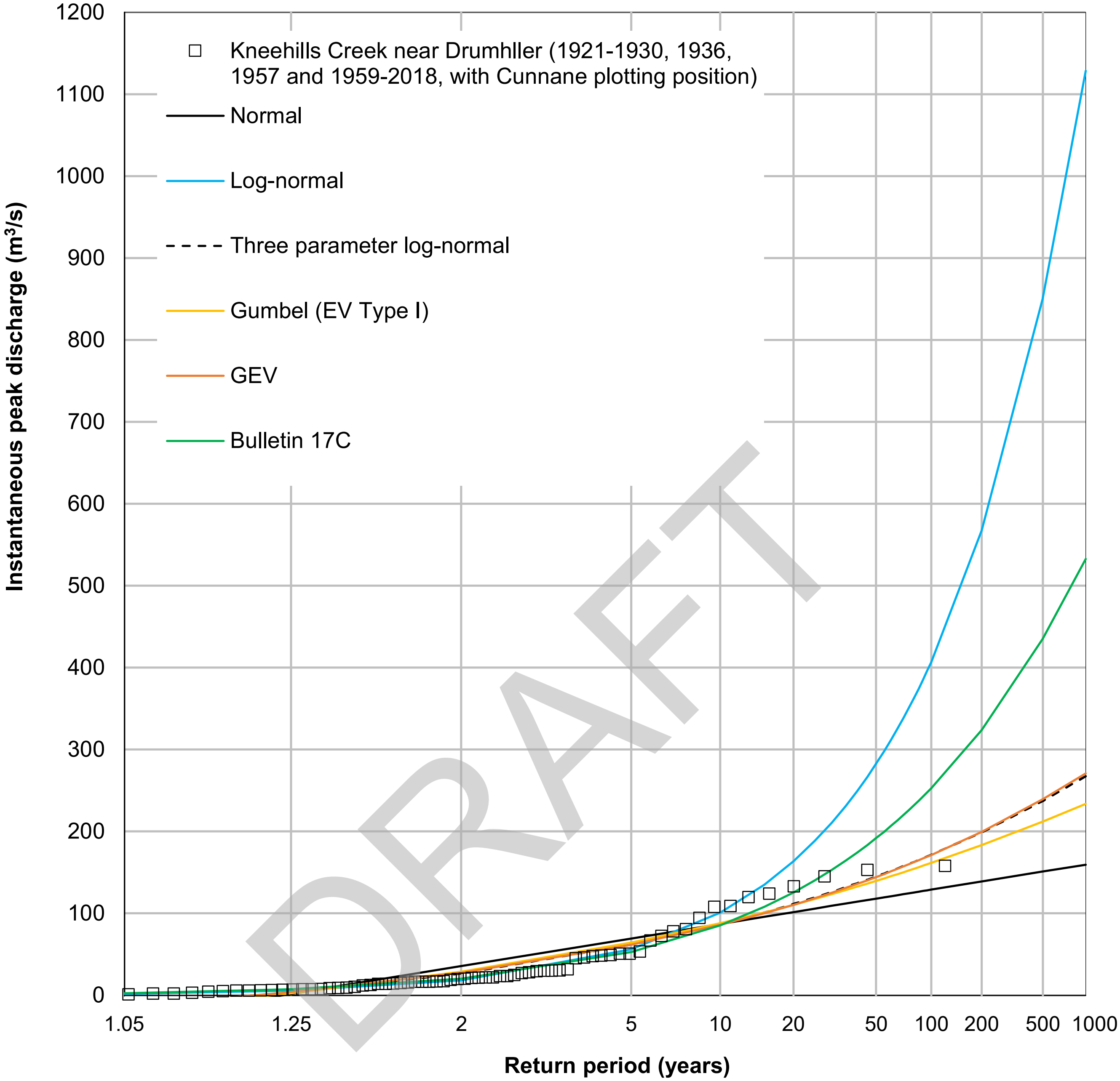
Job: 1003877

Date: Mar-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT
TREND OF NATURALIZED ANNUAL PEAK DISCHARGES FOR RED DEER RIVER AT DRUMHELLER

FIGURE 46

Appendix A
Additional Evaluated Frequency Distributions



Alberta

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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

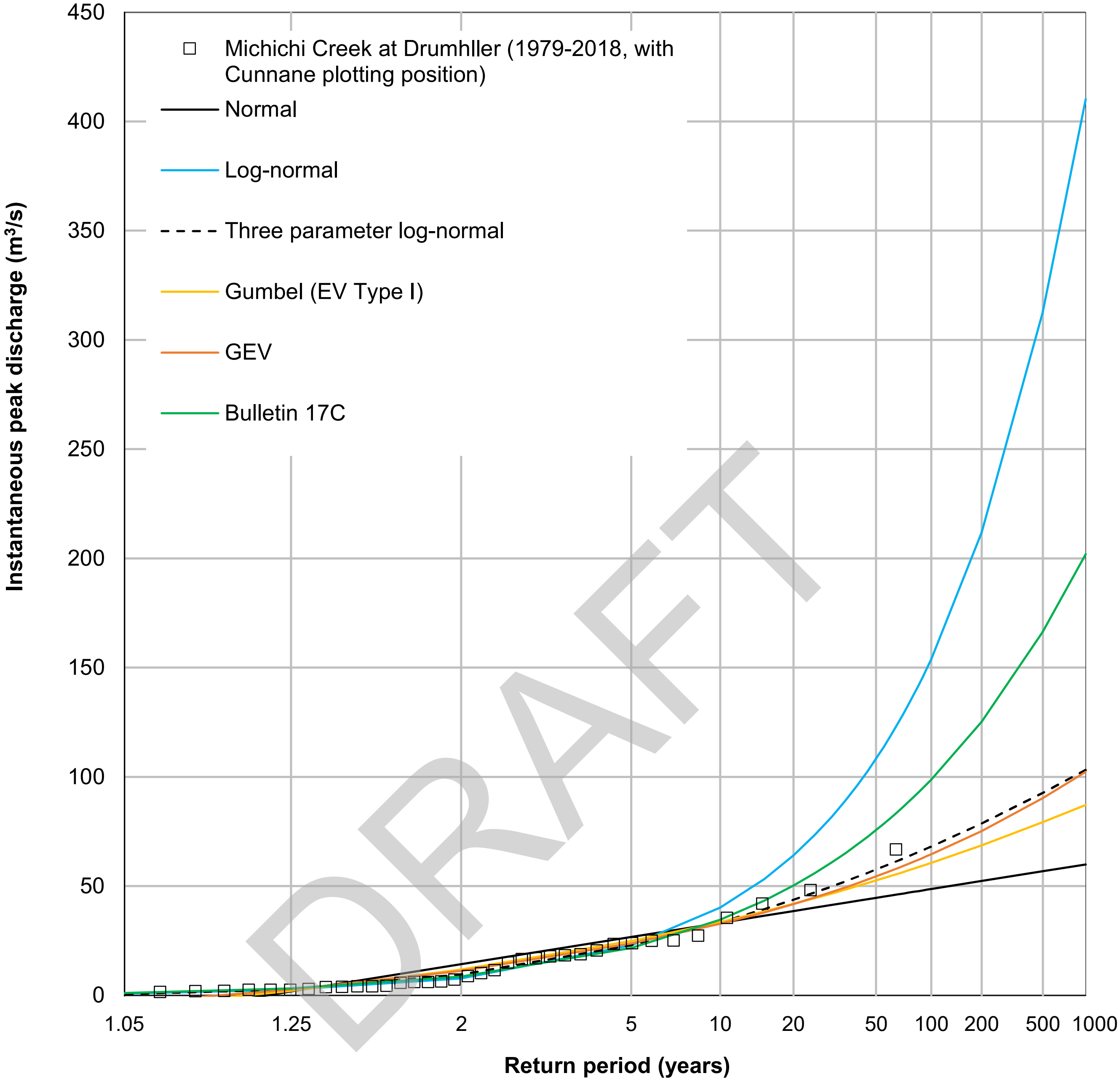
Job: 1003877

Date: Aug-2019

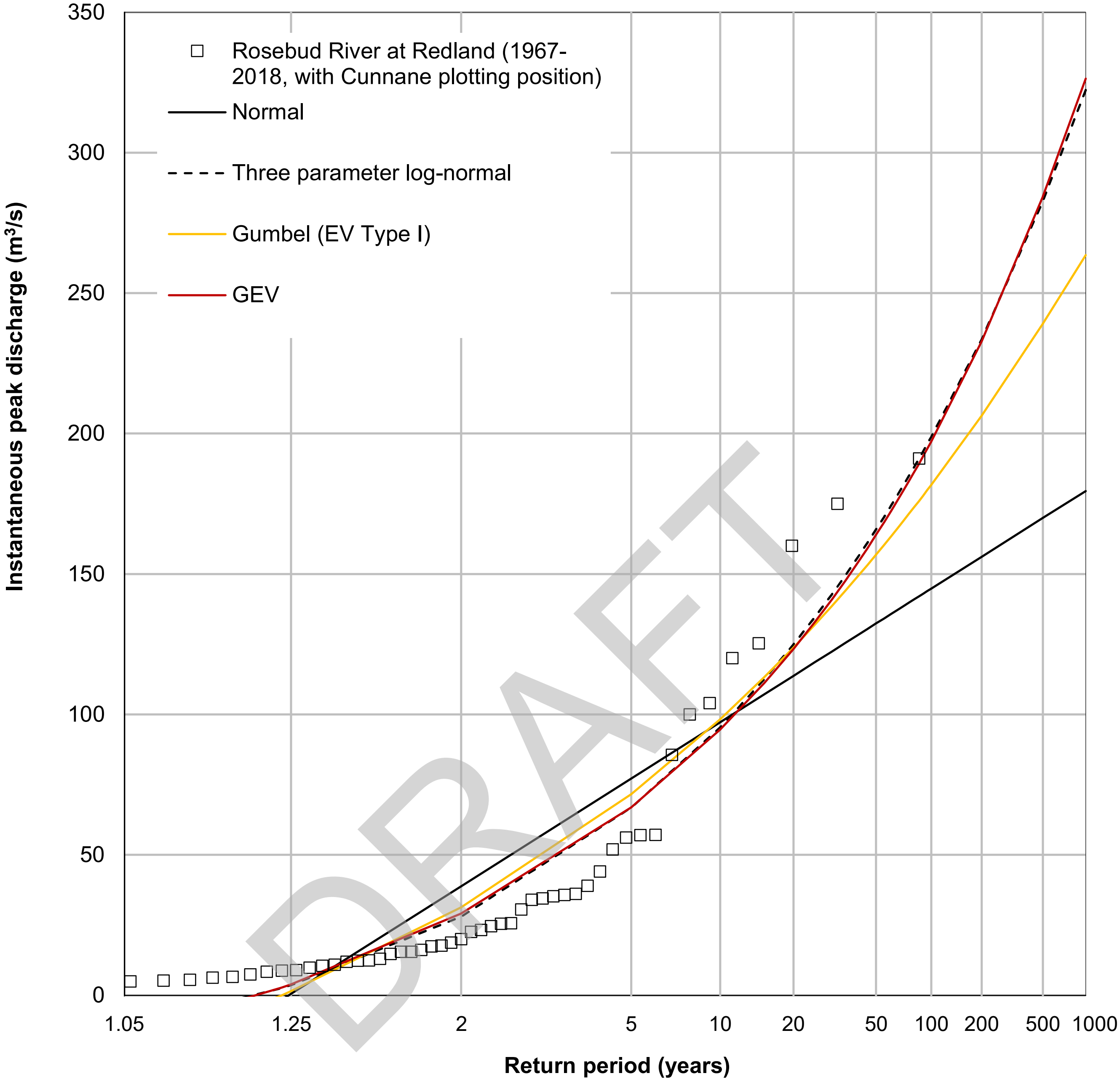
DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF FLOOD FREQUENCY CURVES FOR KNEEHILLS CREEK NEAR DRUMHELLER

FIGURE A-1



Alberta	SCALE – AS SHOWN	*DRUMHELLER RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*COMPARISON OF FLOOD FREQUENCY CURVES FOR MICHICHI CREEK AT DRUMHELLER*
	Job: 1003877 / *Date: Aug-2019*	*FIGURE A-2*



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Aug-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF FLOOD FREQUENCY CURVES FOR ROSEBUD RIVER AT REDLAND

FIGURE A-3

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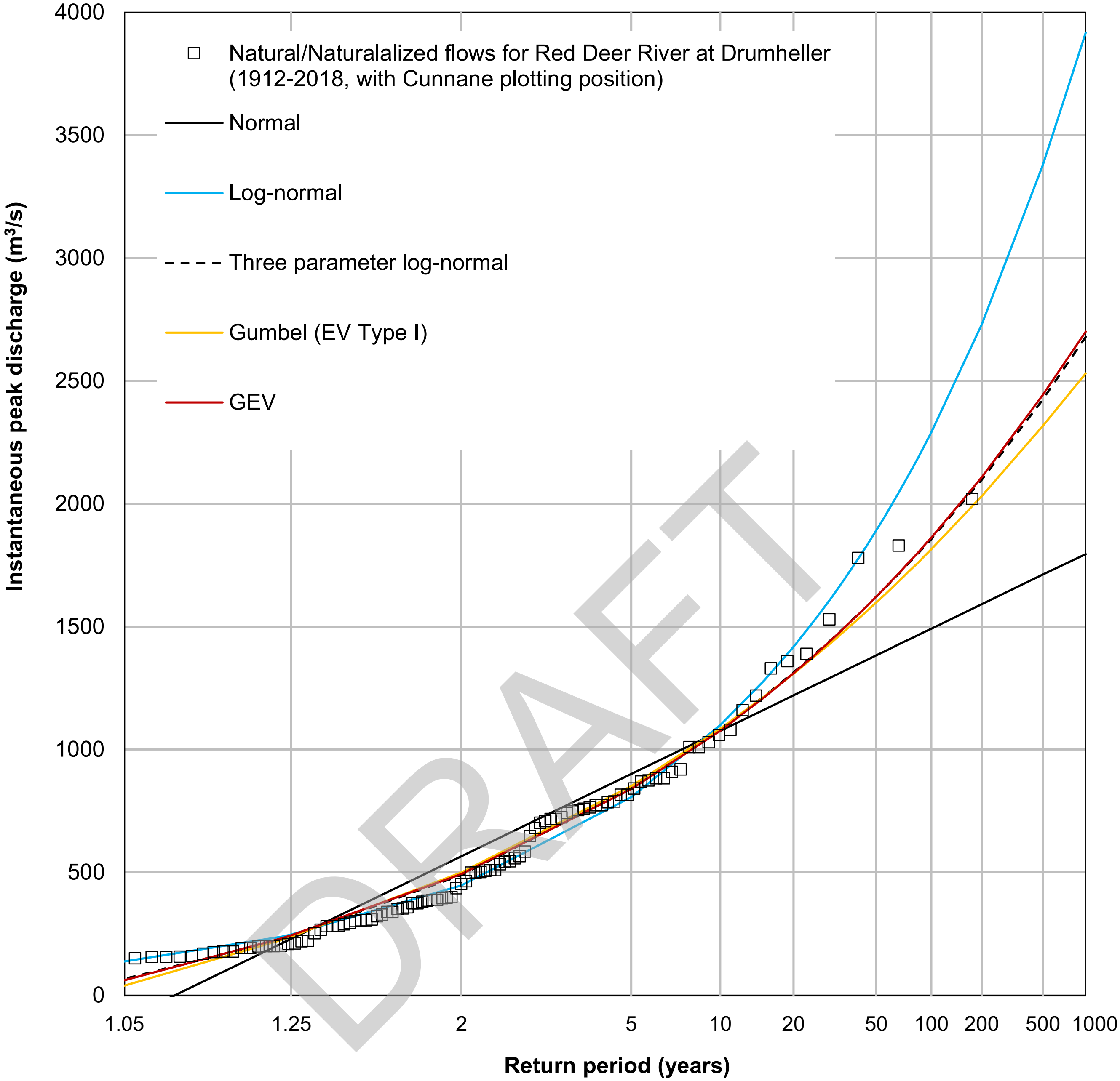


SCALE – AS SHOWN

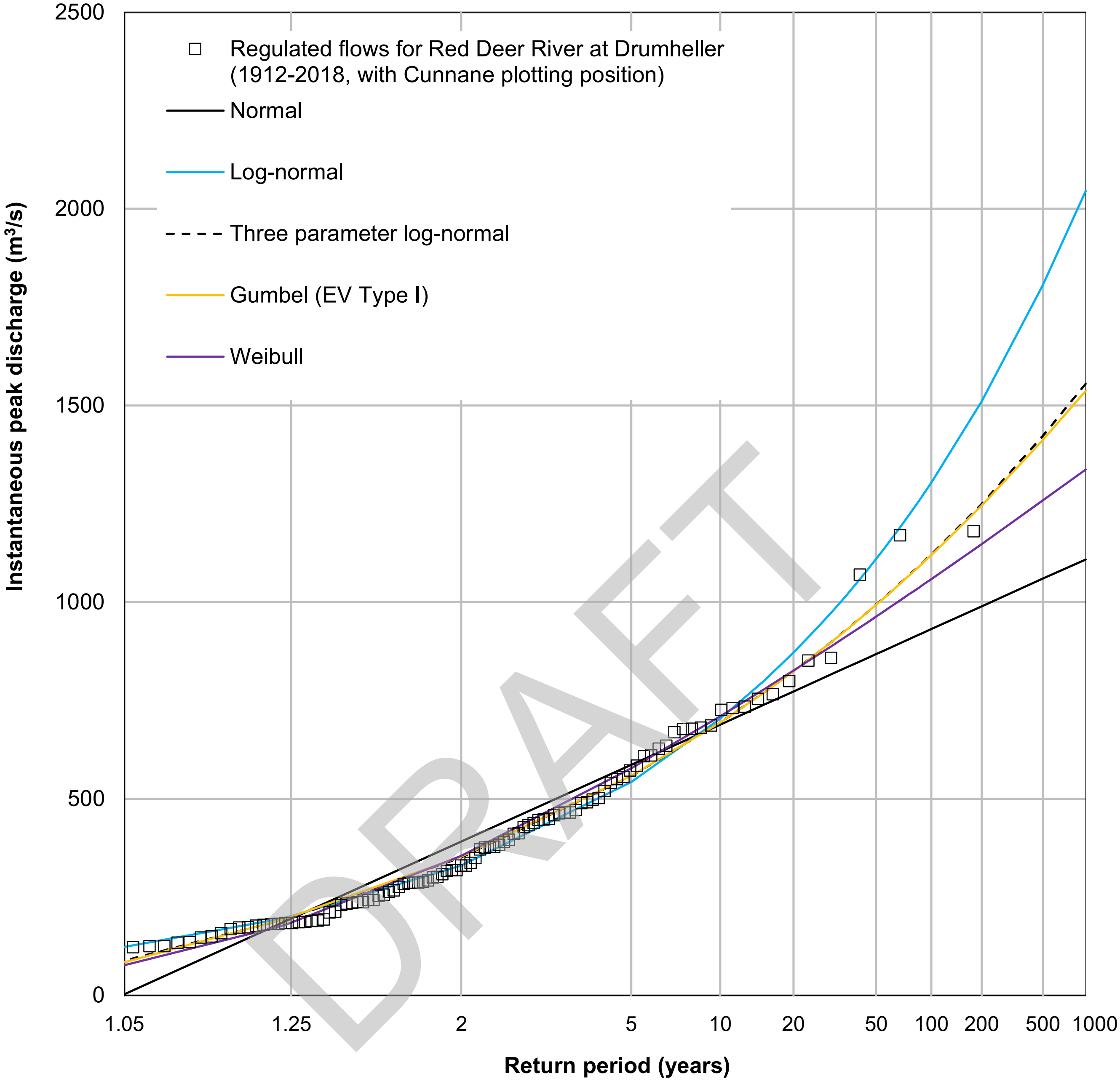
Coordinate System:
Units: As Shown

Job: 1003877

Date: Aug-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT
COMPARISON OF FLOOD FREQUENCY CURVES FOR NATURAL/NATURALIZED FLOWS OF RED DEER RIVER AT DRUMHELLER

FIGURE A-4



Alberta

nhc
northwest hydraulic consultants

SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 1003877

Date: Aug-2019

DRUMHELLER RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF FLOOD FREQUENCY CURVES FOR REGULATED FLOWS OF RED DEER RIVER AT DRUMHELLER

FIGURE A-5