MEDICINE HAT RIVER HAZARD STUDY

OPEN WATER HYDROLOGY ASSESSMENT REPORT

Prepared for:

Alberta Environment and Parks

26 July 2019

NHC Ref. No. 1003094

nhc
northwest hydraulic consultants
water resource specialists

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Edmonton, Alberta

Prepared by:

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Prepared by:

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EXECUTIVE SUMMARY

As part of the Province of Alberta Flood Hazard Identification Program, Northwest Hydraulic Consultants Ltd. was retained by Alberta Environment and Parks to conduct a River Hazard Study for the South Saskatchewan River (SSR), Ross Creek, Seven Persons Creek, and Bullshead Creek through the city of Medicine Hat (further referred to as Medicine Hat) and Cypress County including the town of Redcliff, and the hamlet of Desert Blume. The intent of the study is to support objectives of the provincial Flood Hazard Identification Program, as well as produce enhanced products to assist in reducing potential future flood damage and disaster assistance costs to the federal, First Nations, provincial, and local governments.

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

- South Saskatchewan River at Medicine Hat (Water Survey of Canada – WSC Station 05AJ001)
- South Saskatchewan River below Ross Creek
- Ross Creek at Highway 41 (WSC Station 05AH052)
- Ross Creek below Bullshead Creek
- Ross Creek below Seven Persons Creek
- Seven Persons Creek at Medicine Hat (WSC Station 05AH005)
- Seven Persons Creek at the mouth
- Bullshead Creek at Black and White Trail (WSC Station 05AH053)

The SSR basin upstream of the study limit includes the Bow and Oldman rivers, which together form the South Saskatchewan River downstream of their confluence located at approximately 100 km upstream of Medicine Hat. The basin also includes Ross Creek, which joins the SSR at Medicine Hat. The Bow, Oldman and Ross Creek sub-basins have areas of about 25,600 km^2, 28,300 km^2 and 4,790 km^2, respectively. The local basin area (SSR sub-basin) along the SSR from the Bow and Oldman river confluence to Medicine Hat is about 2,500 km^2.

Flows of the SSR have been regulated by dams on the Bow and Oldman rivers and their tributaries, since the beginning of the 20th century. Flows are also affected by diversions and off-stream reservoirs for irrigation districts within the basin, although these operations would have lower impacts on annual peak flows in the major rivers. Flow naturalization to remove the effects of reservoir storage and major diversions in the Oldman River sub-basin was performed based on available hydrometric and climate data. The major storage projects in the Oldman River sub-basin that were analyzed include:

- Oldman Reservoir
- Waterton Reservoir
- St. Mary Reservoir
- the Willow Creek system, including the Chain Lakes and Pine Coulee projects
- the Little Bow River system, including Twin Valley Reservoir and the CBRH system (primarily Traverse Reservoir).

Naturalized daily flow data series for the 1930-2015 period was developed for the SSR at Medicine Hat by routing the naturalized inflows to the reservoirs in the Oldman River sub-basin, along with downstream tributary inflows including the naturalized Bow River flows, which was provided by Alberta Environment and Parks. The results were combined with the measured flows for the pre-regulation period to provide a record of naturalized daily flows for the SSR at Medicine Hat for the 1902-2015 period. For the regulated flow scenario, operations of the reservoirs in the Oldman River sub-basin were simulated based on the current operating rules. The simulated outflows from the dams were routed to Medicine Hat, along with downstream tributary inflows including the regulated Bow River flows, which was provided by Alberta Environment and Parks. This resulted in a daily time series of regulated flows for the SSR at Medicine Hat from 1930 through 2015.

No attempt has been made to naturalize flows in the Ross Creek sub-basin above Seven Persons Creek due to the lack of data and insignificant effects of flow regulation on Ross Creek flood peaks. However, flow naturalization was performed for Seven Persons Creek at Medicine Hat, where the flows have been affected by operations of the Murray and Seven Persons dams since 1955. The flow naturalization analysis for Seven Persons Creek was based on limited flow and reservoir storage records provided by St. Mary River Irrigation District (SMRID), and resulted in twenty-nine years of high flow estimates over the 1984-2016 period at Medicine Hat. The results were combined with the measured flows for the pre-regulation period to provide 59 years of naturalized annual maximum daily flow discharges over the 1913-2016 period, for Seven Persons Creek at Medicine Hat (WSC Station 05AH005).

Frequency analysis of the instantaneous flood peaks on the SSR was based on the naturalized and regulated annual peaks at Medicine Hat. Maximum daily flows were adjusted to peak instantaneous flows by comparing the ratios of the two peaks. Frequency analysis of the Seven Persons Creek flood peaks was based on the naturalized peaks at Medicine Hat, while flood frequency estimates for Ross Creek and Bullshead Creek were based on measured peak flows and regional analysis. A variety of frequency distributions were fit to the instantaneous peak discharges to estimate the return period of flood events including: normal, log-normal, three-parameter log-normal, Pearson III, log-Pearson III, Gumbel, generalized extreme value, and Weibull. In general, the Pearson III and log-Pearson III provided the best fits for the data. The naturalized flood peaks on the SSR would have been larger than the regulated flood peaks for all of the evaluated return periods.

A summary of the 100-year flood peaks at the required assessment locations, including a comparison of the regulated and naturalized values is provided below.

Summary of estimated 100-year return period peak instantaneous discharges

Flood Frequency Estimate Location	100-year Peak Instantaneous Discharge (m^3/s)			
	Natural or Naturalized Flow		Regulated Flow	
	Value	95% Confidence Limit	Value	95% Confidence Limit
South Saskatchewan River at Medicine Hat (WSC Station 05AJ001)	6,500	5,450 - 8,080	5,260	4,300 - 6,750
South Saskatchewan River below Ross Creek	6,500	5,450 - 8,080	5,260	4,300 - 6,750
Seven Persons Creek at Medicine Hat (WSC Station 05AH005)	104	92 - 120	N/A	N/A
Seven Persons Creek at the Mouth	104	92 - 120	N/A	N/A
Bullshead Creek at Black and White Trail (WSC Station 05AH053)	92.3	N/A	N/A	N/A
Ross Creek at Highway 41 (WSC Station 05AH052)	145	132 - 162	N/A	N/A
Ross Creek below Bullshead Creek	188	N/A	N/A	N/A
Ross Creek below Seven Persons Creek	292	N/A	N/A	N/A

Notes:

1. Peak instantaneous discharges are identical for some locations.
2. The 95% confidence limits are not available for flood frequency estimates from regional analysis.

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 Medicine Hat River Hazard Study. This report summarizes the findings of the Open Water Hydrology Assessment.

NHC gratefully acknowledges the contributions and assistance of James Choles, M.Sc., P.Eng., who managed the project on behalf of AEP and provided valuable support with project management, data collection, and review. Thanks are expressed to Ms. Colleen Walford, Ms. Carmen de la Chevrotière, Mr. Dennis Matis, Ms. Shoma Tanzeeba and other members of AEP for providing relevant information and valuable comments throughout the course of the work. We also thank St. Mary River Irrigation District for providing information of Murray Reservoir on Seven Persons Creek.

This report was prepared by Dr. C.H. (Ken) Zhao, P.Eng., who served as NHC's lead hydrologist for the study. Technical review for the report was provided by Mr. Gary Van Der Vinne, M.Sc., P.Eng. of NHC. Mr. Makamum Mahmood, M.Eng., P.Eng. performed modelling for flow naturalization and regulation. Mr. Chris Schneck, M.Sc., E.I.T. assisted in flood frequency analysis. Mr. Robyn Andrishak, M.Sc., P.Eng. managed the project on behalf of NHC.

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1 INTRODUCTION

1.1 Background

Northwest Hydraulic Consultants Ltd. (NHC) was retained in August 2017 by Alberta Environment and Parks (AEP) to conduct a River Hazard Study (RHS) for the South Saskatchewan River (SSR), Ross Creek, Seven Persons Creek, and Bullshead Creek through the city of Medicine Hat (further referred to as Medicine Hat) and Cypress County including the town of Redcliff (further referred to as Redcliff), and the hamlet of Desert Blume (further referred to as Desert Blume). The intent of the study is to support objectives of the provincial Flood Hazard Identification Program, as well as produce enhanced products to assist in reducing potential future flood damage and disaster assistance costs to the federal, First Nations, provincial, and local governments. The deliverables associated with this study are also intended for the enhancement of public safety, and to support the identification of river hazards and the mitigation of those hazards by informing land use planning decisions within the purview of a variety of stakeholders.

The Medicine Hat River Hazard Study has been structured into the following major project components.

1) Survey and Base Data Collection
2) Open Water Hydrology Assessment
3) Hydraulic Model Creation and Calibration
4) Open Water Flood Inundation Map Production
5) Open Water Flood Hazard Identification
6) Governing Design Flood Hazard Map Production
7) Flood Risk Assessment and Inventory
8) Channel Stability Investigation

This report summarizes the work of the second component – ***Open Water Hydrology Assessment***. Separate reports have also been prepared for each of the other work components listed above.

1.2 Study Objectives

The objective of this component of the overall river hazard study is to provide open water flood frequency estimates for the SSR, Ross Creek, Seven Persons Creek, and Bullshead Creek under naturalized (unregulated) and regulated conditions at the following locations defined by the terms of reference of the Medicine Hat River Hazard Study:

- South Saskatchewan River at Medicine Hat (Water Survey of Canada – WSC Station 05AJ001)
- South Saskatchewan River below Ross Creek
- Ross Creek at Highway 41 (WSC Station 05AH052)
- Ross Creek below Bullshead Creek
- Ross Creek below Seven Persons Creek
- Seven Persons Creek at Medicine Hat (WSC Station 05AH005)
- Seven Persons Creek at the mouth
- Bullshead Creek at Black and White Trail (WSC Station 05AH053)

These locations are shown in **Figure 1**. The flood frequency estimates, which are supported by a brief description of the hydrologic characteristics of the SSR 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

A number of dams and flow diversion structures have been developed in the SSR basin for various purposes including irrigation, low-flow augmentation, water supply for industrial, municipal and domestic users, and hydropower. These developments have affected the SSR flows since the beginning of the 20th century. Given the effects of this 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 Medicine Hat 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,
- naturalization of flows affected by major reservoirs and diversion projects,
- routing of naturalized and regulated flows down the main stem rivers to the Medicine Hat area and the creation of naturalized and regulated daily flow series at the flood frequency estimate sites listed in Section 1.2,
- 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.

The major storage projects that enables regulation of SSR flows are located in the Bow and Oldman river sub-basins. Flow naturalization and regulation for the Bow River sub-basin were performed by Golder (2017). The results, including naturalized and regulated daily flow timeseries for the Bow River at its mouth (1930 – 2015), were provided by AEP and used as inputs for the present study. Flow naturalization and regulation for the SSR in this study focus on developing naturalized and regulated flow timeseries for the Oldman River at its mouth for the period of 1930 – 2015. These naturalized and regulated flow timeseries were routed, together with the Bow River flows, to generate naturalized and regulated flow timeseries in the SSR in the Medicine Hat area.

1.4 Study Area and Reach

While the river hazard study area is limited to a sub-reach of the SSR and its tributaries near Medicine Hat (**Figure 1**), the open water hydrologic assessment has a basin-wide scope that covers the 61,400 km^2 SSR basin extending from its headwaters in the Rocky Mountains to the downstream boundary of the river hazard study area (located about 4 km downstream of the Medicine Hat city limit). A basin map is shown in **Figure 2.**

The SSR basin upstream of the study limit includes the Bow and Oldman rivers, which together form the South Saskatchewan River approximately 100 km upstream of Medicine Hat. The basin also includes Ross Creek, which joins the SSR at Medicine Hat. According to the PFRA drainage area database, the Bow, Oldman and Ross Creek sub-basins have areas of about 25,600 km^2, 28,300 km^2 and 4,790 km^2, respectively. The local basin area (SSR sub-basin) along the SSR from the Bow and Oldman river confluence to Medicine Hat is about 2,500 km^2.

1.4.1 Bow and Oldman Rivers

Both the Bow and Oldman rivers originate in the Rocky Mountains in Alberta. They generally flow southeast and east through the Foothills and Grassland Natural Regions. Most of the runoff from these two sub-basins is typically derived from the mountain and foothill areas due to spring snowmelt augmented by rainfall. The Grassland Region is the largest region within the SSR basin in Alberta, extending from just west of Calgary to the Saskatchewan border. It is the warmest, driest region in Alberta.

Both the Bow and Oldman rivers have been regulated by storage projects and diversions. As noted above, a flow naturalization and regulation study for the Bow River sub-basin has been completed by Golder (2017); so this report focuses on the assessment for the Oldman River sub-basin.

The Oldman River is regulated by the Oldman Dam located on its headwaters near Pincher Creek and about 70 km upstream of Fort MacLeod. Through the approximately 100 km reach from Fort MacLeod to Lethbridge, the Oldman River is joined by Willow Creek, Waterton – Belly River, and St. Mary River. All of these three major tributaries originate in the Rocky Mountains and have been regulated by major storage projects. The Little Bow River is another major tributary which joins the Oldman River about 55 km downstream of Lethbridge. It carries outflows from Travers Reservoir, which is one of the major storage units of the Carseland-Bow River Headworks (CBRH) System and receives regulated flows from Twin Valley Reservoir located on the upper Little Bow River. The Oldman River joins the Bow River about 56 km downstream of the Little Bow River confluence.

1.4.2 Ross Creek Sub-basin

The Ross Creek sub-basin consists of the Ross Creek and Seven Persons Creek watersheds. The headwaters of Ross Creek are located in the Cypress Hills. It drains an area of about 1,510 km^2, which is largely situated over the northwestern slope of the Cypress Hills. Runoff from this area is carried mainly by Ross Creek and its two major tributaries: Bullshead Creek and Gros Ventre Creek. All three streams generally flow north. Bullshead Creek joins Ross Creek immediately upstream of the eastern limit of the city of Medicine Hat, while Gros Ventre Creek joins Ross Creek about 40 km upstream, or approximately 10 km upstream of the hamlet of Irvine. Downstream of the Bullshead Creek confluence, Ross Creek meanders through the southeast part of Medicine Hat before entering the SSR. While high flows on Ross Creek more commonly occur in spring due to snowmelt runoff with or without rainfall, intense summer rainstorm events often result in high annual peak flows as well.

Seven Persons Creek originates in the municipal district of Taber located southwest of Medicine Hat. It drains an area about 3,280 km^2. Most of its drainage area lies on slightly rolling agricultural land with some long, narrow flat-floored valleys, while a relatively small portion drains the northwestern slope of the Cypress Hills. The creek generally flows in a northeastern direction and joins Ross Creek immediately upstream of its confluence with the SSR.

There are a number of relatively small dams and flow diversions in the Ross Creek sub-basin developed for irrigation in 1950s. Most of the dams are located in the headwaters and have relatively small drainage areas.

In the rest of this report, Ross Creek is referred to as the reach upstream of the confluence with Seven Persons Creek unless otherwise specified – such as Ross Creek below Seven Persons Creek.

2 DATA COLLECTION

2.1 Available Data

This study has mostly relied on published streamflow and water level data obtained from Water Survey of Canada (WSC), but preliminary post-2014 data for some stations were obtained from WSC and AEP. Information for the referenced hydrometric stations is summarized in **Table 2-1**, **Table 2-2** and **Table 2-3**.

AEP also provided the following data:

- tables/relationships of flow travel time versus discharge along the Oldman River, SSR and their major tributaries;
- elevation – surface area – storage relationships for major reservoirs in the Oldman River sub-basin;
- operating rule curves for major reservoirs in the Oldman River sub-basin;
- simulated naturalized and regulated daily flow series for the Bow River (1930 – 2015) from Golder (2017); and
- calculated historical monthly evaporation data.

NHC also retrieved and reviewed project data for major dams from the following reports:

- AEP (1994). Oldman River Dam and Reservoir Operational Strategy. Prepared by Alberta Environmental Protection, Water Resources Services, June 1994.
- AMEC (2011). South Saskatchewan River Basin Natural Flow Update, 2002-2009, Final Report. Prepared for Alberta Environment by Amec Earth and Environmental Ltd., June 2011.
- Golder (2009). Dam Breach Inundation Study for the Oldman river Dam, Final Report. Prepared for Alberta Environment by Golder Associates Ltd., February, 2009.
- Golder (2007). Dam Safety Review Pine Coulee project. Prepared for Alberta Environment by Golder Associates Ltd., February, 2007.
- Hatch (2008). Chain Lake Reservoir Conceptual Engineering Study: Assessment of Alternatives to Manage the Inflow Design Flood, Final Report. Prepared for Alberta Transportation by Hatch Acres Incorporated, December 2008.
- KCB (2008). St. Mary Dam Breach Inundation Study – Final Report. Prepared for Alberta Environment by Klohn Crippen Berger., February, 2008.
- NHC (2012b). Waterton Dam – Dam Breach Inundation Study, Final Report. Prepared for Alberta Environment by Northwest Hydraulic Consultants Ltd., March 2012.

Other data were also collected as required for the analysis including precipitation data from the Environment Canada (EC) and Alberta Climate Information Service (ACIS) websites.

Table 2-1: Salient hydrometric stations describing South Saskatchewan River flows

Type	WSC Station No.	Station Name	Drainage Area (km^2)	Period of Record
Streamflow gauge	05AJ001	South Saskatchewan River at Medicine Hat	56,369	1911-1933,1935-2016
	05BN012	Bow River near the Mouth	25,278	1964-2016
	05AG006	Oldman River near the Mouth	27,531	1964-1968, 1982-2016
	05AD007	Oldman River near Lethbridge	17,046	1911-1948,1957-2016
	05AB007	Oldman River near Fort Macleod	5,760	1910-1948
	05AA024	Oldman River near Brocket	4,401	1966-2016
	05AC023	Little Bow River near Mouth	5,900	1973-2016
	05AC012	Little Bow River below Travers Dam	5,376	1957-2016
	05AE006	St. Mary River near Lethbridge	3,527	1911-2016
	05AD005	Belly River near Mountain View	319	1911-2014
	05AD008	Waterton River near Stand Off	1,730	1915-1931, 1935-1966
	05AD028	Waterton River near Glenwood	1,631	1966-2016
	05AB046	Willow Creek at Highway No. 811	2,510	1999-2016
	05AB002	Willow Creek near Nolan	2,290	1909-1924,1942-1999
	05AB021	Willow Creek near Claresholm	1,181	1908,1944-2016
Water level gauge	05AC940	Twin Valley Reservoir at Highway No. 529	1,950	2004-2016
	05AC022	Lake Mcgregor at South Dam	1,001	1926-1928, 1990-2016
	05AC941	Little Bow River Below Twin Valley Reservoir	1,963	2004-2016
	05AE025	St. Mary Reservoir near Spring Coulee	2,290	1951-2016
	05AD026	Waterton Reservoir	1,272	1965-2016
	05AB037	Chain Lake Reservoir near Nanton	213	1972-2016
	05AB044	Pine Coulee Reservoir near Stavely	86	2000-2016
	05AA032	Oldman Reservoir near Pincher Creek	4,380	1992-2016
Diversion/ irrigation flow	05AE021	Magrath Irrigation District Canal near Spring Coulee	N/A	1927-2016
	05AE026	Canadian St. Mary Canal near Spring Coulee	N/A	1952-2016
	05AD021	Belly-St. Mary Diversion Canal	N/A	1959-2016
	05AD027	Waterton-Belly Diversion Canal	N/A	1968-2016
	05AB016	Lethbridge Northern Irrigation District Canal at Menzaghies Bridge	N/A	1925-1985
	05AB019	Lethbridge Northern Irrigation District Canal above Oldman Flume	N/A	1930,1979-1980,1986-2016
	05AD013	United Irrigation District Canal near Hill Spring	N/A	1923-1930,1946-2016

Notes:

1. Drainage area is based on information from WSC.

Table 2-2: Salient hydrometric stations describing Ross Creek sub-basin flows

Type	WSC Station No.	Station Name	Drainage Area (km²)	Period of Record
Streamflow gauge	05AH005	Seven Persons Creek at Medicine Hat	3,276	1910, 1912-1917,1919-1931,1935-1956,1973-2016
	05AH053	Bullshead Creek at Black and White Trail	348	2005-2016
	05AH049	Ross Creek at Medicine Hat	1,490	1985-1995
	05AH052	Ross Creek at Highway 41	808	2000-2016
	05AH003	Ross creek near Irvine	647	1909-1931,1935-2000

Notes:

1. Drainage area is based on information from WSC.

Table 2-3: Selected reference hydrometric stations for hydrologic analysis

Group	WSC Station No.	Station Name	Drainage Area (km²)	Period of Record
Oldman Reservoir	05AA001	Oldman River near Cowley	1,940	1908-1931, 1944-1949
	05AA006	Todd Creek at Elton's Ranch	144	1909-1916, 1974-1993
	05AA008	Crowsnest River at Frank	403	1910-1920, 1949-2016
	05AA011	Mill Creek near the Mouth	179	1910-1920, 1967-2016
	05AA022	Castle River near Beaver Mines	821	1945-2016
	05AA023	Oldman River near Waldron's Corner	1,446	1949-2008
	05AA024	Oldman River near Brocket	4,401	1966-2016
	05AA032	Oldman Reservoir near Pincher Creek	4,380	1992-2016
	05AA921	Oldman River Reservoir Outflow at Oldman Dam[2]		1999-2016
	05AB007	Oldman River near Fort MacLeod	5,760	1910-1948
	05AB013	Beaver Creek near Brocket	256	1921-1925, 1966-2016
Waterton Reservoir	05AD003	Waterton River near Waterton Park	613	1908-1933, 1948-2016
	05AD005	Belly River near Mountain View	319	1911-2016
	05AD008	Waterton River near Stand Off	1,730	1915-1931,1935-1966
	05AD010	Drywood Creek near the Mouth	239	1920-1931, 1966-2016
	05AD026	Waterton Reservoir	1,272	1965-2016
	05AD027	Waterton-Belly Diversion Canal		1968-2016
	05AD028	Waterton River near Glenwood	1,631	1966-2016
	05AD901	Foothills Creek near Pincher Creek	134	1983-1989,1991-1994,1996
	05AD947	Waterton Reservoir Outflow[2]		1999-2016

Group	WSC Station No.	Station Name	Drainage Area (km^2)	Period of Record
St. Mary Reservoir	05AD021	Belly-St. Mary Diversion Canal		1959-2016
	05AE002	Lee Creek at Cardston	312	1909-1914,1920-2016
	05AE005	Rolph Creek near Kimball	222	1911-1916, 1936-2016
	05AE006	St. Mary River near Lethbridge	3,530	1911-2014
	05AE021	Magrath Irrigation District Canal near Spring Coulee		1927-2016
	05AE025	St. Mary Reservoir near Spring Coulee	2,290	1951-2016
	05AE026	Canadian St. Mary Canal near Spring Coulee		1952-2016
	05AE027	St. Mary River at International Boundary	1,210	1902-2016
	05AE029	St. Mary Canal at St. Mary Crossing		1918-2016
	05AE036	Lake Sherburne	166	1915-2016
	05AE918	St. Mary Reservoir Outflow at St. Mary Dam[2]		1999-2016
Willow Creek	05AB007	Oldman River near Fort Macleod	5,760	1910-1948
	05AB021	Willow Creek near Claresholm	1,181	1908,1944-2016
	05AB028	Willow Creek above Chain Lakes	162	1965-1995
	05AB037	Chain Lakes Reservoir near Nanton	213	1972-2016
	05AB041	Willow Creek at Oxly Ranch	833	1997-2016
	05AB042	Pine Coulee Diversion Canal below Head Gates		1999-2016
	05AB045	Pine Coulee Outflow Below Reservoir	86	1999-2014
	05BL007	Stimson Creek near Pekisko	236	
	05BJ004	Elbow River at Bragg Creek	791	1934-2016
Little Bow River	05AC003	Little Bow River at Carmangay	2,778	1918-1930,1955-2016
	05AC034	Little Bow River above Travers Reservoir		1992-1996, 2003-2016
	05AC921	Travers Reservoir Near Enchant	5,336	1990-2016
	05AC940	Twin Valley Reservoir at Highway No. 529	1,950	2004-2016
	05AC941	Little Bow River Below Twin Valley Reservoir	1,963	2004-2016
	05BL015	Little Bow Canal at High River		1910-1931,1933,1935-1936,1938-2016
	05BL025	Highwood Diversion Canal near Headgates		1977-2016
	05BM014	West Arrowwood Creek near Arrowwood	776	1965-2016

Notes:

1. Drainage area is based on information from WSC.

2.2 Historic Flood Data

Historic floods refer to major floods that occurred prior to the creation of the systematic record from periods of hydrometric data collection. If the magnitude of a historic flood can be estimated based on available information, the estimate is often used in a flood frequency analysis to improve the flood frequency determinations. Estimated peak instantaneous discharges for two historic floods occurred on the SSR in 1902 and 1908 are available from Alberta Environment (AENV, 1985). These values were used in the present study. For the other study sites in the Ross Creek sub-basin, it appears that information on historic floods beyond what was measured by WSC, does not exist. Therefore, historic floods were not considered for those sites in this study.

2.3 Previous Studies

Previous flood frequency estimates for the SSR, Ross Creek and Seven Persons Creek are presented in the following studies:

- Flood Frequency Analyses of South Saskatchewan River, Ross Creek and Seven Persons Creek at Medicine Hat by AENV (1985)
- 1995 Flood Frequency Analysis for South Saskatchewan River Basin – Draft Report from AENV (1995)
- Cypress County Flood Hazard Identification Study – Ross Creek at Hamlet of Irvine by NHC (2012a)
- Cypress County Flood Hazard Study – 2010 Flood Event Documentation by NHC (2013)
- Southern Alberta Flood Mitigation Feasibility Study for Sheep, Highwood River Basins and South Saskatchewan River Sub-basin – and South Saskatchewan River Sub-basin Water Management Plan by AECOM (2014)

3 DATA SERIES PREPARATION

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. SSR flows have been regulated by dams on the Bow and Oldman rivers and their tributaries, since the beginning of the 20th century. Flows are also affected by diversions and off-stream reservoirs for irrigation districts within the basin, although these operations would have lower impacts on annual peak flows in the major rivers. The ultimate objective of the flow naturalization process in this study is to estimate natural daily flows of annual open-water peak events at the flood frequency estimate locations, by removing effects imposed by major on-stream reservoirs and flow diversions.

As noted above, naturalized and regulated daily flow timeseries for the Bow River at its mouth for the 1930 – 2015 period from Golder (2017) were provided by AEP and used as inputs for the present study. The present study focuses on developing naturalized and regulated flow timeseries for the Oldman River at its mouth for the period of 1930 – 2015, and routing the flows together with the Bow River flows estimated by Golder (2017) to the Medicine Hat area.

The major storage projects that need to be analyzed in the Oldman River flow naturalization process include:

- Oldman Reservoir
- Waterton Reservoir
- St. Mary Reservoir
- the Willow Creek system, including the Chain Lakes and Pine Coulee projects
- the Little Bow River system, including Twin Valley Reservoir and the CBRH system (primarily Traverse Reservoir)

These projects are summarized in **Table 3-1**.

Table 3-1: Major reservoirs within Oldman River sub-basin

Reservoir	Sub-basin	Storage Capacity at FSL (dam^3)	Starting Year
Chain Lakes	Willow Creek	16,280	1966
Oldman Reservoir	Oldman River	495,000	1991
Waterton Reservoir	Waterton River	173,000	1964
St. Mary Reservoir	St. Mary River	396,000	1951
Pine Coulee	Willow Creek (off-stream)	54,000	1999
Twin Valley	Little Bow River	61,700	2003
Travers Reservoir	Little Bow River	312,000	1954
McGregor Reservoir	Little Bow River (off-stream)	365,800	1920
Little Bow Reservoir	Little Bow River (off-stream)	43,000	1978

The Oldman River flow naturalization process includes the following primary components:

- Water balance analysis (reverse routing) for the major reservoirs that have affected the Oldman River flows to provide daily inflow estimates at the reservoir sites for the regulated period,
- Regional hydrological analysis based on available streamflow gauge data to fill gaps in the natural inflow estimates at the reservoir sites for the regulated period, and/or to extend the natural flow timeseries for the pre-regulation period,
- Channel routing along the Oldman, Waterton-Belly, St. Mary and Little Bow rivers and Willow Creek, to estimate natural tributary inflow (or flow correction) to each of the main stem river reaches between two key gauged locations, and
- Construction of a timeseries of naturalized daily flows for the Oldman River at its mouth by routing the naturalized or recorded natural flows at the reservoir sites and the estimated natural tributary inflows down the main stem rivers to the Oldman River mouth.

Details of the adopted methodology are described in the following sections.

3.1.2 Reservoir Water Balance

Water balance analysis (or reverse routing) was performed at a daily time step for each of the major reservoirs for their respective periods of regulation. The analysis was based on the following equation:

$$Q_{in} = Q_{out} + \Delta V/\Delta t + A \cdot (E - P)/\Delta t \qquad \textbf{(Equation 1)}$$

where Q_{in} and Q_{out} are inflow and outflow discharges respectively; Δt is a time interval (equal to one day in the present study); ΔV is change of reservoir volume over the time interval; E is the evaporation from the reservoir surface; P is direct precipitation on the reservoir surface; and A is the reservoir surface area. Q_{out} is generally measured and available from WSC or AEP. Both the volume and surface area of a reservoir were determined from the elevation-storage volume relationship provided by AEP, based on reservoir level gauge data from WSC or AEP.

Monthly shallow lake evaporation data for Lethbridge, Alberta were obtained from AEP and applied to the water balance analysis. The evaporation values were computed using the Morton method (ESRD, 2013) for each month of each year. Daily values used in the water balance analysis were interpolated from the monthly data. Lethbridge is within reasonable proximity to the reservoirs analyzed within the Oldman River sub-basin, so the data were considered representative. In general, uncertainties in evaporation estimates would lead to only second order errors in the water balance analysis, especially for the present study which focuses on annual peak events.

The AEP evaporation data cover the period up to 2012. For the post-2012 period, monthly averages were adopted without consideration of year to year changes. While this also is an approximation, year to year variations in monthly evaporation are relatively small, and any deviations of mean values from actual values would not result in significant errors.

The direct precipitation volume at each time step was calculated by multiplying the corresponding reservoir surface area by the precipitation values for the day available from the nearest gauge stations shown in **Table 3-2**. Similar to evaporation, uncertainties in direct precipitation estimates would lead to only second order errors in the water balance analysis especially during high flow seasons, because this contribution is subject to reservoir surface area and is generally small compared with reservoir total inflows.

The inflow discharge estimates (Q_{in}) obtained from the water balance analysis were taken as naturalized flows at reservoir sites for the period of regulation. Gaps in the estimates due to missing input data were filled by estimates from regional hydrological analysis. Regional analyses were also performed as needed to provide natural flow estimates for the pre-regulation period. Details for each specific major reservoir are discussed in the following sections.

Table 3-2: Selected precipitation gauges for water balance analysis

Reservoir	Climate ID	Station Name	Elevation (m)	Period of Record
Oldman Reservoir	3035198	Pincher Creek	1189.6	2011-2018
	3035206	Pincher Creek (AUT)	1189.6	1992-2011
	3035202	Pincher Creek A	1189.9	1979-1994
	3031926	Cowley Olin Creek	1234.4	1961-2001
Waterton Reservoir	3032818	Cross Drain 5	1074	2007-2017
	3033281	Hill Spring	1183	1990-2011
	3035201	Pincher Creek	1155.2	1960-1979
	3035206	Pincher Creek (AUT)	1189.6	1992-2011
	3035202	Pincher Creek A	1189.9	1979-1994
St. Mary Reservoir	3057288	St. Mary Reservoir	1128	2007-2017
	3031320	Cardston	1193	1918-2015
Chain Lakes	3057570	Willow Creek	1478	1960-2011
	3055119	Pekisko	1415	1998-2017
	3033240	High River	1219	1902-2006
Twin Valley Reservoir	3031640	Claresholm	1009	1951-2008

3.1.3 Natural Flow Estimates at Oldman Reservoir

Oldman Reservoir is formed by the Oldman Dam located on the Oldman River approximately 8 km north of the town of Pincher Creek. The dam was completed in 1991. The total drainage area upstream of the dam is about 4375 km^2. At its full supply level (FSL), the reservoir provides a storage volume of 495,000 dam^3. Tributaries feeding the reservoir include the Oldman, Crowsnest, and Castle rivers plus a few smaller streams.

Post-regulation Period of 1991 – 2015

Water balance analysis was performed for Oldman Reservoir for the post-regulation period from 1992 to 2015 to estimate natural inflows. Changes in reservoir storage were determined from reservoir level records for WSC Station 05AA032 from 1992 to 2015. Outflows from the reservoir were defined from the WSC flow data for Oldman River near Brocket (WSC Station 05AA024). The daily flow record published by WSC for this gauge spans the 1966 – 2014 period. For the year of 2015, the preliminary hourly/sub-hourly flow data obtained from AEP were converted into daily values. AEP also operates a gauge downstream of Oldman Dam (AEP Station 05AA921) which provides measurements of reservoir outflow discharges at a sub-hourly time step from 1999 to present. This dataset was considered preliminary because it did not undergo a systematic quality check as applied to the data published by WSC. This dataset was used to fill the gaps in the daily flow record of WSC Station 05AA024.

Outflow data were missing from June 1, 1995 through February 6, 1996 at both the WSC and AEP gauge stations downstream of Oldman Dam because the stations were damaged by high flows during the June 1995 high flow event. An hourly inflow hydrograph for this flood event was constructed by Alberta Public Works and used by NHC (1995) in a review of the performance of the Oldman Dam spillway. This hydrograph extends from May 1 to June 12, 1995. It was converted into a daily timeseries for use in the present study. Reservoir daily inflows from June 12, 1995 through February 6, 1996 were estimated from a regional analysis based on flow data for the following gauge stations:

- Oldman River near Waldron's Corner (WSC Station 05AA023),
- Todd Creek at Elton's Ranch (WSC Station 05AA006),
- Crowsnest River at Frank (WSC Station 05AA008),
- Castle River near Beaver Mines (WSC Station 05AA022), and
- Mill Creek near the mouth (WSC Station 05AA011).

Locations of these gauge stations are shown in **Figure 3**. They represent approximately 68% of the total drainage area upstream of Oldman Dam. Daily flows for catchment areas of Oldman Reservoir that are not covered by the selected gauge stations were estimated by prorating the data for reference stations by drainage area ratios. The reference station for an ungauged catchment area was selected based on its proximity, size, and physiographic characteristics. For example, the Todd Creek station (WSC Station 05AA006) was used as a reference station for the Oldman River catchment between the reservoir and Waldron's Corner station (WSC Station 05AA023). Available flow data for Beaver Creek near Brocket (WSC Station 05AB013) were also used to estimate contributions from the ungauged area north of the reservoir and east of the upper Oldman River.

Daily inflows from May 1 though June 12, 1995 were also estimated from this regional analysis to provide a comparison with the 1995 estimates from Alberta Public Works. The two sets of estimates are consistent as shown in **Figure 4**.

The regional analysis was also used to estimate inflows for 1991 when reservoir level data were not available because the dam was under construction or the reservoir was being filled, and to estimate natural flow at the reservoir site for the pre-regulation period as described below.

Pre-regulation Period of 1910 – 1990

Natural daily flows for the pre-regulation period were estimated for all major reservoirs through regional hydrological analyses. Note that this estimation, especially for the period prior to 1951, is not required for flow naturalization in this study, because natural high flows of the Oldman River for this period could be represented by the gauge data near Lethbridge (WSC Station 05AD007), which could be directly used to estimate natural flows for the Oldman River near the mouth and subsequently for the SSR near Medicine Hat. The primary purpose of estimating inflows to each reservoir for the pre-regulation period is to synthesize complete daily inflow timeseries from 1930 to 2015 to enable the flow regulation process described in Section 3.2. Quality and accuracy of the synthetic inflow timeseries vary for different periods and different sites, and may be lower than the estimates for the post-regulation periods, as the analyses are subject to gauge data availability and correlation between flows for a reservoir site and for regional stations. However, these synthetic results represent a best estimate from available data and are considered adequate and reasonable for the flow regulation process of the present study, which is intended to illustrate potential effects of current flow management operations on flood frequency estimates, through simulation of a plausible scenario of regulation.

Natural flows for the 1910-1930 and 1949-1965 periods at the Oldman Reservoir site were estimated using the same regional analysis approach as for the 1991 and 1995 reservoir inflow estimates, except that the available flow data for Oldman River near Cowley (WSC Station 05AA001) was used (instead of WSC Station 05AA023) for the 1910-1930 period.

The estimated 1910-1930 daily natural flows at the reservoir site were compared with the record for Oldman River near Fort MacLeod (WSC Station 05AB007). The two data sets correlate well as shown in **Figure 5.** The relationship was used to estimate daily flows at the reservoir site for the 1931-1948 period from the data for WSC Station 05AB007. It should be noted that the discharge vs. gauge height relationship for WSC Station 05AB007 is highly unstable given the braided channel at this location; so these estimated (or synthesized) daily flows at the Oldman Reservoir site may bear greater uncertainties than the estimates for other periods. However, they still represent a best estimate from available data for the 1931-1948 period, and as stated above, this estimation is not needed for flow naturalization of SSR at Medicine Hat, and is considered reasonable for the flow regulation process of the present study.

For the period from 1966 to 1990, the flow data recorded at Oldman River near Brocket (WSC Station 05AA024) were taken as the natural flows at the reservoir site.

3.1.4 Natural Flow Estimates at Waterton Reservoir

Waterton Reservoir is formed by Waterton Dam located within the Waterton River valley approximately 28 km southeast of the town of Pincher Creek. The project was completed in 1964. The reservoir is replenished by inflows from the Waterton River and Drywood Creek. It has a storage capacity of 173,000 dam^3 at FSL. The total drainage area of the reservoir is about 1270 km^2. Outflows from Waterton Dam are conveyed by the Waterton River, which flows northeasterly for about 40 km to the Belly River. The Belly River then joins the Oldman River about 45 km upstream of Lethbridge. Water is also diverted from the reservoir to the Belly River via a diversion canal.

Locations of reference hydrometric stations used for the analysis of Waterton Reservoir are shown in **Figure 6**.

Post-regulation Period of 1964 – 2015

Water balance analysis was performed for Waterton Reservoir to estimate natural inflows for the post-regulation period from 1965 to 2015.

Changes in reservoir storage were determined from reservoir level records for WSC Station 05AD026 from 1965 to 2015. Outflows from the reservoir include discharges through the dam to the Waterton River and diversions to the Belly River via the Waterton-Belly Diversion Canal. While the diversion discharges are available from WSC Station 05AD027, estimation of outflow discharges through the dam is more complicated.

A streamflow gauge station is located nearly 30 km downstream of Waterton Dam (WSC Station 05AD028 – Waterton River near Glenwood). This station provides a daily flow record from 1966-2015. The drainage area upstream of this station is 1631 km^2, about 28% greater than that of Waterton Dam. The local catchment area between the two locations consists primarily of agricultural area. Flow data for Foothills Creek near Pincher Creek (WSC Station 05AD901, 1983-1996) suggest that this catchment does not generate significant runoff; however, no local tributary records are available for significant high flow events. Continuous outflow records for Waterton Dam are available from AEP Station 05AD947 since 2000; however, this data appears to be inconsistent with reservoir inflows because, when the data was used to estimate inflows, the results were often smaller than the sum of daily flows from Drywood Creek near the mouth (WSC Station 05AD010) and from Waterton River near Waterton Park (WSC Station 05AD003). Note that these two gauge stations represent only about 67% of the total drainage area upstream of Waterton Dam. Therefore, the water balance analysis for Waterton Reservoir used the flow data for Waterton River near Glenwood (05AD028) as the reservoir outflow discharges, without adjustments. Gaps in this data set (1965) were filled with the flow data for Waterton River near Stand Off (WSC Station 05AD008) assuming no inflow between the two gauges.

Water level data of 1964 for Waterton Reservoir were not available as the dam was under construction or the reservoir was being filled up. Natural inflows for that year cannot be estimated from the water balance analysis, nor from the upstream tributary flow data because the data for Drywood Creek near the mouth (WSC Station 05AD010) were not available. In this circumstance, the daily inflow discharges to Waterton Reservoir estimated from the water balance analysis for the period of 1965-2014 were correlated to the flows for Belly River near Mountain View (WSC Station 05AD005), as show in **Figure 7**; and the relationship and Belly River flow data were then used to estimate the 1964 daily natural inflows to Waterton Reservoir. This approach was also used to estimate the natural flows at Waterton Reservoir for the 1931-1934 pre-regulation period, as described in the following section.

Pre-regulation Period of 1930 – 1963

There are gaps in flow records between 1930 and 1967 for Drywood Creek near the mouth (WSC Station 05AD010) and between 1930 and 1948 for Waterton River near Waterton Park (WSC Station 05AD003), which makes it difficult to estimate natural flows at Waterton Reservoir for the pre-regulation period. As discussed above for the regulated period, daily local flows between Waterton Dam and Waterton River near Glenwood (WSC Station 05AD028) could be neglected, and the same assumption could be made for the area between WSC Stations 05AD028 and 05AD008 (Waterton River near Stand Off). Accordingly, daily flows for WSC Station 05AD008 were taken as the natural flows at Waterton Reservoir for the year of 1930 and the 1935-1963 period.

The daily natural flows at Waterton Reservoir for the 1931-1934 period were estimated based on the daily flow data for Belly River near Mountain View (WSC Station 05AD005) and the relationship shown in **Figure 7** – the same approach as that used to estimate the 1964 reservoir inflows described above.

3.1.5 Natural Flow Estimates for St. Mary River

The St. Mary River joins the Oldman River immediately upstream of the city of Lethbridge. Flows in the upper St. Mary River have been affected by diversion to the Milk River via the St. Mary Canal constructed in 1917 in Montana. After entering Alberta, the river is further regulated by St. Mary Dam located about 40 km east of Waterton Dam and 23 km northeast of the town of Cardston. The total drainage area upstream of the dam is about 2290 km^2. The dam was completed in 1951. St. Mary Reservoir provides a storage capacity of 396,000 dam^3 at its FSL. In addition to inflows from the St. Mary River, it receives supplemental inflows diverted from the Belly River. The reservoir discharges to the St. Mary River via a low level outlet and gated service spillway and to the St. Mary – Jensen Canal through an irrigation tunnel.

Flow naturalization for the St. Mary River includes estimation of natural flows for St. Mary River at International Boundary (WSC Station 05AE027) and natural inflows to St. Mary Reservoir.

Locations of reference hydrometric stations used for the analysis of St. Mary Reservoir are shown in **Figure 8**.

St. Mary River at International Boundary

Daily natural flows for St. Mary River at International Boundary (WSC Station 05AE027) were estimated for the 1930-2015 period using the method adopted by the United States Geological Survey (USGS) and Environment and Climate Change Canada (ECCC), as described by Whiteman and McCarthy (2016):

$$Q_{IB,nat} = Q_{IB,rec} + Q_{Sherburne} + Q_{US,div} \qquad \textbf{(Equation 2)}$$

Where $Q_{IB,nat}$ is the daily natural flow estimate for St. Mary River at the international boundary; $Q_{IB,rec}$ is the recorded daily flow for St. Mary River at the international boundary (gauge data from WSC Station 05AE027); $Q_{Sherburne}$ is the daily change of storage volume in Lake Sherburne determined from change of lake level (gauge data from WSC Station 05AE036) with a one-day lag; and $Q_{US,\ div}$ is the flow diverted to the St. Mary Canal by the United States (gauge data from WSC Station 05AE029).

Natural Flows at St. Mary Reservoir

Natural inflows to St. Mary Reservoir for the 1962-2015 period were estimated through the following steps:

1) The streamflow gauge for the St. Mary River below St. Mary Dam is located approximately 85 km downstream (WSC Station 05AE006 – St. Mary River near Lethbridge), and has a drainage area of 3530 km^2 (54% greater than that above the dam). It provides daily flow records from 1911 to present. AEP reports outflow discharges from St. Mary Dam from 1999 to present (AEP Station 05AE918 – St. Mary Reservoir Outflows at St. Mary Dam), while the long-term continuous data series starts in 2010. The two data sets were compared in **Figure 9**, which indicates that there is no lag between daily flow hydrographs for the two locations and daily outflow discharges from

St. Mary Dam could be estimated by multiplying daily flows for the WSC Station 05AE006 by 0.86. The flow data for 05AE006 were then adjusted using this relationship and combined with the St. Mary Dam outflow data from AEP to construct a continuous daily outflow timeseries from 1951 to 2015. It should be noted that the 2014 high flow event on the St. Mary River was a non-typical local runoff event; however, including or excluding this particular event from the analysis does not have effects on the relationship shown in **Figure 9**.

2) A water balance analysis was performed to estimate daily inflows to St. Mary Reservoir for the 1962-2015 period over which continuous reservoir level records are available. The analysis was based the constructed outflow timeseries for the dam, reservoir level records, and diverted inflow and outflow records.
3) The recorded and naturalized daily flows for St. Mary River at International Boundary (WSC Station 05AE027) were routed to St. Mary Reservoir using a channel routing model described in Section 3.1.8. The differences between the two sets of routed flows were then used to adjust the reservoir inflows estimated from the water balance analysis. This resulted in estimates of daily natural inflows to St. Mary Reservoir for the 1962-2015 period.

For the 1936-1961 period, naturalized daily flows for St. Mary River at the international boundary (WSC Station 05AE027, drainage area 1210 km^2) were routed to St. Mary Reservoir. Daily natural tributary inflows to the St. Mary River between the international boundary gauge and the reservoir were estimated by prorating flow data for WSC Station 05AE002 (Lee Creek at Cardston, drainage area 312 km^2) and 05AE005 (Rolph Creek near Kimball, drainage area 222 km^2) by drainage area ratios. Note that these three station represent about 76% of the total basin area of St. Mary Reservoir. The tributary inflow estimates and routed St. Mary River natural flows were summed to obtain the daily natural flow estimates at St. Mary Reservoir. This regional hydrologic analysis approach was also used to estimate the 1930-1935 daily natural flows with the tributary inflows being estimated from the 05AE002 data only as there were no data at WSC Station 05AE005 for this period.

3.1.6 Natural Flow Estimates for Willow Creek

Locations of reference hydrometric stations used for the analysis of Willow Creek flows are shown in **Figure 10**.

Willow Creek flows are regulated through Chain Lakes Reservoir located about 35 km west of Nanton, Alberta. This reservoir was formed in 1966 by constructing two earthfill dams to the north and south of a chain of three small lakes draining south to Willow Creek. It impounds approximately 16,280 dam^3 at FSL. The drainage area upstream of the reservoir is about 213 km^2, which represents less than 10% of the Willow Creek basin area. The north dam has a low level outlet discharging a riparian flow to Meinsinger Creek, which flows north to the Highwood River. This outlet has a capacity of 1.8 m^3/s at FSL. The south dam discharge to Willow Creek via a low level outlet with a capacity of about 9.8 m^3/s and an uncontrolled service spillway with its crest elevation at FSL.

Approximately 42 km downstream of the Chain Lakes south dam, the Willow Creek flows are diverted to Pine Coulee Reservoir, which is an off-stream storage reservoir on Pine Creek – a small intermittent tributary of Willow Creek. This reservoir came into service in 1999. It has a storage capacity of about 54,000 dam^3 at FSL. Diversion from Willow Creek to Pine Coulee Reservoir usually occurs between April and August. It is controlled by a headgate structure. According to the flow data for Pine Coulee Diversion Canal below Head Gates (WSC Station 05AB042), the diverted daily flows were always smaller than 10 m^3/s and representative of a relatively small percent of the Willow Creek flows. The reservoir discharges back to Willow Creek via a gated low level outlet in the main dam. According to the flow data for Pine Coulee Outflow below Reservoir (WSC Station 05AB045), the annual maximum daily discharges from Pine Coulee Dam were smaller than 5 m^3/s over the period of record except 2005. The maximum daily discharge of 2005 was 19.2 m^3/s, which is greater than the values of the other years but negligible when compared with the Willow Creek flow recorded upstream of Pine Coulee Reservoir (WSC Station 05AB041 – Willow Creek at Oxly Ranch) – 510 m^3/s. **Figure 11** shows daily diverted flows to Pine Coulee Reservoir minus its outflow discharges, which represents net effects of this reservoir on Willow Creek. For 98% of the time from 1999 to 2014 the effects were smaller than ±5 m^3/s; and the high and low extremes were 8.4 m^3/s in 2001 and -19.2 m^3/s in 2005, respectively. These effects are negligible when compared with daily flows of Willow Creek (WSC Station 05AB041); and they will not be detectable in the Oldman River or SSR flows.

Downstream of Pine Coulee Reservoir, Willow Creek flows about 130 km before entering the Oldman River immediately downstream of Fort MacLeod.

Since effects of Pine Coulee Reservoir on the Willow Creek flows are negligible, the flow naturalization for Willow Creek for this study consisted of only removing storage effects of Chain Lakes Reservoir.

Post-regulation Period of 1966-2015

Daily water levels for Chain Lakes Reservoir are available from 1995 to 2015 from the WSC Station 05AB037 (Chain Lakes Reservoir near Nanton). So, a water balance analysis was performed to estimate daily natural inflows to Chain Lake Reservoir for this period.

Outflows from Chain Lakes Reservoir were not recorded. Discharges through the ungated service spillway on the south dam were calculated using a stage-discharge curve provided by AEP (**Appendix A**). Riparian flows through the low level outlets on the north and south dams would be relatively small given their capacities and insignificant for the present study so outflows through the north dam (up to 1.8 m^3/s to Meinsinger Creek) were ignored. Monthly average riparian discharges through the low level outlet of the south dam were estimated as:

- March through October: monthly averages of the differences between the calculated daily discharges through the service spillway and measured daily discharges for Willow Creek at Oxly Ranch (WSC Station 05AB041), for the 1997-2015 period; and
- November through February: monthly average discharges for Willow Creek near Claresholm (WSC Station 05AB021).

The monthly average values listed in **Table 3-3** were obtained from the procedure outlined above and used for the Chain Lakes Reservoir water balance analysis for the 1995-2015 period.

Table 3-3: Estimated monthly discharges through Chain Lakes South Dam Low Level Outlet

Month	Flow (m^3/s)
January	0.6
February	0.8
March	1.2
April	1.6
May	3.2
June	9.5
July	1.6
August	0.7
September	1.2
October	0.8
November	1.0
December	0.7

As water levels for Chain Lake Reservoir were not recorded for the 1966-1994 period, inflows cannot be estimated from the water balance analysis. However, the Willow Creek flows for this period were gauged at WSC Station 05AB028 (Willow Creek above Chain Lakes) located immediately upstream of the Chain Lakes south dam and representative of 76% of the reservoir basin area. The daily flow data for this gauge were prorated by the drainage area ratio to provide estimates of natural inflows to Chain Lakes Reservoir.

Pre-regulation Period of 1930-1965

Daily natural flows for 1965 for Willow Creek at Chain Lake Reservoir were estimated from the flow data for WSC Station 05AB028 (Willow Creek above Chain Lakes).

For the period of 1944-1964, daily natural flows at the Chain Lakes Reservoir site were estimated by transferring flow data for Willow Creek near Claresholm (WSC Station 05AB021) using the relationship shown in **Figure 12**, which was based on the naturalized daily flows for Willow Creek near Claresholm and Chain Lake Reservoir inflows for the open water season (May through October) for the regulated period of 1995-2015. Note that the 1995-2015 natural reservoir inflows were from the water balance analysis, and the naturalized daily flows for Willow Creek near Claresholm were developed from the process described in Section 3.1.8.

Daily natural flows of 1939-1943 at the Chain Lakes Reservoir site were estimated from flow data for Stimson Creek near Pekisko (WSC Station 05BL007), using the relationship shown in **Figure 13**. The figure was based on the 1965-1995 daily flow records for Willow Creek above Chain Lakes and Stimson Creek. Although Stimson Creek receives riparian flows from the Chain Lakes north dam for this regulated period (through Meinsinger Creek), the dam riparian flows were relatively small and can be neglected, and the flow data for 05BL007 represent primarily natural runoff from the Stimson Creek basin. Similarly, flow data for Elbow River at Bragg Creek (WSC Station 05BJ004) were used to estimate 1934-1938 daily natural flows for Willow Creek at Chain Lakes, based on the relationship shown in **Figure 14**. For the period of 1930-1933, the daily flow data for Oldman River near Fort MacLeod (WSC Station 05AB007) were prorated by the drainage area ratio to provide estimates of the Willow Creek flows above Chain Lakes.

3.1.7 Natural Flow Estimates for Little Bow River

The Little Bow River is the only major tributary entering the Oldman River downstream of Lethbridge. It has a total basin area of about 5900 km^2, which accounts for about 50% of the total tributary basin area of the Oldman River downstream of Lethbridge. The Little Bow River basin is situated almost entirely within the Grassland Natural Region – the driest region in Alberta. Apart from the upper basin of Mosquito Creek, it consists mainly of relatively flat prairie terrain with significant proportions of ineffective drainage area. In addition to relatively small natural local runoff, the Little Bow River basin receives diverted flows from the Highwood and Bow rivers, and infrequent spill from the Highwood River during high flow events (about seven times over the last 100 years including the 2013 flood event).

The Little Bow River flows are highly regulated primarily through the following major storage reservoirs:

- Twin Valley Reservoir completed in 2003, which is fed by Mosquito Creek and the upper Little Bow River carrying flows diverted from the Highwood River;
- Travers Reservoir completed in 1954, which is fed by outflows from Twin Valley Dam and South McGregor Dam;
- McGregor Reservoir formed by the south and north dams completed in 1920, which is an off-stream storage reservoir fed by flows diverted from the Bow River; and
- Little Bow Reservoir which is an off-stream reservoir and operates as an auxiliary storage unit of Travers Reservoir.

Travers Dam discharges to the lower Little Bow River, which generally flows south and enters the Oldman River about 55 km downstream of Lethbridge.

Locations of the reference hydrometric stations used for the Little Bow River flow analysis are shown in **Figure 15**.

Estimation of Natural Inflows to Twin Valley Reservoir

Daily water levels of Twin Valley Reservoir and outflow discharges to the Little Bow River have been recorded at WSC Stations 05AC940 and 05AC941, respectively, since 2004. Daily inflows were estimated from a water balance analysis for the 2004-2015 period using the data for these two gauge stations. The estimated inflows include flows diverted from the Highwood River, including diversions to Women’s Coulee which discharges to Mosquito Creek, and to the Little Bow Canal at High River. Flows diverted to Women’s Coulee are relatively small – up to 2 m^3/s according to the records for WSC Station 05BL025 (Highwood Diversion Canal near Headgate), and discharges to Mosquito Creek would be smaller and were neglected in this analysis. Flows diverted to the Little Bow Canal (WSC Station 05BL015 – Little Bow Canal at High River) were smaller than 5 m^3/s for most years while in some years they were as high as over 8 m^3/s. The daily flows for the Little Bow Canal with a one-day lag were deducted from the calculated inflows to Twin Valley Reservoir and the results were taken as the natural inflow estimates, for the 2004-2015 period.

Estimation of Natural Inflows to Travers Reservoir

The Little Bow River flows approximately 70 km from Twin Valley Reservoir to Travers Reservoir. Recorded daily flow hydrographs from 2004 to 2013 for Little Bow River below Twin Valley Reservoir (WSC Station 05AC941), and above Travers Reservoir (WSC Station 05AC034) were compared. **Figure 16** shows comparisons of a medium (2006) and high (2013) flow events as examples. The comparison suggests that local tributary inflows within this reach are negligible, and there should be slight attenuation in flows and a one-day lag between these two locations. Accordingly, the 2004-2015 daily natural inflow estimates for Twin Valley Reservoir with a one-day lag were taken as the natural inflows from the Little Bow River to Traverse Reservoir. For the period of 1955-2003, the daily flow data for Little Bow River at Carmangay (WSC Station 05AC003) were taken as the natural Little Bow River flows contributing to Travers Reservoir.

The drainage area of the Little Bow River above Travers Reservoir is 3490 km^2. In addition to Little Bow River inflows, Travers Reservoir also receives discharge from South McGregor Dam, which consists primarily of flows diverted from the Bow River. The water stored in McGregor, Travers and Little Bow reservoirs is mostly diverted to the Bow River Irrigation District (BRID) through an outlet on Little Bow Dam. This system also receives local runoff from a total tributary area of about 1850 km^2, which would contribute to the Little Bow River below Travers Dam under the natural condition without flow diversion and reservoir operation. Due to the relatively short periods of record for flow diversion and reservoir elevations, and complexity of the reservoir system, it is difficult to estimate natural tributary inflows to McGregor and Travers reservoirs.

According to WSC, the effective contributing area of this tributary area is about 1380 km^2. Daily natural flows for the 1965-2015 period from this tributary area were estimated by prorating flow data for West Arrowwood Creek near Arrowwood (WSC Station 05BM014) by the effective drainage area ratio (note that the gross and effective drainage area of WSC Station 05BM014 are 776 and 664 km^2 respectively). For the 1955-1964 period, the estimated natural flows for the Little Bow River above Travers Reservoir were prorated by the ratio of its drainage area to the total drainage area of Travers Reservoir. This resulted in a daily natural flow timeseries for the 1955-2015 period for Little Bow River at Travers Reservoir.

Natural flows of the Little Bow River for the period prior to 1955 were not estimated because there are no suitable local or regional hydrometric data that can be used to develop reasonable estimates, and as discussed in the next section, the Little Bow flows could be neglected when estimating annual natural peak flows for the SSR at Medicine Hat.

3.1.8 Natural Flow Estimates for Downstream Sites from Flow Routing

The ultimate objective of the flow naturalization process in this study is to develop data series of annual naturalized peak flows for the study sites on the SSR near Medicine Hat. To this end, the estimated daily natural flows for the reservoir sites discussed above were routed through the Oldman-SSR river system to Medicine Hat, 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 support 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:

$$T_S = \frac{KTS}{Q^n} \quad \textbf{(Equation 3)}$$

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 17**. It includes:

- the Oldman River from Oldman Dam to the Bow River confluence,
- the Waterton River from Waterton Dam to the Belly River confluence,
- the Belly River from Mountain View (WSC Station 05AD005) to its confluence with the Oldman River,
- the St. Mary River from the international border (WSC Station 05AE027) to its confluence with the Oldman River,
- Willow Creek from Chain Lakes to its confluence with the Oldman River,
- the Little Bow River from Travers Reservoir to its confluence with the Oldman River,

- the Bow River from WSC Station 05BN012 to the mouth, and
- the SSR from the Bow/Oldman river confluence through Medicine Hat

These river reaches have been divided into sub-reaches in the model in accordance with locations of salient hydrometric stations and points of interest, and each has a variety of tributary inflows.

Channel routing in this study was performed at a daily time step. The adopted values of the SSARR routing parameters (that defines discharge – travel time relationships) are shown in **Appendix B**.

AEP provided discharge-travel time relationships for most of the sub-reaches, which have been calibrated against observed hourly flow hydrographs and used for flood forecasting. They were used in the HEC-ResSim model as initial estimates of the SSARR routing parameters, and then adjusted to better suit daily flow routing through calibrations against recorded daily hydrographs for typical low, medium and high flow events. Travel times for the following sub-reaches were estimated with different approaches as they were not included in the data set provided by AEP:

Flow travel times for Willow Creek from WSC Station 05AB046 (Willow Creek at Highway No. 811) to its mouth (about 9 km) and the Little Bow River from WSC Station 05AC023 to its mouth (about 4 km) would be noticeably shorter than one day due to their relatively short lengths. Flows through these sub-reaches were not routed (i.e. no transformation in hydrographs from the upstream to downstream end of the sub-reach).

Travel times for the Little Bow River below Travers Dam were estimated from a HEC-RAS model developed by NHC (2015).

Travel times for Willow Creek from Chain Lakes to Oxly Ranch (WSC Station 05AB041) were estimated by prorating travel times for Willow Creek below Pine Coulee (provided by AEP) by the ratio of the sub-reach lengths.

Flows through the Waterton River sub-reaches from Waterton Dam to Glenwood and from Glenwood to Stand Off were not routed. As discussed in Section 3.1.4, there appear to be no lag and little attenuation between observed daily flow hydrographs at these locations; moreover, estimation of natural inflows to Waterton Reservoir was based on flow data for the WSC gauge stations at Glenwood and Stand Off.

Flow diversions and reservoirs were included in the HEC-ResSim model but they were turned off when routing naturalized flows. Reservoir routing was activated when simulating the flow regulation process described in Section 3.2, while flow diversions were accounted for in both routing of gauged flows and the flow regulation process.

Flow Routing Process

Two rounds of flow routing through the river networks in the HEC-ResSim model were performed in the flow naturalization process.

First, gauged daily flows were routed from an upstream to downstream hydrometric station, together with gauged (routed) tributary inflows. The routed flows at the downstream station were compared with the gauge data, and the daily difference was taken as the lumped ungauged tributary inflow (or gauge correction flow) to that sub-reach for each day over the simulation period. This tributary inflow timeseries was then injected to the sub-reach in the model and used for naturalized flow routing (and flow regulation). While this process was applied to all the river reaches in the model (**Figure 17**), key locations to be noted include Oldman River near Lethbridge (WSC Station 05AD007) and near the mouth (WSC Station 05AG006), and SSR at Medicine Hat (WSC Station 05AJ001), which cover relatively long periods of record and represent the majority of flows through the river network.

Second, the daily natural flow series estimated for those major reservoir sites presented above were routed through the entire river network, together with all tributary flows, without any flow diversion. The objective is to develop daily natural flow estimates for SSR at Medicine Hat for the period of 1930-2015. This simulation used the naturalized daily flows for Bow River near the mouth (WSC Station 05BN012) from Golder (2017).

As noted above, the estimated natural flow timeseries for the Little Bow River does not cover the 1930-1954 period due to the lack of usable data. Naturalized flows for Little Bow River near the mouth (1956-2015) were compared with those for the Oldman River above the Little Bow River confluence in **Figure 18**. The daily natural flows for the Little Bow River are significantly smaller than the Oldman River flows. Annual peak flows on the Little Bow River often occur in late March or April (i.e. one or two months earlier than the peaks on the Oldman River and SSR). **Figure 19** shows a comparison of the annual maximum daily natural flows for SSR at Medicine Hat for the 1955-2015 period, calculated with and without the Little Bow River natural flows. The difference is only about 0.5%. Therefore, the Little Bow River natural flows were ignored in the final flow naturalization process so that a complete daily natural flow series of 1930-2015 for SSR at Medicine Hat could be developed.

3.1.9 Results of Flow Naturalization

The naturalized daily flow timeseries for SSR at Medicine Hat (WSC Station 05AJ001) for the 1930-2015 period is shown in **Figure 20**. The figure also includes the recorded daily flow data from WSC to provide a comparison. Annual maximum daily flows are compared in **Figure 21**. The figure shows that effects of flow regulation on the annual peaks at Medicine Hat appear to become more pronouncing since the 1960s, which is consistent with the timing of the storage reservoir developments in the Oldman River basin. As shown in the plot of the ratios of the naturalized against recorded annual maximum daily flows in **Figure 21**, the naturalized peaks are significantly higher than the observed peaks for lower flows; but for observed flows greater than 1000 m^3/s (which is close to the 2-year flood peak), the ratios are smaller than 1.3 except in 2002 (1.44 with an observed peak of 1800 m^3/s) and in 2008 (1.51 with an observed peak of 1560 m^3/s). This trend (more significant effects on lower flows than on higher flows) is expected because reservoirs are generally more capable of managing lower flows.

The naturalized peak for 1947 (1020 m^3/s) is slightly smaller than the recorded peak (1040 m^3/s, resulting in a ratio of 0.98). This recorded peak occurred on May 13, after the first peak of the year that occurred on March 22 (about 850 m^3/s). While there could be some errors in the flow naturalization process, it is possible that the upstream reservoirs on the Bow River had been over-discharging in the expectation of higher flows that usually occur in late May or June (but higher flows did not happen through the rest of that year). It is also possible that operating rules of some reservoirs require draw down of reservoir levels in early May. Note that during the May 13, 1947 event, the naturalized flows for Bow River near the mouth calculated by Golder (2017) were about 20 m^3/s smaller than their regulated flow estimates, as well.

3.2 Flow Regulation

3.2.1 Methodology

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 that the naturalized flow data series be used to develop a regulated data series in consideration of current flow management operations, and estimates of the regulated flood frequency be provided. 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 estimated daily natural flows at the major reservoir sites for the 1930-2015 period were routed through the reservoirs based on their operating rules, and then through the downstream river reaches to Medicine Hat while adding tributary inflows assembled from the flow naturalization process. This simulation was conducted at a daily time step using the HEC-ResSim model described above. In the model, the reservoirs were represented by their elevation – surface area – storage volume relationships and rating curves of their discharge facilities (e.g. spillways, low level outlets, etc.) shown in **Appendix A**. Flow management operations through the reservoirs were simulated in the HEC-ResSim model based on the operating rule curves provided by AEP, as shown in **Figure 22** and **Figure 23**. For Chain Lakes Reservoir, AEP provided only the FSL (the sill elevation of the ungated spillway) and a winter target level (El. 1295.50 m) as the guidelines of operations. A rule curve with seasonal variation was established based on the daily reservoir level records of 1966-2015 for WSC Station 05AB037, as shown in **Figure 23**.

The Little Bow River basin consists of significant storage capacities in the Twin Valley, McGregor, Travers and Little Bow reservoirs. Water stored in this system is mostly discharged to BRID through McGregor and Little Bow reservoirs, which could be considered as off-stream storage. Flows from the Little Bow River to Oldman River are managed primarily through operations of Twin Valley and Travers dams. From 1957 through 2015, annual maximum daily discharges from the Little Bow River to the Oldman River ranged from less than 5 m^3/s to about 25 m^3/s. The record high daily discharge from Travers Reservoir to the Little River occurred during the June 2013 flood event and was due to spill from the Highwood River. Note that the June 2013 event was also a record high event for the Highwood River. These magnitudes are significantly smaller than the high flows in the Oldman River or SSR.

According to the Little Bow River basin flood management strategy (AMEC, 2006), for an inflow flood that is expected to be smaller than the 1000-year event, both Twin Valley and Travers dams will be operated to provide downstream flood protection with an effort to limit outflow discharges from Travers Dam to about 11 m^3/s – the approximate bank-full capacity of the lower Little Bow River. For a 1000-year event, the maximum outflow discharge from Travers Dam would be about 197 m^3/s according to

AMEC (2006), which is less than 2% of the 1000-year peak discharge for SSR at Medicine Hat, and less than 4% of the 1000-year peak discharge for Oldman River near Lethbridge estimated by AENV (1995).

Because the regulated flows from the Little Bow River system are so small compared with the Oldman River and SSR flows, and also the estimated natural inflow timeseries for the Little Bow River does not cover the 1930-1954 period due to the lack of usable data, the Little Bow River basin was ignored in the flow regulation process of the present study. It is believed that this simplification will not impact the flood frequency estimates for SSR near Medicine Hat.

3.2.2 Results of Flow Regulation

The regulated daily flow timeseries for SSR at Medicine Hat (WSC Station 05AJ001) for the 1930-2015 period is shown in **Figure 24**. The figure also includes the recorded daily flow data from WSC to provide a comparison. The regulated flows are generally consistent with the gauge data, with differences that are more noticeable for some years than for others. The following should be noted:

1) The results from the flow regulation process are to be used to gain an understanding of potential effects of current flow management operations on flood frequency estimates for SSR near Medicine Hat.
2) The simulated flow regulation represents a plausible scenario, which assumes that all reservoirs are managed perfectly following the prescribed rule curves. This may be different than actual or historical operations. In addition to operating rule curves, actual or historical operations would also depend on many other factors such as water supply and flood forecasting, water supply demands, schedule of maintenance, ability to operate a dam in response to changes in hydrologic conditions, etc. As such, it is not unusual that operations of a dam vary between different years and deviate from its rule curves. **Figure 25** shows variation of the historical operations for Oldman Dam and a comparison with its operating rule curve as an example.
3) The flow regulation simulation was based on estimated inflows. As described in Section 3.1, quality and accuracy of the estimates are subject to available data and vary for different periods and different sites.
4) Recorded flows for SSR at Medicine Hat were affected by flow management projects that were constructed in different years and could have been operated differently from the current operating strategies.

3.3 Flow Naturalization for Ross Creek Sub-basin

3.3.1 Ross Creek above Seven Persons Creek

The Ross Creek Irrigation District (RCID) was established in 1954 and began using water from Ross Creek and its tributaries including Gros Ventre Creek. Due to the lack of project information and hydrometric data, it is nearly impossible to perform flow naturalization for Ross Creek and its tributaries that could lead to better flood frequency estimates than from a regional analysis.

The largest storage reservoir in the Ross Creek watershed is Elkwater Lake with a live storage capacity of 3,700 dam^3, located at the headwater of Ross Creek near the top of Cypress Hills (**Figure 26**). The lake has a drainage area of only 29 km^2 (or 3.5% of the drainage area of Ross Creek at Highway 41). This lake, which is fed by local surface runoff and groundwater with no defined inflow streams, has been regulated since 1908 when a weir was constructed at its outlet to Ross Creek (AENV, 2006). Given its location and relatively small drainage area, the regulation would have negligible effects on natural flood peaks at the sites of interest along Ross Creek.

Bullshead Reservoir is another but much smaller reservoir in the Ross Creek watershed, located at the headwater of Bullshead Creek. It has a drainage area of 85 km^2, which accounts for a relatively small portion of the Bullshead Creek catchment of about 350 km^2. The reservoir has a live storage capacity of less than 1000 dam^3. It is not expected that this reservoir would have significant effects on flood frequency estimates for the present study sites.

There are also a number of on-farm storage facilities in the Ross Creek watershed. It is not possible to quantify their effects on natural flows; however, they would tend to be random and would likely vary from year to year.

NHC (2013) presented a regional flood frequency analysis of the north slope of Cypress Hills based on WSC flow data for Ross Creek and other major creeks in the region, including both regulated and unregulated streams. The results indicate that the region is hydrologically homogeneous, which suggests that effects of flow regulation in the Ross Creek watershed are negligible.

As such, no attempt has been made to naturalize flows along Ross Creek and its tributaries in this study except that flow diversion from Gros Ventre Creek to Cavan Lake was considered when estimating Ross Creek peak flows. Detailed discussions on this diversion are presented in Section 4.4.1.

3.3.2 Seven Persons Creek

WSC Station 05AH005 (**Figure 26**) provides flow data for Seven Persons Creek at Medicine Hat from 1912 to 2016. Since 1955, the flows have been noticeably affected by regulation at Murray Reservoir and Seven Persons Reservoir located approximately 60 km upstream of the gauge station.

Murray Reservoir has a surface area of about 8.8 km^2. The total drainage area is about 2550 km^2, which consists primarily of the 1840 km^2 prairie catchment and 440 km^2 Cypress Hills catchment (including Peigan Creek). In addition to inflows from upper Seven Persons Creek and runoff from Cypress Hills, Murray Reservoir also receives diverted flows from Sauder Reservoir located about 18 km northwest near the SSR. Water stored in Murray Reservoir is discharged to Seven Persons Reservoir along Seven Persons Creek and diverted to Bullshead Creek via an irrigation canal.

Seven Persons Reservoir is located about 10 km downstream of Murray Reservoir. It is much smaller with a surface area of about 0.6 km^2.

Neither of the reservoirs is gauged by WSC or AEP. It is not possible to evaluate effects of Seven Persons Reservoir on the natural creek flows. As it is relatively small, the effects are expected to be insignificant and were ignored in this study. While there are no WSC or AEP's standard measurements of water levels, inflows or outflows for Murray Reservoir, seasonal daily records are available from St. Mary River Irrigation District (SMRID) for 1984, 1986 - 1990, and 1994 – 2016. They include diverted inflows to Murray Reservoir from Sauder Reservoir, water levels, estimated storage volumes and outflows from the reservoir. These records were obtained from SMRID and used together with the gauge data for WSC Station 05AH005 to estimate natural peak flows of Seven Persons Creek. The flow travel time from Murray Reservoir to Medicine Hat was assumed to be one day according to the 2010 flood review by NHC (2013) and the assessment of other high flow events. As some of the SMRID data are not continuous records and available information is rather limited, the analysis was carried out on an event basis at a daily time step and only the peak discharge estimates have been adopted. The results are shown in **Figure 27**.

The results from this flow naturalization and available project information are inadequate to simulate flow regulation for Seven Persons Creek. Therefore, no attempt has been made to perform flow regulation, and the flood frequency estimates for Seven Person Creek presented in Section 4 have been developed for the naturalized flow condition only.

4 FLOOD FREQUENCY ANALYSIS

4.1 General

Flood frequency analyses were carried out for the sites of interest on the SSR, Ross Creek, Seven Persons Creek and Bullshead Creek, based on series of annual maximum instantaneous discharges recorded at WSC gauge stations and/or estimated from the results presented in Section 3 and regional analyses. These analyses were undertaken within the framework of the HYFRAN, USACE HEC-SSP (version 2.1) 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 for the sites of interest, including the normal (N), log-normal (LN), three-parameter log-normal (LN3), Pearson III (P3), log-Pearson 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. The Cunnane positioning formula was used to plot data points for visualization purposes.

The goodness of fit of each of the 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

$$SSE = \sqrt{\frac{1}{n-m}\sum_{i=1}^{n}(x_i - y_i)^2} \qquad \textbf{(Equation 4)}$$

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 x_i.

The *SSE* values of the probability distributions for each site 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.

The USGS "Guidelines for Determining Flood Frequency Bulletin 17B" and draft 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. They use the log-Pearson III 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, Draft for public review, December 29, 2015) 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 lower outlier adjustments, regional skew information and historical information. The 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 and theoretical limits were used in the present study.

In the absence of regional skew coefficients, flood frequency estimates for the SSR from the Bulletin 17C method are often identical to those from the regular log-Pearson III distribution based on the method of moments.

4.2 South Saskatchewan River

4.2.1 Site Characteristics

As per the Terms of Reference (TOR) for this study, flood frequency estimates for both naturalized flood peaks and regulated flood peaks are required for the SSR at Medicine Hat (WSC Station 05AJ001) and below Ross Creek. The two sites are located approximately three kilometres apart, with drainage areas of 56,370 km^2 and 61,400 km^2 respectively.

Systematic flow records are available for SSR at Medicine Hat (WSC Station 05AJ001) since 1911. Estimated maximum instantaneous peak discharges for two pre-record large flood events – the 1902 and 1908 events – are also available from a previous study by AENV (1985). Over 90% of the annual peak flow events occurred in late May and June. **Figure 28** shows the relationship between annual instantaneous peak and maximum daily discharges for WSC gauge 05AJ001. The observed instantaneous to daily peak discharge ratio was 1.09. A total of 69 data points with both daily and instantaneous annual peak flows for the 1915 – 2016 period were available for this analysis, with a broad range of instantaneous discharges from 174 m^3/s to 5110 m^3/s.

4.2.2 Flood Frequency Analysis for SSR at Medicine Hat

Naturalized Flood Peaks

Figure 29 and **Table 4-1** show the annual naturalized peak flow series for SSR at Medicine Hat. The data for the 1930 – 2015 period were based on the simulated naturalized flows. To extend the record as far back as possible, the 1911 – 1929 records for WSC Station 05AJ001 and the estimates for the 1902 and 1908 pre-record large events were combined with the naturalized flows. The 1930 – 2015 naturalized instantaneous peak discharges and missing gauge data prior to 1930 were calculated based on the relationship shown in **Figure 28**.

Note that the flow naturalization for the Bow River performed by Golder (2017) does not include the period prior to 1930. The 1912 – 1929 flows recorded at Medicine Hat could have been affected by the Bow River flow regulation due to the following projects:

- The Western Irrigation District (WID) with diversions below the Bow Elbow River confluence (began prior to 1912)
- Lake Minnewanka (began in 1912)
- Bassano Dam (began in 1914)
- Carseland Weir (diversion to Lake McGregor, began in 1918)
- Ghost Reservoir (began in 1929)

Lake Minnewanka was a natural lake fed by the Cascade River and overflow/diversion from the Ghost River. The Cascade Power Plant, which uses Lake Minnewanka as a source of water, started in 1912, while the Ghost diversion started to operate in 1942. According to Golder (2017), the Cascade Power Plant was operated within a relatively small range of lake level variation prior to 1942 when the lake level was significantly lower and surface area much smaller than at present (Alberta Environment Protection, 1998); and it had relatively small impacts on the downstream Bow River flows until 1942. Since then, the lake level has been raised by as much as 30 m. Accordingly, it is not expected that the hydroelectrical operation at Lake Minnewanka prior to 1930 would have affected the SSR flood peaks at Medicine Hat.

Ghost Reservoir was formed in 1929 as a power plant reservoir on the Bow River. It is fed by the Bow and Ghost rivers. The 1929 daily inflow could be approximated as the sum of the flows for Bow River near Seebe (WSC Station 05BE004) and Ghost River near Cochrane (WSC Station 05BG001). The estimated inflow hydrograph for the 1929 annual peak event is shown in **Figure 30** and compared with the downstream Bow River flows at Calgary (WSC Station 05BH004). Note that the drainage area of

Ghost Reservoir is about 82% of that for Bow River at Calgary. The estimated peak daily discharge is about 780 m^3/s, which is about 68% of the Bow River peak discharge at Calgary (about 1150 m^3/s). **Figure 30** indicates that Ghost Reservoir did not seem to have impacts on the downstream Bow River flows during the 1929 annual peak event.

Therefore, among the projects listed above, Bassano Dam was the only primary storage project that might have affected the annual natural peaks of the SSR at Medicine Hat during the 1912 – 1929 period.

As noted in Section 3.1.9, effects of flow regulation on the SSR annual peaks at Medicine Hat were relatively insignificant prior to the major developments in the Oldman River basin (after 1960). Many storage projects were constructed in the Bow River basin during the 1930 – 1960 period, including Glenmore Reservoir, the Kananaskis River developments, the Lake Minnewanka upgrade, the Spray Lake system and Bearspaw Reservoir. Although these projects significantly increased the level of flow regulation on the Bow River, the maximum daily natural flows at Medicine Hat were only about 10% higher than the gauged peaks for the 1930 – 1960 period (Section 3.1.9 and **Figure 21**). Therefore, it is believed that the effects of the projects in the Bow River basin (mainly Bassano Dam) on the annual natural peaks of the SSR at Medicine Hat were much less than 10% during the 1912 – 1929 period; and it is reasonable to take the gauge data without adjustments to represent the annual natural peaks for SSR at Medicine Hat. The combined data series presented in **Figure 29** and **Table 4-1** were consequently used to develop natural flood frequency estimates for SSR at Medicine Hat. Note that a sensitive test was performed by increasing the 1912 – 1929 peak discharges by 10%, which increased the flood frequency estimates by up to 2% only.

Table 4-1: Annual peak instantaneous and daily discharges of naturalized flows for SSR at Medicine Hat

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
1902	5660	-	Jul
1908	5240	-	Aug
1911	**1250**	1140	19-Jun
1912	**1240**	1130	19-Jun
1913	**1070**	974	04-Jun
1914	**787**	722	07-Jun
1915	2550	2400	28-Jun
1916	**2400**	2200	23-Jun
1917	**1780**	1630	05-Jun
1918	**1140**	1040	16-Jun
1919	**1090**	991	01-Jun
1920	**899**	824	10-Jul
1921	**995**	912	10-Jun

Year	Maximum Instantaneous Discharge (m³/s)	Maximum Daily Discharge (m³/s)	Date
1922	**1030**	940	08-Jun
1923	4110	3710	03-Jun
1924	895	821	17-Jun
1925	1050	963	25-May
1926	744	682	14-Sep
1927	**2140**	2090	13-Jun
1928	**1840**	1830	03-Jul
1929	**3450**	3060	05-Jun
1930	**877**	803	Jun-12
1931	**679**	621	Jun-22
1932	**3080**	2820	Jun-05
1933	**1210**	1100	Jun-20
1934	**1660**	1520	Jun-10
1935	**895**	819	Jun-20
1936	**864**	791	Jun-05
1937	**1590**	1450	Jun-16
1938	**1370**	1250	May-29
1939	**1180**	1080	Jun-19
1940	**695**	636	May-28
1941	**537**	491	Jun-07
1942	**2340**	2140	May-14
1943	**936**	857	Jun-21
1944	**455**	416	Jun-17
1945	**1250**	1140	Jun-03
1946	**1210**	1100	Jun-01
1947	**1120**	1020	Jun-12
1948	**2910**	2660	Jun-20
1949	**718**	657	Jun-04
1950	**1370**	1250	Jun-25
1951	**2080**	1900	Jun-27
1952	**1300**	1190	Jun-15
1953	**4730**	4330	Jun-11
1954	**1350**	1230	May-22
1955	**1240**	1130	May-22
1956	**1160**	1060	Jun-05
1957	**929**	850	May-24
1958	**887**	812	Jun-13

Year	Maximum Instantaneous Discharge (m³/s)	Maximum Daily Discharge (m³/s)	Date
1959	**1220**	1110	Jun-30
1960	**745**	682	Jun-07
1961	**1270**	1160	May-30
1962	**627**	574	Jun-22
1963	**1950**	1780	Jul-03
1964	**2550**	2330	Jun-11
1965	**2010**	1840	Jun-20
1966	**1530**	1400	Jun-07
1967	**2680**	2450	Jun-03
1968	**1090**	995	Jun-16
1969	**2170**	1980	Jul-02
1970	**1840**	1680	Jun-17
1971	**1540**	1410	Jun-09
1972	**1760**	1610	Jun-04
1973	**921**	843	May-30
1974	**1840**	1680	Jun-20
1975	**3230**	2950	Jun-23
1976	**976**	893	Aug-09
1977	**583**	533	Jun-13
1978	**1200**	1090	Jun-12
1979	**1050**	960	May-30
1980	**1520**	1390	May-29
1981	**2120**	1940	May-25
1982	**1130**	1030	Jun-20
1983	**800**	732	Jun-03
1984	**699**	640	Jun-21
1985	**810**	741	Sep-16
1986	**1490**	1360	Jun-03
1987	**739**	676	Jul-26
1988	**806**	738	Jun-12
1989	**1130**	1030	Jun-14
1990	**1810**	1650	Jun-01
1991	**1760**	1610	Jun-24
1992	**1260**	1150	Jun-17
1993	**1490**	1360	Jul-16
1994	**1040**	951	Jun-10
1995	**5590**	5110	Jun-09

Year	Maximum Instantaneous Discharge (m³/s)	Maximum Daily Discharge (m³/s)	Date
1996	**1280**	1170	Jun-12
1997	**1470**	1340	Jun-04
1998	**1720**	1570	Jun-22
1999	**871**	797	Jul-18
2000	**572**	523	Jun-21
2001	**966**	884	Jun-09
2002	**2830**	2590	Jun-12
2003	**981**	898	Jun-02
2004	**655**	599	Jun-16
2005	**4240**	3880	Jun-10
2006	**1870**	1710	Jun-18
2007	**1250**	1140	Jun-09
2008	**2580**	2360	May-27
2009	**717**	656	Jun-03
2010	**2340**	2140	Jun-20
2011	**2570**	2350	May-30
2012	**1690**	1540	Jun-27
2013	**5290**	4840	Jun-23
2014	**3440**	3150	Jun-21
2015	**1020**	931	Jun-06

Notes:

1. The 1902 and 1908 data are estimates from AENV (1985); the 1911-1929 data are recorded flows from WSC; while the others are simulated natural flow data.
2. The bolded and underlined values are based on Q_i=1.09Q_d.

The 1902 and 1995 annual peak events are the two largest events with similar magnitude, followed by two slightly smaller events – 2013 and 1908. **Table 4-2** summarizes the statistical parameters of the complete natural flow data set.

Table 4-2: Summary of statistical parameters of the simulated natural annual instantaneous peak flood series for the SSR at Medicine Hat

Parameter	Natural Flood Series 1902, 1908, 1911-2015
Years of record	107
Mean (m^3/s)	1660
Median (m^3/s)	1250
Standard deviation (m^3/s)	1120
Coefficient of variation	0.675
Skew coefficient (minimum, maximum, actual)	1.35, 1.86, 1.94

Each of the frequency distributions in the adopted suite were fitted to the instantaneous flood peaks shown in **Table 4-1**. The goodness of fit analysis (K-S test and least squares method) described earlier was undertaken for each distribution as shown in **Table 4-3**.

Table 4-3: Goodness-of-fit comparison for probability distributions applied to naturalized flood peaks for SSR at Medicine Hat

Distribution	D_n	Normalized *SSE* (Q_{pm} = 1660 m^3/s)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.171	0.324	8	8	8
Log-normal(LN)	0.096	0.160	4	5	5
Three parameter log-normal (LN3)	0.092	0.136	3	2	2
Pearson III (P3)	0.089	0.114	2	1	1
Log-Pearson III (LP3)	0.057	0.153	1	4	2
Gumbel (G)	0.124	0.187	6	7	6
Generalized extreme value (GEV)	0.098	0.148	5	3	4
Weibull (W)	0.143	0.183	7	6	6

The LP3 distribution produces the smallest D_n value but its *SSE* value is slightly higher than the values for the P3, LN3 and GEV distributions. The GVE curve is virtually identical to the LN3 curve. The P3 distribution has the lowest *SSE* value and second lowest D_n value. In the combined ranking, it is ranked the best, followed by LP3 and LN3. These three distributions are compared in **Figure 31**, while the other evaluated distributions are shown graphically in **Appendix C**.

As shown in **Figure 31**, The P3 curve is very similar to the LN3 curve, while its lower part fit the data points slightly better. The P3 and LP3 curves are nearly identical for the lower part but the LP3 distribution results in greater flood peaks for return periods longer than 50 years. The 100 and 1000-year values are about 15% and 56% greater than those from the P3 distribution, respectively. While the P3 tends to fit the 1902 data point (one of the largest events), the LP3 represents other large events better;

and it should be noted that the peak discharge for the 1902 (a pre-record event) was an estimate. Therefore, it is recommended that the LP3 distribution be used herein to described the naturalized flood peaks for SSR at Medicine Hat. The adopted LP3 curve with 95% confidence limits is shown in **Figure 32**.

Regulated Flood Peaks

Figure 33 and **Table 4-4** shows the regulated annual peak flow series for SSR at Medicine Hat (1930-2015). The maximum daily discharges were based on the simulated regulated flows. The ratio of instantaneous to daily discharge of 1.09 (**Figure 28**) was applied to the maximum daily discharges to estimate the maximum instantaneous discharges.

Table 4-4: Annual peak instantaneous and daily discharges of simulated regulated flows for SSR at Medicine Hat

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
1930	**682**	624	Jun-12
1931	**519**	475	Jun-22
1932	**2870**	2620	Jun-05
1933	**905**	828	Jun-20
1934	**1410**	1290	Jun-10
1935	**664**	608	Jun-20
1936	**642**	587	Jun-05
1937	**1250**	1140	Jun-16
1938	**1050**	957	May-29
1939	**982**	899	Jun-19
1940	**546**	500	May-28
1941	**369**	337	Mar-26
1942	**2070**	1890	May-14
1943	**659**	603	Jun-22
1944	**290**	265	Jun-17
1945	**991**	907	Jun-10
1946	**963**	881	Jun-01
1947	**1010**	922	May-13
1948	**2650**	2420	Jun-20
1949	**539**	493	Jun-04
1950	**1070**	977	Jun-25
1951	**1810**	1650	Sep-02
1952	**1110**	1010	Jun-15
1953	**4370**	4000	Jun-11
1954	**1200**	1090	May-22

Year	Maximum Instantaneous Discharge (m³/s)	Maximum Daily Discharge (m³/s)	Date
1955	**1060**	965	May-22
1956	**966**	884	Jun-05
1957	**786**	719	May-24
1958	**700**	641	May-15
1959	**960**	879	Jun-30
1960	**591**	541	May-16
1961	**1040**	952	May-30
1962	**410**	375	Jun-22
1963	**1660**	1520	Jul-03
1964	**2240**	2050	Jun-11
1965	**1750**	1600	Jun-20
1966	**1320**	1200	Jun-07
1967	**2400**	2190	Jun-03
1968	**936**	857	Jun-12
1969	**1880**	1720	Jul-02
1970	**1540**	1410	Jun-17
1971	**1360**	1240	Jun-09
1972	**1540**	1410	Jun-04
1973	**745**	682	May-30
1974	**1500**	1370	Jun-20
1975	**2960**	2710	Jun-23
1976	**872**	798	Aug-09
1977	**461**	422	Jun-13
1978	**985**	902	Jun-11
1979	**870**	796	May-30
1980	**1330**	1210	May-29
1981	**1850**	1690	May-25
1982	**880**	805	Jun-20
1983	**651**	596	Jun-02
1984	**528**	483	Jul-04
1985	**723**	662	Sep-16
1986	**1320**	1200	Jun-03
1987	**668**	611	May-16
1988	**706**	646	Jun-12
1989	**889**	814	Jun-14
1990	**1580**	1440	Jun-01
1991	**1490**	1360	Jun-24

Year	Maximum Instantaneous Discharge (m³/s)	Maximum Daily Discharge (m³/s)	Date
1992	**<u>1060</u>**	968	Jun-17
1993	**<u>1280</u>**	1170	Jul-16
1994	**<u>882</u>**	807	Jun-10
1995	**<u>5160</u>**	4720	Jun-09
1996	**<u>1070</u>**	972	Jun-12
1997	**<u>1240</u>**	1130	Jun-04
1998	**<u>1480</u>**	1350	Jun-22
1999	**<u>694</u>**	635	Jul-18
2000	**<u>419</u>**	383	Jun-13
2001	**<u>720</u>**	659	Jun-09
2002	**<u>2510</u>**	2290	Jun-12
2003	**<u>781</u>**	715	Jun-02
2004	**<u>479</u>**	438	Jul-06
2005	**<u>3890</u>**	3560	Jun-10
2006	**<u>1540</u>**	1410	Jun-18
2007	**<u>1080</u>**	989	Jun-09
2008	**<u>2250</u>**	2060	May-27
2009	**<u>494</u>**	452	Jun-03
2010	**<u>2080</u>**	1900	Jun-20
2011	**<u>2240</u>**	2050	May-30
2012	**<u>1490</u>**	1360	Jun-27
2013	**<u>4600</u>**	4210	Jun-24
2014	**<u>3100</u>**	2830	Jun-21
2015	**<u>835</u>**	764	Jun-06

Notes:

1. The bolded and underlined values are based on Q_i=1.09Q_d.

The statistics of the simulated regulated peak flow series from 1930 to 2015 are provided in **Table 4-5.** These values are comparable to those for the naturalized flows shown in **Table 4-2**.

Table 4-5 Summary of statistical parameters of the simulated regulated annual instantaneous peak flood series on the SSR at Medicine Hat

Parameter	Regulated Flood Series 1930-2015
Years of record	86
Mean (m^3/s)	1350
Median (m^3/s)	1060
Standard deviation (m^3/s)	946
Coefficient of variation	0.701
Skew coefficient (minimum, maximum, actual)	1.40, 1.79, 2.01

Each of the frequency distributions in the adopted suite were fitted to the instantaneous flood peaks shown in **Table 4-4**, and the results of the goodness of fit analysis are shown in **Table 4-6**. The LP3 distributions produces the smallest D_n and *SSE* values, and is ranked the best in the combined ranking, followed by the LN, LN3 and P3 distributions with comparable D_n and *SSE* values. These curves are compared in **Figure 34**, while the others are presented in **Appendix C**. As shown in **Figure 34**, the LP3 curve represents the flood series reasonably well. The other three curves are nearly identical while they are clearly different from the LP3. Using the same rationale as presented for the naturalized flows, the LP3 distribution is recommended for the regulated flood peaks for SSR at Medicine Hat. The adopted curve with 95% confidence limits is shown in **Figure 35**. The frequency curve recommended for the naturalized flood peaks is also shown for a comparison.

Table 4-6: Goodness-of-fit comparison for probability distributions applied to the regulated flood peaks at the for SSR at Medicine Hat

Distribution	D_n	Normalized *SSE* ($Q_{pm} = 1350\ m^3/s$)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.165	0.327	8	8	8
Log-normal(LN)	0.070	0.124	2	4	2
Three parameter log-normal (LN3)	0.073	0.112	3	3	2
Pearson III (P3)	0.094	0.104	5	2	4
Log-Pearson III (LP3)	0.046	0.092	1	1	1
Gumbel (G)	0.111	0.179	6	7	6
Generalized extreme value (GEV)	0.084	0.125	4	5	5
Weibull (W)	0.120	0.171	7	6	6

4.2.3 Flood Frequency Analysis for SSR below Ross Creek

The Ross Creek confluence with the SSR is located about three kilometers downstream of WSC Station 05AJ001. The drainage area of the SSR below Ross Creek is about 9% greater than at WSC Station 05AJ001. The difference is mainly due to the Ross Creek basin (about 4790 km^2). The flows at the downstream location are best determined from those at WSC Station 05AJ001 plus the inflows from Ross Creek. There are no gauge data for Ross Creek at the mouth, so the 1930-2015 Ross Creek daily inflows were estimated as the sum of daily flows for Seven Person Creek at Medicine Hat (WSC Station 05AH005), Ross Creek at Highway 41 (WSC Station 05AH052) and Bullshead Creek at Black and White Trail (WSC Station 05AH053) with a one-day lag. In this process, the records for Ross Creek at Highway 41 and Bullshead Creek were extended, by prorating daily flow data for Ross Creek near Irvine (WSC Station 05AH003) and Gros Ventre Creek near Dunmore (05AH037) by the drainage area ratios, respectively. This results in relatively crude estimates of the Ross Creek inflows to the SSR, which, however, could be used to assess effects of the Ross Creek inflows on the SSR flood peaks. As shown in **Figure 36**, there is virtually zero difference between the flood peaks at WSC Station 05AJ001 and downstream of Ross Creek because the flood peaks on the two streams do not typically occur simultaneously. Even if they did, the magnitude of the peak on Ross Creek would be relatively small and equivalent to errors in the estimation of the SSR peak flow. Note that the comparison shown in **Figure 36** was made on the regulated SSR flows and the difference between the downstream and upstream naturalized flows would be even smaller. Therefore, it is recommended that the frequency estimates for WSC Station 05AJ001 also be applied to the SSR below Ross Creek.

4.3 Seven Persons Creek

4.3.1 Flood Characteristics

The TOR requires flood frequency estimates to be developed for Seven Persons Creek at Medicine Hat (WSC Station 05AH005) and at the mouth. Seven Persons Creek has a complex heterogeneous catchment with significant systematic regulation. The total drainage area at Medicine Hat is about 3275 km^2. As described in Section 1.4.2, the upper catchment lies on mostly agricultural land in an arid region, which accounts for about 75% of the total drainage area. Snowmelt with or without rain in spring dominates peak runoff from this area, while flows tend to vanish in the summer during periods of limited rainfall. Before arriving at Medicine Hat, Seven Persons Creek receives runoff from west and northwest slopes of Cypress Hills, including Peigan Creek and Paradise Creek, which enter Seven Persons Creek just upstream of Murray Reservoir and downstream of Seven Persons Reservoir, respectively. This hill catchment area represents about 25% of the Seven Persons Creek drainage area at Medicine Hat. Peak discharges from this area are commonly associated with snowmelt in spring and sometimes caused by rainstorms in summer. As described in Section 3.3.2, the creek has been regulated by the Murray and Seven Persons dams since 1955.

The naturalized annual peak discharges developed in Section 3.3.2 are combined with the WSC gauge data at Medicine Hat for the pre-regulation period to provide an extended data series, as shown in **Table**

4-7 and **Figure 37**. While the combined data series spans from 1913 to 2016, there are a number of years with missing data. Instantaneous peaks are not provided in many of the years, and where missing, they are calculated on the basis of the correlation between the instantaneous and daily peaks for years when both were measured for the pre-regulation period prior to 1955, as shown in **Figure 38**. The relationship shows a maximum instantaneous to daily discharge ratio of 1.19. Although there are only 10 data points available for this period, they are distributed over a relatively broad range of daily peak discharges from 1.76 m^3/s to the record high 119 m^3/s.

Most of the annual peak discharges on Seven Persons Creek occurred in March and April. The largest event on the record, with a peak discharge of 136 m^3/s, occurred in April 1952 due to snowmelt. It is more than twice as high as the peaks of the second and third largest events (April 2011 and June 2010). While the 2011 and 2010 events are similar in magnitude, their differences are noted as follows:

- The 2011 event was associated with snowmelt while the 2010 event was due to an intense rainstorm in summer.
- The 2010 peak at Medicine Hat was dominated by high runoff from Cypress Hills, while during the 2011 event, flows from the Cypress Hills tributaries were much less severe, indicating that most runoff would have been derived from the prairie catchment area.

Table 4-7: Annual peak instantaneous and daily discharges of natural flows for Seven Persons Creek at Medicine Hat

Year	Maximum Instantaneous Discharge (m^3/s)	Date	Maximum Daily Discharge (m^3/s)	Date
1913	**13.4**		11.30	08-Apr
1914	**3.7**		3.11	08-Apr
1915	**15.1**		12.70	04-Apr
1916	**25.2**		21.20	13-Mar
1917	**25.8**		21.70	31-Mar
1919	**0.6**		0.50	27-Apr
1920	**13.7**		11.50	23-Mar
1921	**16.9**		14.20	16-Apr
1922	**28.7**		24.10	24-Apr
1923	**2.2**		1.81	17-Jun
1924	**0.4**		0.31	12-Oct
1925	**27.7**		23.30	31-Mar
1926	**8.9**		7.45	07-Mar
1927	**25.3**		21.3	27-Apr
1928	**64.7**		54.4	23-Mar
1929	**1.3**		1.13	19-Mar
1930	**1.3**		1.10	19-Feb

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Year	Maximum Instantaneous Discharge (m³/s)	Date	Maximum Daily Discharge (m³/s)	Date
1935	**13.8**		11.6	19-Apr
1936	**17.6**		14.8	07-Mar
1938	**7.7**		6.46	30-Mar
1939	19.3	21-Mar	12.5	21-Mar
1940	10.1	25-Apr	9.15	25-Apr
1941	11.7	24-Mar	11.4	24-Mar
1943	46.2	25-Mar	26.2	25-Mar
1945	4.25	10-Mar	1.76	11-Mar
1947	48.4	22-Mar	41.1	24-Mar
1948	39.1	22-Mar	21.9	22-Mar
1951	33.4	31-Mar	28.9	01-Apr
1952	136	31-Mar	119	31-Mar
1953	15	04-Jun	11.6	07-Jun
1954	**5.5**		4.64	08-Apr
1984	**13.4**		11.24	26-Sep
1986	**25.1**		21.1	04-Sep
1987	**24.7**		20.8	04-Sep
1988	**13.1**		11.0	09-Jun
1989	**17.9**		15.1	08-May
1994	**6.7**		5.64	22-May
1995	**5.3**		4.46	08-Oct
1996	**15.4**		12.9	13-Mar
1997	**17.5**		14.7	21-Mar
1998	**18.1**		15.2	30-Jun
1999	**8.1**		6.79	13-Oct
2000	**13.5**		11.3	23-Sep
2001	**1.6**		1.36	11-Oct
2002	**5.6**		4.73	11-Jun
2003	**5.7**		4.79	06-May
2004	**8.3**		6.98	24-May
2005	**12.9**		10.9	18-Jun
2006	**14.0**		11.8	15-Jun
2007	**5.6**		4.71	20-Sep
2008	**18.1**		15.2	22-May
2009	**5.9**		4.99	07-Jun
2010	**67.9**		57.1	19-Jun
2011	**75.5**		63.4	13-Apr

Year	Maximum Instantaneous Discharge (m^3/s)	Date	Maximum Daily Discharge (m^3/s)	Date
2012	**7.3**		6.16	29-May
2013	**7.1**		5.95	20-Sep
2014	**20.0**		16.8	05-Sep
2015	**7.2**		6.01	07-Sep
2016	**9.5**		7.97	08-Aug

Notes:

1. The 1913-1954 data are recorded flows from WSC; while the others are estimated natural flows.
2. The bolded and underlined values are based on Q_i=1.19Q_d.

4.3.2 Flood Frequency Analysis for Seven Persons Creek at Medicine Hat

Each of the frequency distributions in the adopted suite were fitted to the maximum instantaneous discharges of the 59 natural flow events shown in **Table 4-7**. The statistical parameters for the data set are summarized in **Table 4-11**.

Table 4-8 Summary of statistical parameters of natural annual instantaneous peak flood series on Seven Persons Creek at Medicine Hat

Parameter	Natural Flood Series 1913-1930, 1935-1954, 1984-1989, and 1994-2016
Years of record	59
Mean (m^3/s)	19.2
Median (m^3/s)	13.5
Standard deviation (m^3/s)	22.3
Coefficient of variation	1.16
Skew coefficient (minimum, maximum, actual)	2.32, 2.37, 3.15

The goodness of fit analysis (K-S test and least squares method) described earlier was undertaken for each distribution as shown in **Table 4-12**.

Table 4-9: Goodness-of-fit comparison for probability distributions applied to natural flood peaks for Seven Persons Creek at Medicine Hat

Distribution	D_n	Normalized *SSE* ($Q_{pm} = 19.2\ m^3/s$)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.215	0.714	8	8	8
Log-normal(LN)	0.118	0.268	2	2	1
Three parameter log-normal (LN3)	0.121	0.278	3	3	2
Pearson III (P3)	0.127	0.233	5	1	2
Log-Pearson III (LP3)	0.086	0.403	1	6	4
Gumbel (G)	0.191	0.488	7	7	7
Generalized extreme value (GEV)	0.122	0.320	4	5	5
Weibull (W)	0.160	0.282	6	4	6

The LP3 distribution produces the smallest D_n value but its SSE value is relatively high, while the values for the P3 distribution are in the opposite order. The LN distribution ranks the second best based on earther D_n or *SSE* value, followed by the LN3 distribution. In the combined ranking, the LN distribution is ranked the best, followed by LN3, P3 and LP3. These four distributions are compared in **Figure 39**, while the other evaluated distributions are shown graphically in **Appendix C**. Although the LP3 results in the smallest D_n value, it does not fit the highest flood peaks as well as the others, which explains its high *SSE* value. All the other three curves fit the data reasonably well. While the LN3 and P3 curves are very similar, the LN curve tends to predict higher flood peaks for longer return periods. If the LN distribution is applied, the return periods for the 2010 and 2011 flood events would be about 20 years; and the largest event on the record (1952) would be a 75-year event. Note that the flood data series for Seven Persons Creek consists of significant gaps – 45 years of missing data over the 104 year period. Therefore, the LN distribution is likely overly conservative. The differences between the LN3 and P3 curves are rather small. They result in nearly the same 100-year value, while the 1000-year value from the LN3 curve is about 16% higher. It is worth to note that the LN3 distribution uses a location parameter that is in part a complicated function of the skew coefficient from a statistical perspective, and for the Seven Persons Creek data series it takes on a negative discharge value that cannot be justified from a process perspective. Also, it results in negative flood peaks for very low return period. As such, it is recommended that the P3 distribution be used herein to described the Seven Persons natural flood peaks. This is also consistent with the selection of the P3 curve for Ross Creek described in the next section. The adopted P3 curve with 95% confidence limits is shown in **Figure 40**.

4.3.3 Flood Frequency Estimates for Seven Persons Creek at the Mouth

This site is located just 3.5 km downstream of WSC Station 05AH005. Local tributary runoff contributing to this relatively short reach is from a 6 km^2 urban area in the city of Medicine Hat (0.2% of the Seven Persons Creek watershed area). Peak runoff from this area would be undetectable during high flow events on Seven Persons Creek and would have passed before the flood peak of the creek arrives.

Therefore, it is recommended that the frequency estimates for WSC Station 05AH005 be applied to Seven Persons Creek at the mouth with no adjustments.

4.4 Ross Creek and Bullshead Creek

4.4.1 Flood Characteristics

As described in Section 1.4.2, the Ross Creek watershed upstream of the Seven Persons Creek confluence is largely situated over the northwestern slope of the Cypress Hills, consisting of upper Ross Creek, Bullshead Creek and Gros Ventre Creek (**Figure 26**). The catchment areas of these three tributaries are comparable in sizes, physiographic characteristics and hydro-climate conditions. High flows on these tributaries commonly occur in March and April due to snowmelt runoff with or without rainfall, but annual peak events due to intense rainstorm in summer are not unusual. For example, the record high event on Ross Creek was the June 2010 rainstorm event, while the second, third and fourth largest (1955, 1994 and 1952) events occurred in spring.

There are/were a number of hydrometric stations over the Ross Creek sub-basin and its vicinity. The four most salient stations that provide insight into the flood characteristics are:

- Gros Ventre Creek near Dunmore (WSC Station 05AH037), with a period of record from 1921 to the present with some missing year;
- Ross Creek near Irvine (WSC Station 05AH003), with a period of record from 1911 to 2000 with some missing years;
- Ross Creek at Highway 41 (WSC Station 05AH052), with a period of record from 2000 to the present; and
- Cavan Lake Diversion near Dunmore (WSC Station 05AH044), with a period of record from 1981 to the present.

The drainage area at the Gros Ventre gauge (WSC Station 05AH037) is 215 km^2. It provides a good record of the historical flood peaks up to the present, and ostensibly its record should correlate reasonably well with those at the Ross Creek gauges. The gauge on Ross Creek at Irvine (WSC Station 05AH003) was replaced by the Highway 41 gauge (WSC Station 05AH052) in 2000 without any overlap with the record at Irvine. The Ross Creek drainage area at the Highway 41 gauge is 808 km^2 – about 25% greater than at Irvine (647 km^2).

The Cavan Lake Diversion diverts water from Gros Ventre Creek at a point just below the WSC gauge and conveys it to Cavan Lake for local irrigation use. As a general rule, water is diverted into Cavan Lake from Gros Ventre Creek during spring runoff (March to April) and during unusual events like winter Chinooks and summer floods. The operation began in 1981. For most of the time, the diversion rates are smaller than 0.5 m^3/s, while the maximum on the record is 4.2 m^3/s. Given the relatively low diversion rates, they would not significantly affect flood peaks on Ross Creek; however, they could account for more than 50% of the Gros Ventre Creek discharges in many dry years, and need to be included in the correlation analysis of Ross Creek and Gros Ventre Creek flows as described in the next section.

Bullshead Creek generally parallels Gros Ventre Creek (**Figure 26**). It enters Ross Creek downstream of Highway 41, just before Ross Creek crosses the eastern limit of the city of Medicine Hat. Its drainage area at WSC Station 05AH053 (Bullshead Creek at Black and White Trail) is about 350 km^2.

In accordance with the Terms of Reference (TOR) for this study, flood frequency estimates were developed in the following sections for:

- Ross Creek at Highway 41;
- Bullshead Creek at Black and White Trail;
- Ross Creek below Bullshead Creek; and
- Ross Creek below Seven Persons Creek.

4.4.2 Flood Frequency Analysis for Ross Creek at Highway 41

Annual Peak Flow Series

WSC Station 05AH052 – Ross Creek at Highway 41 provides 17 years of flow data (2000 – 2016). While the record high peak event (the 2010 event) occurred during this period, most of the other years had relatively low annual peaks. The data are not adequate to develop flood frequency estimates. The gauge near Irvine (WSC Station 05AH003) is located approximately 30 kilometers upstream and provides 85 years of flow data; but it has no overlap of the record at Highway 41. As such, it is necessary to extend the flow data series for the Highway 41 station through a regional analysis based on the data for the Irvine station and Gros Ventre Creek near Dunmore (WSC Station 05AH037).

NHC (2012a) investigated correlations between peak discharges for the three gauge stations. In that study, peaks of Gros Ventre Creek were compared to Ross Creek peaks plus corresponding diversion from Gros Ventre Creek to Cavan Lake (WSC Station 05AH044), and the spring and summer peaks were examined separately. The results indicated that peak flow ratios of Ross Creek near Irvine vs. Gros Ventre Creek were about two for both spring and summer. This suggest that it is unlikely necessary to analyze spring and summer peaks separately. Given the similarity of the hydrological characteristics and proximity of the upper Ross Creek and Gros Ventre Creek catchments, it is reasonable to expect that there a strong correlation between flood peaks on the two creeks and the relationship should not vary by season. The spring peak relationship for Ross Creek at Highway 41 vs. Gros Ventre Creek was based on shorter records and appeared to be skewed by a number of low flow events. The analysis was revisited and updated with additional years of record as part of the present study. While a similar approach was undertaken, spring and summer peaks were not evaluated separately. The updated relationships are shown in **Figure 41**. Note that the daily peak discharges used for this analysis include not only the annual maximum values, but also the peaks of some secondary runoff events to overcome the shortage of data points from flow records (especially for WSC Station 05AH052).

As shown in **Figure 41**, the daily peak discharges of Ross Creek at Highway 41 and near Irvine would be about 3.1 and 2.1 times the Gros Ventre Creek discharges, respectively. Note that these ratios are close to their drainage area ratios to the power of 0.8 (which are 2.9 and 2.4 respectively) – an approach often used in Alberta to approximate flood peaks at an ungauged site from a gauged site. Based on the relationships, annual maximum daily discharges for Ross Creek at Highway 41 could be estimated as:

$$Q_{05AH052} = 3.1 \times Q_{05AH037} \qquad \textbf{(Equation 5)}$$

Or

$$Q_{05AH052} = 1.5 \times (Q_{05AH003} + Q_{05AH044}) \qquad \textbf{(Equation 6)}$$

Both equations were used to estimated the maximum daily discharges for Ross Creek at Highway 41 for the period prior to 2000. The estimates were combined with the post-2000 data at Highway 41. The resultant two data series are plotted in **Figure 42**, which suggests that flood frequency estimates from the two data sets would have negligible differences. As the series based on **Equation 6** covers a longer period, it has been adopted to develop flood frequency estimates for Ross Creek at Highway 41. Note that **Equation 5** was used to provide an estimate for 1919 when the data at WSC Station 05AH003 was missing. The adopted maximum daily discharges are summarized in **Table 4-10**.

Figure 43 shows the relationship between annual instantaneous peak and maximum daily discharges for WSC gauges 05AH003 and 05AH052 (combined). The observed instantaneous to daily peak discharge ratio was 1.29. The relationship was used to estimate instantaneous peak discharges at Highway 41 prior to 2000 and missing gauge data after 2000, as shown in **Table 4-10**. The final peak flow series are also shown in **Figure 44**.

The 2010 annual peak event is the largest event with the peak discharge being almost double the second largest event – the 1955 event. The 1955, 1954 and 1952 peak events are similar in the magnitude. Among the 100 annual peak events analyzed, three were zero flows (1961, 1992 and 2000).

Table 4-10: Annual peak instantaneous and daily discharges for Ross Creek at Highway 41

Year	Maximum Instantaneous Discharge (m^3/s) (1)	Date	Maximum Daily Discharge (m^3/s) (2)	Date
1911	**9.7**		7.5	Mar-19
1913	**16.7**		12.9	Apr-04
1914	**18.1**		14.1	Apr-01
1915	**17.1**		13.2	Mar-18
1916	**41.2**		32.0	Mar-11
1917	**40.1**		31.1	Apr-09
1918	**46.2**		35.9	Mar-23

nhc

Year	Maximum Instantaneous Discharge (m^3/s) [(1)]	Date	Maximum Daily Discharge (m^3/s) [(2)]	Date
1919	**30.0**		23.3	Apr-14
1920	**39.3**		30.5	Mar-22
1921	**40.2**		31.2	Apr-14
1922	**56.5**		43.8	Apr-21
1923	**23.4**		18.2	Jun-16
1924	**4.3**		3.3	Apr-07
1925	**38.1**		29.6	Mar-29
1926	**7.0**		5.4	Apr-11
1927	**43.9**		34.1	May-30
1928	**36.0**		27.9	Mar-20
1929	**39.9**		30.9	Mar-29
1930	**32.1**		24.9	Feb-18
1935	**40.4**		31.4	Apr-13
1937	**6.5**		5.0	Apr-10
1938	**33.7**		26.1	Apr-11
1939	**55.3**		42.9	Mar-20
1940	**42.4**		32.9	Apr-22
1941	**20.3**		15.8	Mar-19
1942	**8.8**		6.8	Jun-09
1943	**56.9**		44.1	Mar-24
1944	**1.2**		1.0	Apr-01
1945	**16.1**		12.5	Mar-11
1946	**14.2**		11.0	Mar-04
1947	**64.0**		49.7	Mar-18
1948	**71.2**		55.2	Apr-17
1949	**2.5**		2.0	Mar-06
1950	**9.5**		7.4	Apr-02
1951	**84.4**		65.4	Mar-31
1952	**102.0**		79.1	Apr-07
1953	**88.2**		68.4	Jun-04
1954	**18.4**		14.2	Apr-06
1955	**114.0**		88.4	Apr-09
1956	**39.3**		30.5	Mar-20
1957	**16.1**		12.5	Feb-28
1958	**9.5**		7.4	Mar-31
1959	**10.5**		8.1	Mar-18

Year	Maximum Instantaneous Discharge (m³/s) (1)	Date	Maximum Daily Discharge (m³/s) (2)	Date
1960	30.4		23.6	Mar-19
1961	0.0		0	Mar-01
1962	7.0		5.4	Mar-21
1963	15.5		12.0	Feb-07
1964	31.7		24.6	May-08
1965	29.2		22.7	Jun-27
1966	30.8		23.9	Mar-11
1967	70.0		54.3	May-08
1968	1.9		1.5	Mar-07
1969	31.7		24.6	Mar-19
1970	14.5		11.3	Apr-08
1971	48.8		37.8	Feb-15
1972	20.5		15.9	Mar-12
1973	7.3		5.7	Jun-19
1974	26.9		20.9	Mar-29
1975	40.6		31.5	May-07
1976	9.8		7.6	Mar-19
1977	0.1		0.1	Apr-08
1978	7.1		5.5	Mar-08
1979	35.4		27.5	Mar-08
1980	0.5		0.4	Apr-07
1981	2.9		2.2	Feb-18
1982	28.3		21.9	Jun-03
1983	4.0		3.1	Feb-14
1984	0.1		0.1	Apr-11
1985	22.3		17.3	Apr-03
1986	30.6		23.7	Sep-27
1987	8.6		6.7	Mar-07
1988	2.2		1.7	Mar-23
1989	1.4		1.1	Mar-12
1990	1.7		1.3	Mar-31
1991	14.3		11.1	May-15
1992	0.0		0	Jan-27
1993	13.5		10.5	Jul-22
1994	106.2		82.4	Mar-03
1995	1.9		1.4	Apr-16

Year	Maximum Instantaneous Discharge (m³/s) (1)	Date	Maximum Daily Discharge (m³/s) (2)	Date
1996	**62.4**		48.4	Mar-11
1997	**52.9**		41.0	Mar-20
1998	**63.7**		49.4	Jun-29
1999	**2.1**		1.6	May-16
2000	0		0	
2001	0.122	Mar-26	0.09	Mar-08
2002	44.6	Jun-12	30.3	Jun-12
2003	15.1	Mar-17	13.5	Mar-17
2004	3.03	May-29	1.14	May-29
2005	10.7	Jun-17	1.96	Jun-17
2006	0.236	Jun-14	0.147	Jun-15
2007	**0.5**		0.4	Mar-04
2008	**0.4**		0.3	Mar-01
2009	**0.6**		0.482	Mar-20
2010	209	Jun-19	172	Jun-19
2011	29.9	Jun-05	25.4	Apr-13
2012	6.22	Jun-22	5.85	Jun-22
2013	2.05	Jun-22	1.07	Jun-22
2014	**6.4**		4.98	Mar-12
2015	**1.0**		0.796	Mar-11
2016	0.66	May-26	0.519	May-27

Notes:

1. The bolded and underlined values are based on Qi=1.29Qd.
2. The 1911-1918 and 1920-1999 data are estimates from 05AH003; the 1919 data is an estimate from 05AH037; and the 2015 and 2016 data are preliminary from AEP.
3. The daily discharge on date of 2011 maximum instantaneous discharge was 24.6 m³/s.

Flood Frequency Analysis

Flood frequency analyses were performed on the instantaneous peak discharges shown in **Table 4-10**. Each of the frequency distributions in the adopted suite were fitted to the instantaneous flood peaks shown in **Table 4-10** excluding the zero flow years. The resulting frequency curves were then adjusted by multiplying the exceedance probabilities by the ratio of the number of non-zero flows against the total record years (97/100=0.97) to produce the final frequency curve. **Table 4-11** summarizes the statistical parameters of both the complete data set and the censored one.

Table 4-11: Summary of statistical parameters of annual maximum instantaneous discharge series for Ross Creek at Highway 41

Parameter	Complete Flow Series 1911, 1913-1930, 1935, 1937-2016	Censored Flow Series [1] 1911, 1913-1930, 1935, 1937-2016
Years of record	100	97
Mean (m^3/s)	27.1	28.0
Median (m^3/s)	16.9	18.1
Standard deviation (m^3/s)	31.5	31.6
Coefficient of variation	1.16	1.13
Skew coefficient (minimum, maximum, actual)	2.32, 2.32, 2.60	2.26, 2.27, 2.59

Notes:

1. Zero-flow years (1961, 1992, and 2000) are excluded.

The goodness of fit analysis described earlier was undertaken for each distribution as shown in **Table 4-12**.

Table 4-12: Goodness-of-fit comparison for probability distributions for Ross Creek at Highway 41

Distribution	D_n	Normalized *SSE* (Q_{pm} = 28.0 m^3/s)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.183	0.574	8	7	8
Log-normal(LN)	0.133	2.711	6	8	7
Three parameter log-normal (LN3)	0.101	0.196	4	1	1
Pearson III (P3)	0.083	0.211	2	3	1
Log-Pearson III (LP3)	0.078	0.299	1	5	4
Gumbel (G)	0.170	0.346	7	6	6
Generalized extreme value (GEV)	0.118	0.216	5	4	5
Weibull (W)	0.085	0.202	3	2	1

The LP3 distribution produces the smallest D_n value; however, it does not fit the data very well (**Appendix C**) and results in a relatively high *SSE* value. Overall, the best-fit curves are P3, Weibull and LN3 as indicated by the combined ranking. These three distributions are compared in **Figure 45**, while the other evaluated distributions are shown graphically in **Appendix C**. As shown in **Figure 45**, the three top-ranked curves are almost identical and fit the data well. Similar to the analysis for Seven Persons Creek, the LN3 distribution for Ross Creek requires a negative value (location parameter) to offset the peak discharges which lacks justifications from a process perspective; and it results in negative flood peaks for very low return period. 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 and is favored by Alberta Environment (AT, 2001). Consequently, it is recommended that the P3 distribution be used herein to described the Ross Creek flood peaks. The adopted P3 curve with 95% confidence limits is shown in **Figure 46**.

Note that the GEV distribution also fits the data reasonably well in general (**Appendix C**); however, it produces negative flows at very short return periods.

4.4.3 Flood Frequency Estimates for Bullshead Creek at Black and White Trail

Bullshead Creek has been gauged at this site since 2005 (WSC Station 05AH053); so the period of record is relative short. The highest instantaneous peak discharge on record was 81.6 m^3/s in 2010, which is almost eight times the second largest event – the 2011 event. For the other years of record, the annual peak discharges range from 0.2 to 6 m^3/s. A discontinued WSC gauge station is located on Bullshead Creek just upstream of this site (WSC Station 05AH013 – Bullshead Creek near Woolchester) and has a drainage area about 10% less than that at Black and White Trail. The gauge provides 13 years of seasonal flow data between 1915 and 1936, with the highest daily peak of 15.5 m^3/s. Clearly, these data are inadequate to develop flood frequency estimates for Bullshead Creek at Black and White Trail. As such, a regional analysis was performed to estimate flood frequency for this site.

The analysis includes stations shown in **Table 4-13**. Their locations are shown in **Figure 26**.

Table 4-13: Reference stations for regional analysis for Ross Creek Sub-basin

WSC Station No.	Station Name	Drainage Area (km^2)
05AH037	Gros Ventre Creek near Dunmore	215
05AH002	Mackay Creek at Walsh	437
05AH003	Ross Creek near Irvine	648
05AH052	Ross Creek at Highway 41	808

Flood frequency analyses were performed on annual instantaneous peak discharges for Gros Ventre Creek near Dunmore (WSC Station 05AH037) and Mackay Creek at Walsh (WSC Station 05AH002). Similar to the analysis presented above for Ross Creek, the P3 distribution can fit the data reasonably well, as shown in **Figure 47**. Flood frequency estimates for Ross Creek near Irvine were developed by NHC (2012a), which also used the P3 distribution. All of these estimates, together with the estimates for Ross Creek at Highway 41 from Section 4.4.2, are plotted against drainage area of each station in **Figure 48** to develop a set of regional relationships, which can be described by:

$$Q_T = kA^b \qquad \text{(Equation 7)}$$

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 with their values shown in **Table 4-14**. This equation was used to develop flood frequency estimates for Bullshead Creek at Black and White Trail (WSC Station 05AH053) based on its drainage area of 350 km^2. The results are presented in Section 5.

Table 4-14: Constants for regional flood frequency relationships of Ross Creek Sub-basin

Return Period (Years)	*k*	*b*
1000	13.14	0.41
750	11.91	0.42
500	10.02	0.44
350	9.00	0.44
200	7.20	0.46
100	5.23	0.49
75	4.59	0.50
50	3.67	0.51
35	3.00	0.53
20	1.98	0.56
10	1.07	0.61
5	0.45	0.68
2	0.04	0.90

4.4.4 Flood Frequency Estimates for Ross Creek below Bullshead Creek

A discontinued WSC station is located on Ross Creek immediately upstream of its confluence with Seven Persons Creek (WSC Station 05AH049 – Ross Creek at Medicine Hat). The data for this station could represent Ross Creek flows below Bullshead Creek. However, this gauge provides seasonal flow measures from 1985 to 1995 and during this period the recorded maximum discharges are less than 8 m^3/s. So, the data cannot be used for flood frequency analysis. As no other streamflow measurements are available for Ross Creek below Bullshead Creek, flood frequency estimates for this reach were based on the regional analysis presented above. The drainage area of Ross Creek at WSC Station 05AH049 (1490 km^2) was used in **Equation 7** to estimate flood frequencies for Ross Creek below Bullshead and the results are presented in Section 5.

4.4.5 Flood Frequency Estimates for Ross Creek below Seven Persons Creek

The total drainage area of Ross Creek below Seven Persons Creek is about 4770 km^2, including the 3280 km^2 Seven Persons Creek watershed area. No streamflow measurements are available for Ross Creek below Seven Persons Creek. When **Equation 7** is used for flood frequency estimate for this site, the resulting flood peaks for return periods longer than 100 years are only slightly higher than the sum of the estimates for Seven Persons Creek at the mouth and Ross Creek below Bullshead Creek (above Seven Persons Creek); while the estimates for shorter return periods are noticeably higher. This indicates that the estimates from the regional relationships are likely too conservative. Note that the relationships represent flows from the Cypress Hills catchment area while about 75% of the Seven Persons Creek watershed area is prairie area. It is recommended that the sums of the flood frequency estimates for Seven Persons Creek and Ross Creek below Bullshead Creek be taken as the flood frequency estimates for Ross Creek below Seven Persons Creek. This approach is one of the main methods that are used for estimating flood frequencies for ungagged sites downstream of the confluence of two rivers (Watt et al., 1989). It implies the assumption that flood peaks of Ross Creek are coincident with Seven Persons Creek at their confluence. The results are presented in Section 5.

4.5 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 another methodology 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 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 is adopted. Unfortunately, there is insufficient data to properly define the regional skewness and so, by default, the station skewness has been used herein for both natural and regulated flows. Deference to this approach has been made in some instances where theoretical limits have been placed on the sample skewness as presented in AENV (2008).

The application of statistical procedures that demand year to year randomness, independence, and stationarity in the flood peaks may also be somewhat problematical. While stationarity appears not to be a problem, one could argue that no flood peaks are independent from each other due to storage-related, year to year, 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 industrial standards and is based on the best available information. The results are reasonable and adequate for the river flood hazard study. For return periods longer than 200 years, the estimates could be in more considerable error as shown by the confidence limits on each of the frequency plots.

5 SUMMARY OF ADOPTED FLOOD FREQUENCIES

This report provides a summary of the available hydrometric data, as they pertain to flood peaks along the South Saskatchewan River, Seven Persons Creek, Ross Creek and Bullshead Creek in the Medicine Hat area, for both natural and regulated conditions.

Water balance analyses and regional hydrological analyses were performed to provide a simulation of daily inflows to major storage reservoirs within the Oldman River sub-basin. Those inflows were routed to Medicine Hat under the natural and regulated conditions, along with simulated natural and regulated flows from the Bow River provided by AEP and estimated tributary inflows (or gauge corrections). The results from these analyses consist of natural and regulated annual peak flow series for the South Saskatchewan River near Medicine Hat for the 1902 – 2015 and 1930 – 2015 periods respectively. They were used to develop flood frequency estimates for Medicine Hat.

Flood frequency analyses were also performed for the sites of interest on Seven Persons, Ross and Bullshead creeks. Annual instantaneous peak discharges were fitted to a variety of distributions and the most appropriate distributions were selected based on a goodness-of-fit test.

The adopted flood frequency estimates for naturalized or both naturalized and regulated flood peaks are provided for the eight locations within the study area as follows:

5.1 South Saskatchewan River at Medicine Hat and below Ross Creek

The flood frequency estimates for SSR at Medicine Hat (WSC Station 05AJ001) for both the naturalized and regulated flow conditions are presented in **Table 5-1**. They are based on the log-Pearson Type III distribution, which provides the best representation of the flood peaks among all assessed distributions. These flood frequency estimates are also applicable to the SSR below Ross Creek within the study area as effects of the Ross Creek inflows are determined to be negligible. Note that the naturalized flood peaks are about twenty to thirty percent higher than the regulated flood peaks. The flood frequency estimates were compared with values from previous studies **Table 5-2**. Note that the previous studies were simply based on flow data measured under various level of flow regulation from a barely regulated to the present regulated condition; and assumed that flow regulation effects are negligible. The present estimates for regulated flows are slightly (less than 10%) smaller than the estimates from AENV (1995) and AECOM (2014); however, the estimates for naturalized flows are higher. The 100 and 200-year estimates from AENV (1985) are smaller as the analysis did not include the large events which have occurred over the last three decades.

Table 5-1: Flood frequency estimates for South Saskatchewan River at Medicine Hat and below Ross Creek

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge			
		Naturalized Flow (m^3/s)		Regulated Flow (m^3/s)	
		Value	95% Confidence Limit	Value	95% Confidence Limit
1000	0.10	12,700	10,000 - 17,100	9,680	7,450 - 13,500
750	0.13	11,700	9,310 - 15,600	9,020	6,990 - 12,400
500	0.20	10,500	8,390 - 13,800	8,130	6,370 - 11,100
350	0.29	9,470	7,660 - 12,300	7,420	5,870 - 9,980
200	0.50	8,030	6,590 - 10,200	6,390	5,130 - 8,410
100	1.0	6,500	5,450 - 8,080	5,260	4,300 - 6,750
75	1.3	5,950	5,020 - 7,320	4,840	3,990 - 6,150
50	2.0	5,210	4,450 - 6,320	4,280	3,570 - 5,350
35	2.9	4,630	4,000 - 5,540	3,820	3,220 - 4,720
20	5	3,810	3,340 - 4,460	3,170	2,720 - 3,830
10	10	2,930	2,620 - 3,350	2,460	2,150 - 2,880
5	20	2,180	1,980 - 2,430	1,830	1,630 - 2,090
2	50	1,320	1,210 - 1,450	1,080	970 - 1,200

Table 5-2: Comparison with previous flood frequency estimates for South Saskatchewan River at Medicine Hat

Return Period (Years)	Peak Instantaneous Discharge (m^3/s)				
	Present Study for Naturalized Flows	Present Study for Regulated Flows	AENV (1985)	AENV (1995)	AECOM (2014)
1000	12,700	9,680	-	10,400	-
750	11,700	9,020	-	-	-
500	10,500	8,130	-	-	-
350	9,470	7,420	-	-	-
200	8,030	6,390	5,990	7,000	7,110
100	6,500	5,260	5,230	5,690	5,690
75	5,950	4,840	-	-	-
50	5,210	4,280	4,480	4,670	4,510
35	4,630	3,820	-	-	-
20	3,810	3,170	3,490	3,440	3,240
10	2,930	2,460	2,750	2,630	2,470
5	2,180	1,830	2,010	-	-
2	1,320	1,080	1,060	1,060	-

5.2 Seven Persons Creek at Medicine Hat and at the Mouth

The flood frequency estimates for Seven Persons Creek at Medicine Hat (WSC Station 05AH005) for the natural flow condition are presented in **Table 5-3**. They are based on the Pearson Type III distribution. These flood frequency estimates are also applicable to Seven Persons Creek at the mouth. For reference, the previous flood frequency estimates by AENV (1985) are also presented in the table. They are higher than the current estimates. Note that the AENV estimates were based on the shorter pre-regulation record (31 years) between 1913 and 1954.

Table 5-3: Flood frequency estimates for Seven Persons Creek at Medicine Hat and at the Mouth

Return Period (Years)	Annual Probability of Exceedance (%)	Natural Peak Instantaneous Discharge (m^3/s)		
		Value	95% Confidence Limit	AENV (1985)
1000	0.1	162	142 - 188	-
750	0.13	155	136 - 180	-
500	0.2	144	127 - 167	-
350	0.29	136	119 - 157	-
200	0.5	121	107 - 140	141
100	1	104	92 - 120	121
75	1.3	97	86 - 112	-
50	2	87	77 - 100	102
35	2.9	78	69 - 90	-
20	5	64	57 - 74	76
10	10	48	42 - 55	56.9
5	20	31	26 - 37	38.2
2	50	12	6 - 16	14.9

5.3 Bullshead Creek at Black and White Trail

The flood frequency estimates for Bullshead Creek at Black and White Trail (WSC Station 05AH053) are presented in **Table 5-4**. They are based on the regional flood frequency relationships shown in **Figure 48**. There are no previous estimates for this site; however, AENV (1985) provides estimates for Bullshead Creek near Woolchester (WSC Station 05AH013), which was located just upstream of WSC Station 05AH053 with about a 10% smaller drainage area. These estimates are also shown in **Table 5-4** for reference. The current estimates are significantly higher than the values from AENV (1985) except the 2-year flood peak. The AENV estimates were based on the 13 year gauge record for 05AH013 between 1915 and 1936, the highest peak of which was less than 20% of the 2010 flood peak on Bullshead Creek, as noted earlier.

Table 5-4: Flood frequency estimates for Bullshead Creek at Black and White Trail

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	
		Current Estimate	AENV (1985)
1000	0.1	145	-
750	0.13	139	-
500	0.2	132	-
350	0.29	118	-
200	0.5	107	41.2
100	1	92.3	36.9
75	1.3	85.9	-
50	2	72.8	32.5
35	2.9	66.9	-
20	5	52.6	26.6
10	10	38.1	21.8
5	20	24.2	16.8
2	50	7.79	9.37

5.4 Ross Creek

The flood frequency estimates for Ross Creek at Highway 41 (WSC Station 05AH052) are presented in **Table 5-5**. They are based on the Pearson Type III distribution. There are no previous estimates for this site. NHC (2012a) provides estimates for Ross Creek near Irvine (WSC Station 05AH003), which are about 15% - 24% smaller, consistent with the drainage area ratio of the two sites – the drainage area at WSC Station 05AH003 is about 20% smaller.

Table 5-5: Flood frequency estimates for Ross Creek at Highway 41

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	95% Confidence Limit
1000	0.1	225	204 - 251
750	0.13	215	195 - 240
500	0.2	201	182 - 224
350	0.29	189	171 - 211
200	0.5	169	153 - 188
100	1	145	132 - 162
75	1.3	136	123 - 151
50	2	121	111 - 135
35	2.9	110	100 - 122
20	5	91	82 - 101
10	10	68	61 - 75
5	20	45	40 - 51
2	50	17	11 - 22

The flood frequency estimates for Ross Creek below Bullshead Creek are based on regional flood frequency relationships. The results are summarized in **Table 5-6**. The table also includes the estimates by AENV (1985) for comparison, which were also developed from a regional analysis. The current flood peak estimates are higher by up to 23%.

Table 5-6: Flood frequency estimates for Ross Creek below Bullshead Creek

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	
		Current Estimate	AENV (1985)
1000	0.1	263	-
750	0.13	256	-
500	0.2	249	-
350	0.29	224	-
200	0.5	207	173
100	1	188	152
75	1.3	177	-
50	2	152	130
35	2.9	144	-
20	5	118	102
10	10	92.3	79.9
5	20	64.7	57.5
2	50	28.7	27.0

Table 5-7 shows the flood frequency estimates for Ross Creek below Seven Persons Creek, defined as the sum of flood peaks for Ross Creek below Bullshead Creek (**Table 5-6**) and Seven Persons Creek at the mouth (**Table 5-3**).

Table 5-7: Flood frequency estimates for Ross Creek below Seven Persons Creek

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)
1000	0.1	425
750	0.13	411
500	0.2	393
350	0.29	360
200	0.5	328
100	1	292
75	1.3	274
50	2	239
35	2.9	222
20	5	182
10	10	140
5	20	95.7
2	50	40.7

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 SSR 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 and earlier snowmelt runoff.

Martz et al. (2007) assessed effects of climate change on the SSR flows 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 SSR 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 in the SSR basin, 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 have considerable variation across the SSRB sub-basins and among different scenarios: from -26% to -7% with an average of -18% for the Bow River near the mouth; from -14% to +7% with an average of -4% for the Oldman River near the mouth; and from -17% to +6% with an average of -6% for the SSR at Medicine Hat.

Poitras et al. (2011) investigated projected changes in average and extreme streamflows of ten major river basins across western Canada. The streamflows were derived from climate simulations performed with the fourth generation of the CRCM forced with the A2 emission scenario. Mean annual flows are projected to increase in all basins, with a 12% increase in the SSR basin. Peak discharges are predicted to increase by about 20% and occur one or two weeks earlier.

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 expected in winter compared to summer. Type of precipitation will 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 SSR basin under combined impacts of climate change and El Niño Southern Oscillation (ENSO). Under climate projections alone or under the combined condition with ENSO, annual mean flows are projected to decrease. However, the mean spring (March to May) flows under climate projections alone are projected to increase by 6%, 16% and 23% for the Bow River at Calgary, and by 9%, 22% and 29% for the Oldman River near Lethbridge, in 2020s, 2050s and 2080s, respectively. In contrast, 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 Bow and Oldman river basins 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 Bow and Oldman river basins, between May and August in 2050s and 2080s, which implies the increasing flood risk along the SSR in the future.

The implications of climate change on the hydrologic characteristics of the Ross Creek basin is not defined. Gizaw (2017) noted that climate change appears to have marginal impacts on the lower Bow and Oldman river basins. This may be applicable to the Ross Creek basin.

Overall, the annual and season temperatures are expected to increase over the next 50 years or so as what has been experienced in the last 100 years. The expected changes in annual precipitation over the SSR basin are somewhat equivocal with the GCMs suggesting that the annual precipitation could change by between a 3.8% decrease and 11.5% increase, reflecting an increase in rainfall and a decrease in snowfall. Projected changes in annual mean flows in the SSR basin are also different among different studies, while more studies predicted a decreasing trend. However, increase in spring flows is expected although the forecast becomes more complicated and inconclusive in some recent studies that considers ENSO effects.

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 flood peaks. The most judicious approach would be to assume no changes to flood peaks for the study area over the next number of decades.

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 – possibly even having a greater impact than the changing climate.

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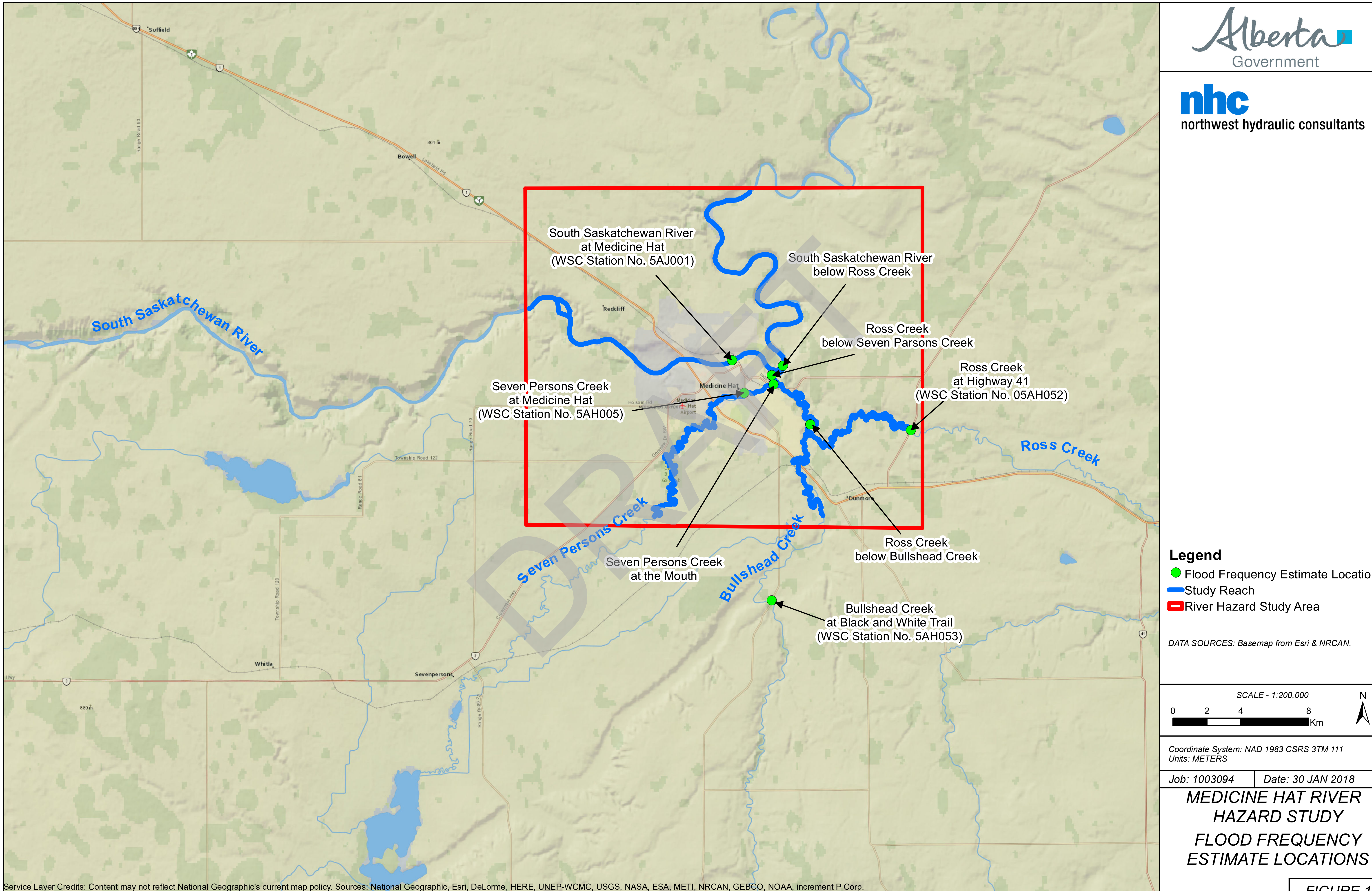
Figures



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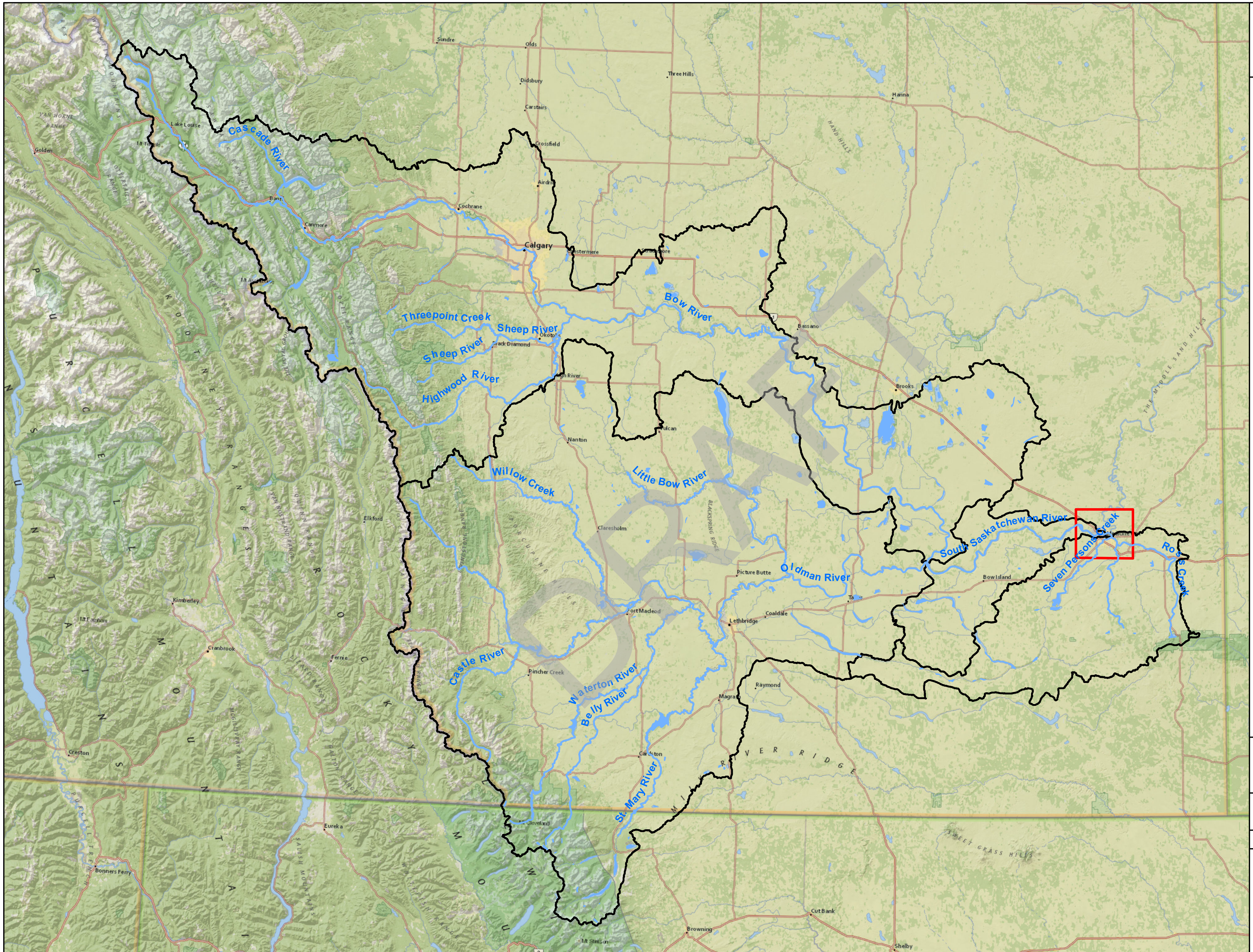

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Legend

- River Hazard Study Area
- Watershed Boundary

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

SCALE - 1:1,500,000

0 15 30 60 Km

N

Coordinate System: NAD 1983 CSRS 3TM 111
Units: METERS

Job: 1003094	Date: 30 JAN 2017

MEDICINE HAT RIVER HAZARD STUDY

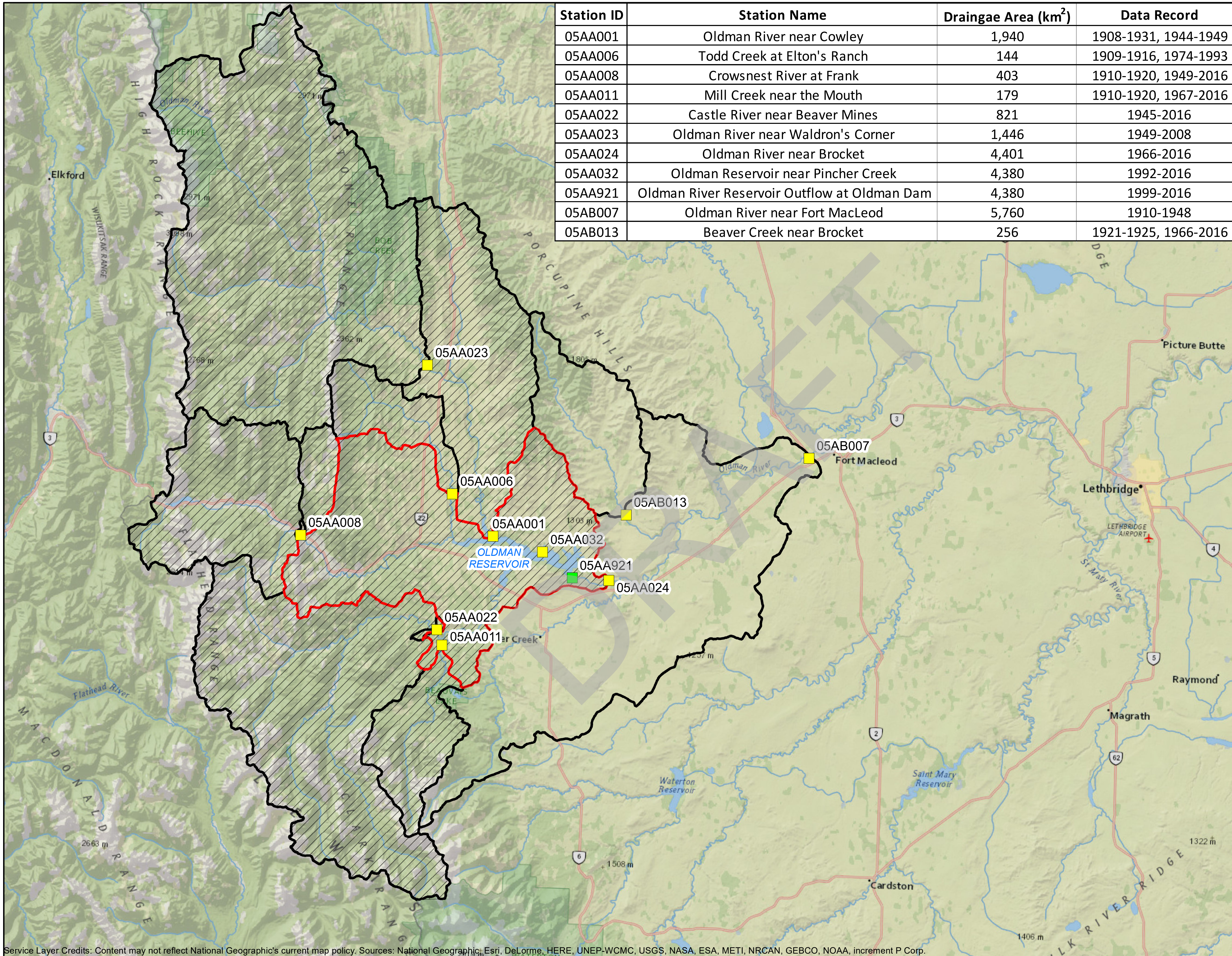
PROJECT LOCATION AND BASIN OVERVIEW

FIGURE 2

MSN, P:_Projects (Active)\1003094 Medicine Hat River Hazard Study\03 Calculations\0200 Open Water Hydrology\GIS_Analysis\Figures\MXD\Figure 2_Project_Location_and_Basin_Overview.mxd

Classification: Public

Station ID	Station Name	Draingae Area (km^2)	Data Record
05AA001	Oldman River near Cowley	1,940	1908-1931, 1944-1949
05AA006	Todd Creek at Elton's Ranch	144	1909-1916, 1974-1993
05AA008	Crowsnest River at Frank	403	1910-1920, 1949-2016
05AA011	Mill Creek near the Mouth	179	1910-1920, 1967-2016
05AA022	Castle River near Beaver Mines	821	1945-2016
05AA023	Oldman River near Waldron's Corner	1,446	1949-2008
05AA024	Oldman River near Brocket	4,401	1966-2016
05AA032	Oldman Reservoir near Pincher Creek	4,380	1992-2016
05AA921	Oldman River Reservoir Outflow at Oldman Dam	4,380	1999-2016
05AB007	Oldman River near Fort MacLeod	5,760	1910-1948
05AB013	Beaver Creek near Brocket	256	1921-1925, 1966-2016



Alberta Government

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Legend

- AEP Hydrometric Station
- WSC Hydrometric Station
- Oldman Reservoir Watershed
- Ungauged Area
- Gauged Area with Longer Period of Record

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

SCALE - 1:500,000

0 5 10 20 Km

N

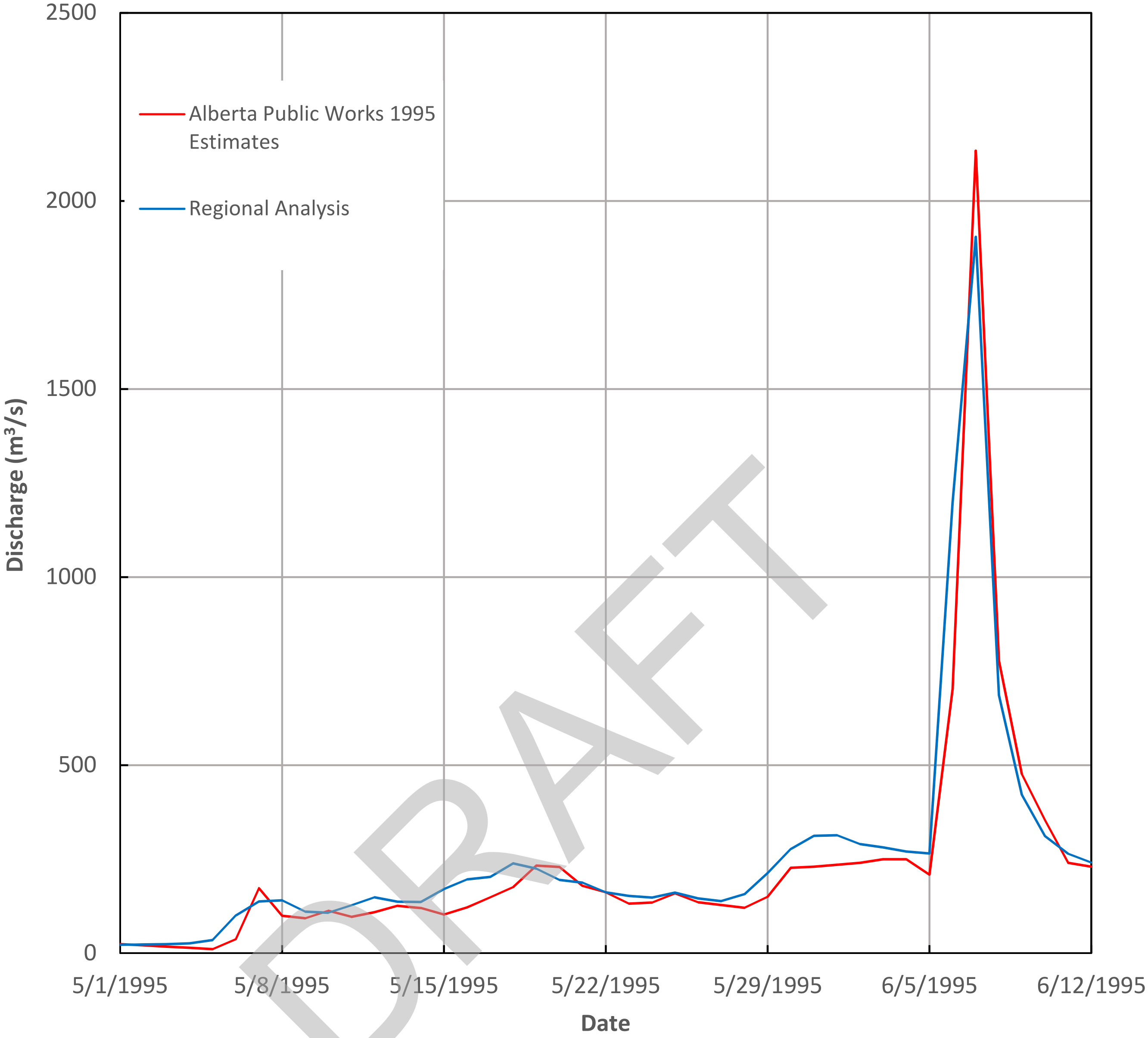
Coordinate System: NAD 1983 CSRS 3TM 111
Units: METERS

Job: 1003094 | *Date: 30 JAN 2018*

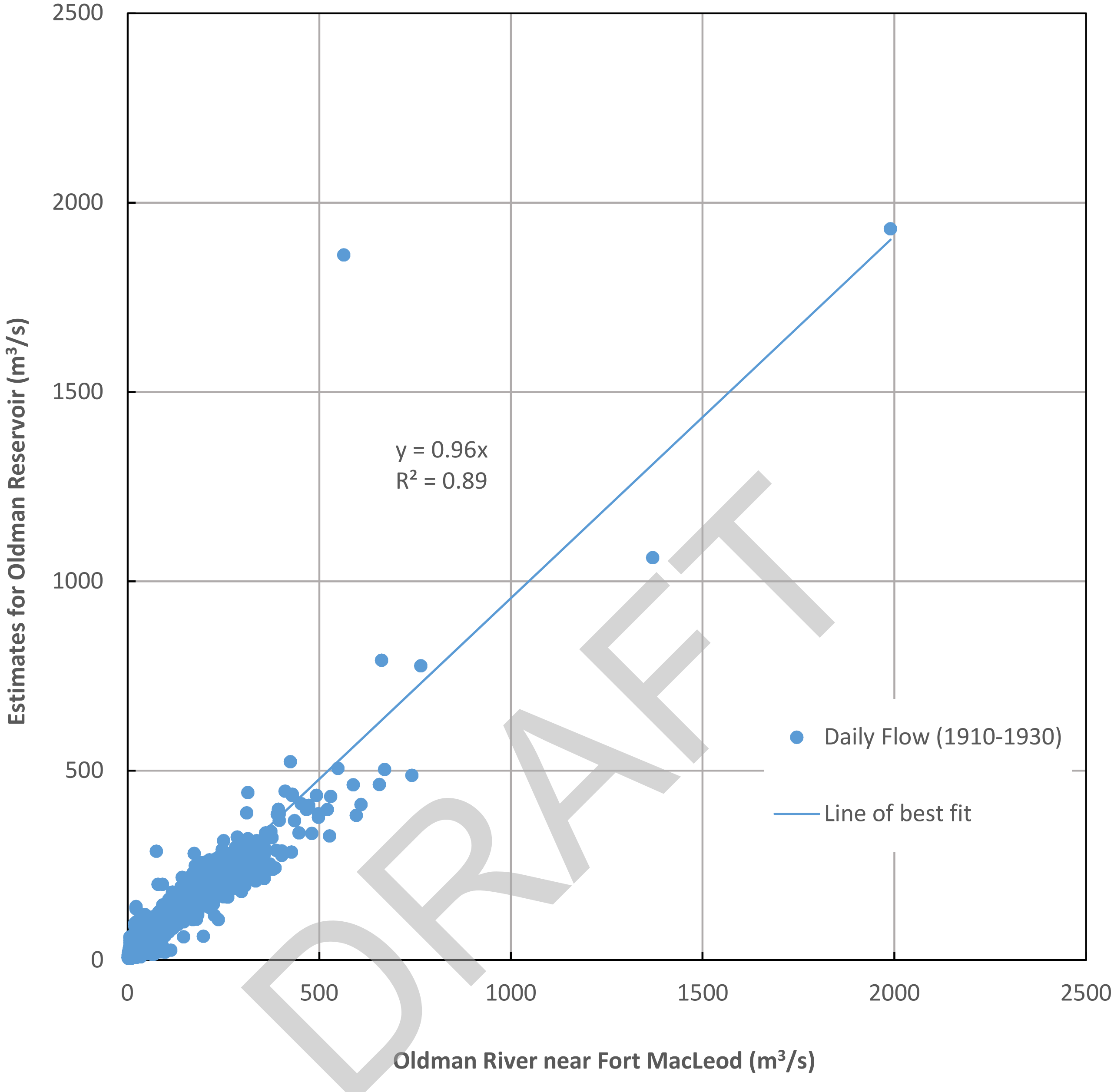
MEDICINE HAT RIVER HAZARD STUDY

OLDMAN RIVER SUB-BASIN UPSTREAM OF FORT MACLEOD

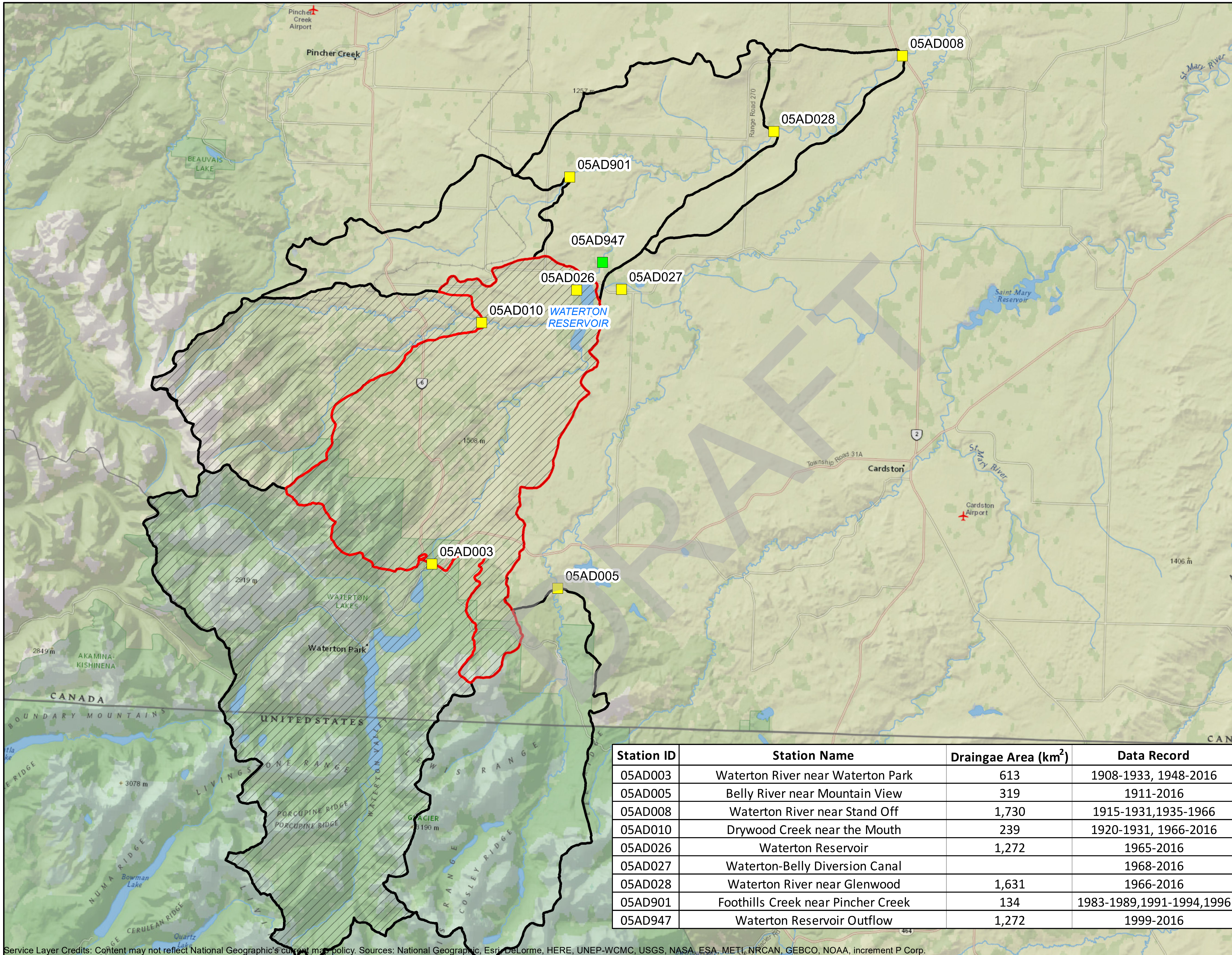
FIGURE 3



Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*ESTIMATED INFLOWS TO OLDMAN RIVER RESERVOIR FOR JUNE 1995 EVENT*
	Job: 1003094 / *Date: JUL-2019*	*FIGURE 4*



Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*RELATIONSHIP BETWEEN ESTIMATED DAILY FLOWS AT OLDMAN RESERVOIR AND MEASURED FLOWS NEAR FORT MACLEOD*
	Job: 1003094 / *Date: JUL-2019*	*FIGURE 5*



Station ID	Station Name	Drainage Area (km^2)	Data Record
05AD003	Waterton River near Waterton Park	613	1908-1933, 1948-2016
05AD005	Belly River near Mountain View	319	1911-2016
05AD008	Waterton River near Stand Off	1,730	1915-1931,1935-1966
05AD010	Drywood Creek near the Mouth	239	1920-1931, 1966-2016
05AD026	Waterton Reservoir	1,272	1965-2016
05AD027	Waterton-Belly Diversion Canal		1968-2016
05AD028	Waterton River near Glenwood	1,631	1966-2016
05AD901	Foothills Creek near Pincher Creek	134	1983-1989,1991-1994,1996
05AD947	Waterton Reservoir Outflow	1,272	1999-2016

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Legend
- AEP Hydrometric Station
- WSC Hydrometric Station
- Waterton Reservoir Watershed
- Ungauged Area
- Gauged Area with Longer Period of Record

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

SCALE - 1:300,000
0 3 6 12 Km
N

Coordinate System: NAD 1983 CSRS 3TM 111
Units: METERS

Job: 1003094 | *Date: 01 FEB 2018*

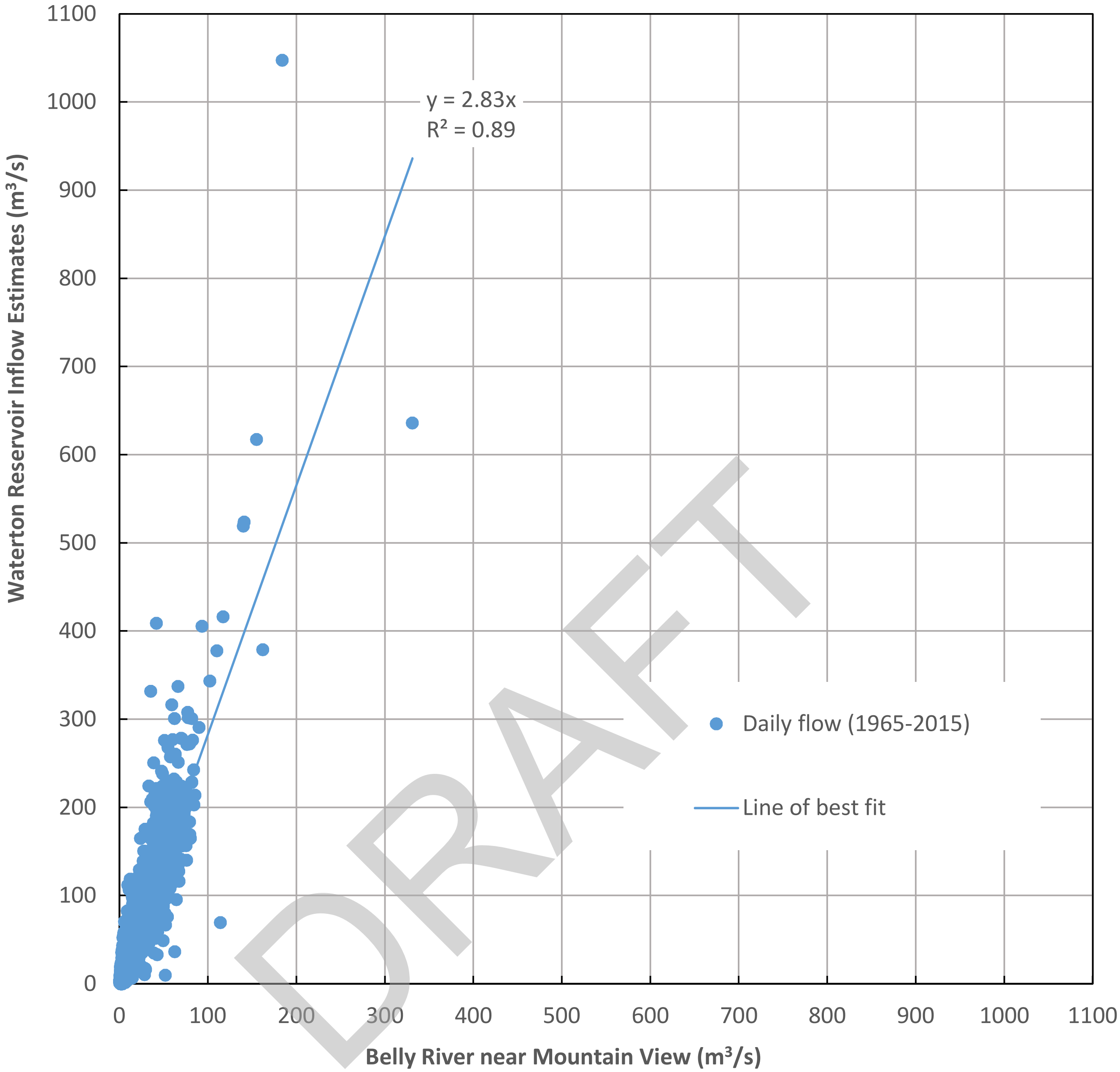
MEDICINE HAT RIVER HAZARD STUDY

REFERENCE STATIONS FOR WATERTON RESERVOIR HYDROLOGY

FIGURE 6

MSN, P:_Projects (Active)\1003094 Medicine Hat River Hazard Study\03 Calculations\0200 Open Water Hydrology\GIS_Analysis\Figures\MXD\Figure 6_Waterton_Reservoir_Hydrology.mxd

Classification: Public



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SCALE – AS SHOWN

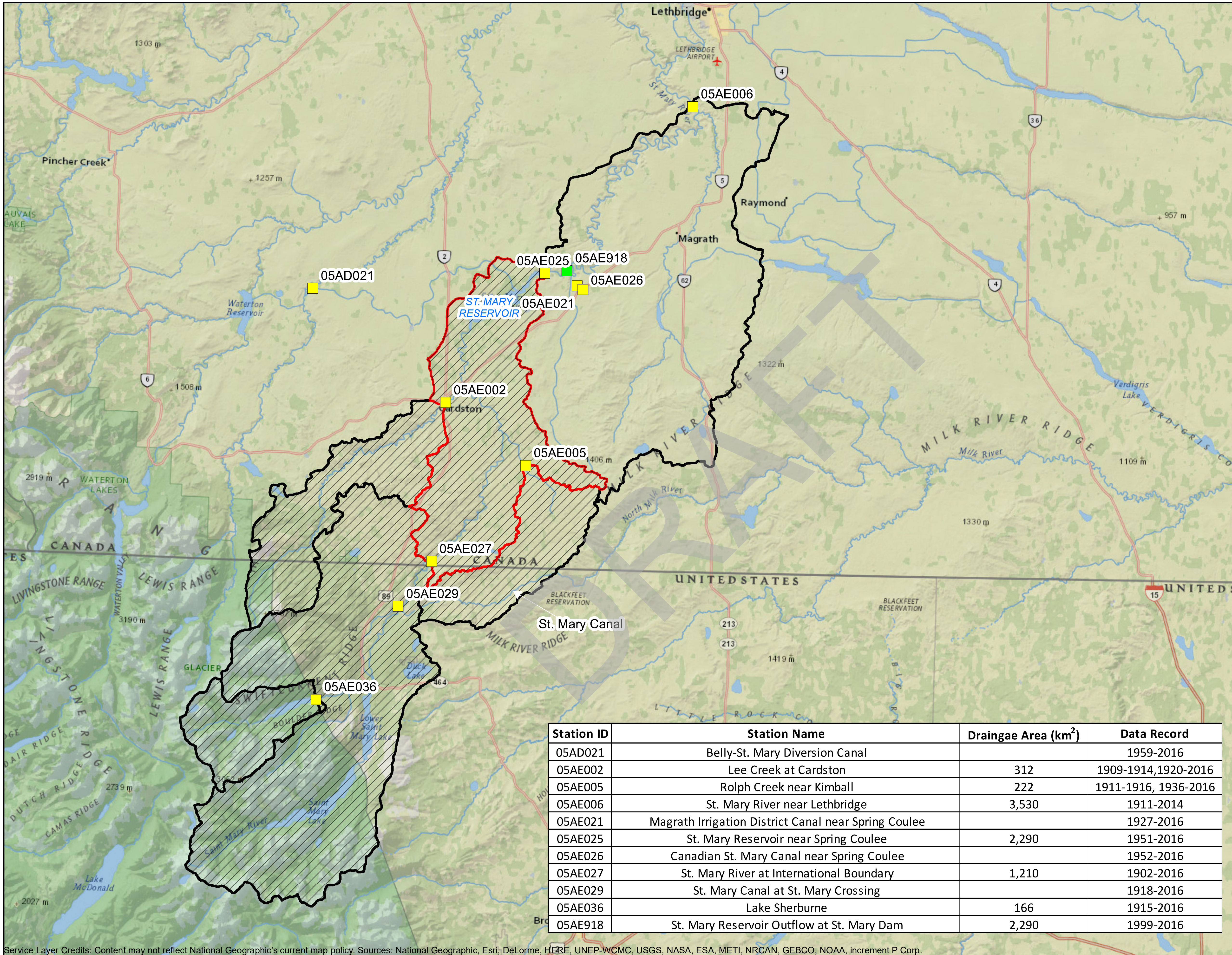
Coordinate System:
Units: As Shown

Job: 1003094 | *Date: JUL-2019*

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ESTIMATED DAILY INFLOWS TO WATERTON RESERVOIR VS. BELLY RIVER FLOWS NEAR MOUNTAIN VIEW

FIGURE 7



Station ID	Station Name	Draingae Area (km^2)	Data Record
05AD021	Belly-St. Mary Diversion Canal		1959-2016
05AE002	Lee Creek at Cardston	312	1909-1914,1920-2016
05AE005	Rolph Creek near Kimball	222	1911-1916, 1936-2016
05AE006	St. Mary River near Lethbridge	3,530	1911-2014
05AE021	Magrath Irrigation District Canal near Spring Coulee		1927-2016
05AE025	St. Mary Reservoir near Spring Coulee	2,290	1951-2016
05AE026	Canadian St. Mary Canal near Spring Coulee		1952-2016
05AE027	St. Mary River at International Boundary	1,210	1902-2016
05AE029	St. Mary Canal at St. Mary Crossing		1918-2016
05AE036	Lake Sherburne	166	1915-2016
05AE918	St. Mary Reservoir Outflow at St. Mary Dam	2,290	1999-2016

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Classification: Public

Alberta Government

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Legend

- AEP Hydrometric Station
- WSC Hydrometric Station
- St. Mary Reservoir Watershed
- Ungauged Area
- Gauged Area with Longer Period of Record

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

SCALE - 1:500,000

0 5 10 20 Km

N

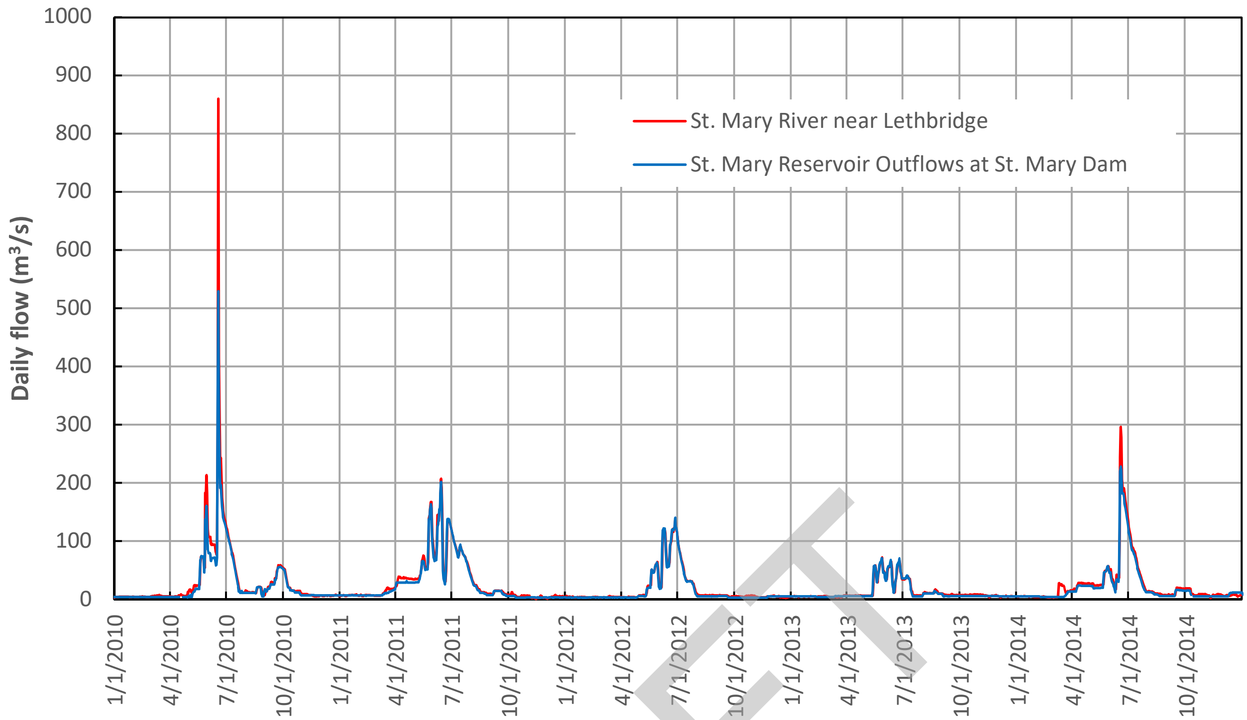
Coordinate System: NAD 1983 CSRS 3TM 111
Units: METERS

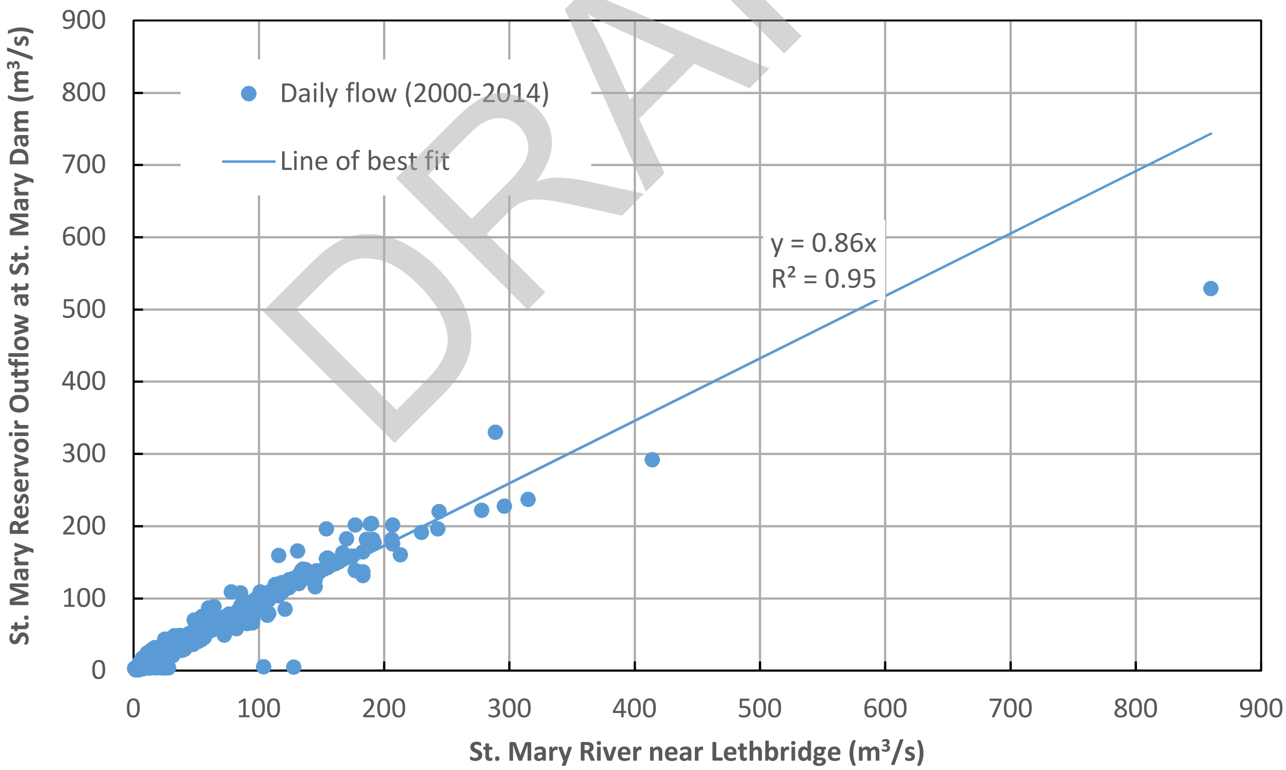
Job: 1003094 | *Date: 16 FEB 2018*

MEDICINE HAT RIVER HAZARD STUDY

REFERENCE STATIONS FOR ST. MARY RESERVOIR HYDROLOGY

FIGURE 8





DRAFT

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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

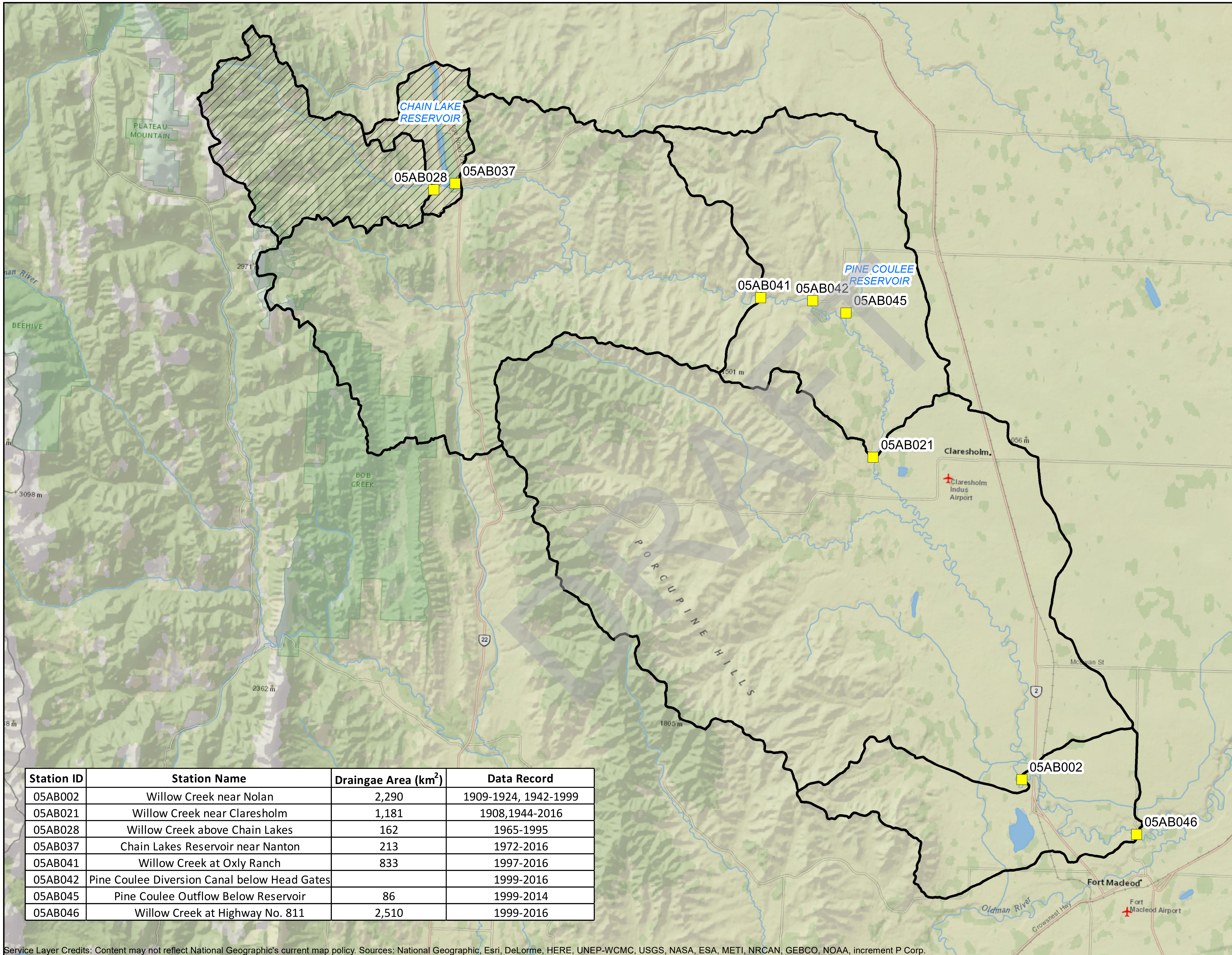
Job: 1003094

Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF ST. MARY DAM DAILY OUTFLOWS WITH FLOWS FOR ST. MARY RIVER NEAR LETHBRIDGE

FIGURE 9



Station ID	Station Name	Draingae Area (km^2)	Data Record
05AB002	Willow Creek near Nolan	2,290	1909-1924, 1942-1999
05AB021	Willow Creek near Claresholm	1,181	1908,1944-2016
05AB028	Willow Creek above Chain Lakes	162	1965-1995
05AB037	Chain Lakes Reservoir near Nanton	213	1972-2016
05AB041	Willow Creek at Oxly Ranch	833	1997-2016
05AB042	Pine Coulee Diversion Canal below Head Gates		1999-2016
05AB045	Pine Coulee Outflow Below Reservoir	86	1999-2014
05AB046	Willow Creek at Highway No. 811	2,510	1999-2016

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Legend
- WSC Hydrometric Station
- Chain Lakes Watershed
- Gauged Area with Longer Period of Record

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

SCALE - 1:289,116

0 3 6 12 Km

N

Coordinate System: NAD 1983 CSRS 3TM 111
Units: METERS

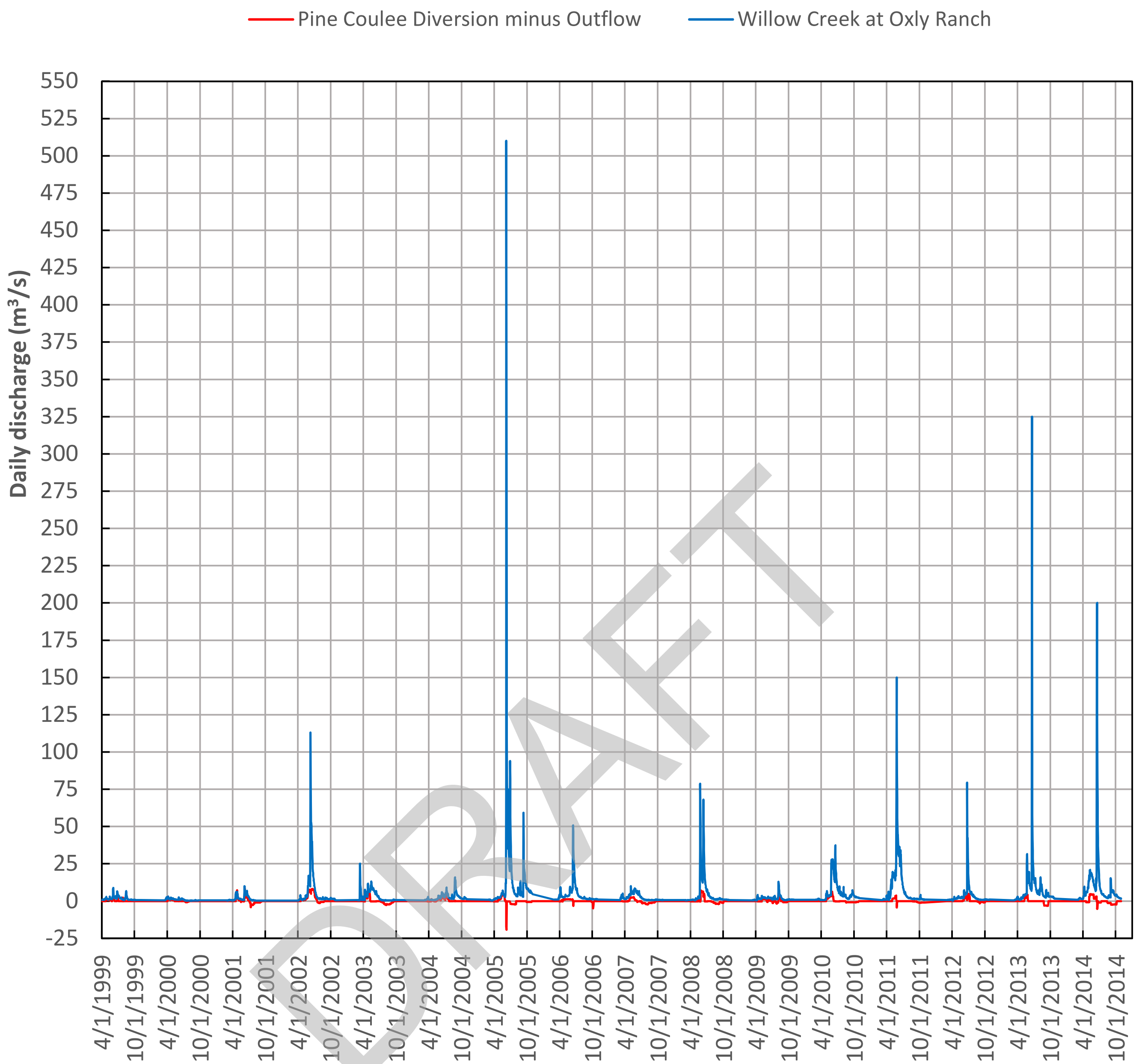
Job: 1003094 | *Date: 26 JUL 2018*

MEDICINE HAT RIVER HAZARD STUDY

REFERENCE STATIONS FOR WILLOW CREEK FLOW NATURALIZATION

FIGURE 10

MSN, P:_Projects (Active)\1003094 Medicine Hat River Hazard Study\03 Calculations\0200 Open Water Hydrology\GIS_Analysis\Figures\MXD\Figure 10_Willow_Creek_Flow_Naturalization.mxd



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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

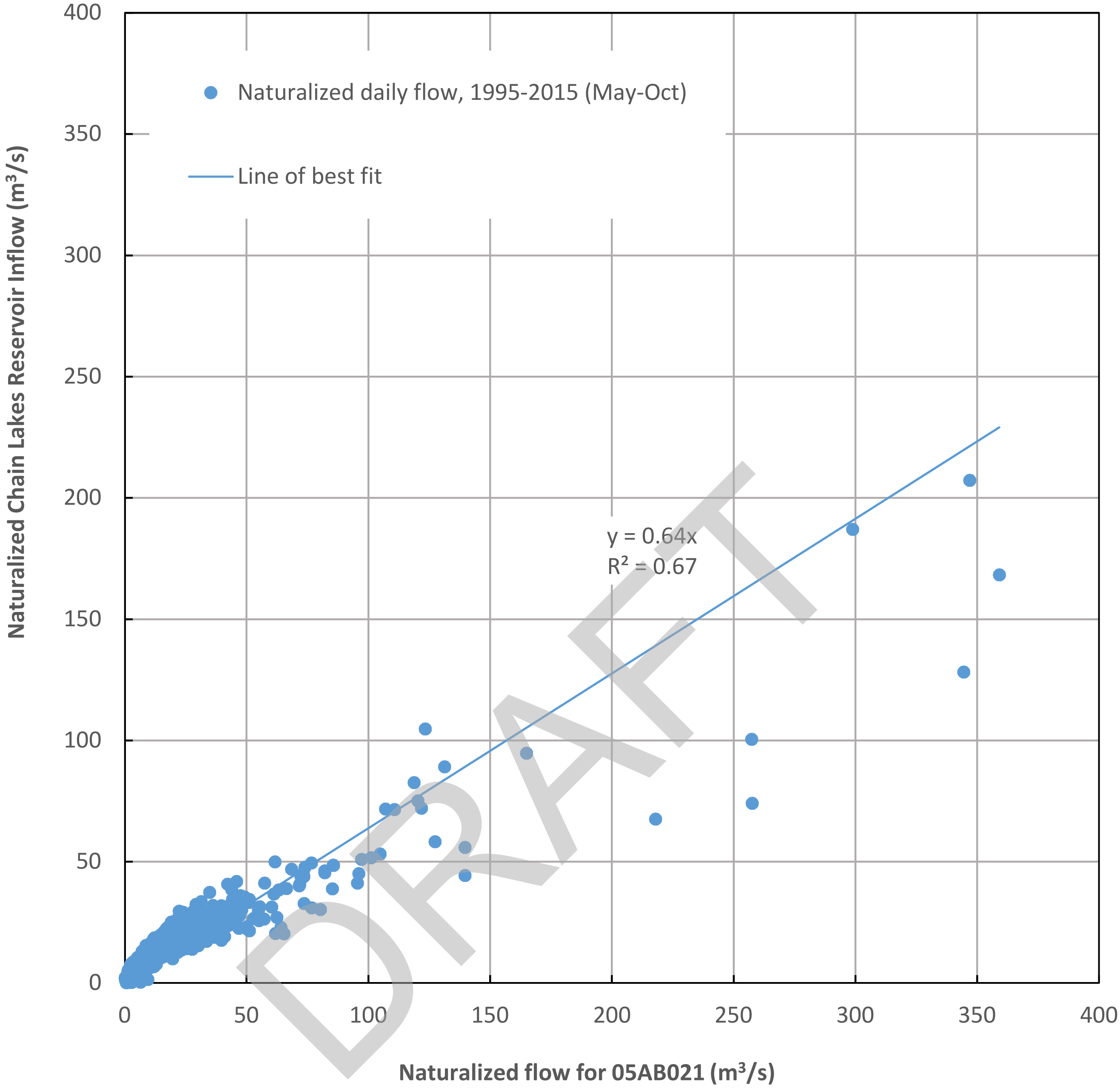
Job: 1003094

Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

EFFECTS OF PINE COULEE RESERVOIR ON WILLOW CREEK FLOWS

FIGURE 11



Notes: 1. Data shown are modelled results for flow naturalization.

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SCALE – AS SHOWN

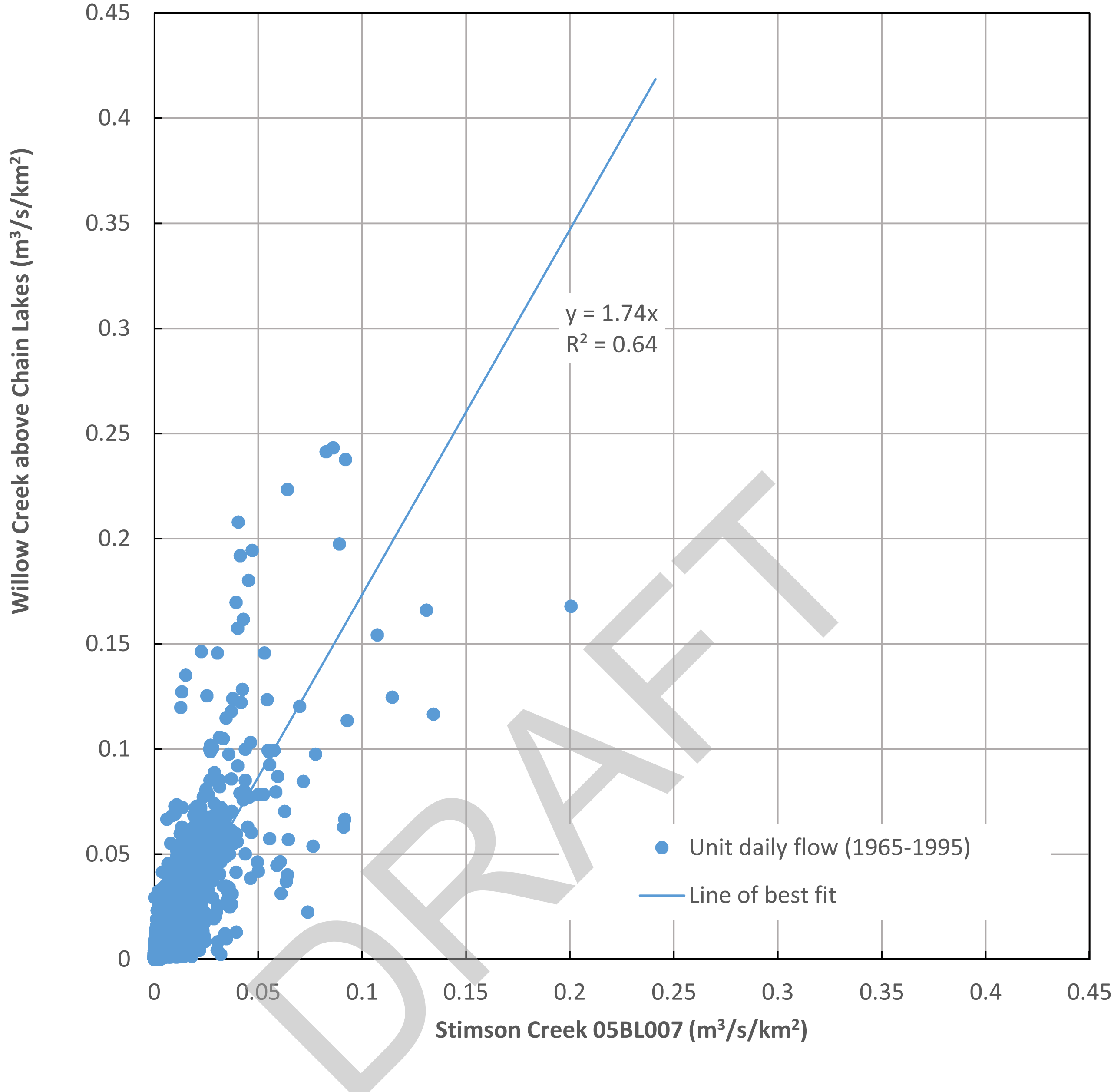
Coordinate System:
Units: As Shown

Job: 1003094 *Date: JUL-2019*

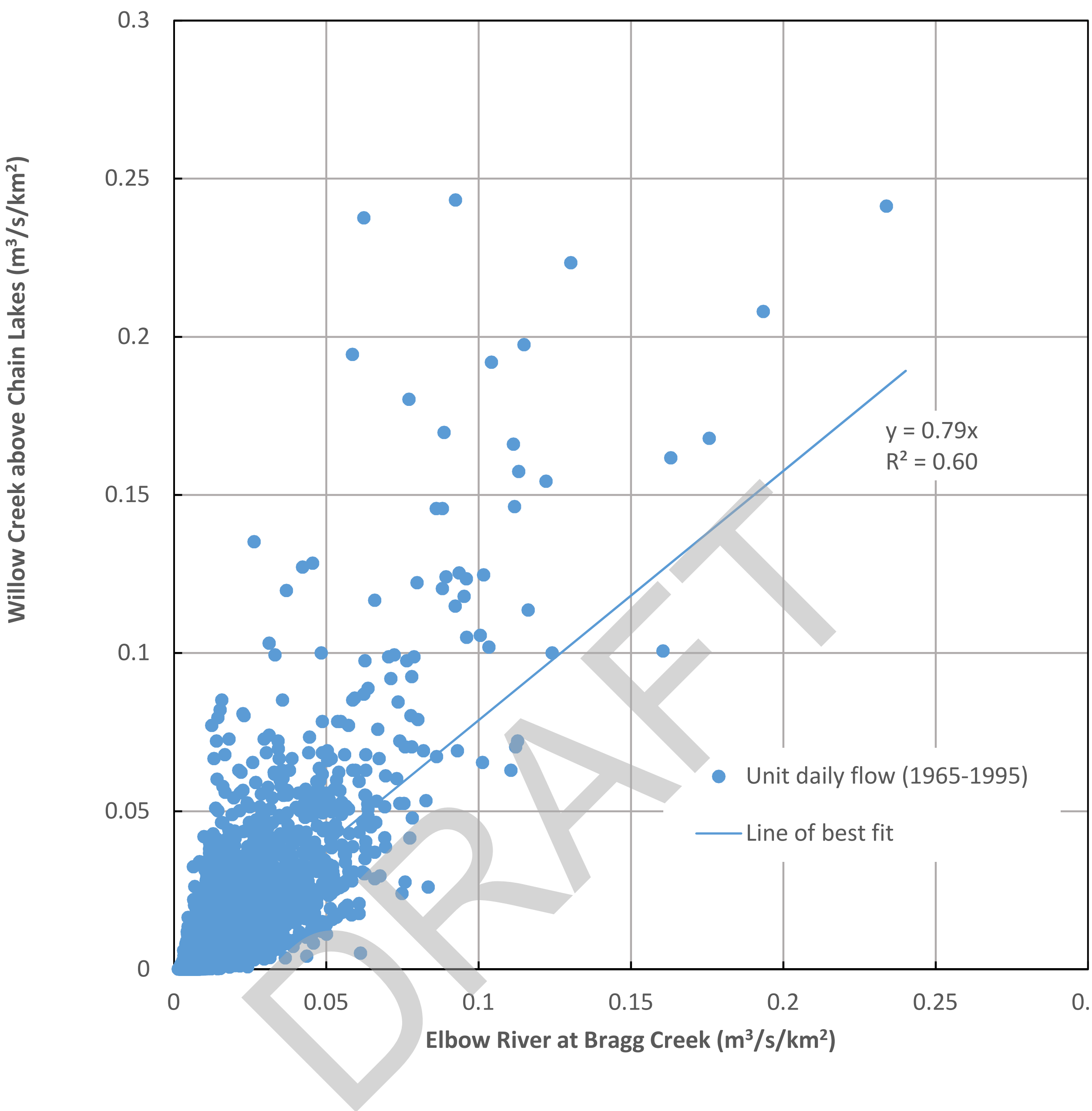
MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

RELATIONSHIP BETWEEN NATURALIZED DAILY FLOWS FOR WILLOW CREEK AT CHAIN LAKE RESERVOIR AND NEAR CLARESHOLM

FIGURE 12

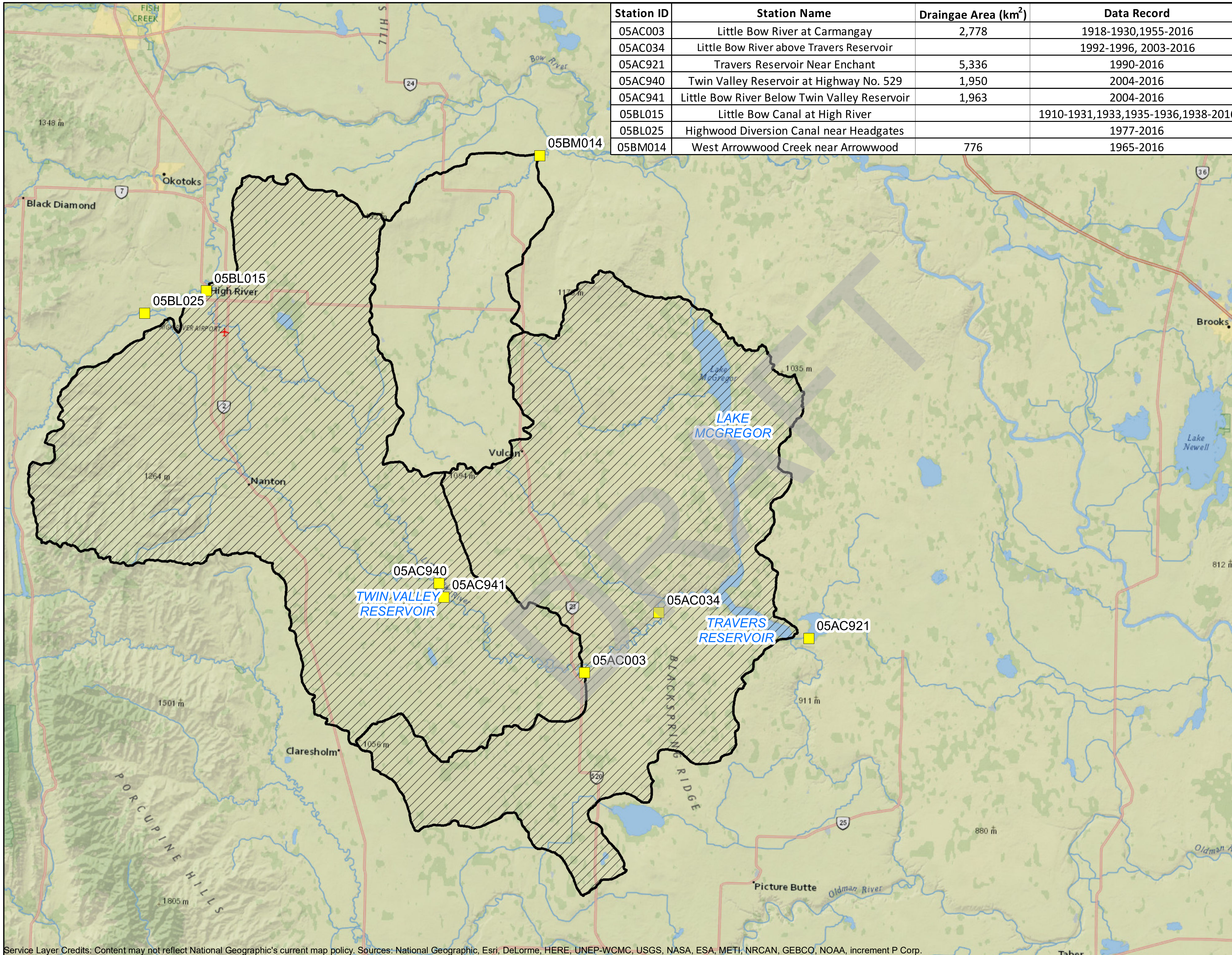


Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*RELATIONSHIP BETWEEN DAILY FLOWS FOR WILLOW CREEK ABOVE CHAIN LAKES AND STIMSON CREEK NEAR PEKISKO*
	Job: 1003094 *Date: JUL-2019*	*FIGURE 13*



Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*RELATIONSHIP BETWEEN DAILY FLOWS FOR WILLOW CREEK ABOVE CHAIN LAKES AND ELBOW RIVER AT BRAGG CREEK*
	Job: 1003094 / *Date: JUL-2019*	*FIGURE 14*

Station ID	Station Name	Draingae Area (km^2)	Data Record
05AC003	Little Bow River at Carmangay	2,778	1918-1930,1955-2016
05AC034	Little Bow River above Travers Reservoir		1992-1996, 2003-2016
05AC921	Travers Reservoir Near Enchant	5,336	1990-2016
05AC940	Twin Valley Reservoir at Highway No. 529	1,950	2004-2016
05AC941	Little Bow River Below Twin Valley Reservoir	1,963	2004-2016
05BL015	Little Bow Canal at High River		1910-1931,1933,1935-1936,1938-2016
05BL025	Highwood Diversion Canal near Headgates		1977-2016
05BM014	West Arrowwood Creek near Arrowwood	776	1965-2016



Alberta Government

nhc northwest hydraulic consultants

Legend

- WSC Hydrometric Station
- Travers Reservoir Watershed
- Gauged Area with Longer Period of Record

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

SCALE - 1:500,000

0 5 10 20 Km

N

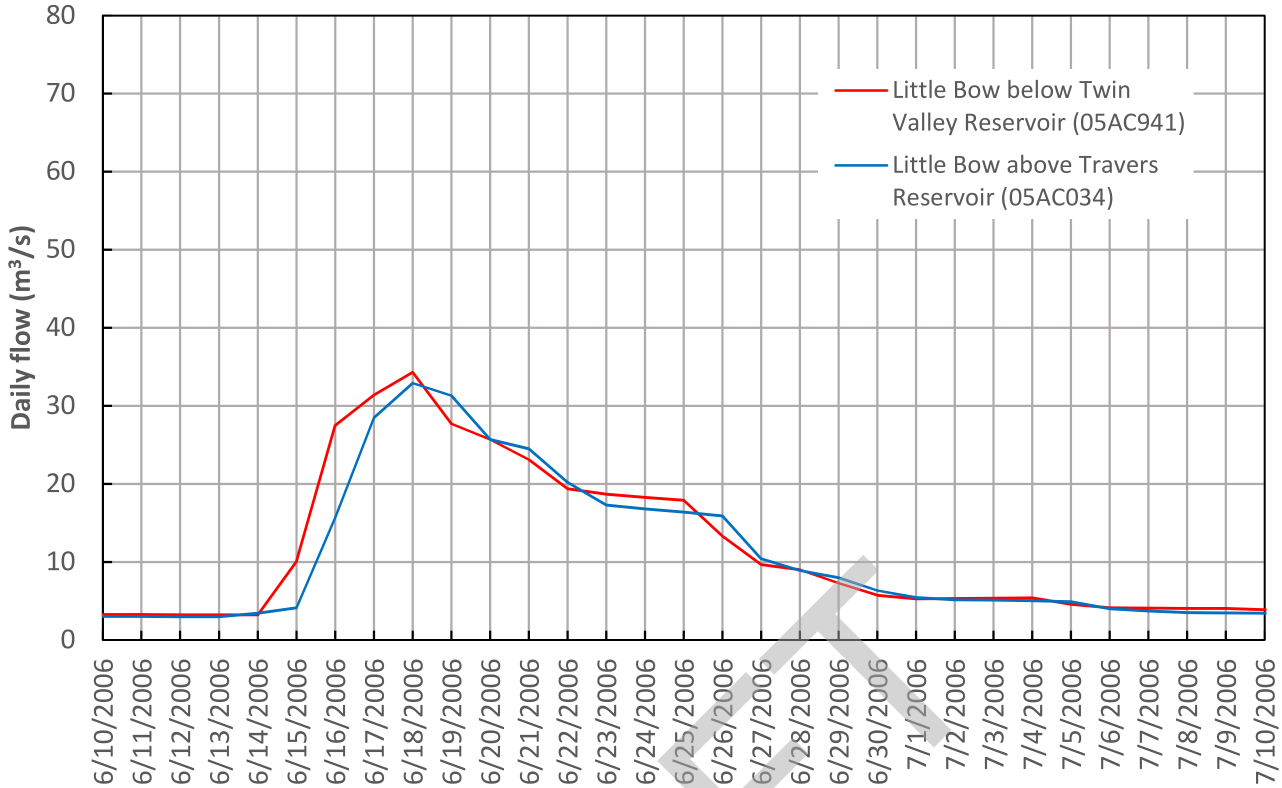
Coordinate System: NAD 1983 CSRS 3TM 111
Units: METERS

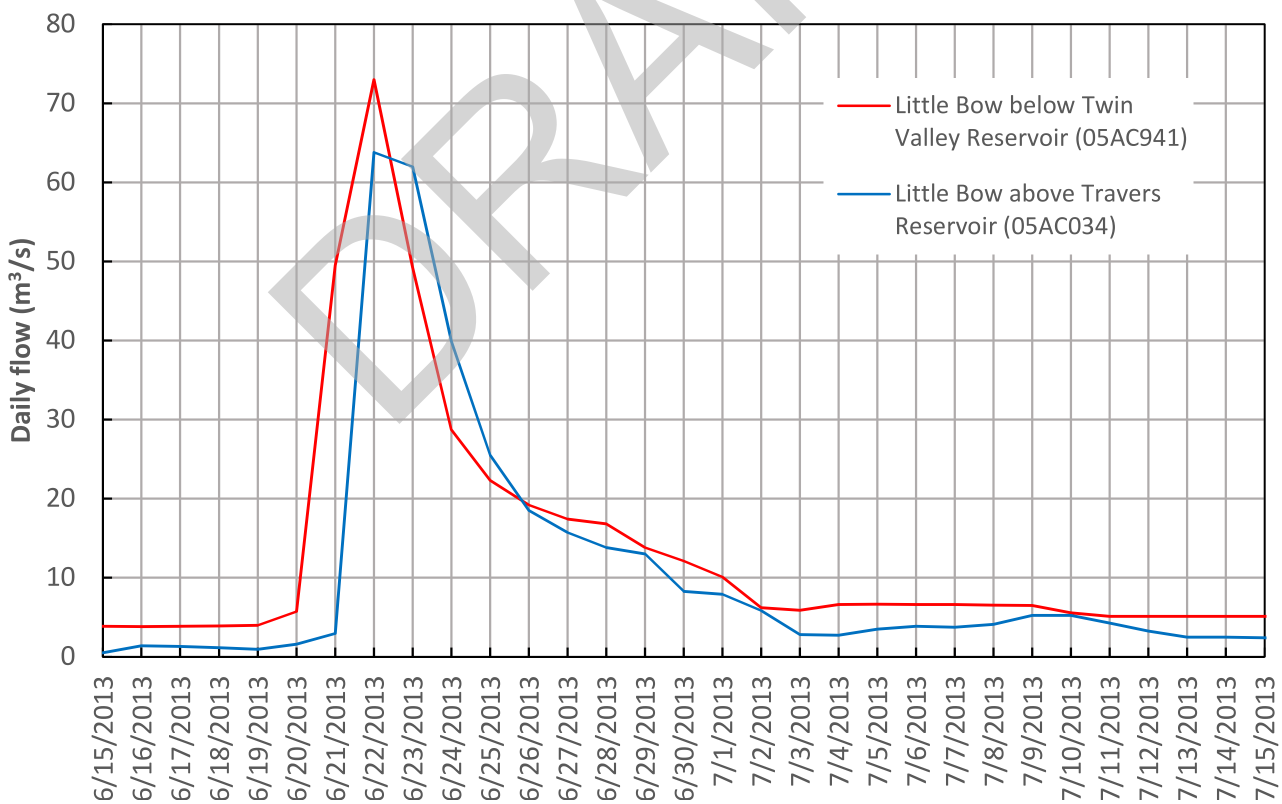
Job: 1003094 | *Date:01 FEB 2018*

MEDICINE HAT RIVER HAZARD STUDY

REFERENCE STATIONS FOR LITTLE BOW RIVER HYDROLOGY

FIGURE 15





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Coordinate System:
Units: As Shown

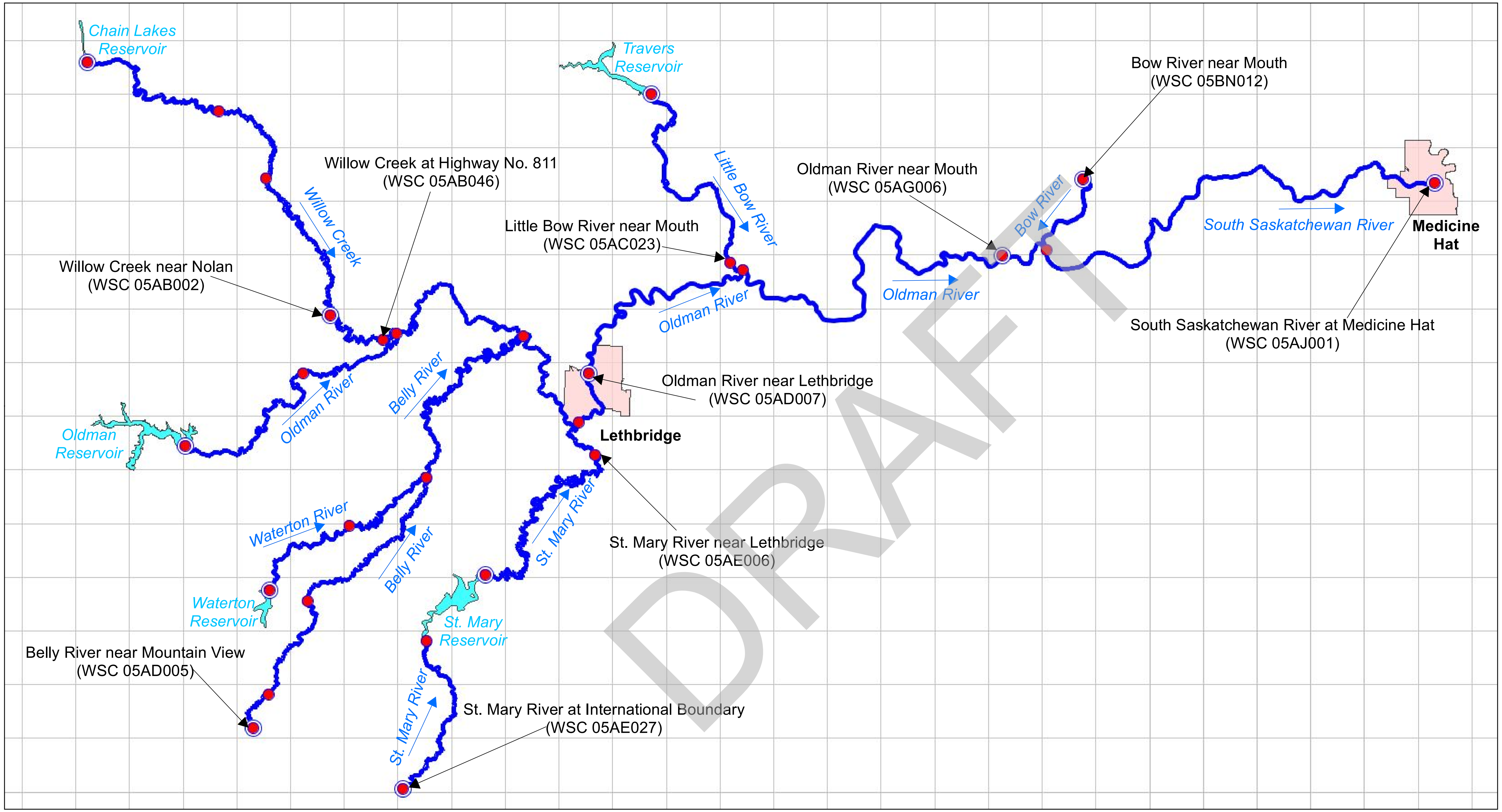
Job: 1003094

Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF DAILY FLOW HYDROGRAPHS FOR LITTLE BOW RIVER BELOW TWIN VALLEY RESERVOIR AND ABOVE TRAVERS RESERVOIR

FIGURE 16



Government of Alberta

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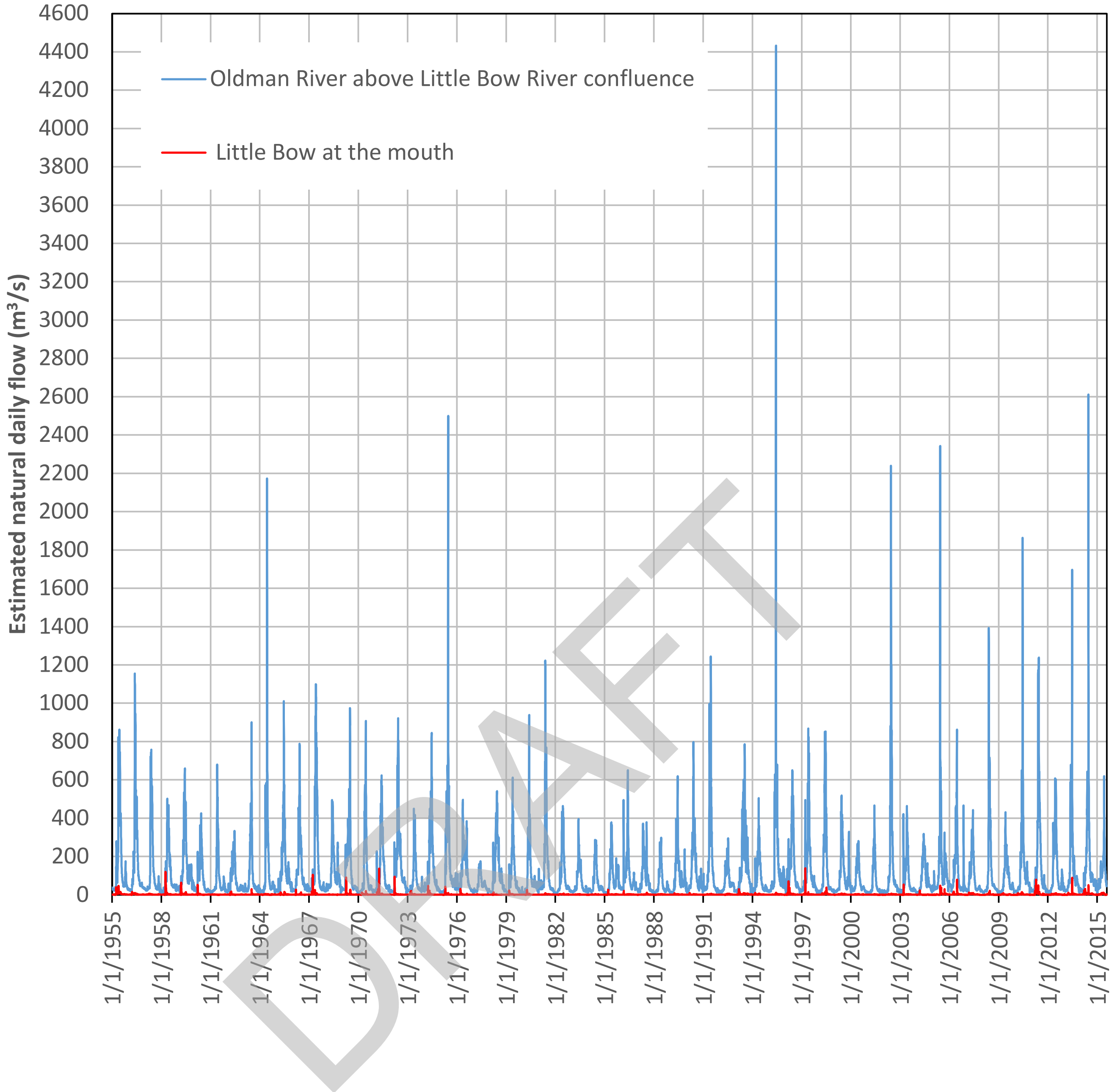
Job: 1003094 | Date: 14 JAN 2019

MEDICINE HAT RIVER HAZARD STUDY

HEC-RESSIM MODEL SCHEMATIC

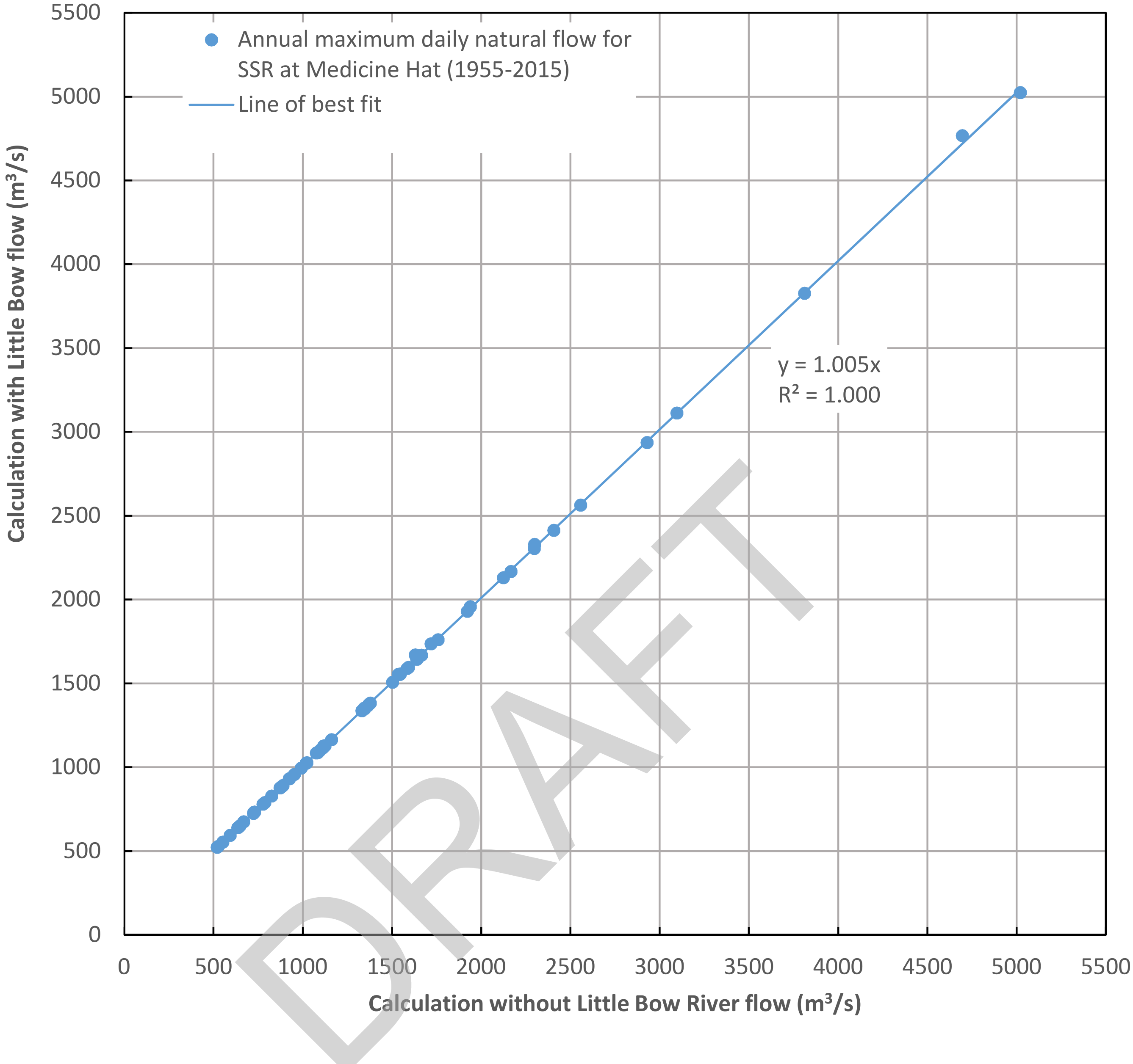
FIGURE 17

Classification: Public



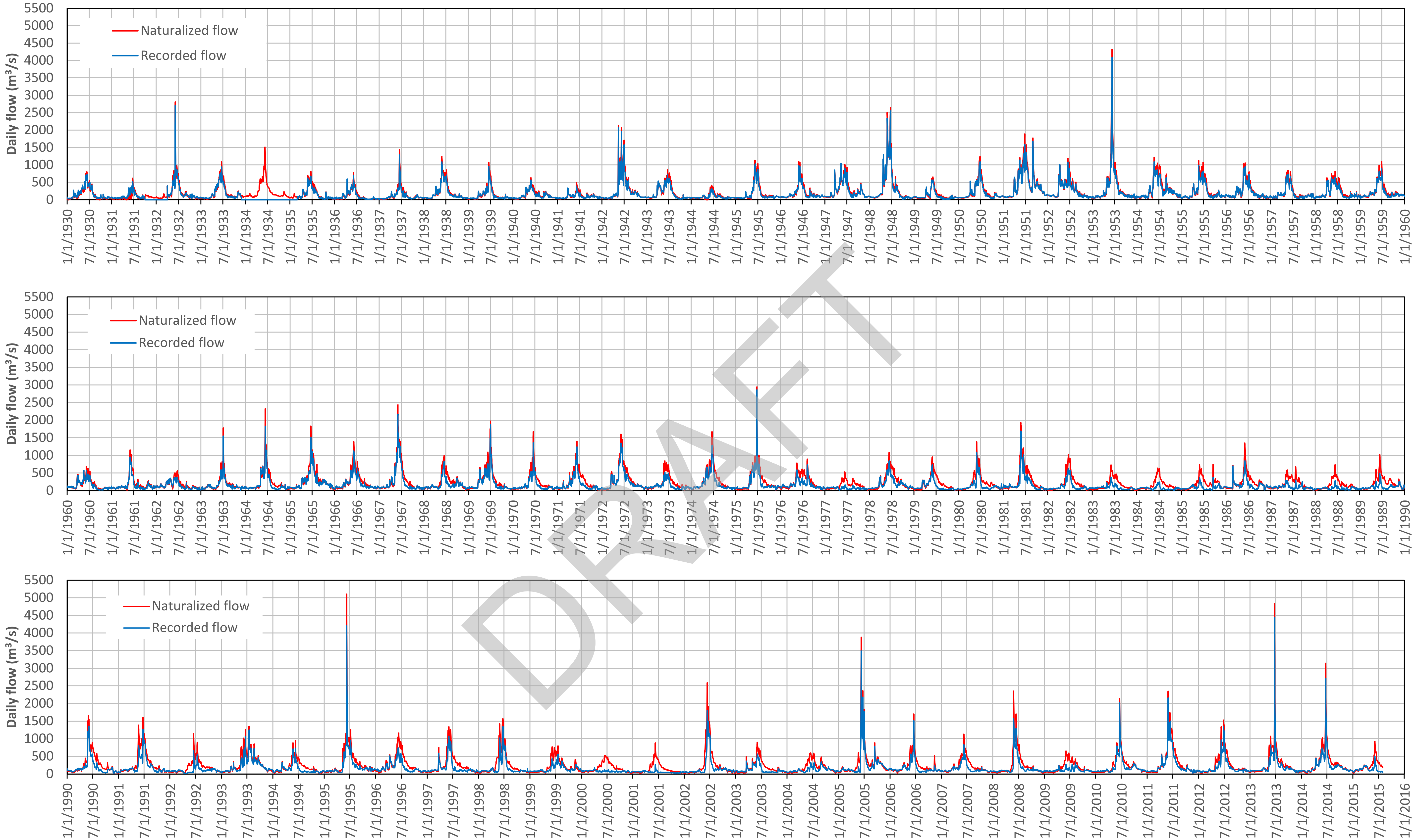
Notes: 1. Time series shown are modelled results for flow naturalization.

Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*COMPARISON OF DAILY NATURAL FLOWS FOR OLDMAN AND LITTLE BOW RIVERS*
	Job: 1003094 | *Date: JUL-2019*	*FIGURE 18*



Notes: 1. Data shown are modelled results for flow naturalization.

Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*COMPARISON OF ANNUAL MAXIMUM DAILY NATURAL FLOWS FOR SSR AT MEDICINE HAT CALCULATED WITH AND WITHOUT LITTLE BOW RIVER FLOW*
	Job: 1003094 *Date: JUL-2019*	*FIGURE 19*



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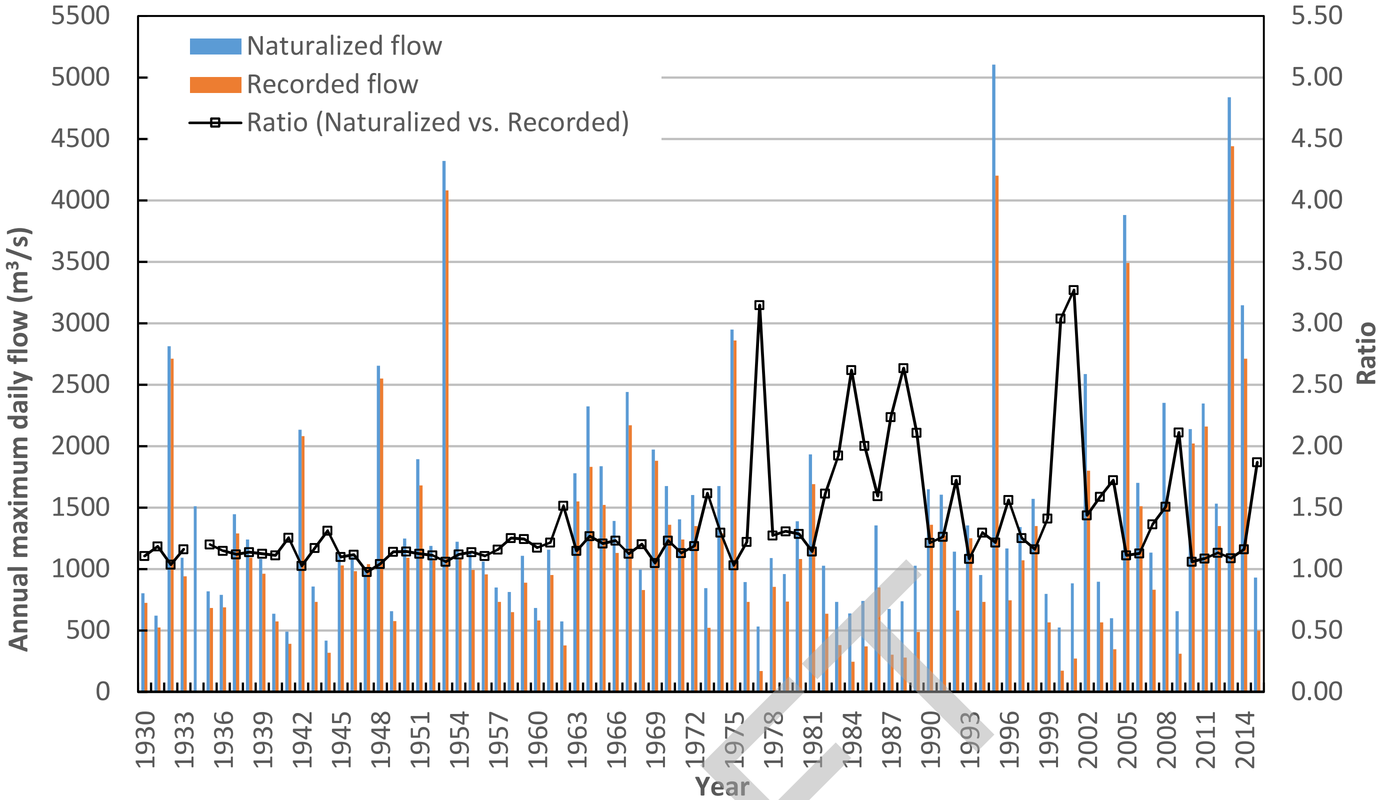
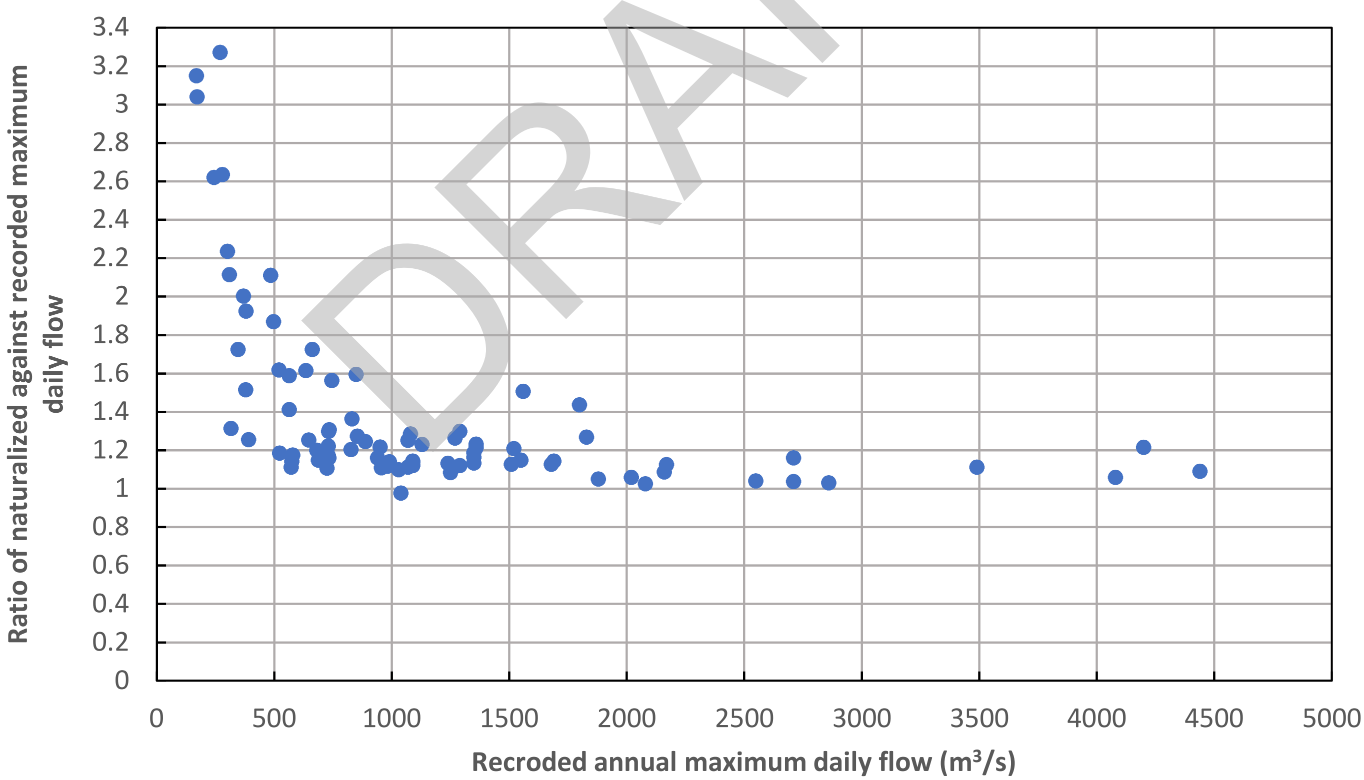
MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

NATURALIZED AND RECORDED DAILY FLOWS FOR SSR AT MEDICINE HAT

FIGURE 20





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Coordinate System:
Units: As Shown

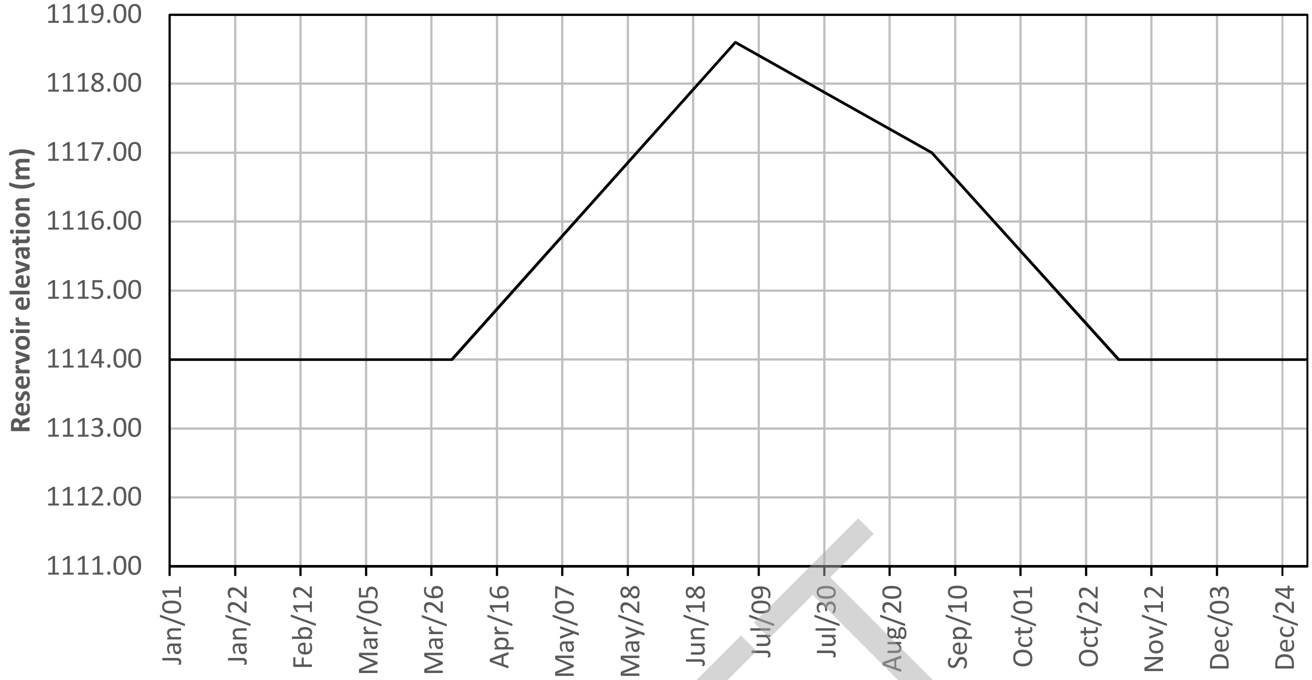
Job: 1003094 | *Date: JUL-2019*

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF NATURALIZED AND RECORDED ANNUAL MAXIMUM DAILY FLOWS FOR SSR AT MEDICINE HAT (1930-2015)

FIGURE 21

Oldman Reservoir Operating Rule Curve



Waterton Reservoir Operating Rule Curve

Notes:
1. The operating rule curves were provided by Alberta Environment and Parks.
2. The operating rule curve for Oldman Reservoir was from the 1994 Operational Strategy Study by AEP.
3. The operating rule curve for Waterton Reservoir was from the Waterton Dam operational study by UMA (2005).

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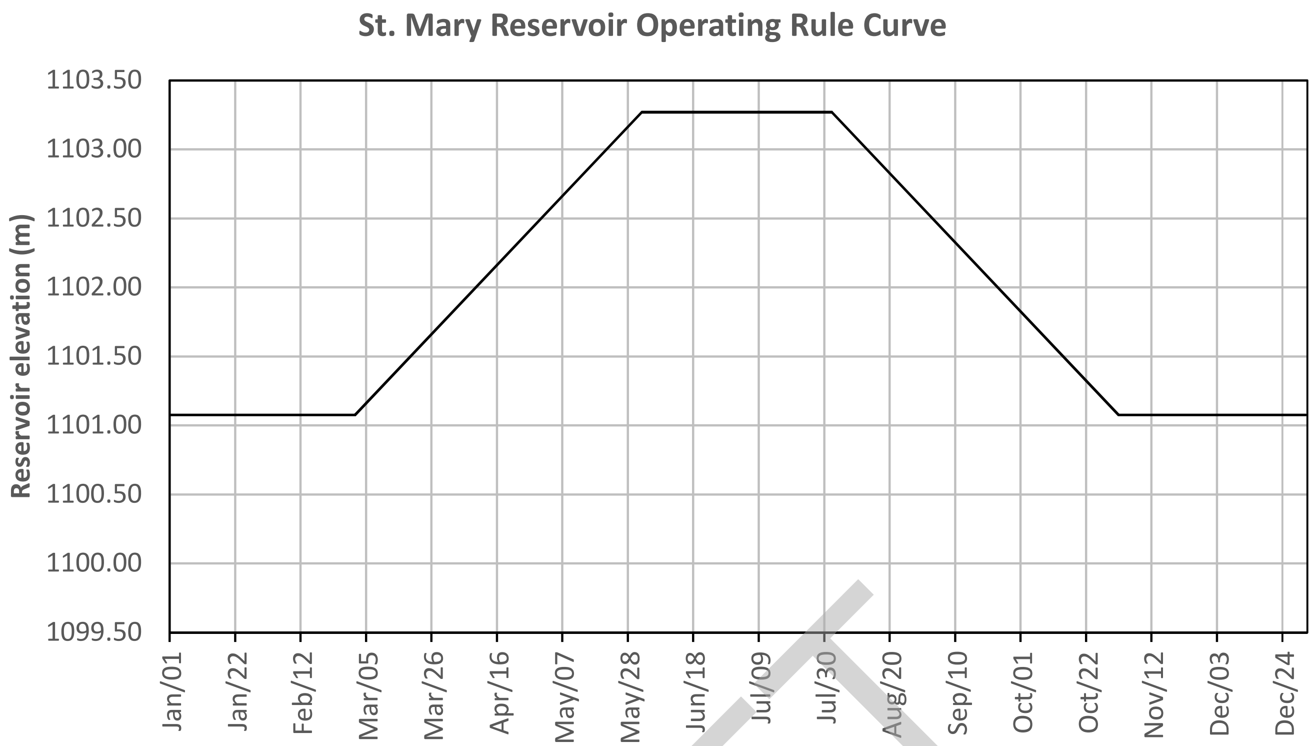
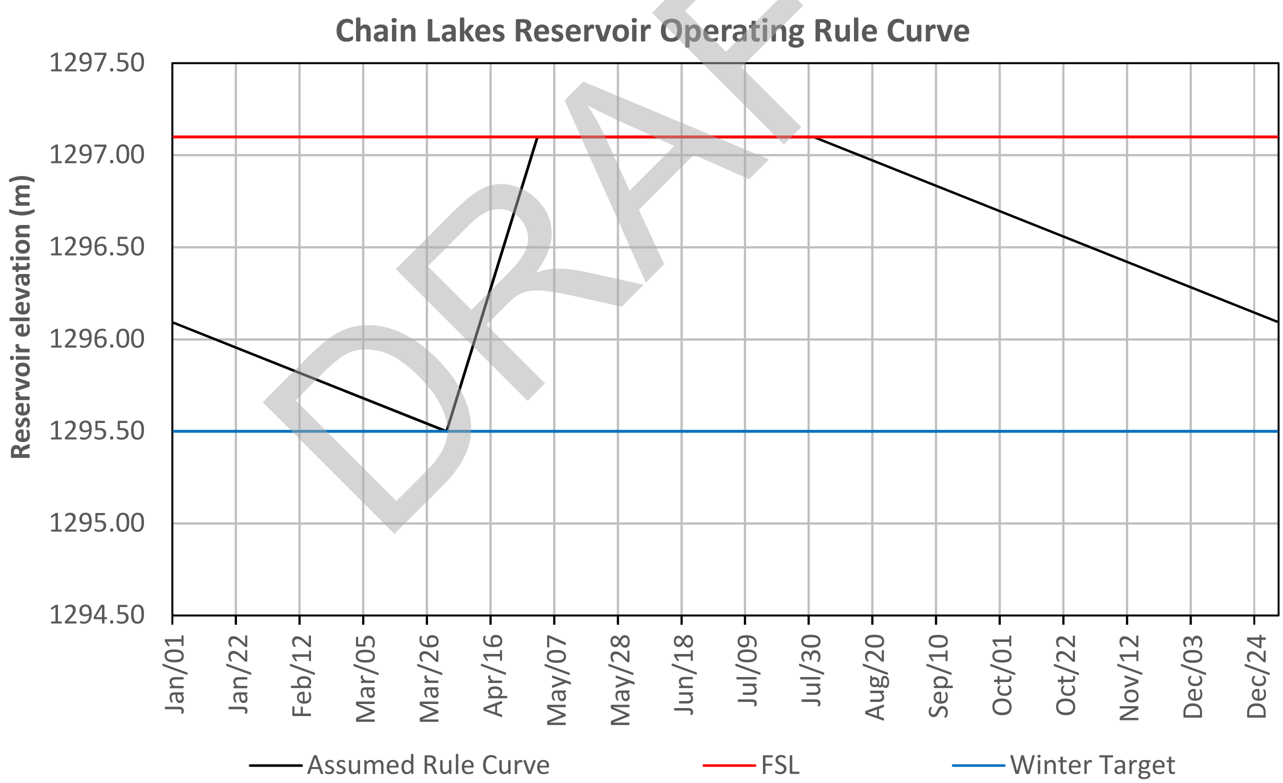
	Job: 1003094 | *Date: JUL-2019*	*FIGURE 22*





Notes:

1. The operating rule curve for St. Mary Reservoir was provided by Alberta Environment and Parks and from the operational study by Acres (2005).
2. For Chain Lakes Reservoir, Alberta Environment and Parks provided the FSL and winter target level only. The assumed seasonal variation was established from the historical reservoir level record.

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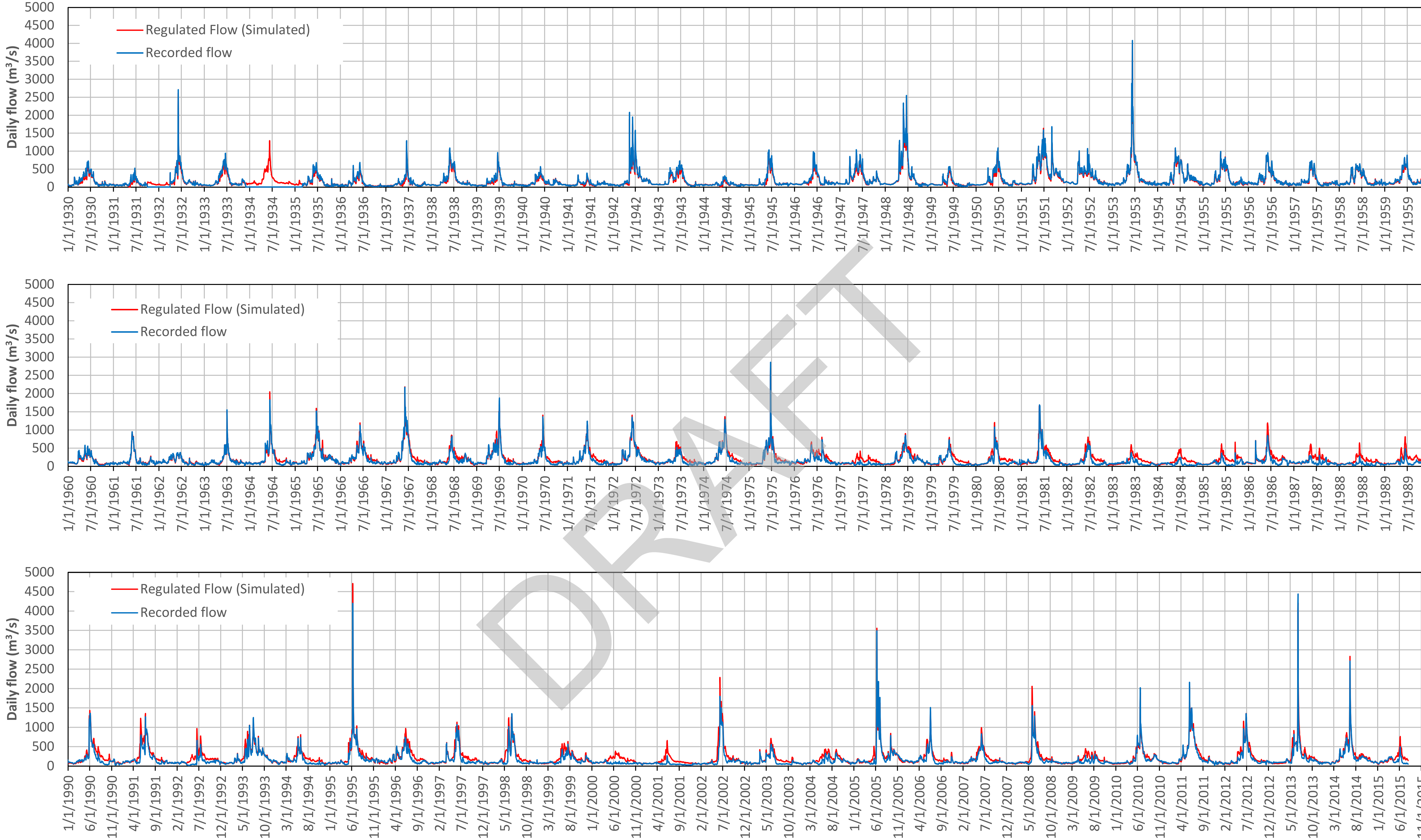
Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

OPERATING RULE CURVES FOR ST. MARY AND CHAIN LAKES RESERVOIRS

FIGURE 23



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SCALE – AS SHOWN

Coordinate System:
Units: As Shown

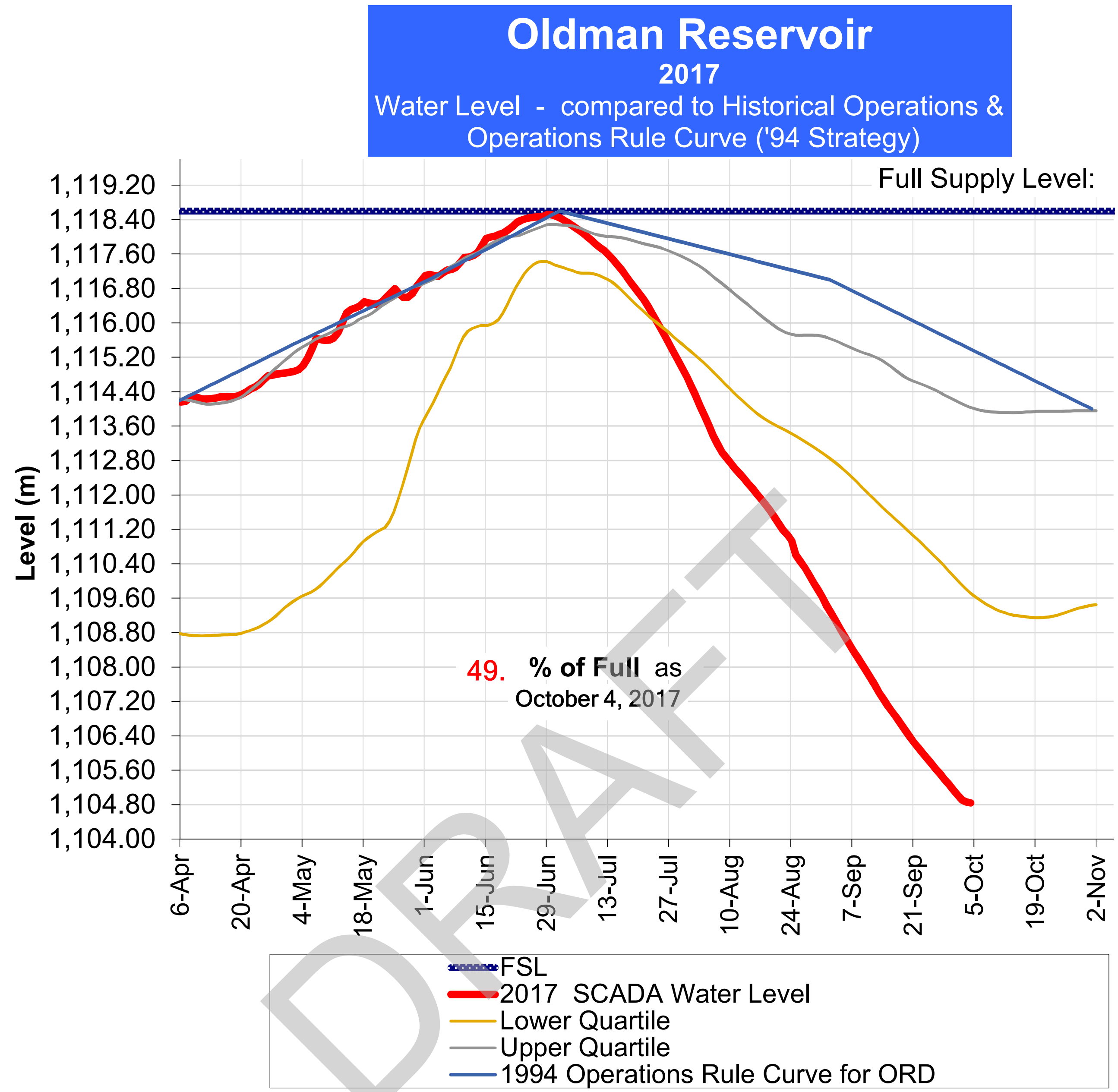
Job: 1003094

Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

REGULATED AND RECORDED DAILY FLOWS FOR SSR AT MEDICINE HAT

FIGURE 24



Notes: 1. Information provided by AEP.

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Coordinate System:
Units: As Shown

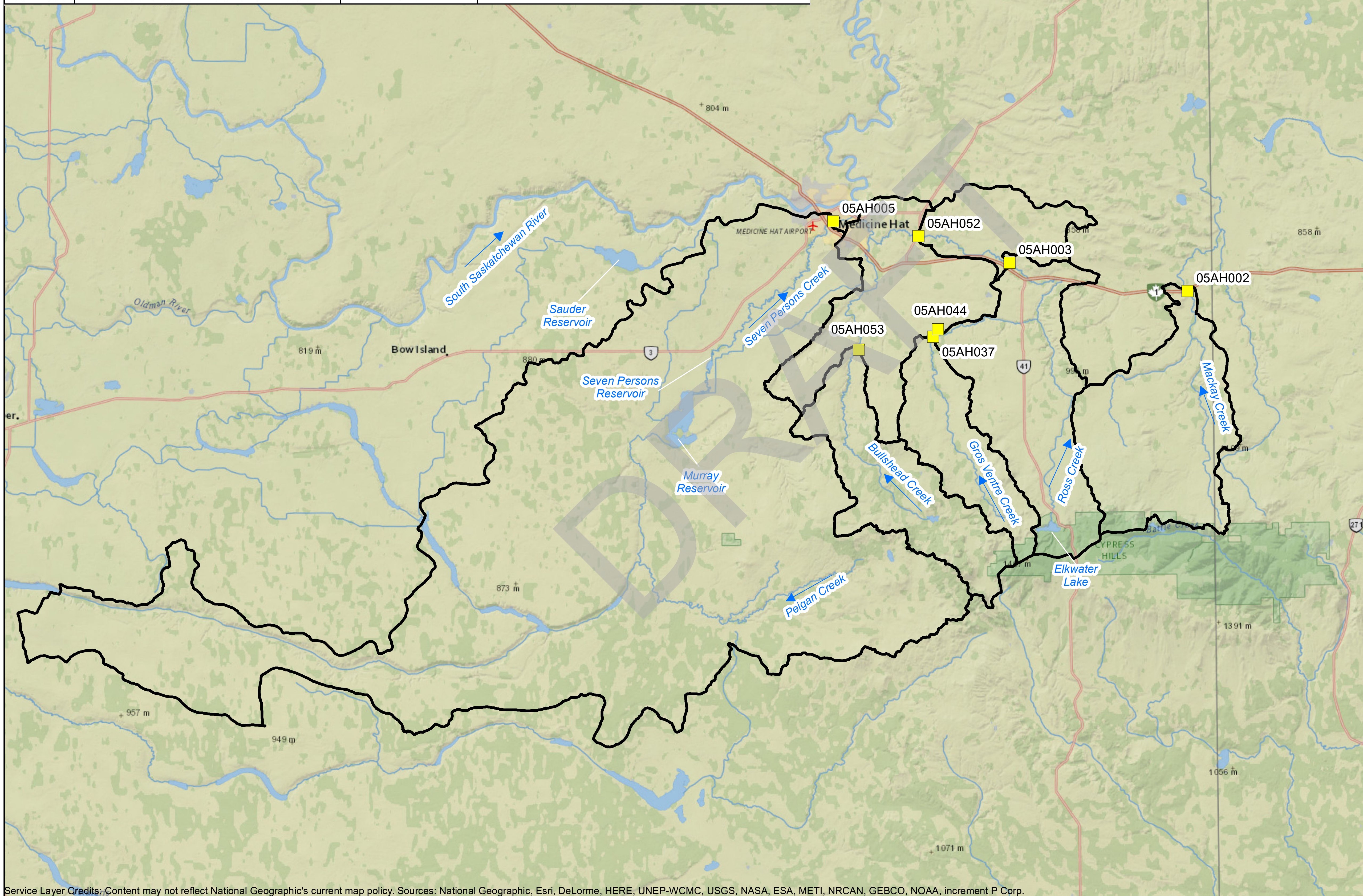
Job: 1003094 | Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF OLDMAN RESERVOIR OPERATING RULE CURVE WITH HISTORICAL OPERATIONS

FIGURE 25

Station ID	Station Name	Draingae Area (km^2)	Data Record
05AH002	Mackay Creek at Walsh	437	1911-1919,1936,1956-2016
05AH003	Ross Creek near Irvine	647	1909-2000
05AH005	Seven Persons Creek at Medicine Hat	3,280	1910,1912-1917,1919-1931,1935-1956, 1973-2016
05AH037	Gros Ventre Creek near Dunmore	215	1921-1922,1944-2016
05AH044	Cavan Lake Diversion near Dunmore		1981-2016
05AH052	Ross Creek at Highway No. 41	808	2000-2016
05AH053	Bullshead Creek at Black and White Trail	348	2005-2016



Service Layer Credits: Content may not reflect National Geographic's current map policy. Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

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Legend

WSC Hydrometric Station

Catchment Boundary

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

SCALE - 1:520,000

0 5 10 20 Km

N

Coordinate System: NAD 1983 CSRS 3TM 111
Units: METERS

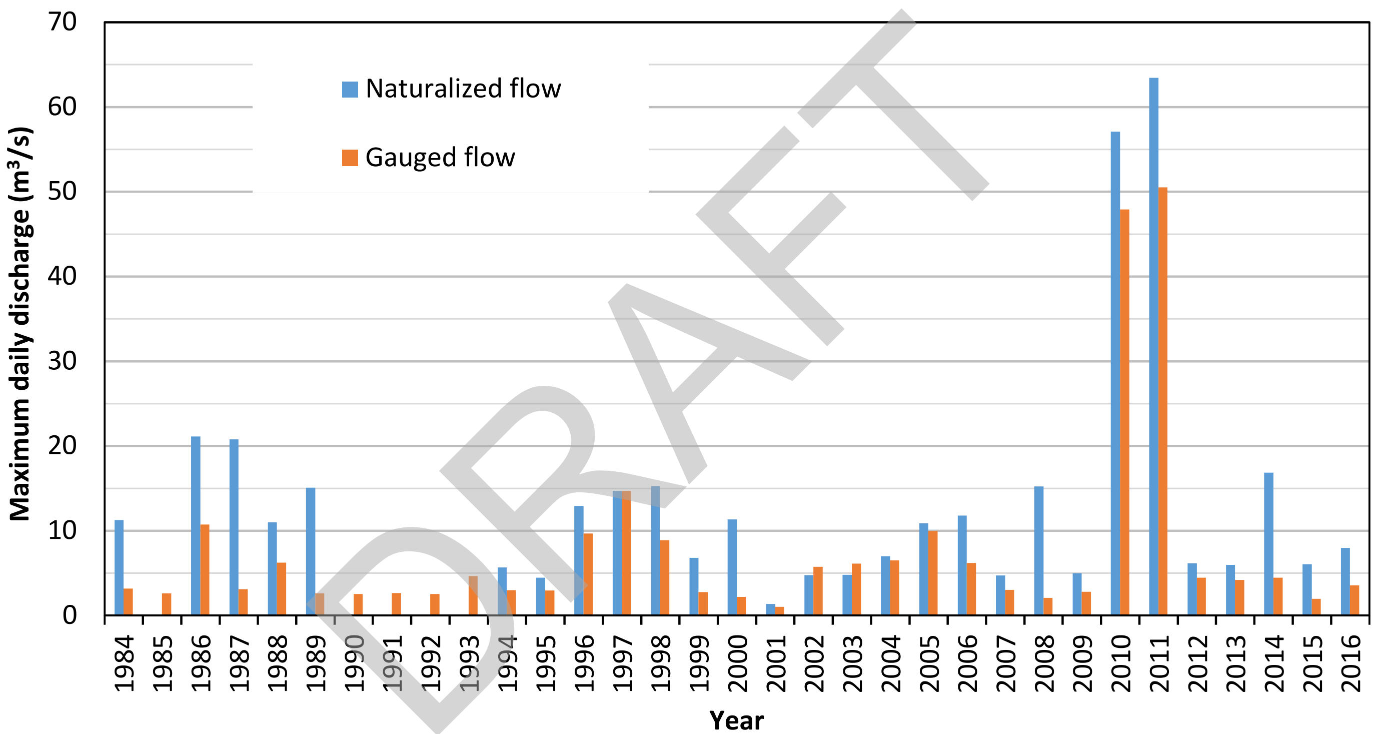
Job: 1003094 | *Date: 06 MAR 2018*

MEDICINE HAT RIVER HAZARD STUDY

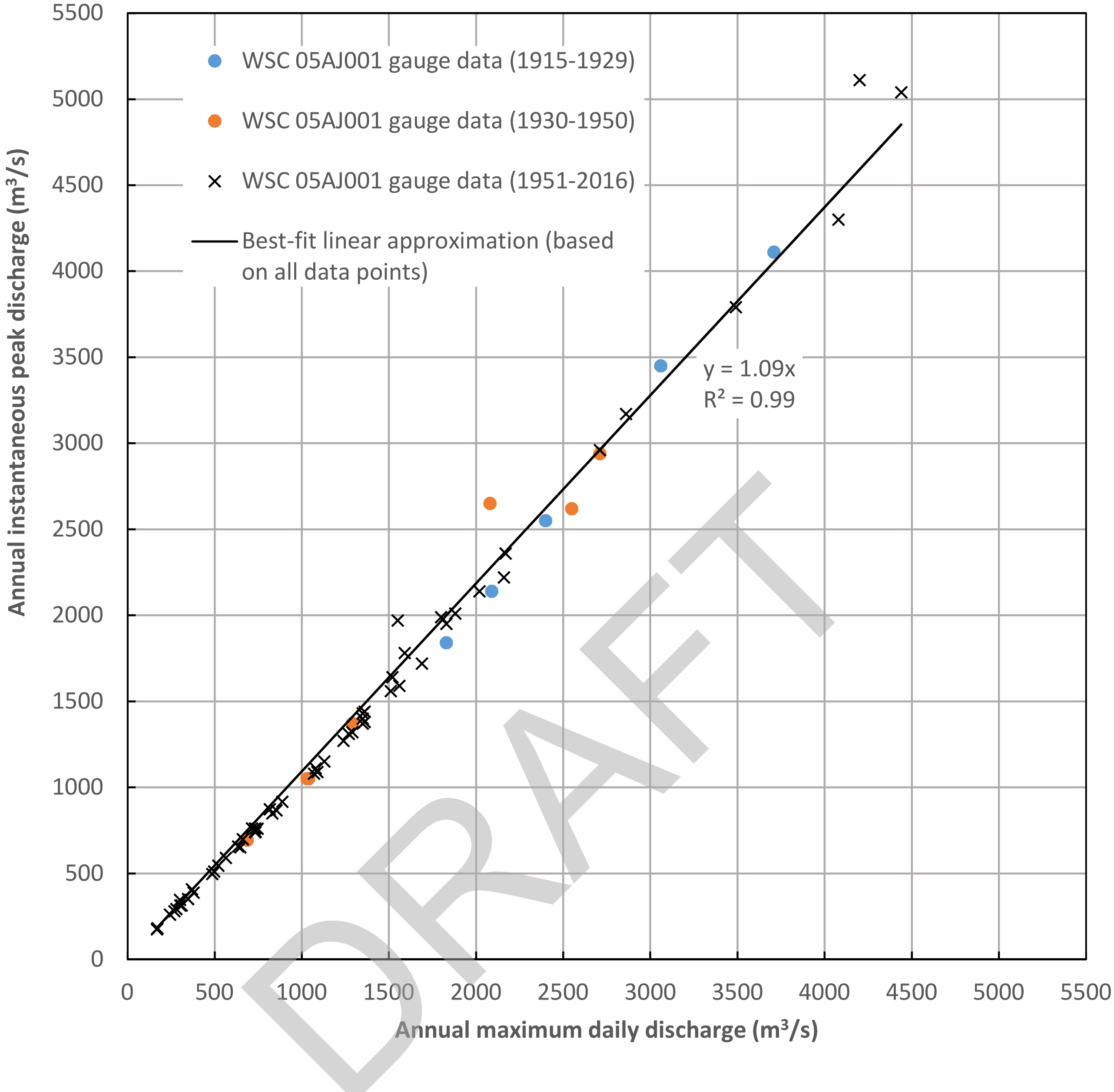
Ross and Seven Persons Creek Sub-basin Overview

FIGURE 26

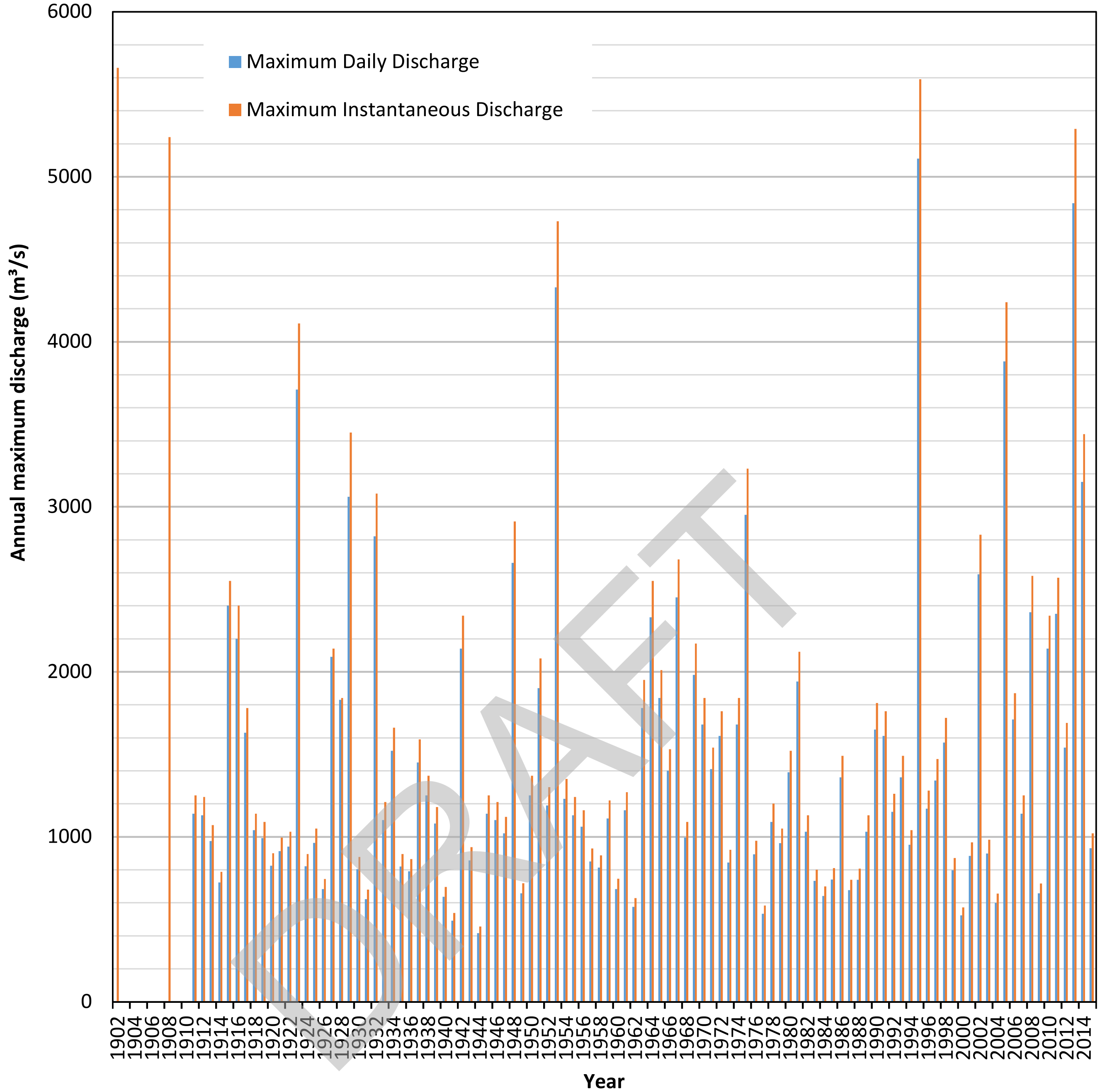
Classification: Public



Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*NATURALIZED AND GAUGED MAXIMUM DAILY DISCHARGES FOR SEVEN PERSONS CREEK AT MEDICINE HAT*
	Job: 1003094 | *Date: JUL-2019*	*FIGURE 27*



Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*SOUTH SASKATCHEWAN RIVER AT MEDICINE HAT MAXIMUM INSTANTANEOUS TO DAILY DISCHARGE RATIO*
	Job: 1003094 / *Date: JUL-2019*	*FIGURE 28*



Notes:
1. The 1902 and 1908 data are estimates for historic events
2. The 1911-1929 data are gauge data
3. The 1930-2015 data are modelled results for flow naturalization.

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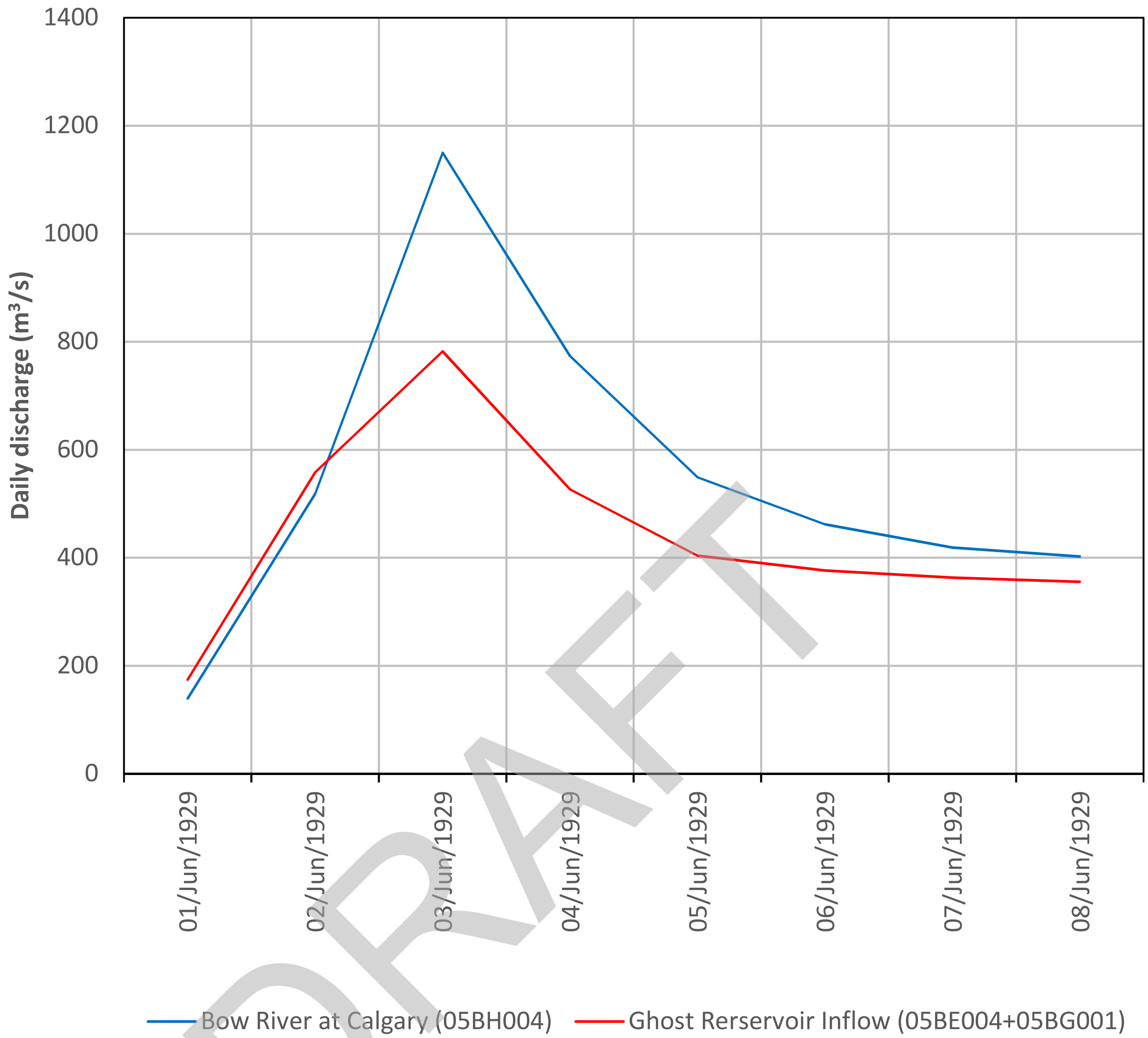
Coordinate System:
Units: As Shown

Job: 1003094 | *Date: JUL-2019*

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

MAXIMUM INSTANTANEOUS AND DAILY DISCHARGES FOR NATURALIZED FLOW SSR AT MEDICINE HAT

FIGURE 29



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Coordinate System:
Units: As Shown

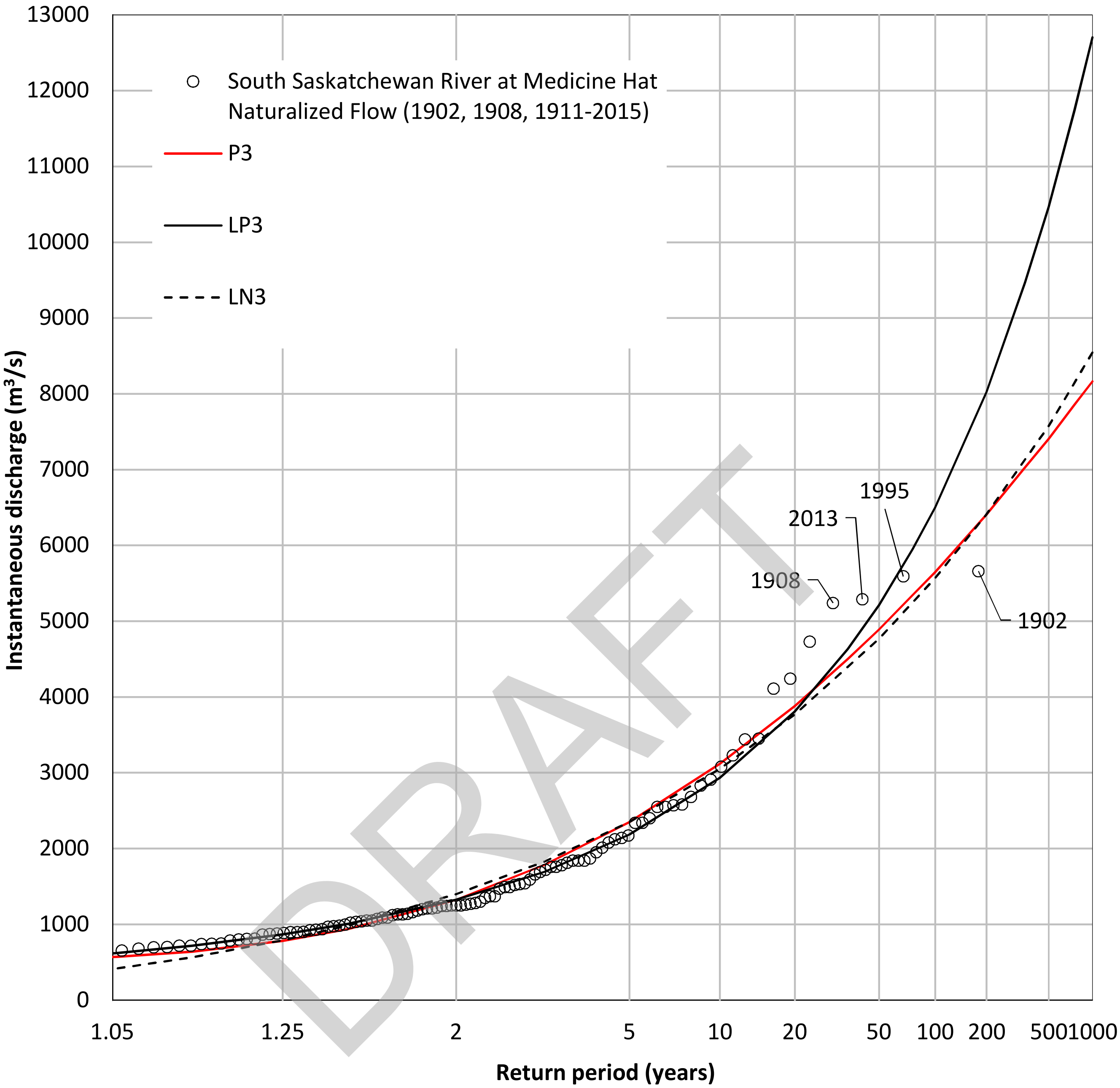
Job: 1003094

Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ESTIMATED 1929 GHOST RESERVOIR INFLOWS VS. BOW RIVER FLOWS AT CALGARY

FIGURE 30



Notes:
1. The 1902 and 1908 data are estimates for historic events
2. The 1911-1929 data are gauge data
3. The 1930-2015 data are modelled results for flow naturalization.

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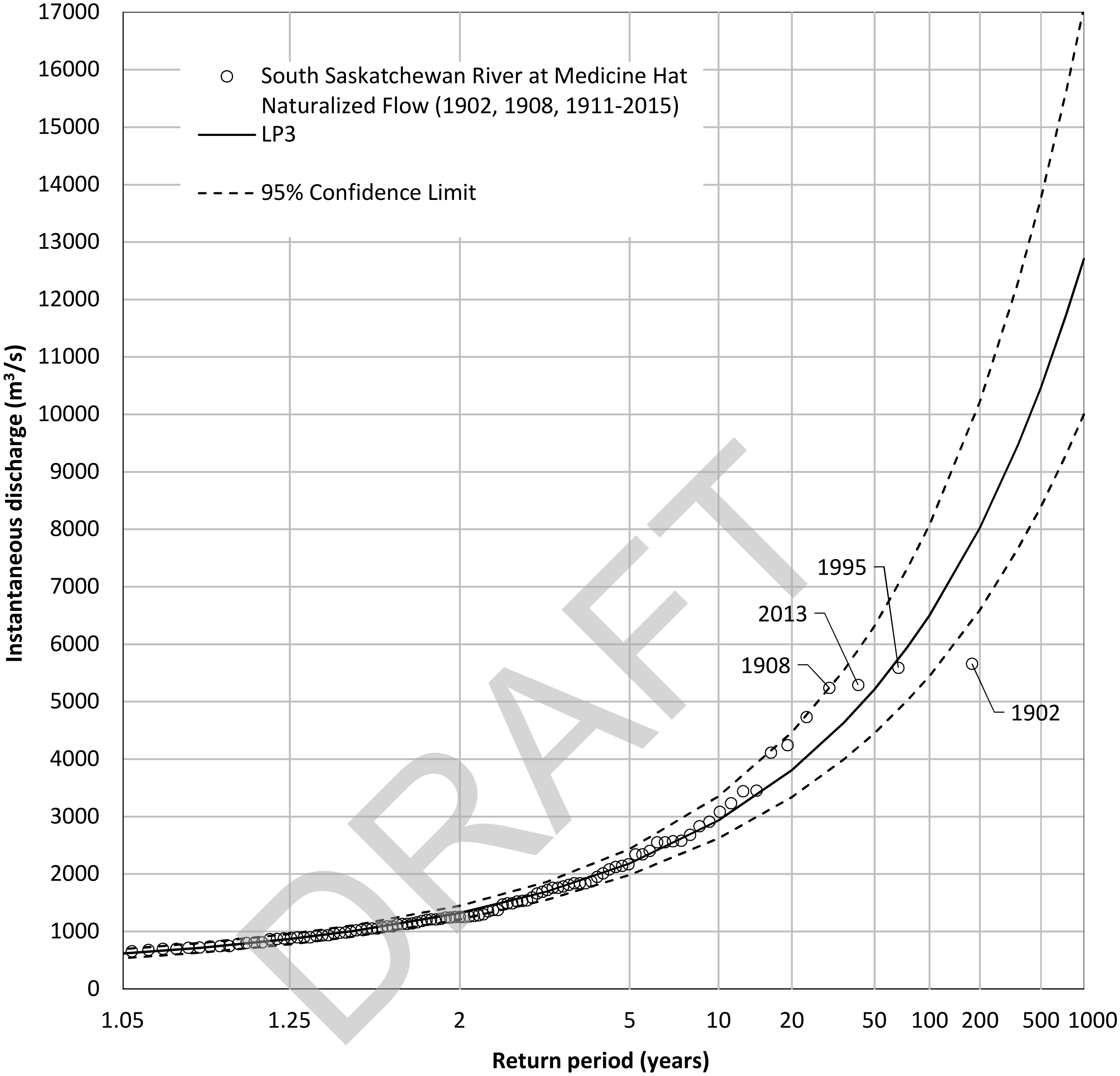
Coordinate System:
Units: As Shown

Job: 1003094 | *Date: JUL-2019*

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF NATURALIZED FLOOD FREQUENCY CURVES FOR SSR AT MEDICINE HAT

FIGURE 31



Notes:
1. The 1902 and 1908 data are estimates for historic events
2. The 1911-1929 data are gauge data
3. The 1930-2015 data are modelled results for flow naturalization.

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Coordinate System:
Units: As Shown

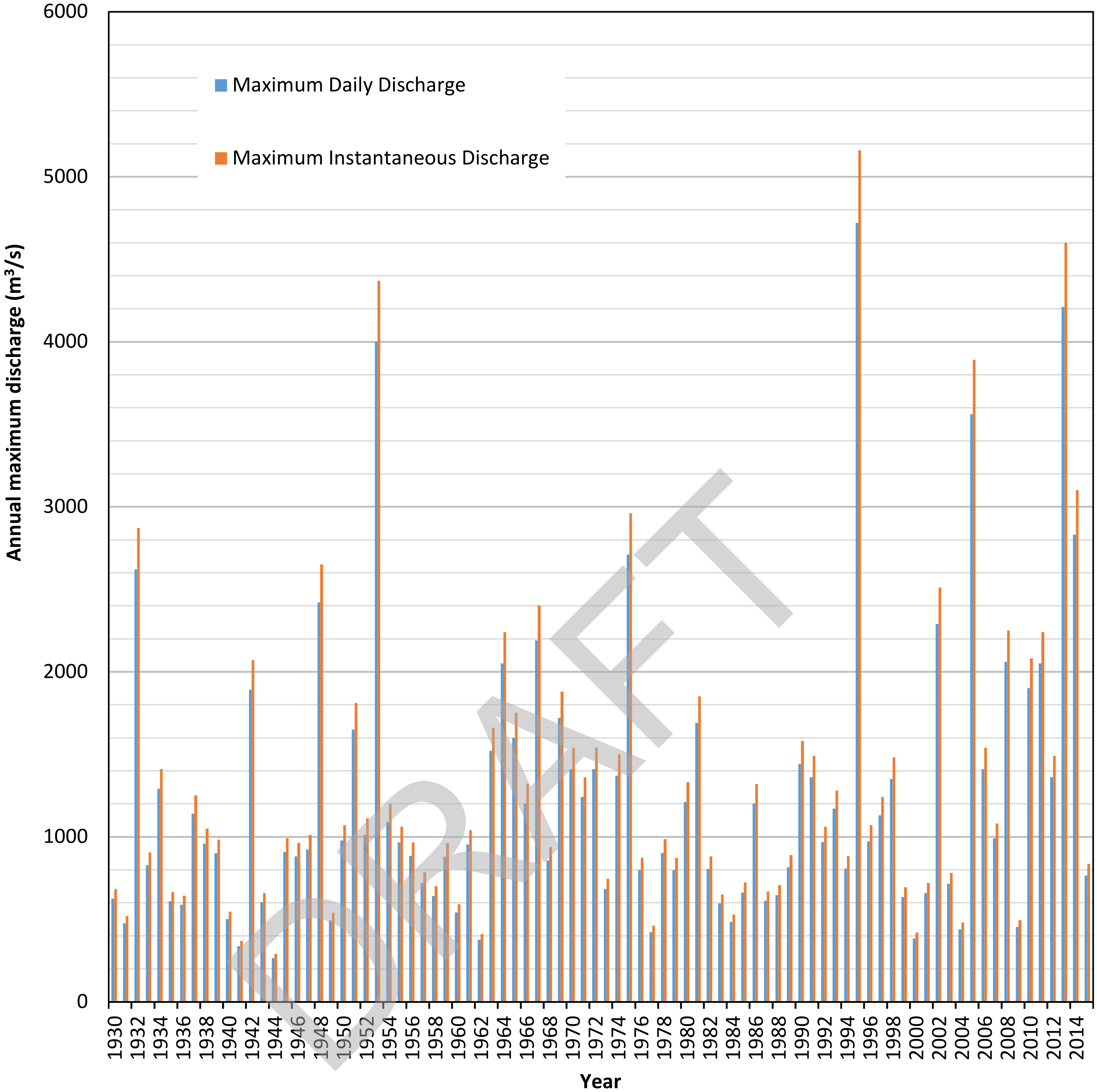
Job: 1003094

Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

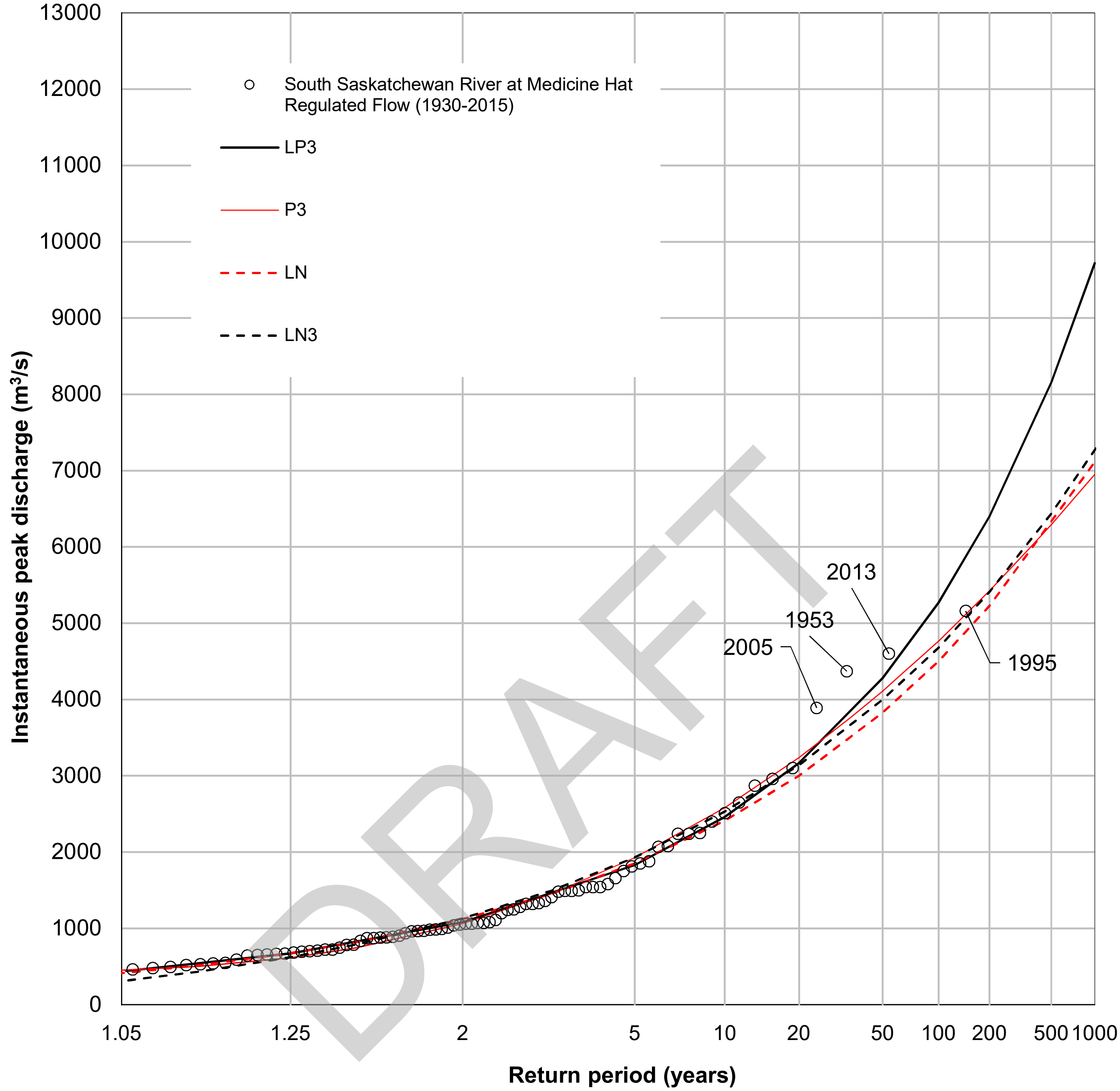
NATURALIZED FLOOD FREQUENCY ESTIMATES FOR SSR AT MEDICINE HAT

FIGURE 32



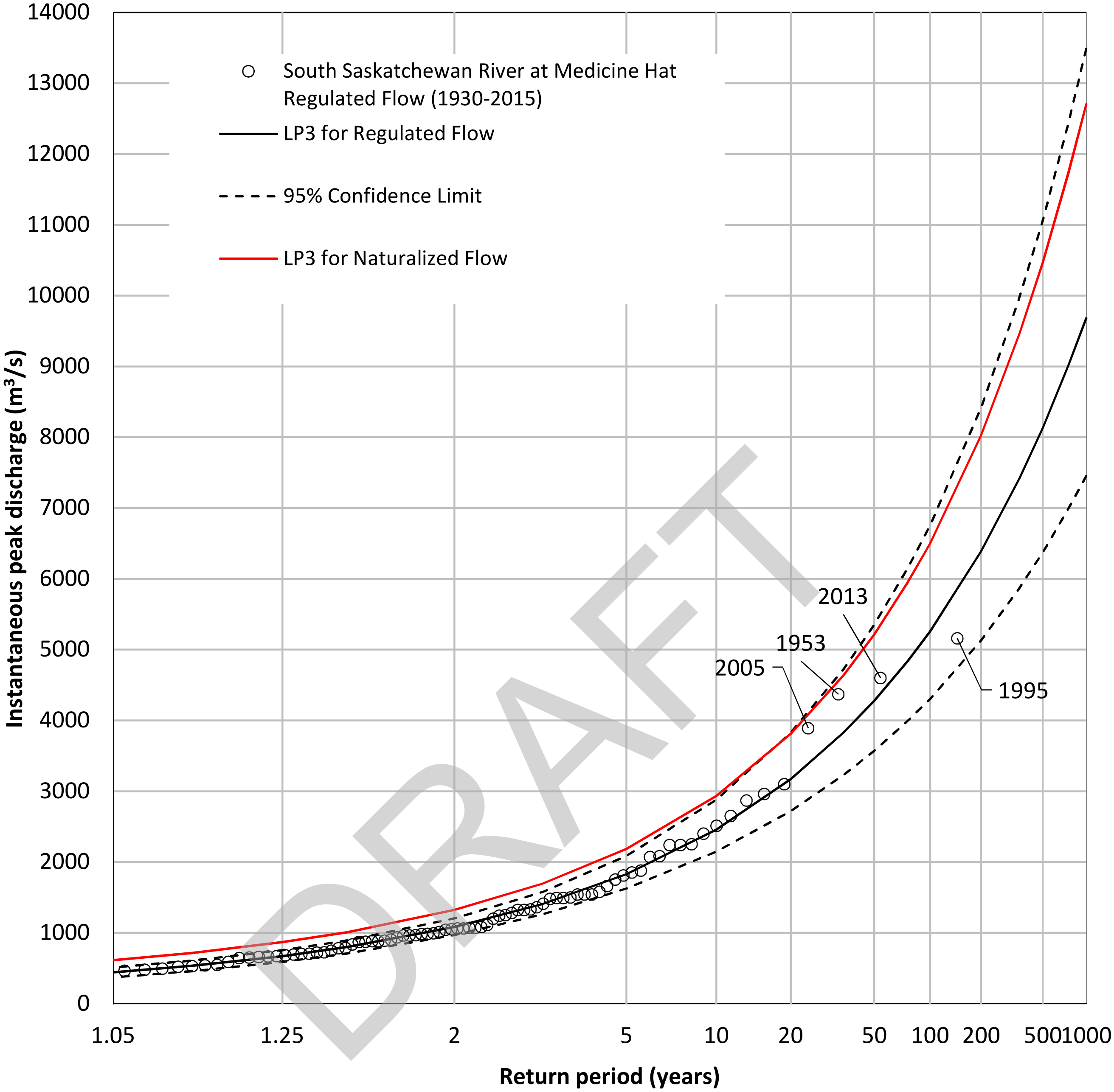
Notes: 1. Regulated flows are from simulation results.

Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*MAXIMUM INSTANTANEOUS AND DAILY DISCHARGES FOR REGULATED FLOW SSR AT MEDICINE HAT*
	Job: 1003094 | *Date: JUL-2019*	*FIGURE 33*



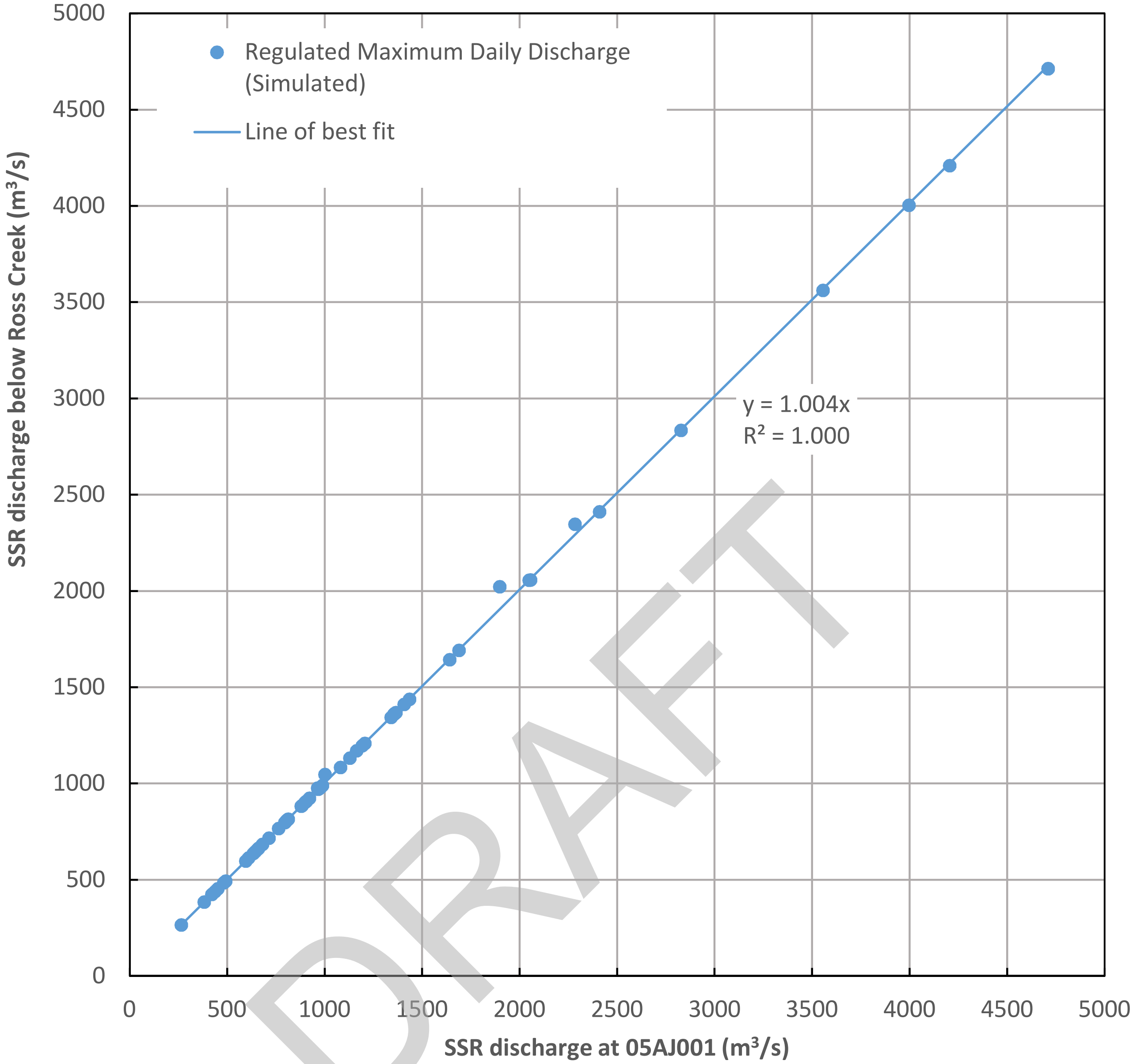
Notes: 1. Regulated flows are from simulation results.

Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*COMPARISON OF REGULATED FLOOD FREQUENCY CURVES FOR SSR AT MEDICINE HAT*
	Job: 1003094 / *Date: JUL-2019*	*FIGURE 34*



Notes: 1. Regulated flows are from simulation results.

Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*REGULATED FLOOD FREQUENCY ESTIMATES FOR SSR AT MEDICINE HAT*
	Job: 1003094 / *Date: JUL-2019*	*FIGURE 35*



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SCALE – AS SHOWN

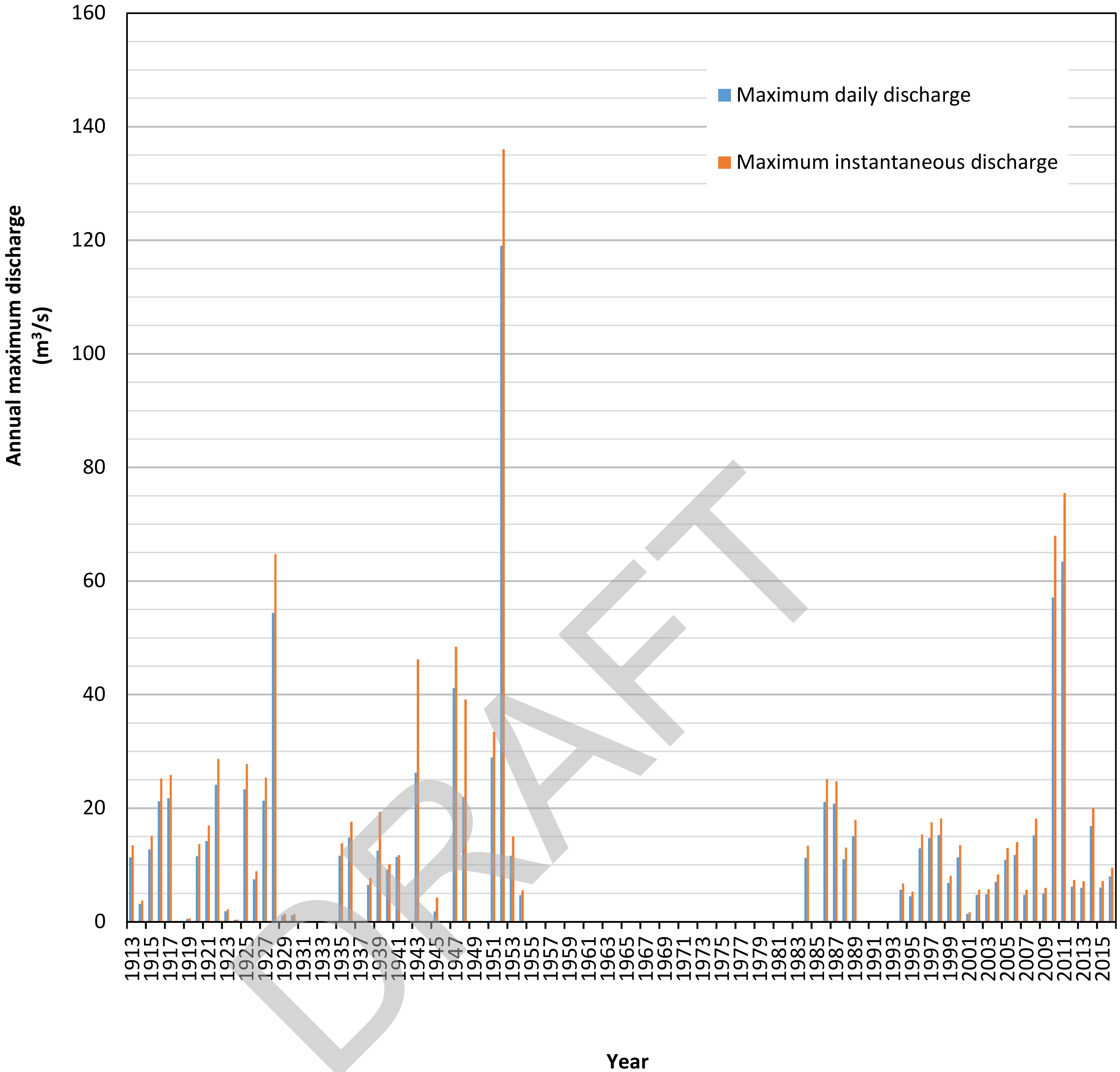
Coordinate System:
Units: As Shown

Job: 1003094 | Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

EFFECTS OF ROSS CREEK INFLOWS ON REGULATED PEAK DISCHARGES ON SSR

FIGURE 36



Notes:
1. The 1913-1954 data are gauge data
2. The 1984-2016 data are modelled results for flow naturalization.

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Coordinate System:
Units: As Shown

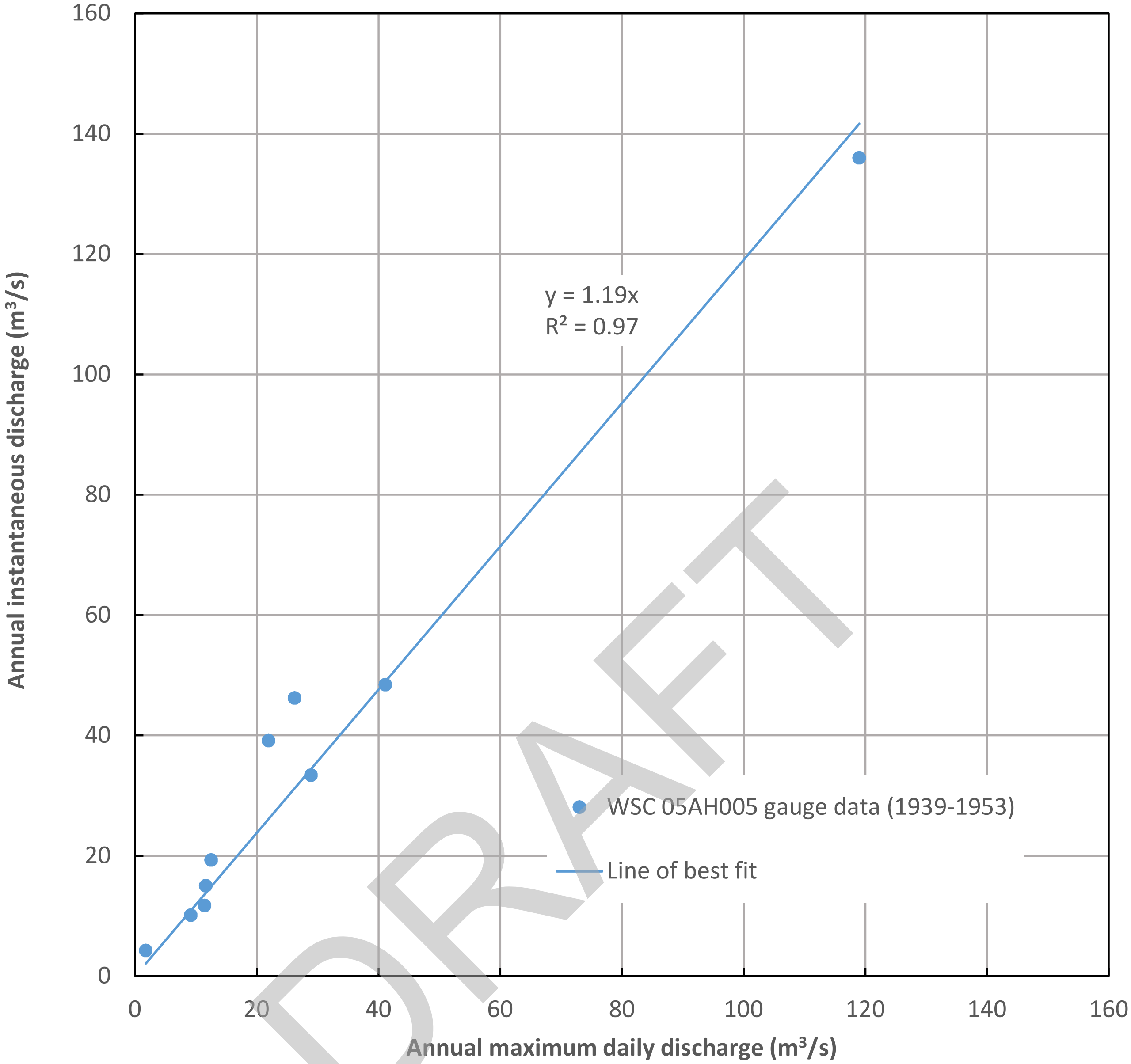
Job: 1003094

Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

MAXIMUM INSTANTANEOUS AND DAILY DISCHARGES FOR SEVEN PERSONS CREEK NATURAL FLOW AT MEDICINE HAT

FIGURE 37



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Coordinate System:
Units: As Shown

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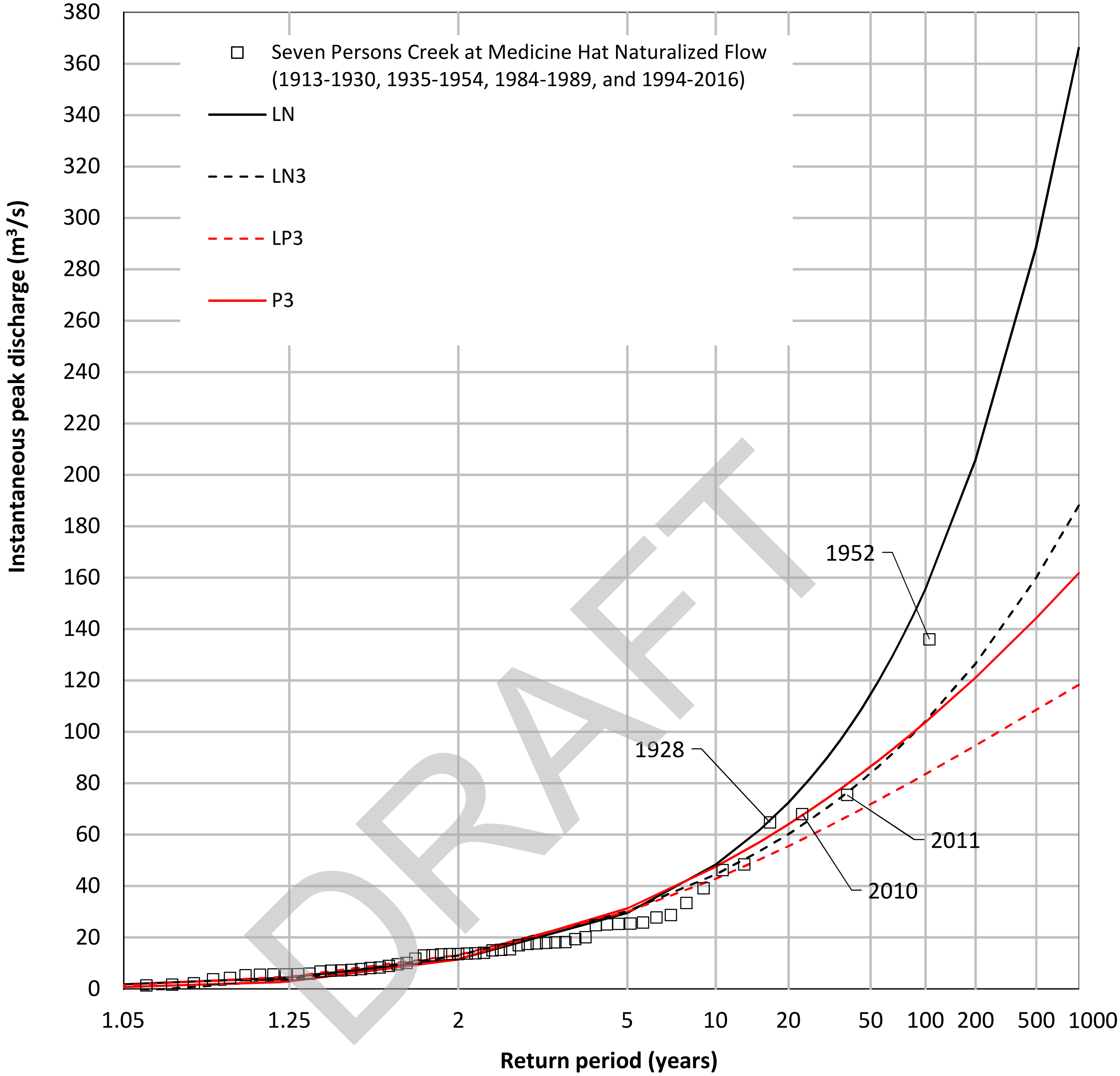
Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

SEVEN PERSONS CREEK AT MEDICINE HAT INSTANTANEOUS PEAK TO MAXIMUM DAILY DISCHARGE RATIO

FIGURE 38



Notes:
1. The 1913-1954 data are gauge data
2. The 1984-2016 data are modelled results for flow naturalization

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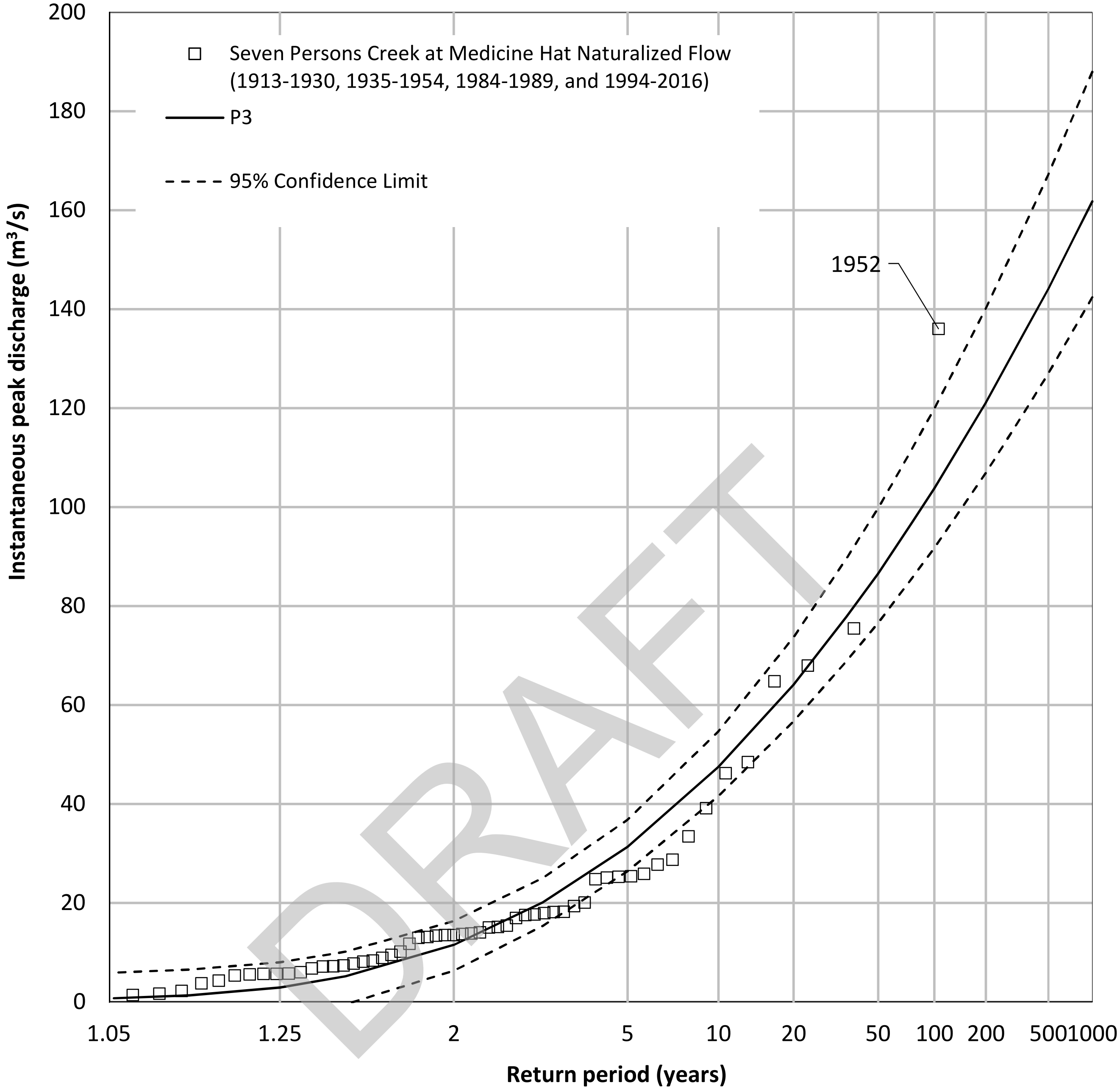
Coordinate System:
Units: As Shown

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

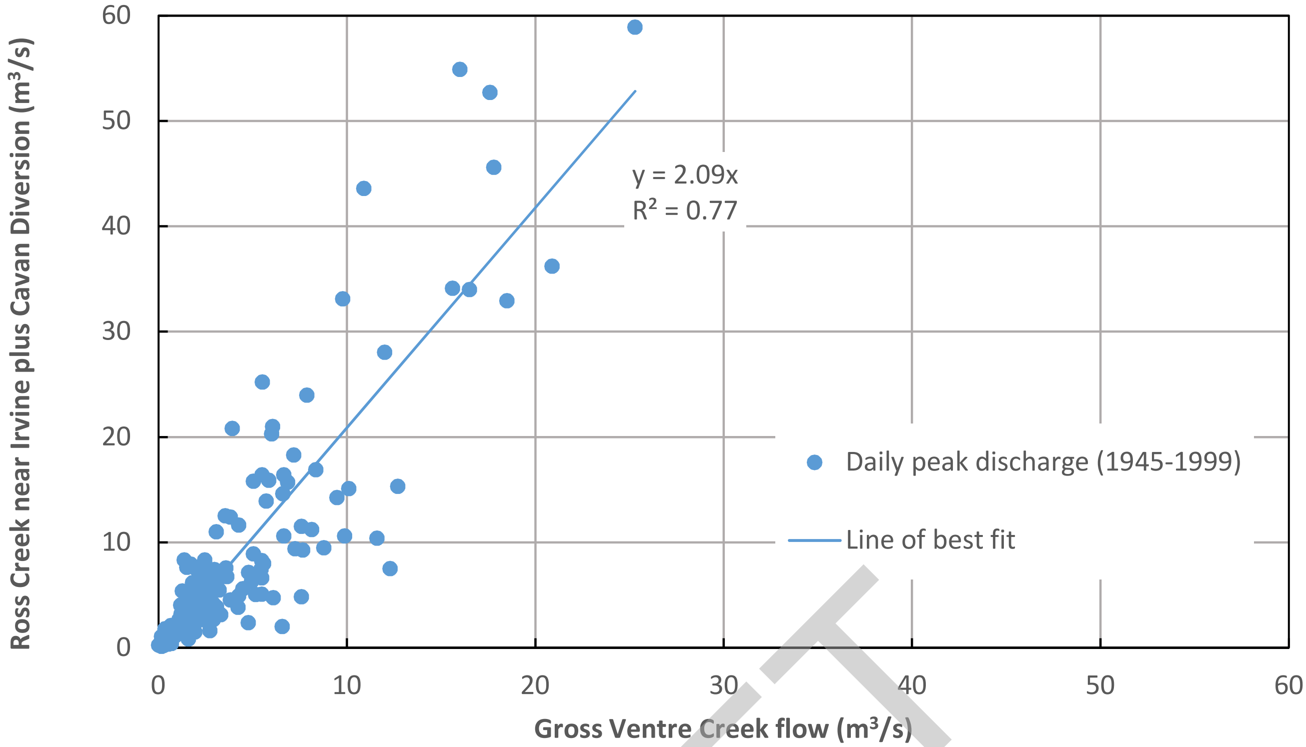
COMPARISON OF NATURAL FLOOD FREQUENCY CURVES FOR SEVEN PERSONS CREEK AT MEDICINE HAT

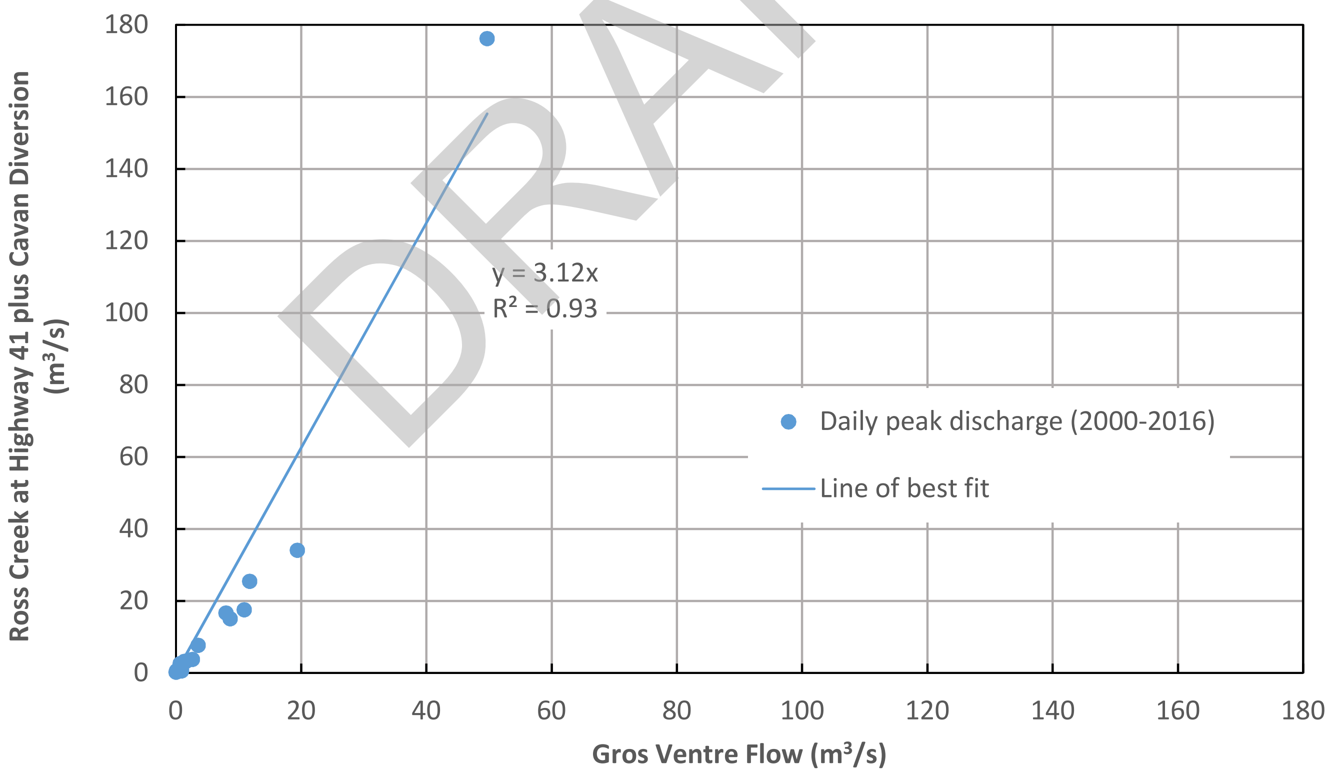
Job: 1003094 | *Date: JUL-2019* | *FIGURE 39*



Notes:
1. The 1913-1954 data are gauge data
2. The 1984-2016 data are modelled results for flow naturalization

Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*NATURAL FLOOD FREQUENCY ESTIMATES FOR SEVEN PERSONS CREEK AT MEDICINE HAT*
	Job: 1003094 | *Date: JUL-2019*	*FIGURE 40*





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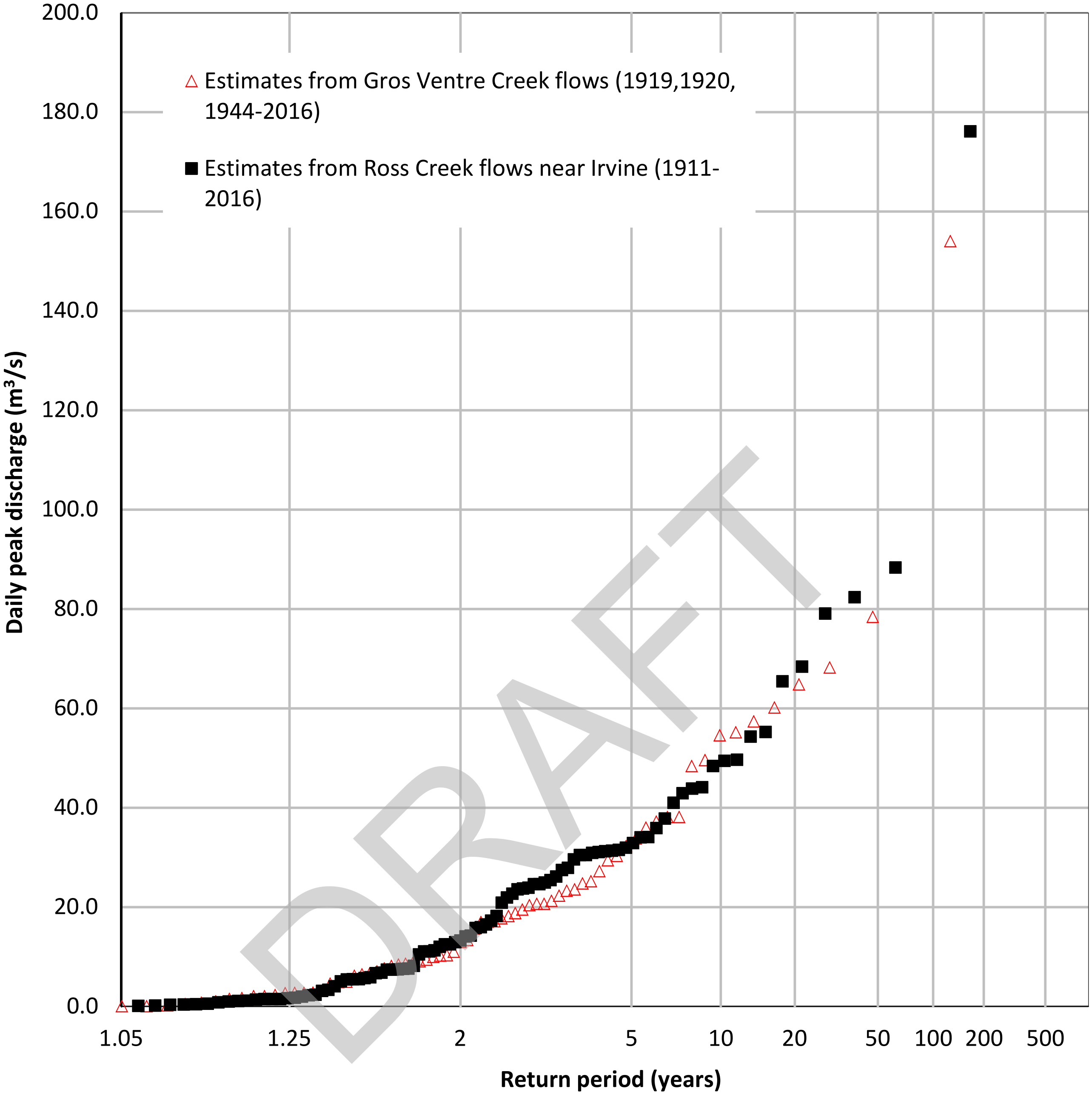
Coordinate System:
Units: As Shown

Job: 1003094 | *Date: JUL-2019*

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

CORRELATION OF PEAK FLOWS ON ROSS CREEK AND GROS VENTRE CREEK

FIGURE 41



	Estimates from Gros Ventre Creek flows (1919,1920, 1944-2016)	Estimates from Ross Creek flows near Irvine (1911-2016)
Average (m^3/s)	20.4	21.2
Standard Deviation (m^3/s)	24.4	25.4
Skew	2.7	2.9
Median (m^3/s)	13.0	13.2

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Units: As Shown

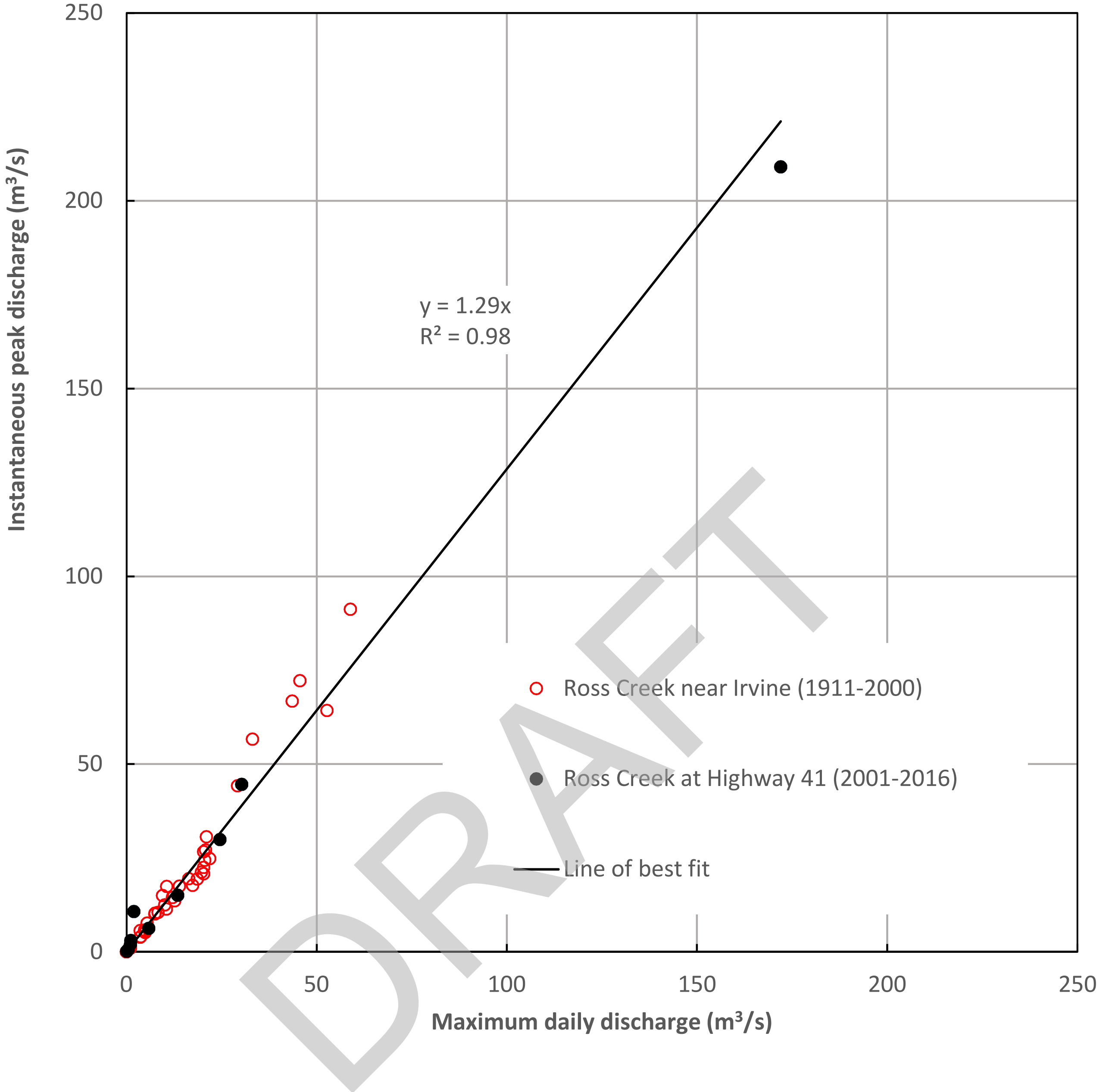
Job: 1003094

Date: JUL-2019

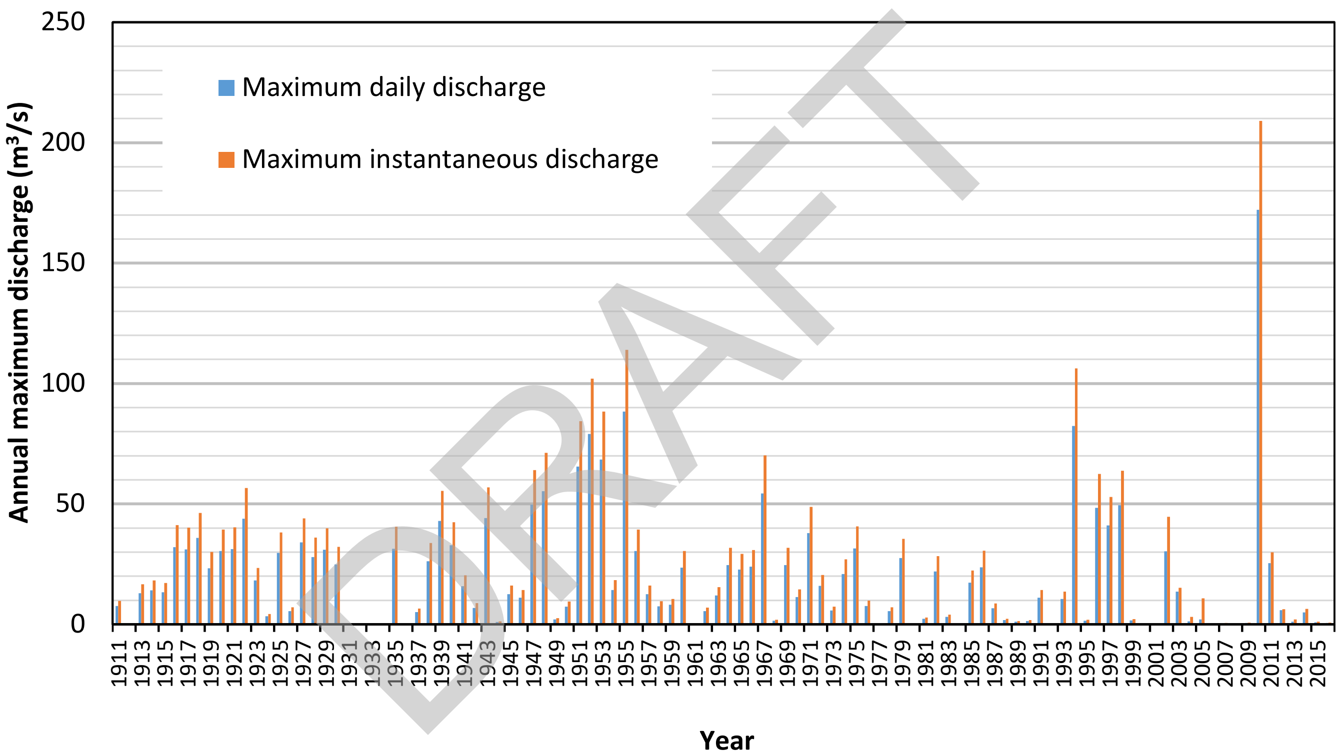
MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF ESTIMATED ANNUAL MAXIMUM DAILY FLOWS FOR ROSS CREEK AT HIGHWAY 41

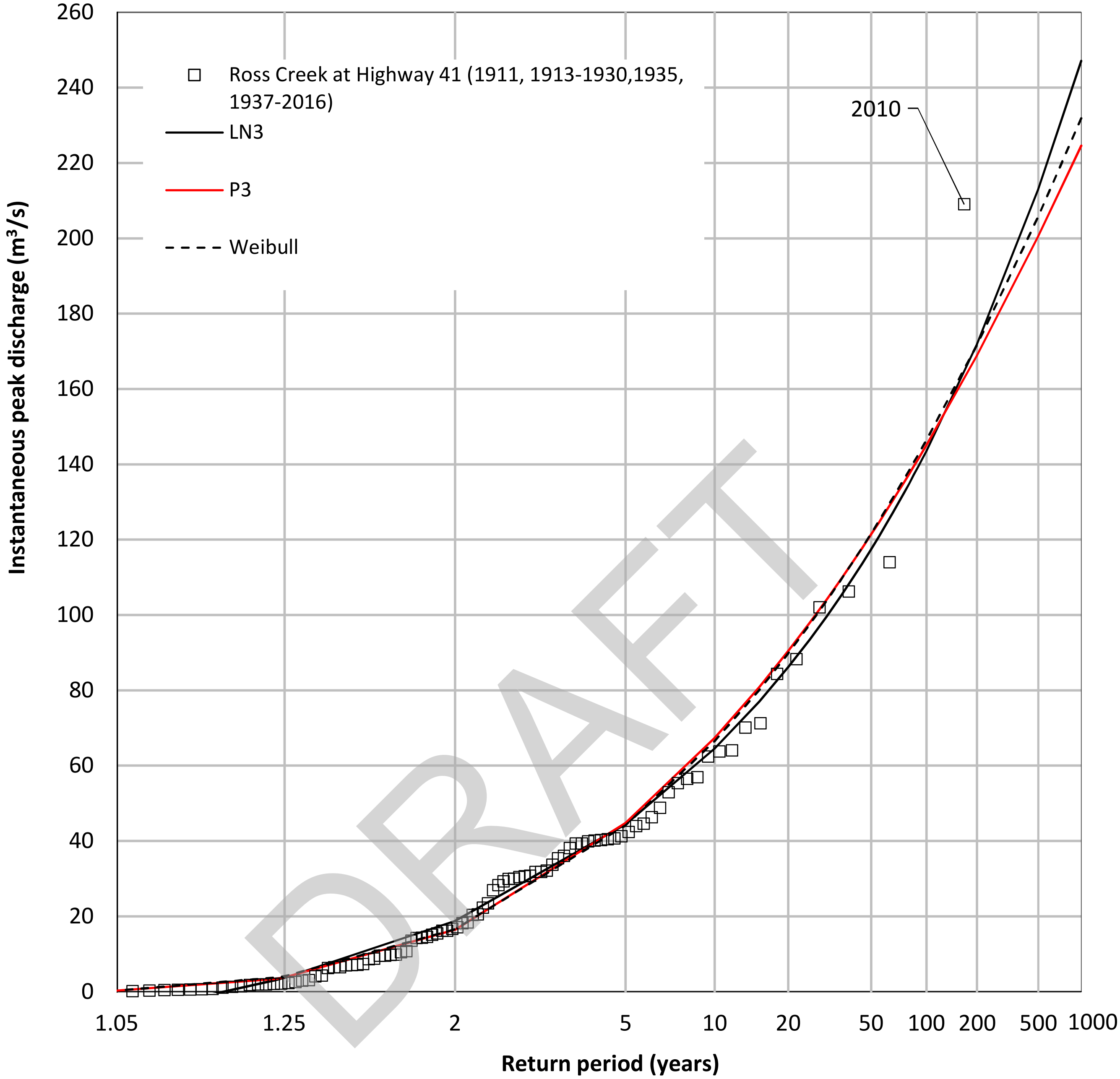
FIGURE 42



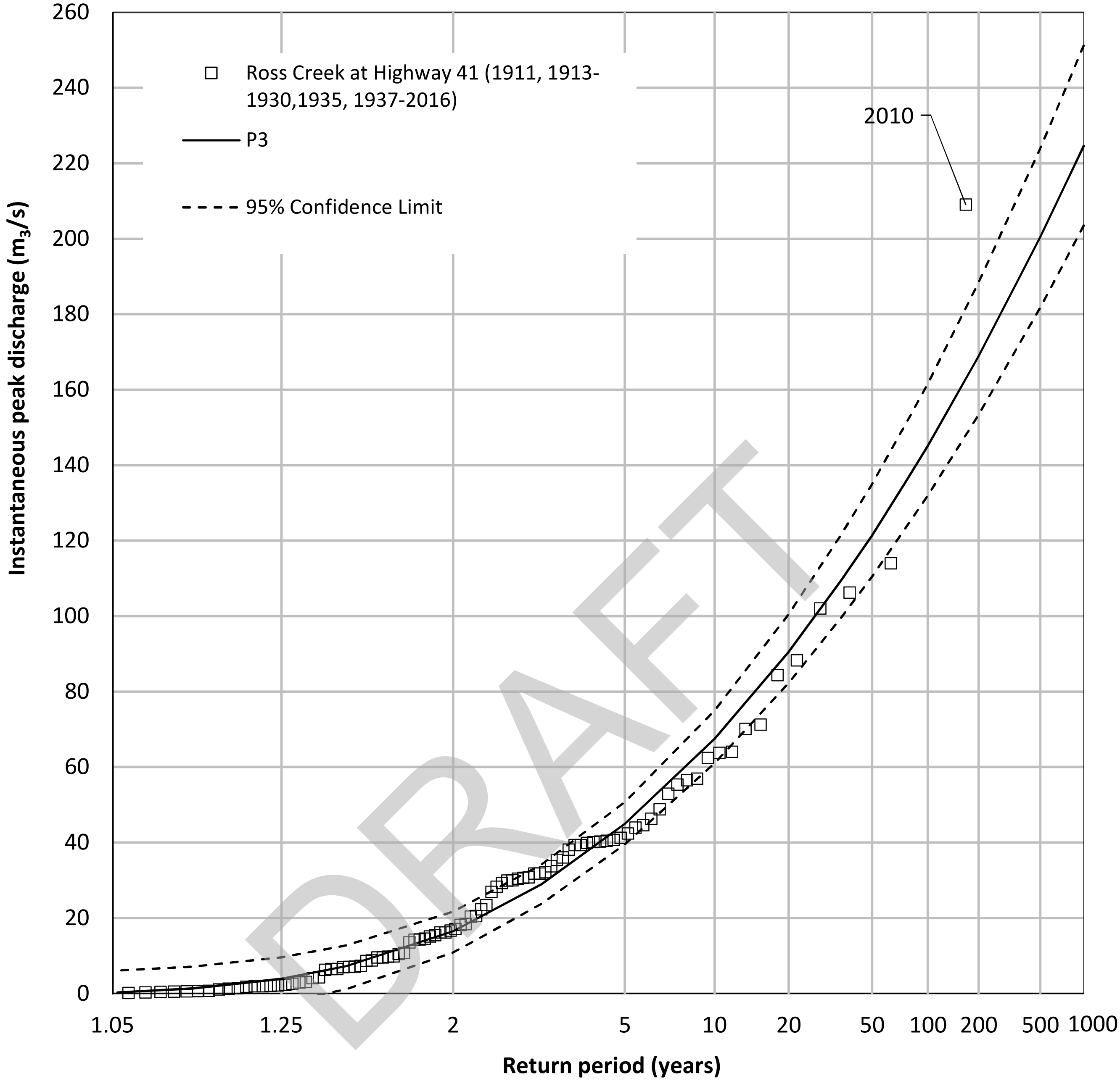
Alberta Government	SCALE – AS SHOWN	MEDICINE HAT RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	ROSS CREEK INSTANTANEOUS PEAK TO MAXIMUM DAILY DISCHARGE RATIO
	Job: 1003094 / Date: JUL-2019	FIGURE 43



Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*MAXIMUM INSTANTANEOUS AND DAILY DISCHARGES FOR ROSS CREEK AT HIGHWAY 41*
	Job: 1003094 *Date: JUL-2019*	*FIGURE 44*



Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*COMPARISON OF FLOOD FREQUENCY CURVES FOR ROSS CREEK AT HIGHWAY 41*
	Job: 1003094 / *Date: JUL-2019*	*FIGURE 45*



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SCALE – AS SHOWN

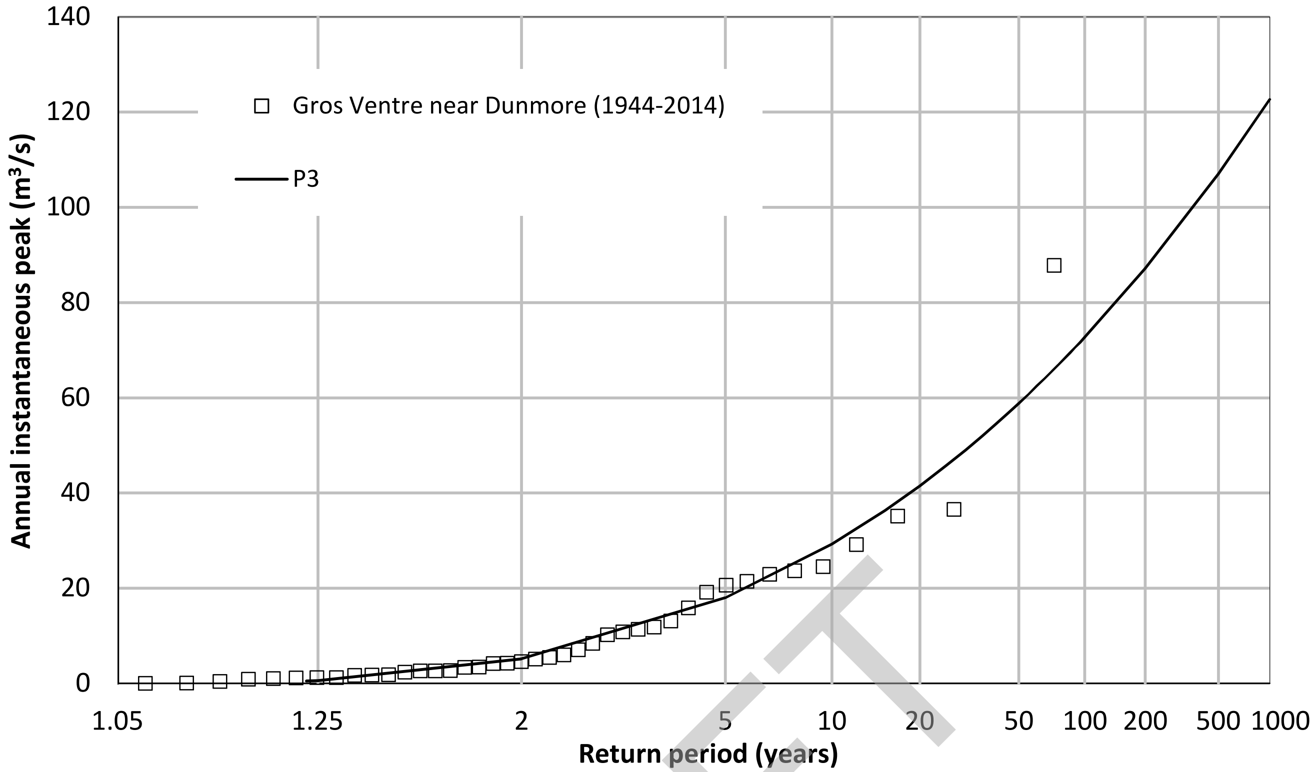
Coordinate System:
Units: As Shown

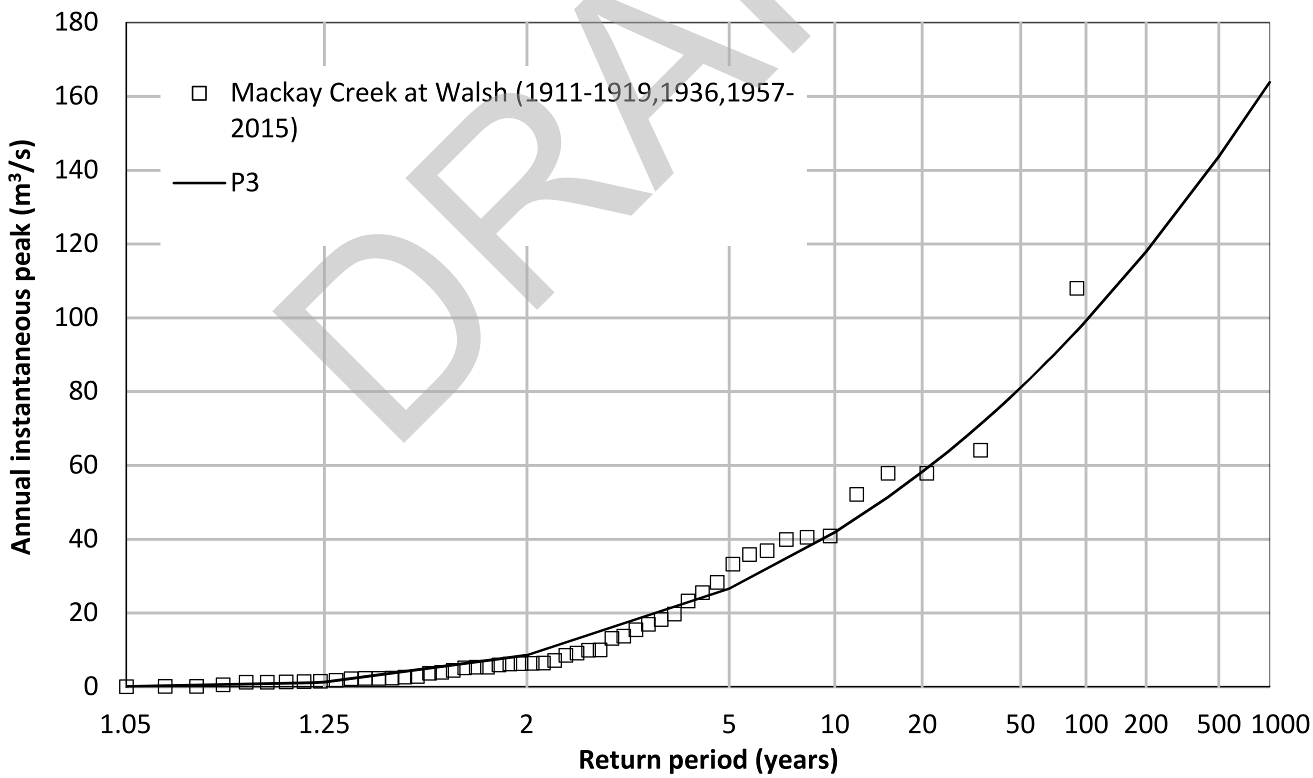
Job: 1003094	Date: JUL-2019

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

FLOOD FREQUENCY ESTIMATES FOR ROSS CREEK AT HIGHWAY 41

FIGURE 46





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SCALE – AS SHOWN

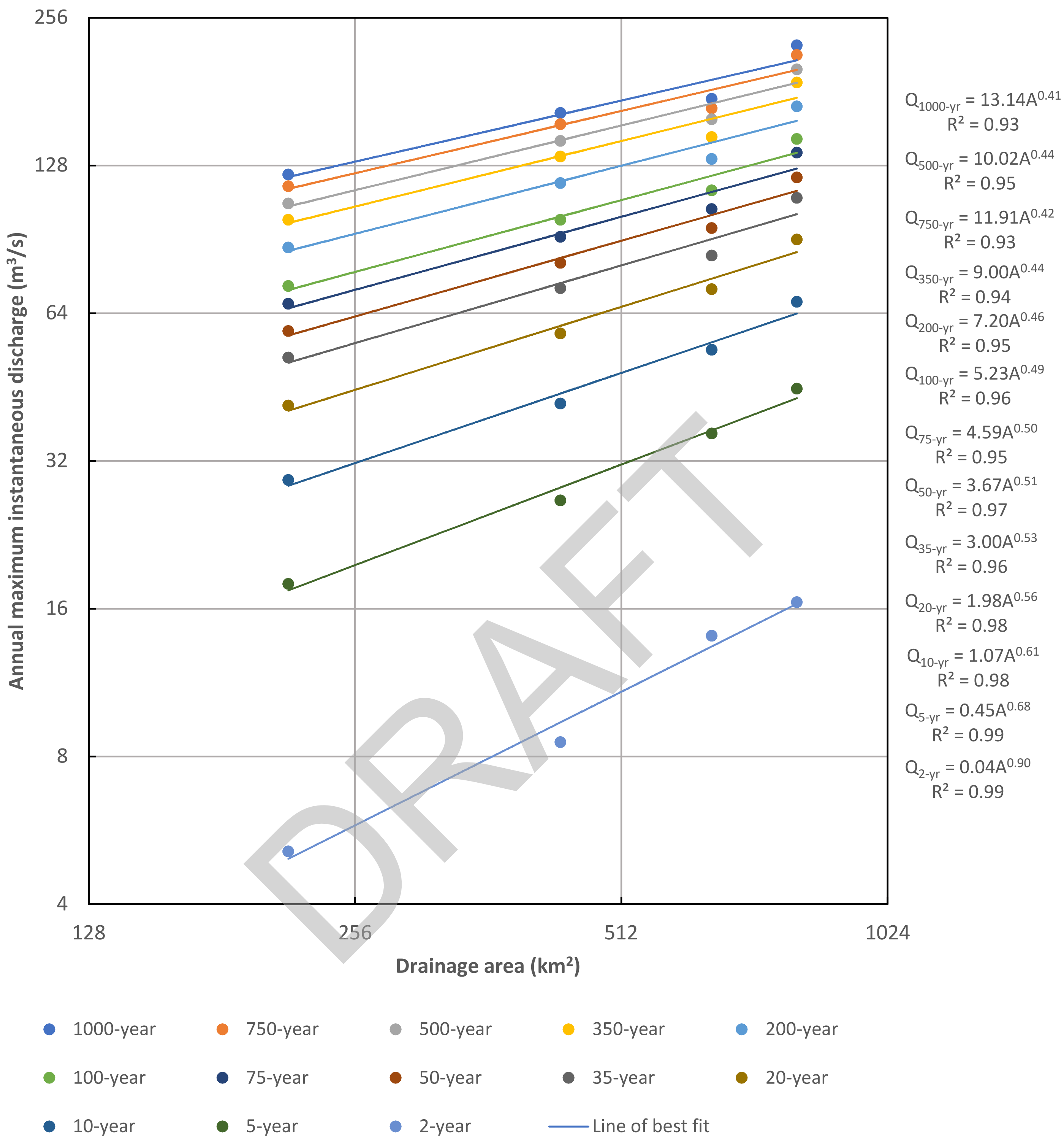
Coordinate System:
Units: As Shown

Job: 1003094 | *Date: JUL-2019*

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

FLOOD FREQUENCY ESTIMATES FOR GROS VENTRE CREEK AND MACKAY CREEK

FIGURE 47



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Units: As Shown

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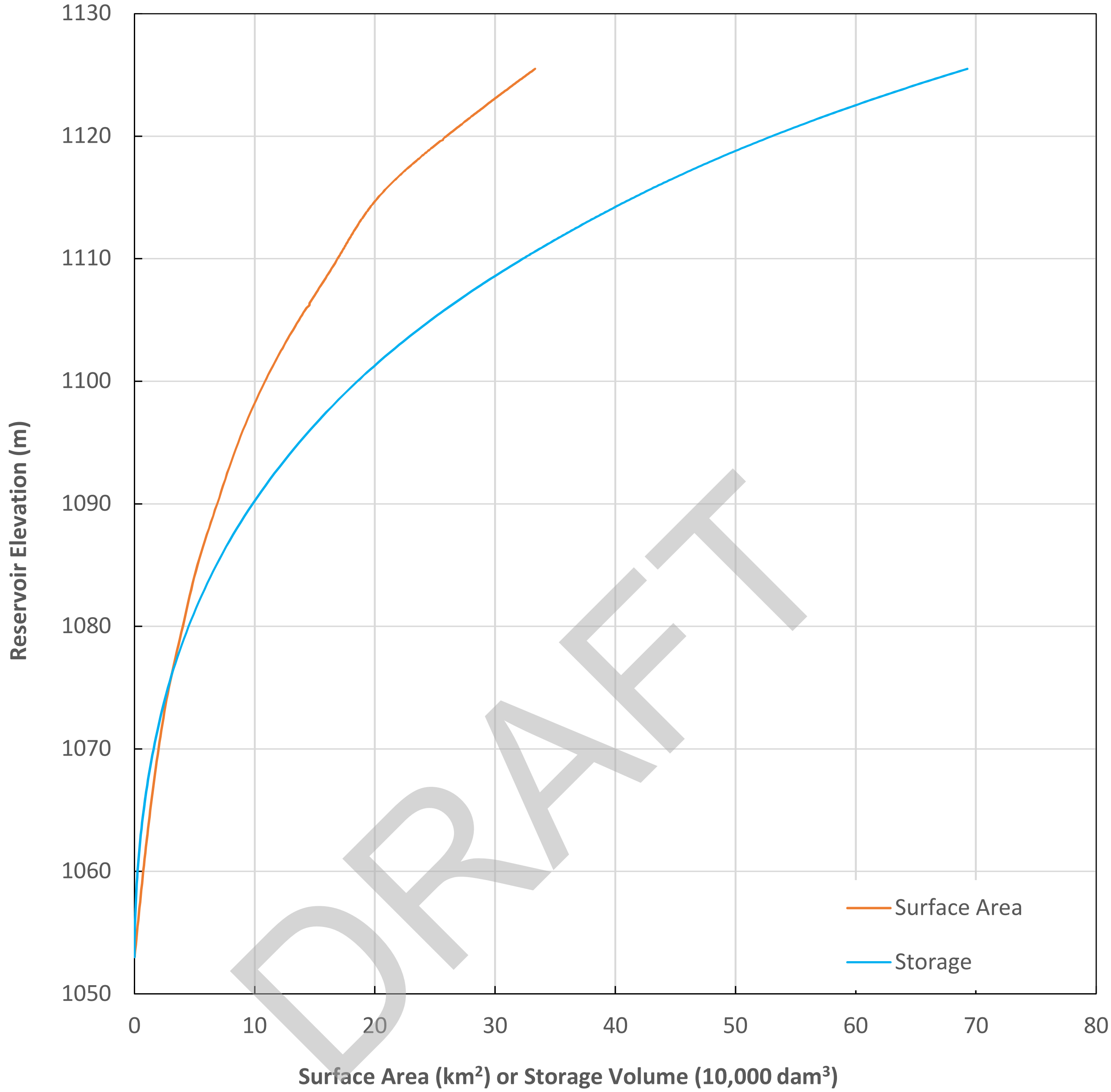
MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

REGIONAL FLOOD FREQUENCY CURVES FOR ROSS CREEK SUB-BASINS

FIGURE 48

Appendix A
Characteristics of Major Reservoirs



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Units: As Shown

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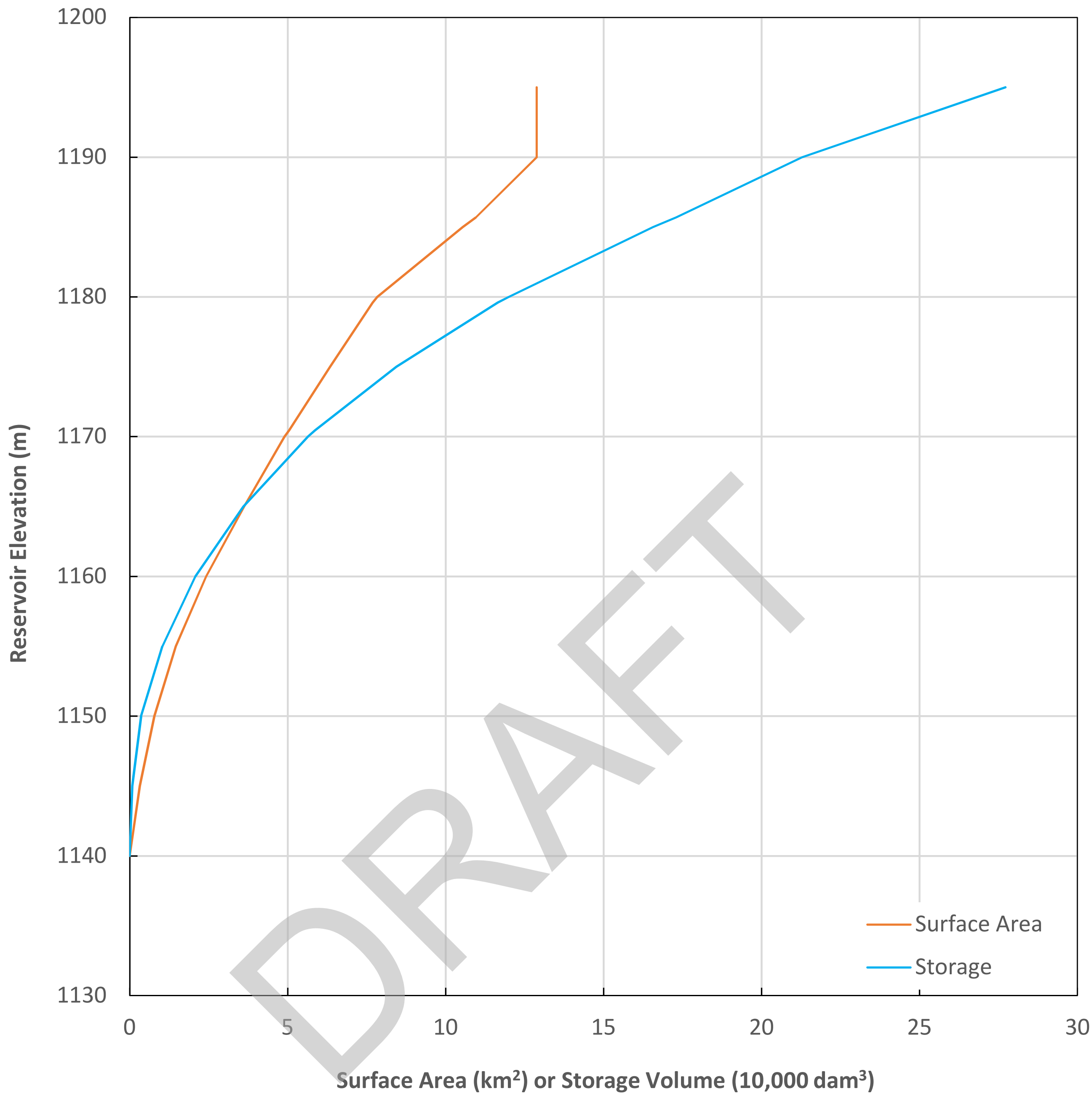
MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

OLDMAN RESERVOIR
ELEVATION-SURFACE AREA-STORAGE RELATIONSHIP

FIGURE A-1



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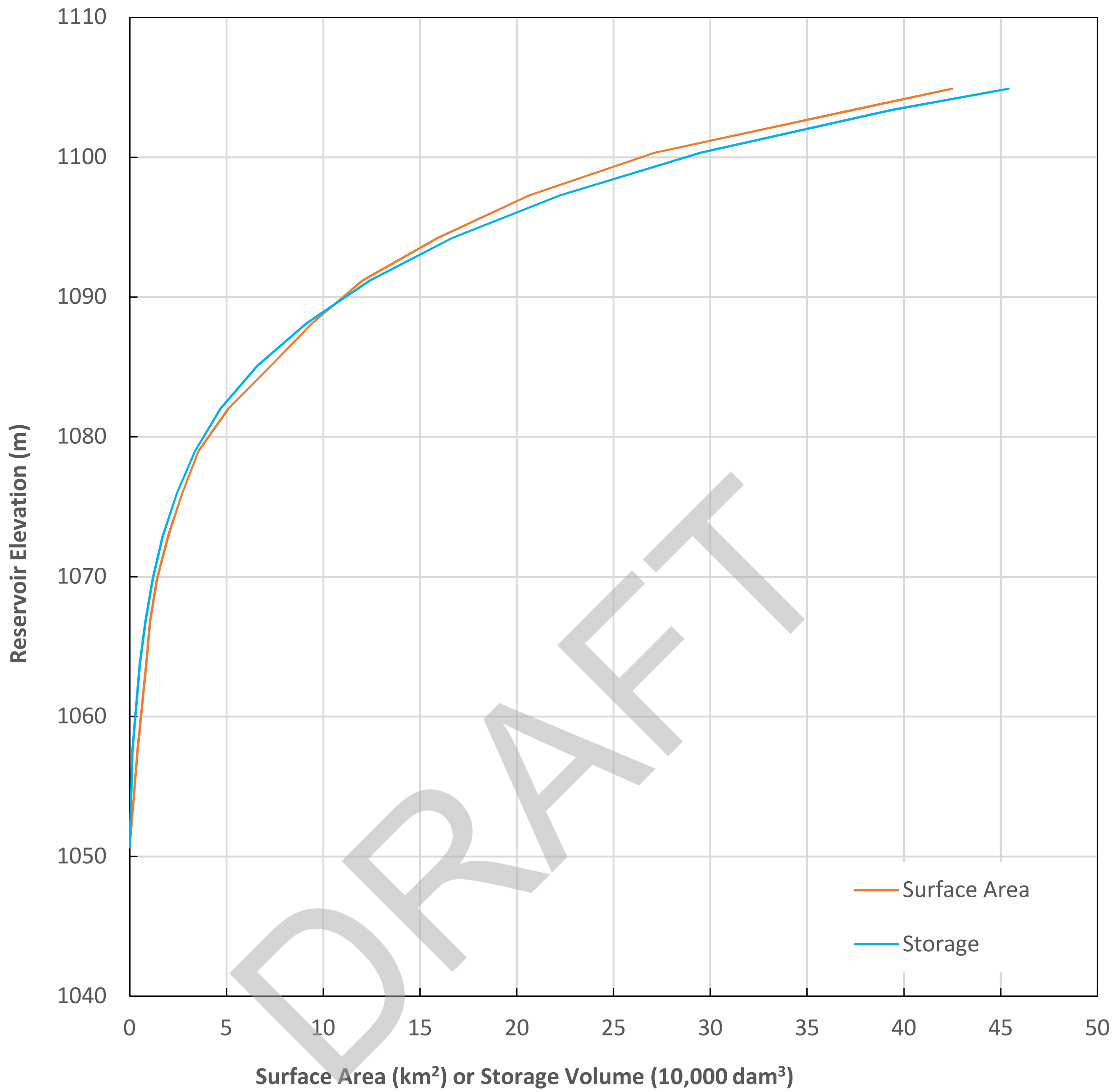
Coordinate System:
Units: As Shown

Job: 1003094 | *Date: JUL-2019*

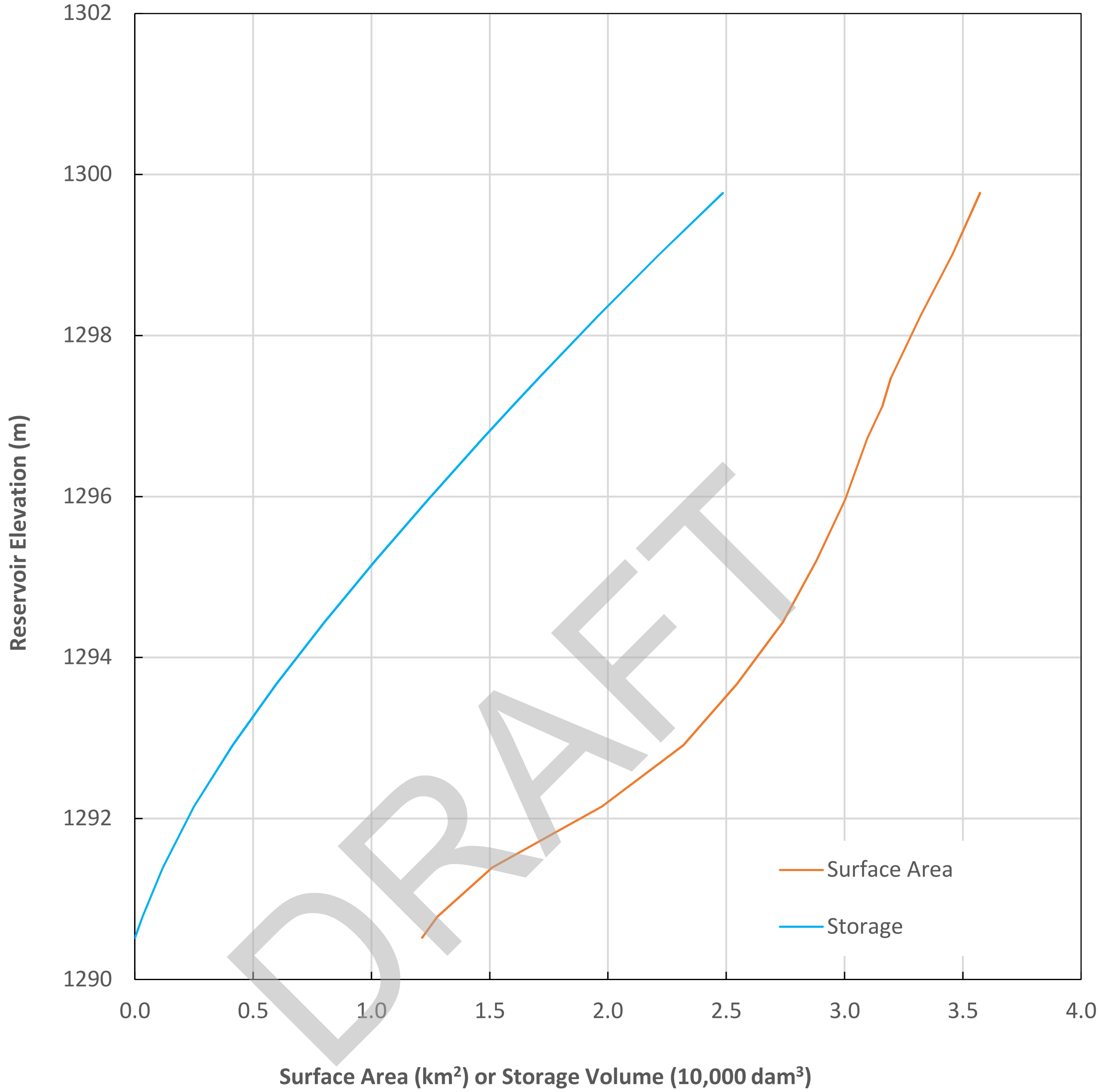
MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

WATERTON RESERVOIR ELEVATION-SURFACE AREA-STORAGE RELATIONSHIP

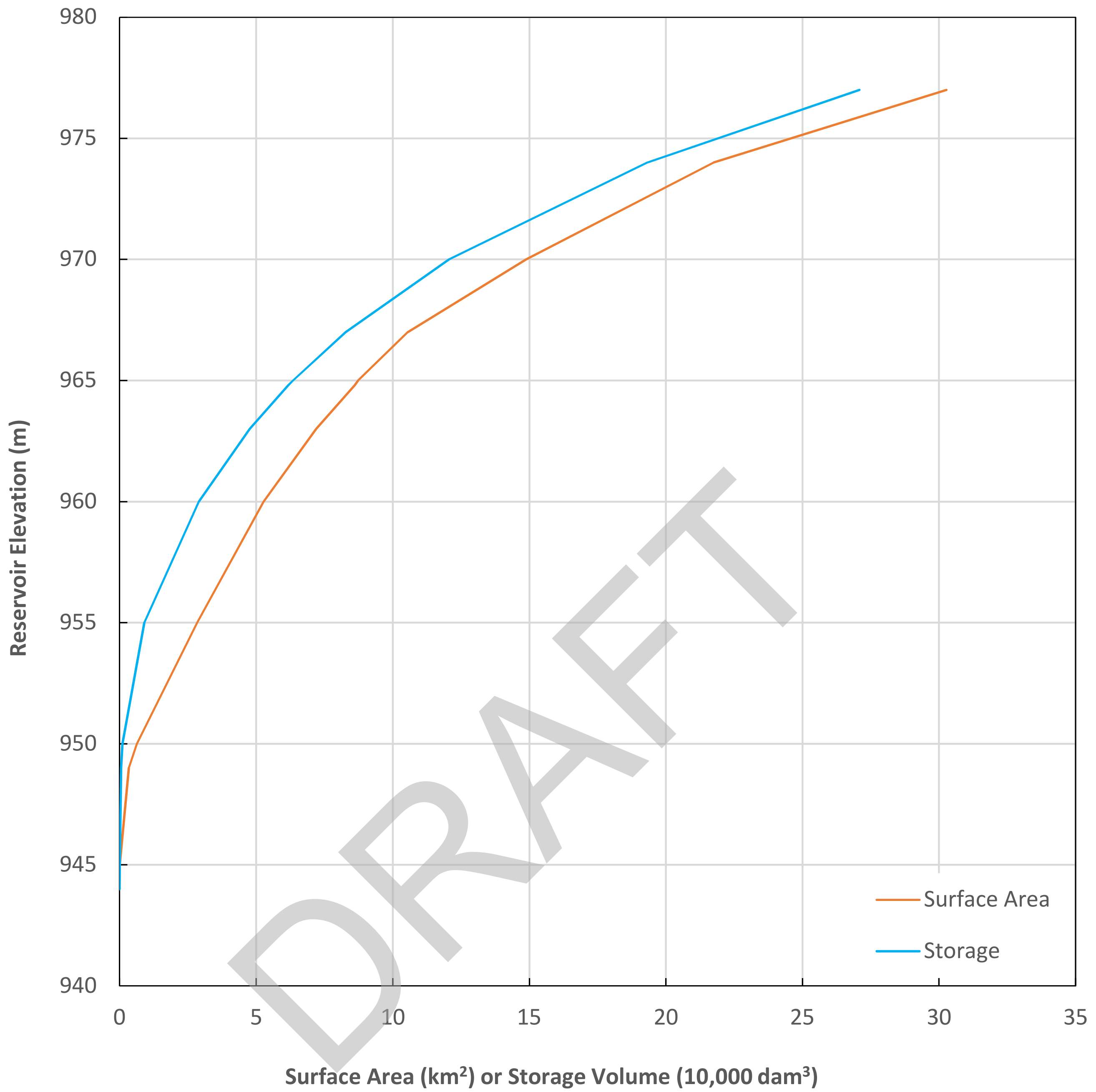
FIGURE A-2



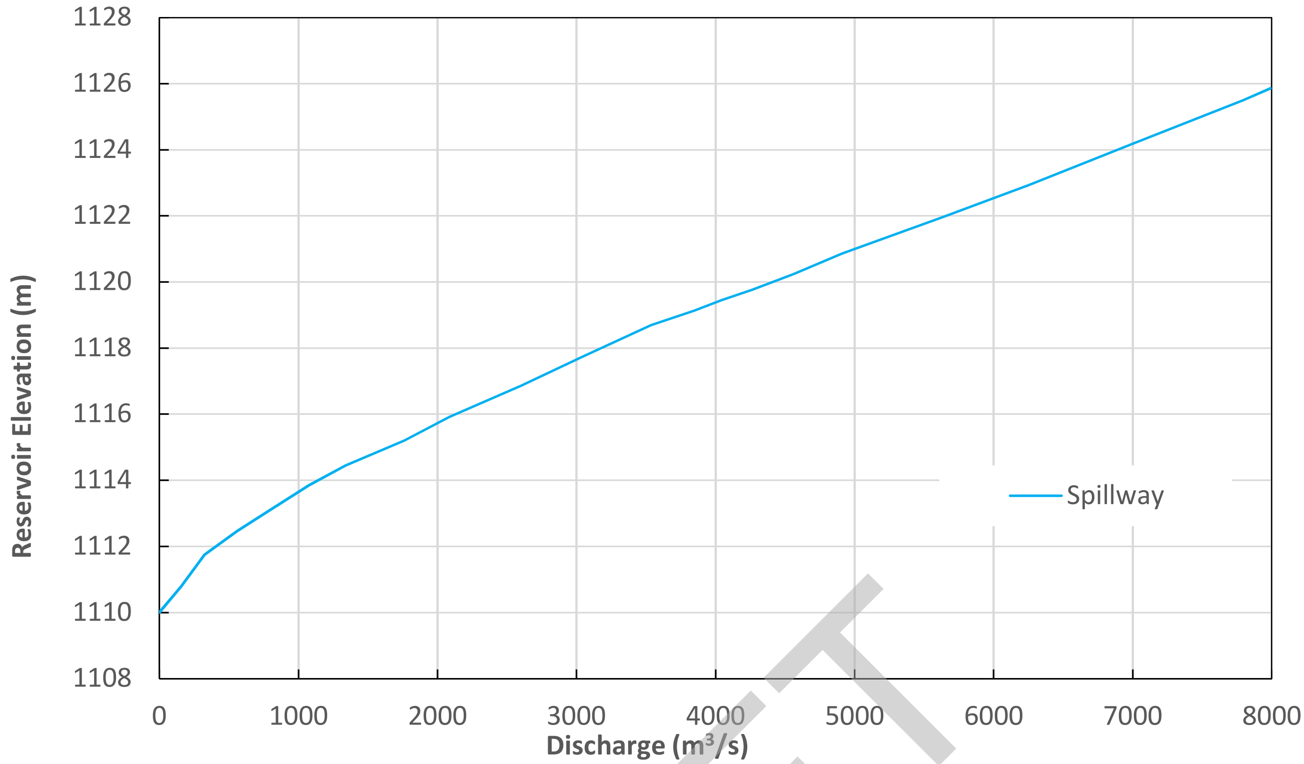
Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*ST. MARY RESERVOIR ELEVATION-SURFACE AREA-STORAGE RELATIONSHIP*
	Job: 1003094 / *Date: JUL-2019*	*FIGURE A-3*

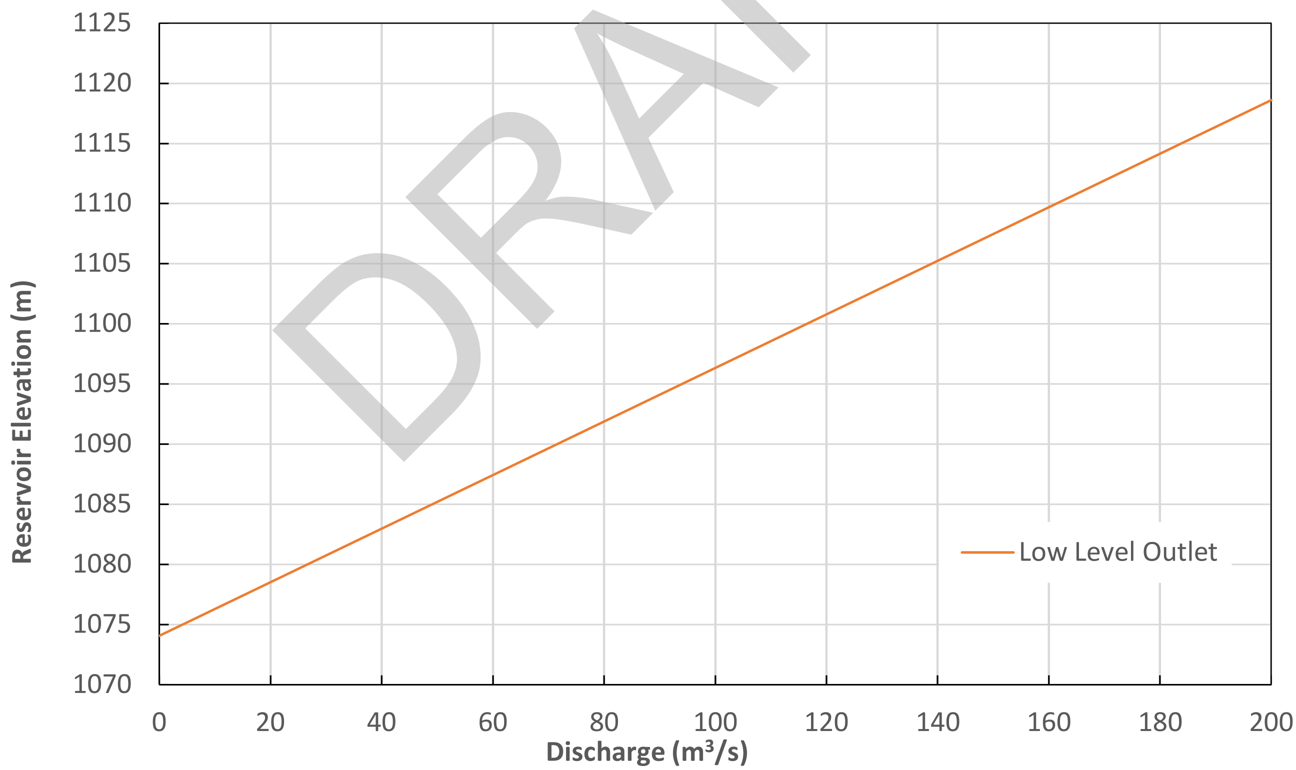


Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*CHAIN LAKE RESERVOIR ELEVATION-SURFACE AREA-STORAGE RELATIONSHIP*
	Job: 1003094 / *Date: JUL-2019*	*FIGURE A-4*



Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*TWIN VALLEY RESERVOIR ELEVATION-SURFACE AREA-STORAGE RELATIONSHIP*
	Job: 1003094 | *Date: JUL-2019*	*FIGURE A-5*





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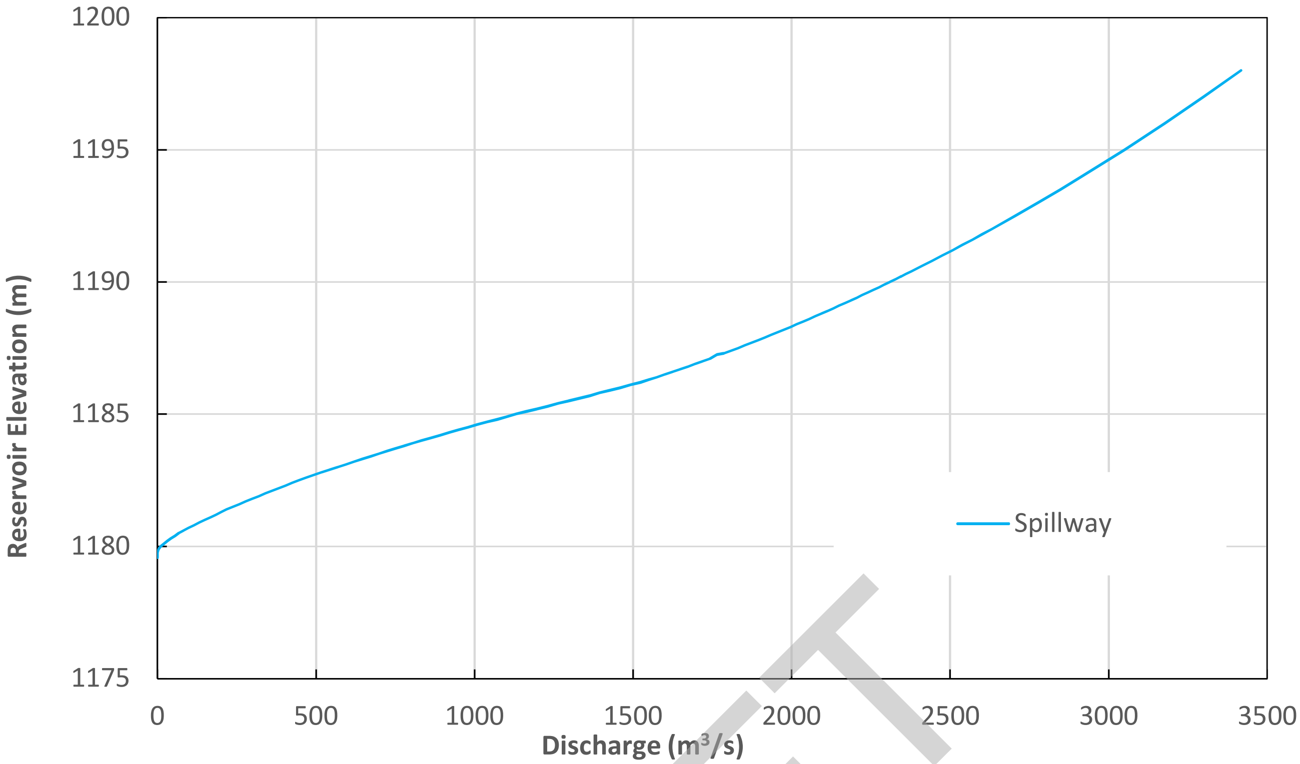
Coordinate System:
Units: As Shown

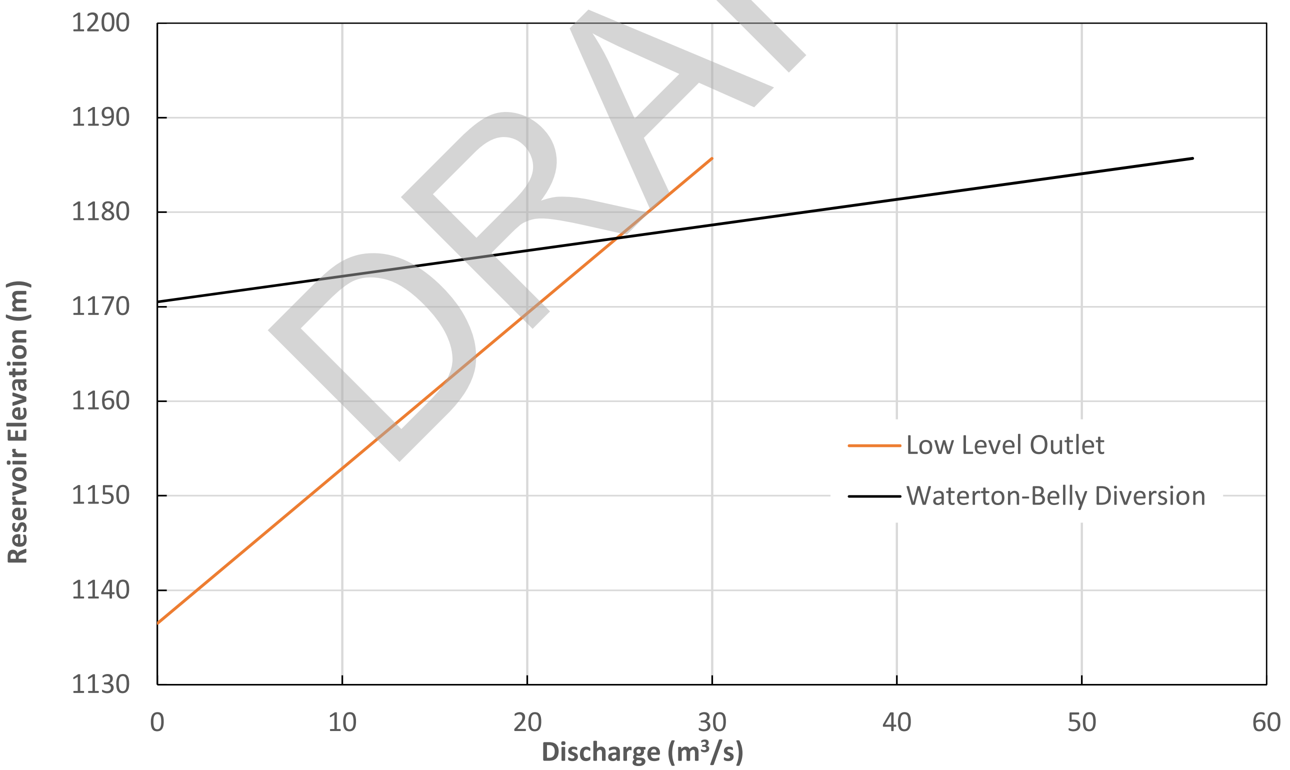
Job: 1003094 | *Date: JUL-2019*

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

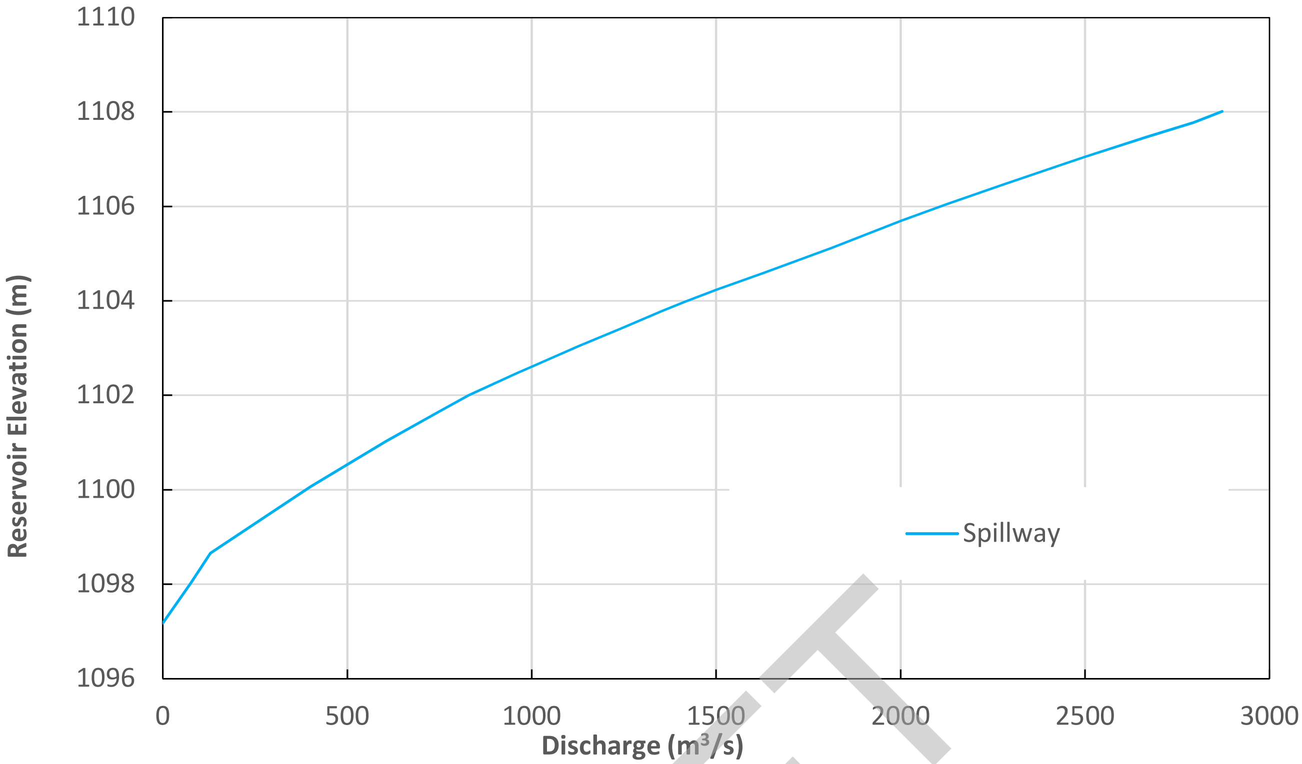
OLDMAN RESERVOIR
RATING CURVES FOR DISCHARGE FACILITIES

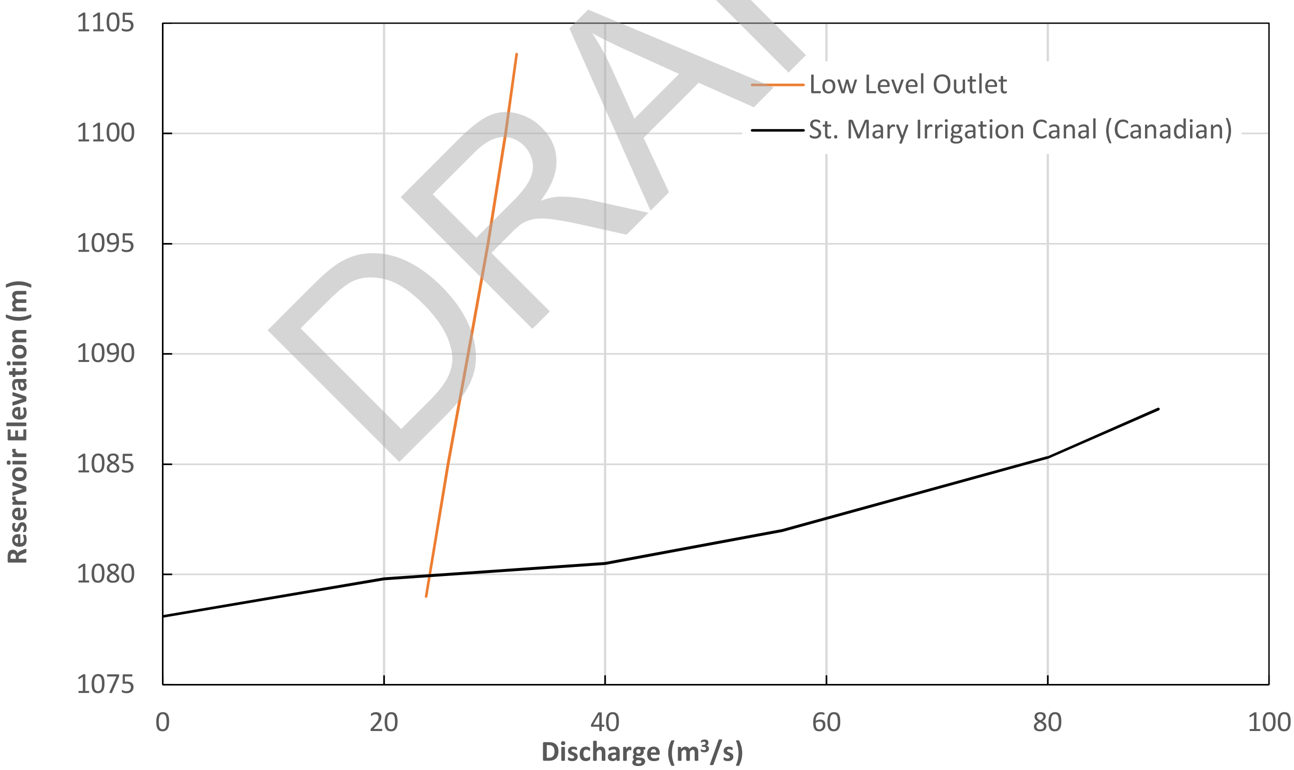
FIGURE A-6





Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*WATERTON RESERVOIR* *RATING CURVES FOR DISCHARGE FACILITIES*
	Job: 1003094 | *Date: JUL-2019*	*FIGURE A-7*





Alberta Government

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SCALE – AS SHOWN

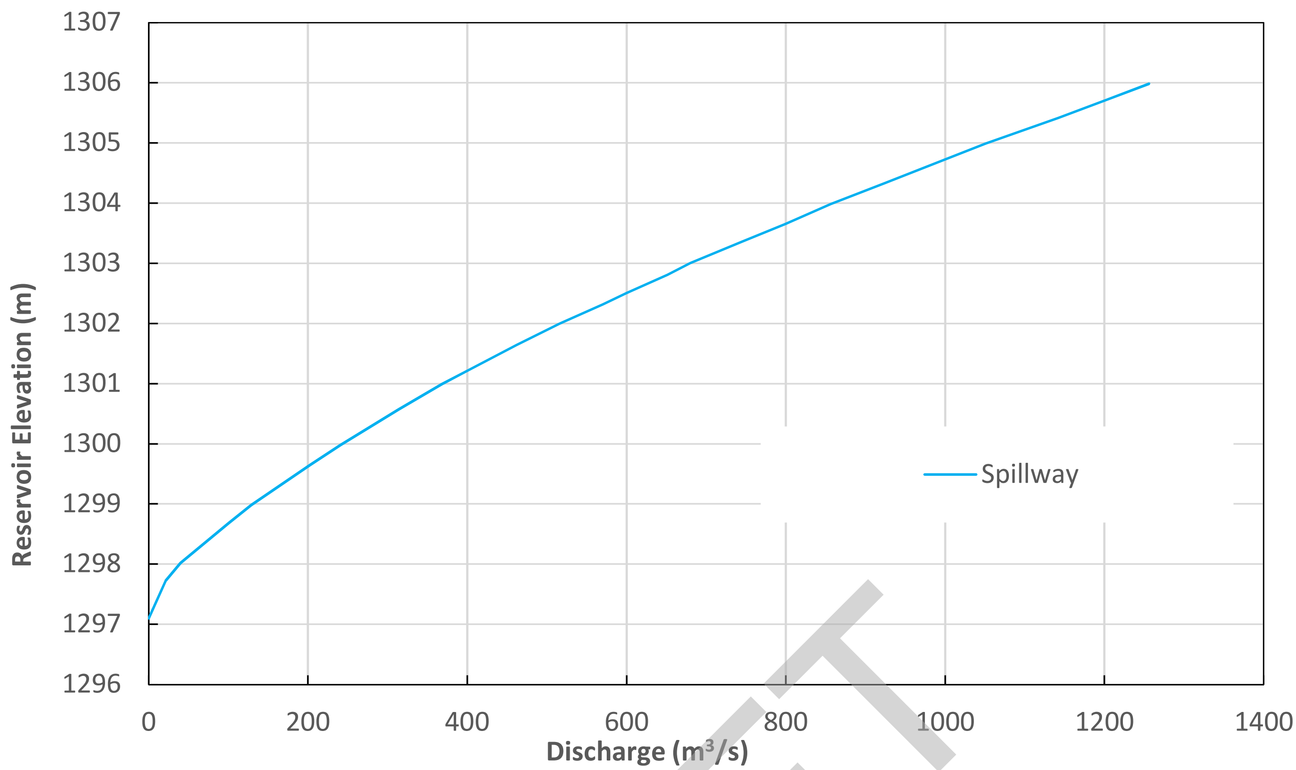
Coordinate System:
Units: As Shown

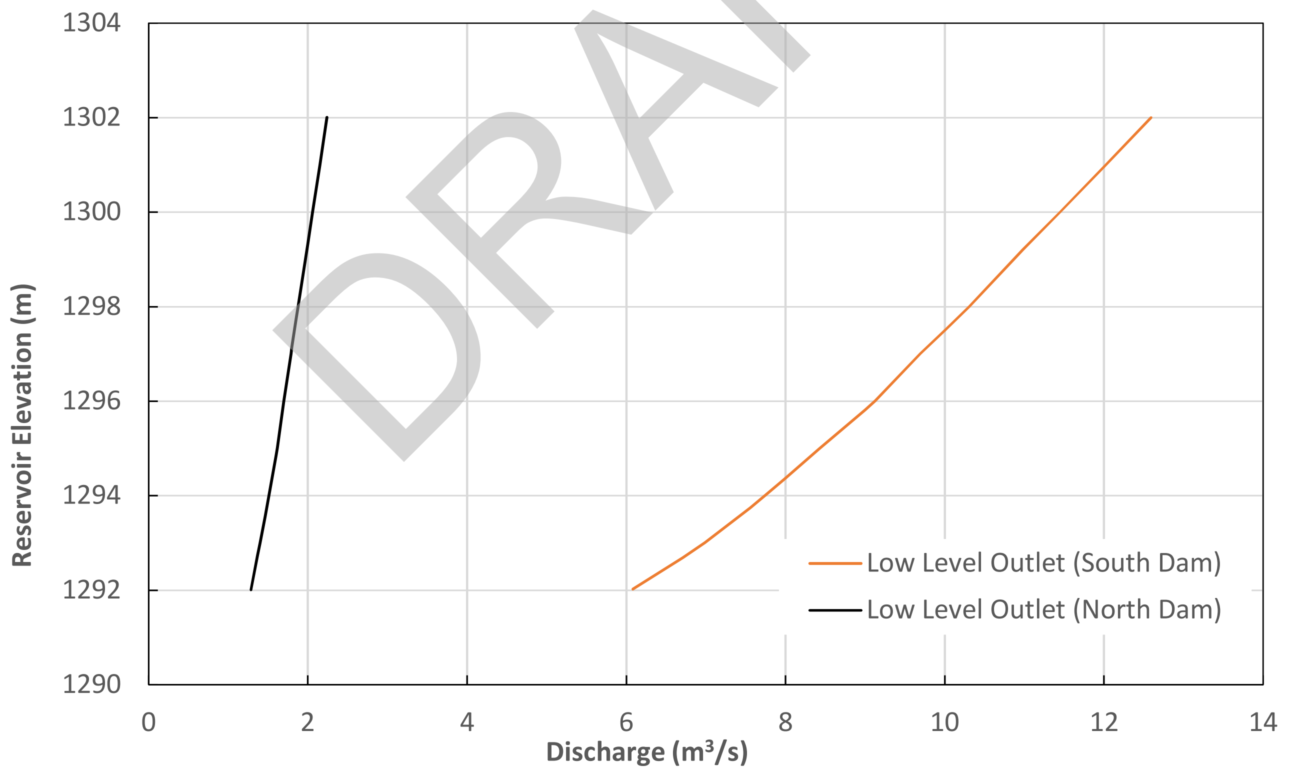
Job: 1003094 | *Date: JUL-2019*

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

ST. MARY RESERVOIR
RATING CURVES FOR DISCHARGE FACILITIES

FIGURE A-8





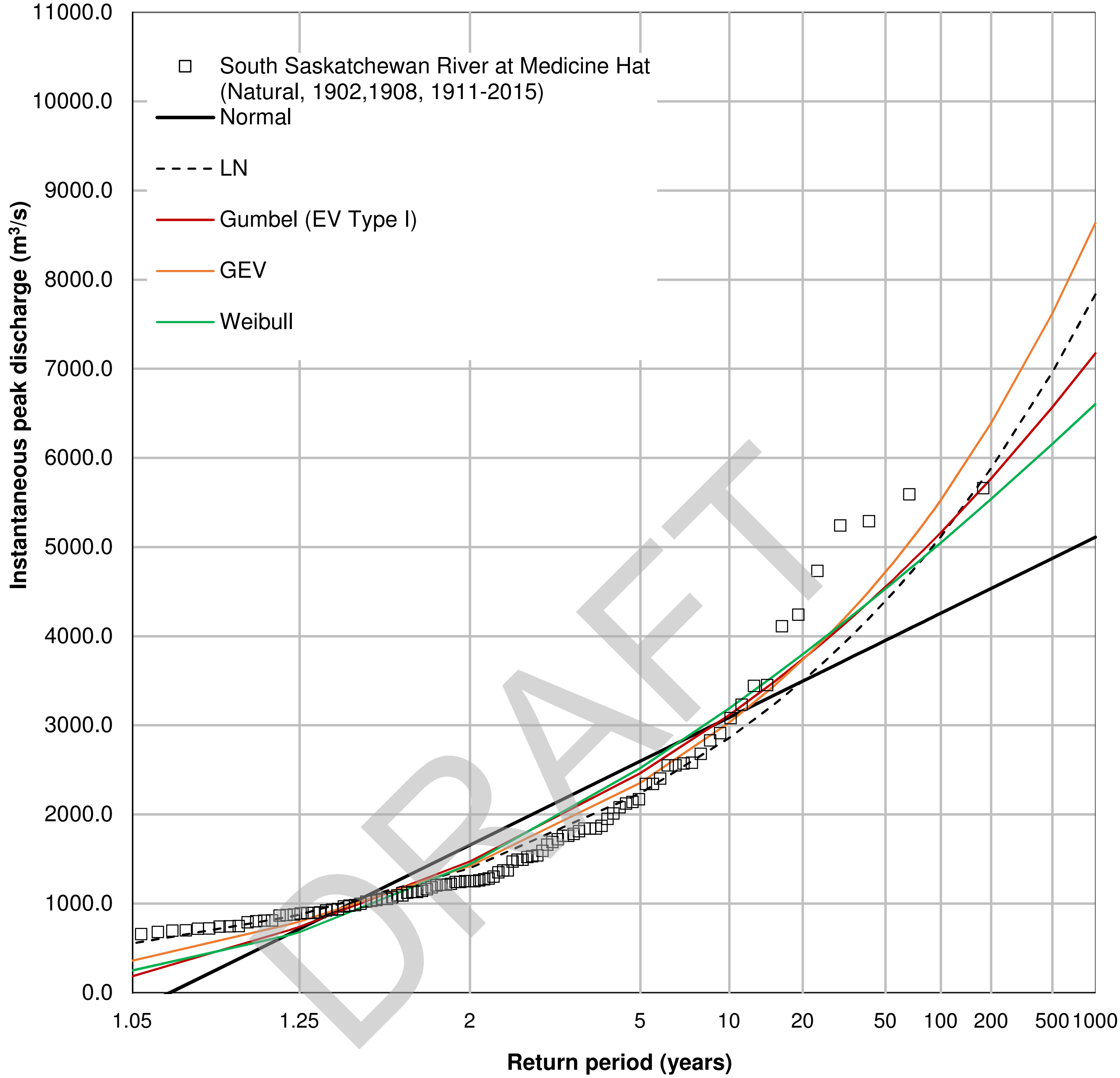
Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*CHAIN LAKE RESERVOIR RATING CURVES FOR DISCHARGE FACILITIES*
	Job: 1003094 / *Date: JUL-2019*	*FIGURE A-9*

Appendix B
Adopted SSAR Routing Parameters

Table B-1 Adopted SSAR Routing Parameters

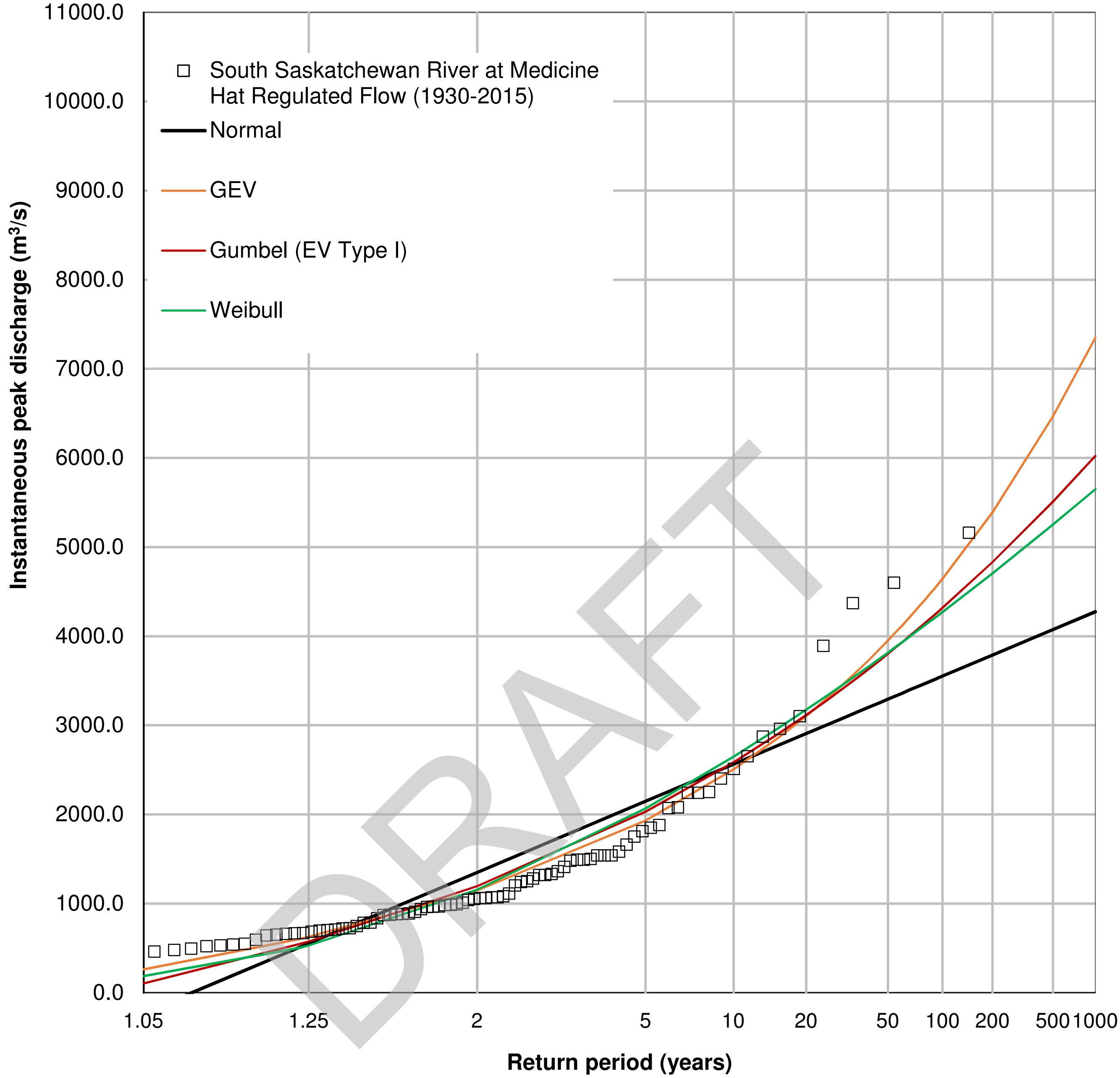
		Routing Parameters			
River	**Reach**	**N**	**n**	**KTS**	**Approximate Reach Length (km)**
South Saskatchewan River	Bow and Oldman River Confluence to Medicine Hat	8	0.36	20.3	102
Bow River	WSC Station 05BN012 to the Mouth	1	0.36	22.6	20
Oldman River	WSC Station 05AG006 to the Mouth	1	0.36	9.1	12
	Little Bow River Confluence to WSC Station 05AG006	12	0.15	4	87
	Lethbridge to Little Bow River Confluence	3	0.15	1.5	60
	St. Mary River Confluence to Lethbridge	2	0.272	4	15
	Belly River Confluence to St. Mary River Confluence	2	0.202	5	31
	Willow Creek Confluence to Belly River Confluence	2	0.144	7	47
	LNID to Willow Creek Confluence	2	0.19	7	28
	Oldman Dam to LNID	2	0.19	7	60
Little Bow River	Travers Dam to WSC Station 05AC023	2	0.208	24.65	55
St. Mary River	Pothole Creek to Oldman Confluence (St. Mary near Mouth)	1	0.35	10.94	11
	St. Mary Dam to Pothole Cr Confl	8	0.2	5.26	96
	International Boundary to St. Mary Reservoir	10	0.42	6.71	45.5
Belly River	Waterton River Confluence to the Mouth	1	0.1	40	72
	Belly/Waterton Diversion to Waterton River Confluence	1	0.21	22	58
	Mountain View to Belly/Waterton Diversion	1	0.21	18	27
Waterton River	Glenwood to the Mouth	1	0.25	28	27
Willow Creek	Nolan to Highway 811	1	0.325	25	24
	Claresholm to Nolan	2	0.32	20	42
	Oxly Ranch to Claresholm	2	0.25	10	21
	Chain Lake Reservoir to Oxyl Ranch	2	0.25	15	42

Appendix C
Additional Evaluated Frequency Distributions



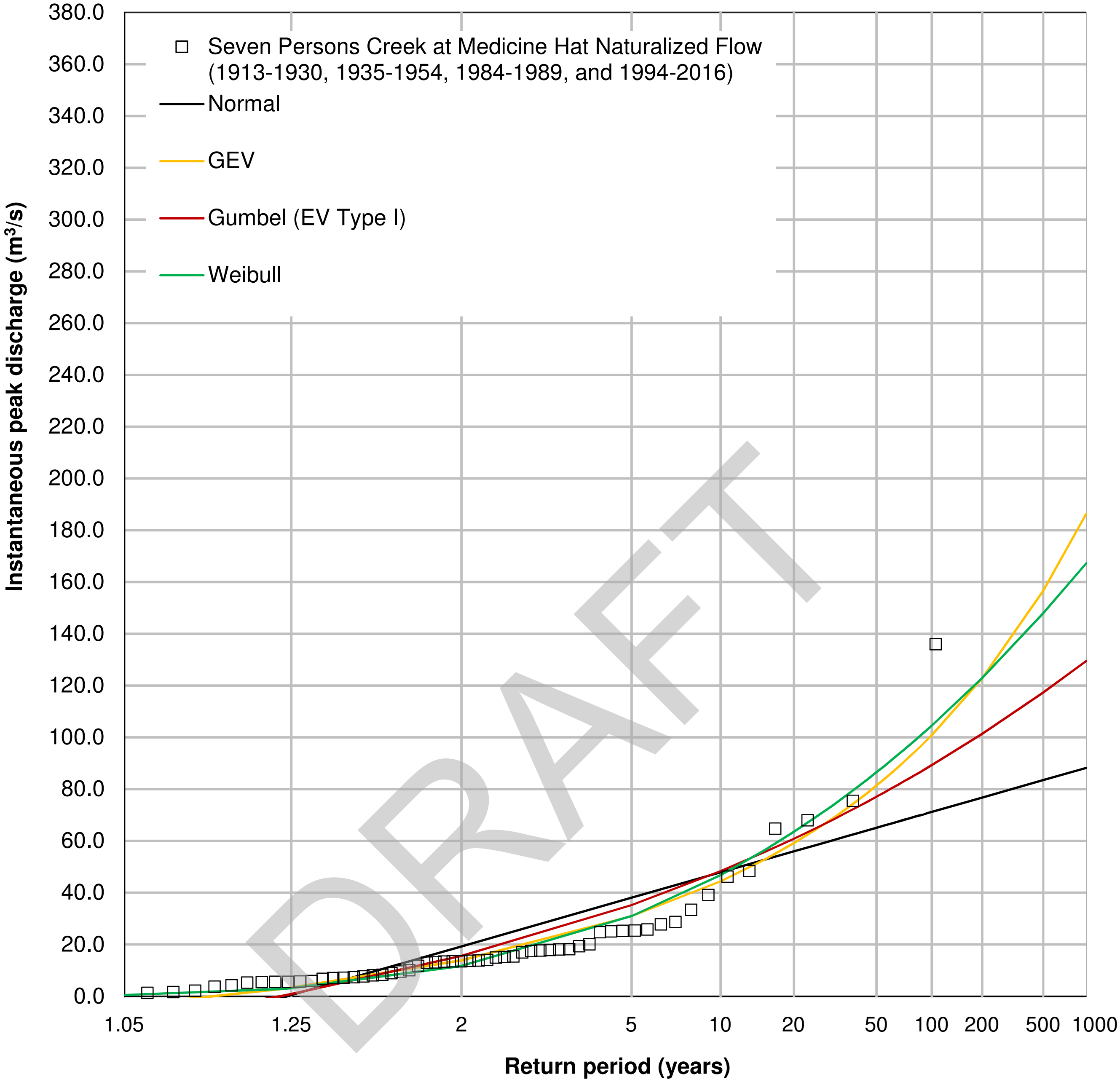
Notes:
1. The 1902 and 1908 data are estimates for historic events
2. The 1911-1929 data are gauge data
3. The 1930-2015 data are modelled results for flow naturalization.

Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*COMPARISON OF NATURALIZED FLOOD FREQUENCY CURVES FOR SSR AT MEDICINE HAT*
	Job: 1003094 | *Date: 18-JUL-2018*	*FIGURE C-1*



Notes: 1. Regulated flows are based on simulation results.

Alberta Government	SCALE – AS SHOWN	*MEDICINE HAT RIVER HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT* *COMPARISON OF REGULATED FLOOD FREQUENCY CURVES FOR SSR AT MEDICINE HAT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	
	Job: 1003094 | *Date: 18-JUL-2018*	*FIGURE C-2*



Notes: 1. The 1913-1954 data are gauge data

2. The 1984-2016 data are modelled results for flow naturalization

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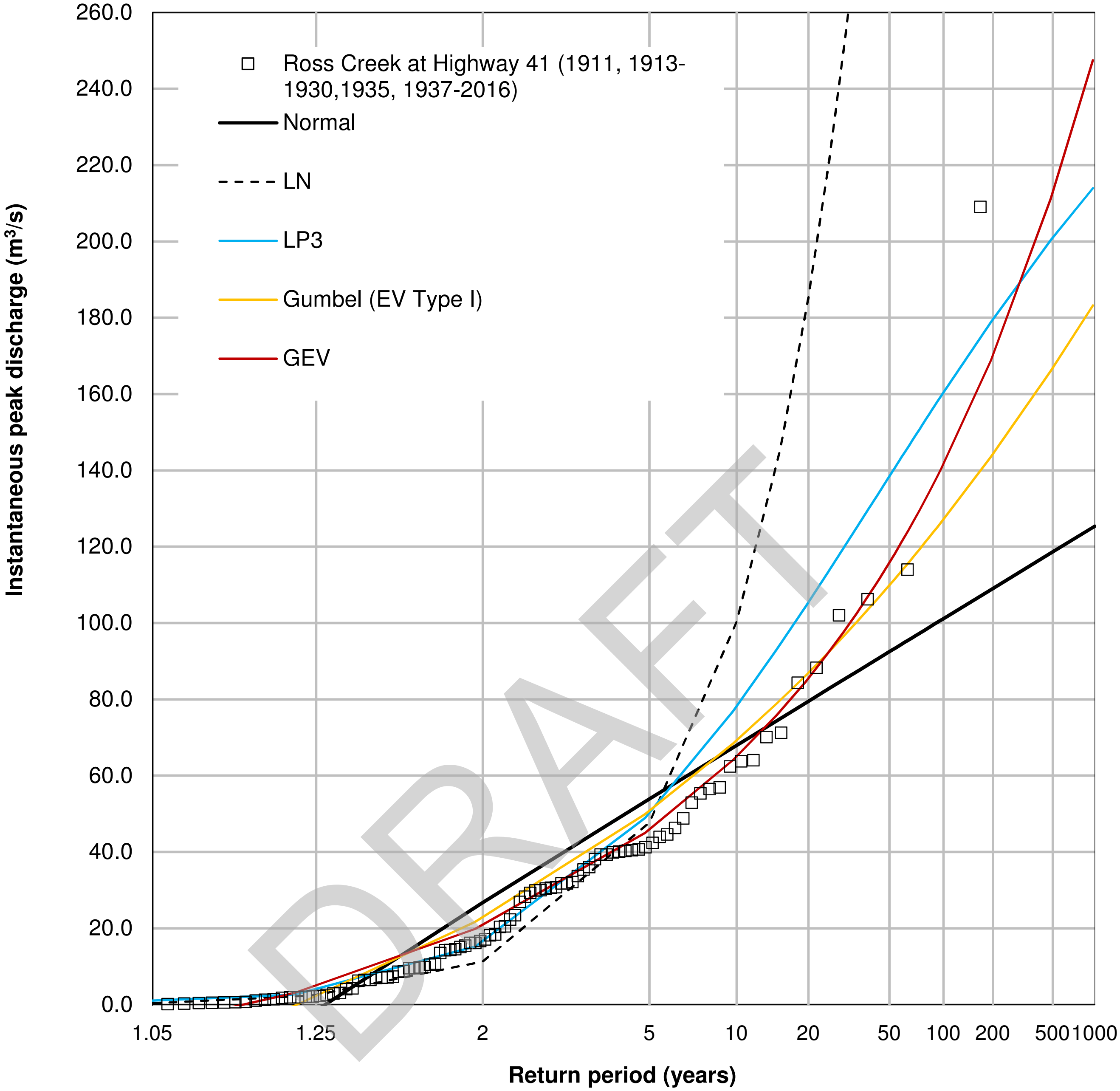
MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF NATURALIZED FLOOD FREQUENCY CURVES FOR SEVEN PERSONS CRREK AT MEDICINE HAT

FIGURE C-3



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

MEDICINE HAT RIVER HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF FLOOD FREQUENCY CURVES FOR ROSS CREEK AT HIGHWAY 41

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Job: 1003094 | *Date: 18-JUL-2018*

FIGURE C-4